Application of Ichnology Towards a Geological Understanding of the Ferron Sandstone in Central Utah

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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ABSTRACT

Ichnology has long been used as a tool to aid in environmental interpretation, but has rarely been used as an ethological assessment tool in the Cretaceous Ferron Sandstone of central Utah. This study focuses on using trace fossils with detailed sedimentological analyses to describe continental, paralic, and shallow marine clastic lithologies from extensive outcrop and cores of the Ferron. In addition to applications for environmental interpretation, the toponomy and taxonomy of both vertebrate and invertebrate trace fossils are examined. The traces are examined in terms of assemblages, and important aspects such as palimpsest overprinting by deep-tiered burrowers and trace suites are discussed.

Three new morphotypes of funnel-aperture trace fossils are described from the Ferron Sandstone representing two types of funnel-feeding behaviors. Most are representative of a head-to-tail circulation, however, one represents a tail-to-head circulation, with a branch interpreted to represent an inhalant tube. This study includes first descriptions of vertebrate taxa from the Ferron of *Iguanodontipus*, *Amblydactylus*, *Chelonipus*, and *Characichnos*. Additionally, morphotypes of small to medium theropods, and possible wading birds are identified. Identification of vertebrate traces during this time period (Turonian) is important due to the limited global preservation. The meniscate backfilled invertebrate trace *Beaconites* discussed herein is the first example of this trace from the Ferron. The rare occurrence of *Rhizocorallium* in continental settings is also described and discussed.

This study of the Ferron Sandstone provides a rare insight into the interrelationship of continental and marine traces, as well as provides trace assemblages from both environmental examples in temporally related deposits. Most studies often focus on one environment or the other; the same applies to vertebrate and invertebrate taxonomy, for which the focus is often one or the other. In the Ferron Sandstone, continental traces may display more complex behaviors than typically reported. Channel sandstone contains traces

ascribed to the plowing of molluscs, mayfly filter-feeding (*Rhizocorallium*), turtle movement (*Chelonipus*), and vertebrate swim tracks (*Characichnos*). Fluvial-lacustrine floodplains contain ornithopod tracks (*Iguanodontipus* and *Amblydactylus*), root traces, and often heavy burrowing of meniscate backfilled traces (*Beaconites*). Drier continental floodplains in contrast contain vertebrate tracks with roots and rare, small diameter *Skolithos*. In paralic environments such as tidal flats and shallow bays, a greater diversity of vertebrate tracks were preserved in assemblages containing marine-associated traces such as *Thalassinoides* and *Ophiomorpha*. Vertebrate trace fossils also occurred as large deformational structures along the tops of deltaic mouthbars: this is important to recognize since deformation in delta mouthbars is typically associated with the rapid loading of sediment. Tidal channels contained assemblages of *Ophiomorpha*, occasionally *Siphonichnus*, with interbedded mudstones with heavy bioturbation by *Thalassinoides*. Distal deltaic deposits have assemblages comparable to the proximal to archetypal expressions of the *Cruziana* Ichnofacies. The proximal deposits are more representative of the *Skolithos* Ichnofacies. When compared to other Cretaceous delta deposits, *Palaeophycus* is grossly underrepresented as a critical component of these assemblages. In the case, of *Palaeophycus heberti*, this may be the result of the trace fossils' often cryptic appearance. Proximal deltaic deposits may show additional diversity in the form of deep-tiered overprinting taxa.

The most commonly observed overprinting ichnotaxon was *Ophiomorpha* subtending down from the transgressive surface of erosion. The transgressive overprinting occurred mainly on proximal delta front or nearshore complex (washover fan) facies associations. The trace overprint of palimpsest deposits was very similar regardless of whether the overlying environment was a tidal channel, thin transgressive lag, or middle to upper shoreface. This is likely because the overlying environments were all shallow, with *Ophiomorpha* being a conspicuous deep tiered representative of these conditions.

PREFACE

All work herein is the author's, with the final product also being representative of his doctoral committee's input and edits (i.e., suggestions of Dr. George Pemberton, Dr. Murray Gingras, Dr. J-P Zonneveld, Dr. Phil Currie, and Dr. Per Pederson). Chapter 2 was previously published in the 42nd Utah Geological Association Publication (2013, The San Rafael Swell and Henry Mountains Basin-Geologic Centerpiece of Utah, p. 319-340). This chapter presented within is slightly modified and formatted differently from the published version, but still contains some modifications and contributions from others. Most notably, the coauthor, Paul Anderson, provided the second figure in this chapter, as well as input and numerous edits during many conversations. Tiffany Playter, Mark Kirschbaum, and Dr. Thomas Morris helped contribute to manuscript edits in this chapter. Chapter 5 is the only other chapter with external input. Eric Timmer engaged in many conversations that helped shape this chapter and provided edits on the initial draft of this chapter.

DEDICATION

This thesis is dedicated first and foremost to my wife, Tara, who has been very patient and supportive during this long endeavor. Tara, I couldn’t have done it without you. Additionally, I dedicate this to the rest of my family, particularly my parents, Bob and Tina, who instilled a love of science in me at a very young age, and to my brother, Matt, who accompanied me on many of these earlier scientific journeys. I could not have made it this far without the support and guidance of my family and friends, which have helped to shape me into the person that I am today. Thank you all.

ACKNOWLEDGEMENTS

I really appreciate all of the help I received in getting and maintaining the proper permits and procedures for fieldwork in Utah from the Bureau of Land Management (Scott Foss, ReBecca Hunt-Foster, Mike Leschin, Michelle Mary, and Amber Koski) and the Utah Geological Survey (Jim Kirkland and Martha Hayden). The core research at the Utah Geological Survey for this student project could not have been completed without the generous donation of the space and time of staff (Thomas Chidsey, Thomas Dempster, Peter Nielsen, Brad Wolverton, and Michael Laine) at the Utah Core Research Center. Thank you to Steve Behling and Consolidation Coal for allowing me access to some of their land. The core could not have been drafted without the software (Applecore) and permissions provided by Mike Ranger. The funding for this work was provided by National Sciences and Engineering Research Council of Canada Discovery Grants to Dr. S. George Pemberton and Dr. Murray K. Gingras, as well as a grant from The Jurassic Foundation to M. Ryan King.

My long stay in the town of Ferron would not have been such a seamless transition without the help, conversation, occasional temporary residence, and welcoming arms of the Braun/Brown family, Paul Anderson, and Mary Ann Wright throughout my time there. Additionally, thanks to Taina and Mark Benson for their help in Ferron my first field season. Thank you to Tom Ryer and Andy Pulham for our brief, but meaningful conversations on the Ferron. Tom, you will be sorely missed by me and the other researchers of the Ferron Sandstone. Thanks to Rob Gaston for his help in casting/molding advice and material, and for allowing me temporary refuge when passing through the area. I appreciate the constructive conversations with Paul Anderson, Mark Kirschbaum, Dr. Thomas Morris, Dr. Larry Heaman, and Dr. Alison Murray on projects stemming from this work. Thanks to Rares Bistran, Tara and Heather Allman, Bob and Tina King, and Brett Walisser for their help in the field. Thanks to all of the summer students that helped with lab work, especially David Herbers, Eric Timmer, and Joel Gagnon. Thanks to my committee members, Dr. Phil Currie, Dr. John-Paul Zonneveld, and Dr. Per Pedersen, for taking the time to be a part of this process. Dr. Currie was an early inspiration for my path towards geology and paleontology. I need to thank Dr. Octavian Catuneanu for the chats and for continuing to champion my teaching assistantship.

I need to thank people such as Dr. Eric Roberts, Dr. Erik Kvale, Dr. Greg Nadon, Dr. Pat O' Connor, Dr. Nancy Stevens, and Debra Mickelson for their help in starting me on the graduate school path. Dr. George Pemberton and Dr. Murray Gingras have shown incredible patience and kindness to me throughout this process, as well as provided me with a vast amount of knowledge, resources, and funding by which to use. These two along with Dr. Zonneveld have been daily guiding forces during this process, in both life and research.

None of this would be possible without the initial faith that Dr. George Pemberton had in me as a student, and later the extreme amounts of patience to let me finish down this path. Throughout the ebb and flow of my degree he still supported my goals. Dr. Pemberton always had an answer when you hit that brick wall on your path, or needed to find a rare book. He has stories galore, but it is not the really crazy stories that stick with you so much as it is the life lessons he teaches. You can see this through the stellar children he raised both inside and outside of the lab. Dr. Pemberton tells his students “Remember those who come before you”, and Dr. Pemberton, I will always remember and be indebted to you. Thank you.

Dr. Murray Gingras was also a profound influence on my time in Edmonton. He is a man who always kept his door and his ears open. There is many a day that I can credit Murray for keeping me going. You can tell how much Murray loves science. It sometimes doesn’t seem possible that anybody could be more excited than you about an idea, but you can almost bet that Murray will match or beat you in your excitement for what you have found. He really pushes you to explore, develop your ideas, and to help fund your exploration down the rabbit hole. It is his constant child-like excitement that not only helps drive you, but that makes him such a great teacher. Murray has become more than just a mentor to me; he has also become a close friend. Murray, I only hope that I can repay you, for all of the times that you have inspired me and helped fish me out of the endless ocean. Thank you.

There are so many people to thank from our research lab (Ichnology Research Group) as well as outside the lab for their support, help, and conversation that I am sure that I will miss a few somehow. These people, in no particular order, are Dr. Lynn Dafoe, Curtis Lettley, Zaki Abdel-Fattah, Beverly DeJarnett, David Herbers, Dr. Stacy Gibbs, Dr. Ryan McKellar, Ryan Lemiski, Greg Baniak, Dr. Andrew Lawfield, Andrew La Croix, Tiffany Playter, Luke McHugh, Jesse Schoengut, Jenna Phillips, Chelsea Rommens, Camilo Andrés Polo, Rares Bistran, Tibor Lengyel, Cheryl Hodgson, Carolyn Furlong, Reed Myers, Brad Bobey, Alina Shchepetkina, Scott Botterill, Gordon Campbell, Eric Timmer, Naomi Miles, Jamie Robbins, Andy Mumpy, Morgan Snyder, Aleks Mloszewska, Merilie Reynolds, Ben Collins, Nabeel Khan, Brette Harris, Grayson Bilak, Sarah Schultz, Aimee Gegolick, Shelby Sanders, Donald Prenoslo, Daniel Petrash, Robert Dokken, Merilie Reynolds, Allison Neumann, Eric Webb, Cliff and Row Manuel, Viv Robertson, Josh Smith, Sarah Gammie, Shyra Craig, Igor Jakab, Mark Labbe, Martin Von Dollen, Dr. Thomas Chacko, Dr. Wayne Leimer, Dr. Mark Leckie, and Dr. Eva Koppelhus. I could not have made it through the first semester without the guidance of Curtis Lettley and Dr. Lynn Dafoe. Thanks for David Herbers and his family for always including me. I cannot show enough appreciation to Eric Timmer and his family for letting me stay, through sickness and health, at their house for an extended period of time while I prepared for and defended my thesis. Also thanks to my shuttle buddies Rares, Cheryl, and Nabeel.

Thanks to Drs. Tobin Hieronymus, Bucky Gates, Lindsay Zanno, B.N. Tiwari, and Sunil Bajpai for including me in their research endeavors and for their friendship. Additionally, I would like to thank the department for letting me use lab space, and to all of the faculty and staff of the department for their assistance over the years. I would also like to thank the Interlibrary Loan staff for their help in obtaining numerous papers over the years.

Thank you to everyone who has helped to make a difference, as part of my journey, and hopefully it is just the start of many more to come.

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

The Ferron Sandstone, of the Last Chance Delta depocenter, represents deposition from fluvio-deltaic systems along the western edge of the Cretaceous Western Interior Seaway (in the Sevier foreland basin) during Turonian to Coniacian time (Garrison, 2003; Garrison and van den Bergh, 2004). The Ferron Sandstone overlies and grades basinward into the Tununk Shale and is capped by the Blue Gate Shale (Ryer, 1983; Garrison and van den Bergh, 2004). A portion of the Ferron fluvio-deltaic deposits outcropping in the Castle Valley region of Utah, along the western portion of the San Rafael Swell, forms a belt 100 km long (Moiola et al., 2004). This extensive outcrop has made it the focus of copious studies on stratigraphic architecture and heterogeneity within deltaic deposits. Numerous approaches have been applied to the Ferron Sandstone providing data on petrology, sedimentology, paleontology, stratigraphy, structural geology, petrophysics, geophysics, architecture, and reservoir characteristics (Garrison, 2003; Ryer, 2004). However, data provided through ichnology and the examination of mud-dominated intervals has been underutilized in constraining Ferron sequence stratigraphic models.

Ichnologic data abounds in the Ferron Sandstone, and numerous authors have reported specific ichnogenera; but did not fully utilize biogenic character as an interpretative tool, relying instead on the physical sedimentary structures, facies successions, and sandstone architecture to dictate their environmental interpretation. This has resulted in questions as how to assess the relative influence of basinal processes and resulted in the overall omission of mudstone facies in building genetic interpretations (briefly noted by Ryer and Anderson (2004) on classifying environments based on architectural position). The mudstone problem is largely a byproduct of sand-centric lithostratigraphic nomenclature and industry driven studies, which have led to a focus on the upper Ferron rather than the Last Chance Delta as a whole. Such focus ignores the interrelationship between the coarse and fine deposits, even in a stratigraphic model that implies mud-dominated maximum flooding surfaces as sequence boundaries. Gardner et al. (2004) also illustrates the fact that delta front parasequences have been investigated to the near exclusion of the accumulation of more proximal marginal-marine and continental strata.

This project builds on the extensive research compiled for the Ferron by integrating ichnological analyses with more traditional sedimentology studies, and incorporating the study of underutilized fine-grained facies. The extensive outcrop allows for three-dimensional examination of ichnotaxa and investigation of lateral relationships between facies and trace assemblages, which can be directly related to the core drilled behind the outcrop in the study area. Identification of ichnotaxonomy in outcrop provides greater precision and accuracy when trying to relate trace form to interpreted behavior (ethology). Determining accurate ethological assessment of a trace assemblage is vital to interpretation of the depositional environment, and can allow for high-resolution (<2m) depositional environment interpretation when utilizing ichnofacies analysis, especially in deltaic deposits (e.g., Gani et al, 2009). The strength and weakness of sequence stratigraphic models lies in the interpretation of depositional environments. Hence, the dependability of any sequence stratigraphic model is based on the diversity and caliber of the data that is used in its construction (Catuneanu 2006). Trace assemblages provide an underutilized data set to increase the resolution in the stratigraphic architecture of the Ferron Sandstone, especially since much of the focus of initial works has been on defining the large scale stratigraphy of sand bodies based on architectural position (e.g., Cotter, 1975; 1976; Ryer, 1980; 1981; 1983; Gardner, 1995; Anderson et al, 1997; Garrison and van den Bergh, 1997). The core from behind the outcrop also allows for investigation of trace fossils in mud-dominated intervals, which are typically not visible in outcrop. Conversely, the outcrop provides exposure to the under investigated trace assemblages in lower delta plain and paralic deposits that lie landward of the drilled core. This provides a means by which to compile trace assemblage models for future workers to relate delta front parasequences to these landward expressions. This study also provides a means by which to test current delta front ichnological models, as well as, the utility of ichnology as a stratigraphic tool.

1.2 ORGANIZATION OF THE DISSERTATION

This dissertation focuses on the second and the fourth parasequence set of the upper Ferron Sandstone in the Last Chance Delta. The third parasequence set is not addressed within because of the lack of development of these facies in the study area (e.g., Garrison and van den Bergh, 2004). The study area in the Last Chance Delta lies between Ivie Creek at Interstate 70, northwest to the northern gooseneck of Muddy Creek. Since the endgame of this research is publications, this is a paper-based dissertation. Therefore each location and the related background are discussed in detail at the beginning of each chapter. The dissertation is organized with Chapters 2-4 representing studies on lower delta plain and non-deltaic paralic settings, whereas Chapter 5-6 focus more on delta front related deposits.

The initial research chapter (Chapter 2) focuses on the overly thickened, landward preservation of the sand body representing the fourth parasequence set. In the landward basal portion of the sandstone, ichnological analysis helps to differentiate previously unrecognized paralic deposits (washover fan, tidal flat, and shallow bay) that were overprinted by a deeper marine environment, which overprinted the palimpsest paralic deposits with deep-tiered *Ophiomorpha* traces. This partitioning of trace assemblages allowed for the recognition of a cryptic transgressive erosive surface and associated marine flooding surface that occurs higher in the section than previously believed. This chapter has implications for the importance of ichnology in identifying cryptic stratigraphic boundaries, and what this means in terms of the subtle classification differences in the Ferron Sandstone where intra-sand transgressive surfaces result in naming discrepancies in regressive-transgressive versus transgressive-regressive cycle classification that were not apparent in the original sand-centric architectural classification. Chapter 2 provides an example of the trace assemblages associated with non-deltaic paralic facies deposited during transgression in an overall deltaic setting.

Chapter 3 examines the trace assemblage present in a small fluvial channel landward from the deposits in Chapter 2. This trace assemblage contains both *Rhizocorallium* and *Chelonipus* (turtle tracks), which are rarely reported within fluvial channels. Additionally, this is the first report of these traces together in the rock record. *Rhizocorallium* is commonly represented in modern fluvial settings as the behavior of mayflies. While all of the traces noted in the assemblage can be attributed to subaqueous behaviors, *Rhizocorallium* likely requires a firmer substrate conditions than many of the other behaviors. Additionally, this chapter examines *Teredolites* at the base of a channel, and discusses how the traces were reworked into the channel from an underlying brackish floodplain. The overlapping of the brackish traces (clasts) in close proximity to the fluvial traces assemblage shows the importance of examining the underlying and adjacent deposits, and hints towards this occurrence hindering interpretations of other fluvial trace assemblages. This is especially true in deltaic deposits where fluvial channels can subsequently rework allochtonous traces of brackish deposits as the system progrades. This is important for honing in trace assemblage interpretations of channels deposits. A minor discussion is also included into the current explanation of vertebrate versus invertebrate trace classification, where it is argued that vertebrate traces (*Chelonipus* and *Characichnos*) actually should be considered ethological classifications since they are associated with a behavior (swimming).

Chapter 4 delves more into the invertebrate and vertebrate trace relationship. This mainly focuses of the landward reaches of the parasequence set two to four in the study area, but also a few intervals above this for completeness. This increases the number of known vertebrate tracks (e.g., Jones, 2001) in the Ferron Sandstone over ten times, and adds new occurrences of tracks attributed to *Amblydactylus*, *Iguanodontipus*, small to medium theropods, as well as, possible wading shorebirds. Chapter 4 on a larger scale provides a view into Turonian vertebrate tracks in the Western Interior Seaway during a time of limited terrestrial deposit preservation. This chapter also examines preservation according to depositional environment, with the preservation of mold reliefs relying on flooding events, or environment shifts. Additionally, this chapter examines environments heavily bioturbated by invertebrates as well as vertebrate mechanical deformation in paralic environments. In paralic or deltaic settings, where soft sediment deformation is common, these vertebrate tracks are likely overlooked, especially in the context of the sediments surrounding them (i.e., heavily bioturbation or brackish body fossils). This may lead to confusion in depositional environmental interpretation (loading of soft sediment versus compaction and deformation by vertebrates). Two distinctive heavily bioturbated trace assemblages are notable: a *Beaconites*-ornithopod track assemblage and a *Thalassinoides*-ornithopod track assemblage. The *Beaconites*-ornithopod track assemblages are recurrent in the Lower Cretaceous of England, and likely represents fluvial-lacustrine interdistributary deposits. Conversely, the *Thalassinoides*-ornithopod track assemblage may constitute a new model for tidal-flat to shallow bay deposits.

Chapter 5 follows the theme of Chapter 4 in using outcrop to differentiate ichnotaxa, and the theme of Chapter 2 in terms of under represented modern behaviors in the rock record. This study examines several locations in parasequence sets of two and four where ichnotaxa is preserved with a funnel-shaped aperture. Funnel-shaped apertures are commonly formed in modern intertidal and shallow subtidal settings by funnel-feeding (infaunal deposit feeding) vermiforms (e.g., Richter, 1924; Thamdrup, 1935; Linke, 1939; Wells, 1945; 1966; Duncan, 1987). Most funnel-shaped or "V"-shaped ichnotaxa nucleating from a center shaft (e.g., *Cylindrichnus*, *Rosselia*, *Lingulichnus*, *Monocraterion*, and *Altichnus*) are not attributed to this behavior (e.g., Howard, 1966; Chamberlain, 1971; Hakes, 1976; Szmuc et al, 1976; Crimes, 1977; Frey and Howard, 1985; Nara, 1995; Bromley and Hanken, 1991; Zonneveld and Pemberton, 2003; Gaillard and Rachebouef, 2006). This chapter reviews some of the most prolific organisms associated with these behaviors and their burrows. From this review, it is determined that the funnel-shaped aperture is the most consistent feature of these vermiforms' burrows, and should be the key taxonomic indicator of funnel-shape aperture traces. The trace *Altichnus* is redefined, from Bromley and Hankin (1991) along with dividing three new distinct morphotypes of the trace from example in the Ferron Sandstone. One of these trace morphologies is distinctly different with a forward inhalant pipe that allows the circulation of water towards the rear instead of the front. Additionally, it is noted that preservation of *Altichnus* traces requires some form of heterogeneity in the sediment for toponomic expression.

The final research chapter, Chapter 6, focuses on assemblages of deltaic deposits in parasequence set two. The trace assemblages from distributary channel/mouthbar, proximal delta front, distal delta front, and prodelta are compared with trace assemblages from these environments in other Cretaceous deltaics of the Western Interior Seaway. Comparison yields a greater occurrence of *Palaeophycus* in proximal delta deposits of the Ferron Sandstone, and a possible underrepresentation of this trace in deltaic facies models. Similarly, *Scolicia* is underrepresented in models for the distal delta front/prodelta. These distal trace assemblages comprise expressions similar to the proximal and archetypal *Cruziana* Ichnofacies. The more proximal occurrence of *Scolicia* in deltaic settings may be a result of the greater heterogeneity of sediment in distal deltaics and the differences in the food resource paradigm, as compared to the typical shoreface model ichnofacies expressions. The distributary channel/mouthbars contain comparable assemblages to those of similar Cretaceous deltaics, but close examination herein, suggests most of these traces (e.g., *Ophiomorpha*) are deep-tiered overprinting during transgression. Additionally, mud-lined traces like *Astersoma* may comprise the base of similarly cross-bedded, although transgressive sandstone atop the distributary channel. As seen in the Ferron Sandstone, the overprint versus inherent traces may be the key to separating the distributary channel deposits, from those of the transgressive tidal channel.

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CHAPTER 2: A CRYPTIC TRANSGRESSIVE SURFACE OF EROSION AND THE ROLE OF INCIPIENT BIOTURBATION IN MASKING TRANSGRESSIVE NEARSHORE FACIES IN THE LANDWARD TURNAROUND

2.1 INTRODUCTION

The Turonian-Coniacian Ferron Sandstone has been widely recognized and heavily studied due to the large area of available outcrop exposure in Utah. Numerous studies have focused on the fluvial deltaic nature of these outcrops (e.g., Buckley et al., 2010; Enge and Howell, 2010; Enge et al., 2010; Fielding, 2010; Deveugle et al., 2011; Li et al., 2011; and Li et al., 2012). Due to the deltaic character, the overall framework of the Ferron Sandstone has been established based on transgressive-regressive cycles or genetic stratigraphic cycles. This has been done using paralic sand body and coal relationships coupled with biostratigraphic data (Cotter, 1975a, b; 1976; Ryer et al., 1980; Ryer, 1981, 1983; Gardner, 1992, 1993, 1995a, b; Anderson et al., 1997; Garrison and van den Bergh, 1997). Typically, these studies document regressive sandstone bodies, however, transgressive sand bodies, such as lags, washover fans, and tidal inlets have also been reported in the Ferron Sandstone (e.g. Anderson et al., 2004; Barton et al., 2004; Dewey and Morris, 2004; Garrison and van den Bergh, 2004; Ryer and Anderson, 2004). These sandy transgressive deposits are usually thin (lags and washover fans) or localized (tidal inlets) which makes identifying them difficult over a large outcrop area.

While these deposits may be difficult to locate due to their scale, they are frequently recognized as a result of the finer transgressive sediments that often overlie them. The most landward shoreline expression of the transgression is more problematic to identify because the transgressive erosion may result in a sandstone-on-sandstone contact. This intra-sandstone cryptic contact can lead to the transgressive, or transgressive stillstand facies being grouped in with the regressive facies.

Transgressive deposits can leave partial remnants (i.e. deltaics and backbarrier deposits) during stillstand and/or with increased accommodation during transgressive erosion (e.g., Swift, 1975; Cattaneo and Steel, 2003). This will lead to trapped wedges of sandy sediment under the ravinement surface. The cryptic landward shift will result in erosion of the lower sand and overprinting by the subsequent bottom-water community. The bioturbators of the newly emplaced (landward shifted) environment will modify the sediment under the erosional surface.

For example, a seaward shift, from nearshore (foreshore/upper shoreface) to that of middle shoreface (or proximal lower shoreface), above the ravinement surface, should result in prominent reworking by *Ophiomorpha* of the sediment below this surface. This reworking also occurs during subsequent middle shoreface (or proximal lower shoreface) deposition. The ichnological signature is similar to event bedding of Pemberton and MacEachern (1997) where r-strategists' trace morphologies (e.g. *Ophiomorpha*) predominate after erosion. The subsequent top down reworking by the trace makers begins overprinting the previous (palimpsest) facies. There is a decrease in bioturbation intensity and abundance with depth. *Ophiomorpha* (constructed by *Callianassa major*) in the modern have been known to extend downward for over 3 meters (Frey et al., 1978). In the Ferron outcrop they have been observed to penetrate over 1 meter.

This study examines and identifies intra-sandstone ravinement surfaces in order to document the effects of erosion on facies preservation and biogenic overprinting. The Bear Gulch study area (Figure 2.1a), in central Utah, provides an example of transgressive modification of palimpsests deposits in the landward portion of the shoreline. The palimpsests deposits consist of landward facies trapped during transgression.

The contribution of relative sea-level mechanisms to the deposition of these sandstone bodies (i.e. autocyclic or allocyclic); is still debated (e.g. Dewey and Morris, 2004; Garrison and van den Bergh, 2004; Moiola et al., 2004). This study instead focuses on the stratigraphic record rather than base level change mechanisms. Regardless, of the implications related to relative sea level, these small sandstone bodies constitute an important piece of the stratigraphic story.

2.2 GEOLOGIC BACKGROUND

2.2.1 Regional Framework

The Ferron Sandstone of the Mancos Shale is a Turonian-Coniacian (Gardner, 1995a, b; Garrison and van den Bergh, 2004) clastic wedge which prograded into a foreland basin in association with the Sevier orogeny along the western edge of North America (Bhattacharya and Tye, 2004; Garrison and van den Bergh, 2004). Progradation occurred along the western shoreline of the Western Cretaceous Interior Seaway, near the middle of Utah (Figure 2.1b). The Ferron Sandstone is broken up into three spatially disparate

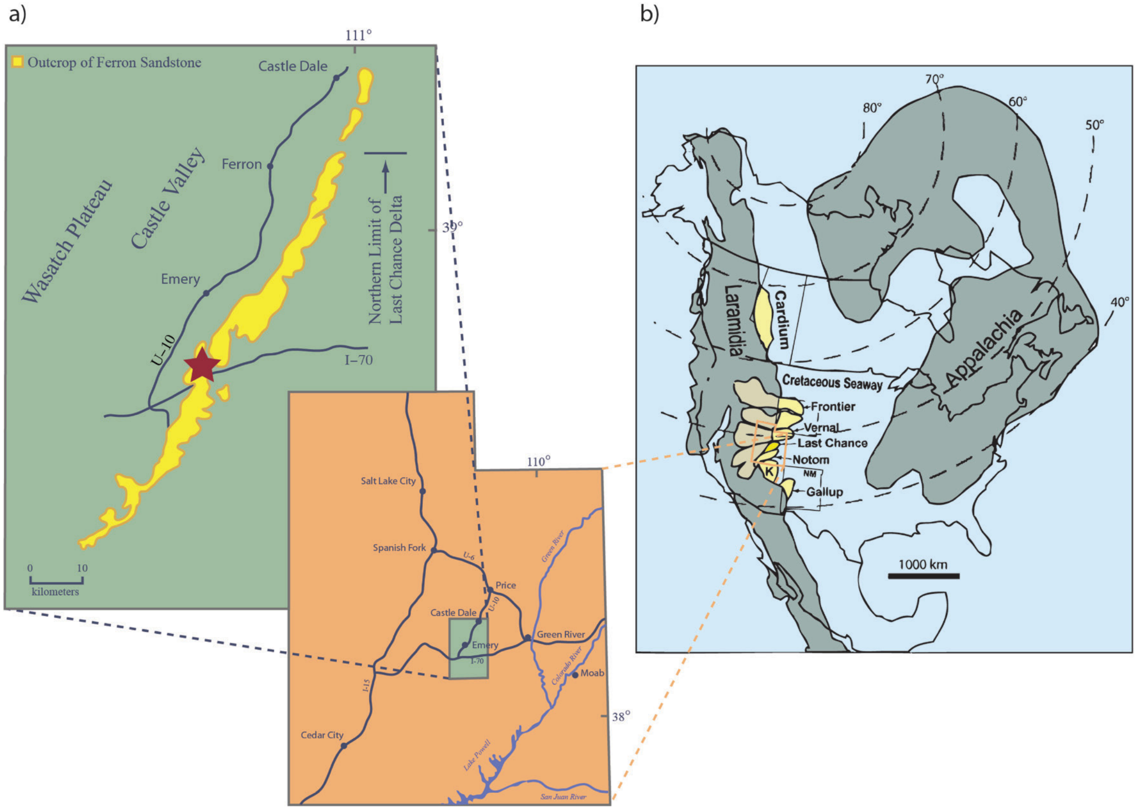

Figure 2.1: Location of study area: a) Geographical location of outcrops (modified from Garrison and van den Bergh, 2004; after Cotter, 1975b) Red star indicates study area location. b) Locations of major clastic depocenters, during Turonian time, along the western margin of the Interior Seaway (modified from Bhattacharya and MacEachern, 2009; which was derived from a compilation of a large body of work by other authors).

depocenters: the Vernal, the Notom, and the Last Chance areas or “deltas”(Garrison and van den Bergh, 2004). The area of interest in this study is the Last Chance depocenter.

Ryer (2004) provides an excellent summary on the upper sandstone-dominated portion of the Ferron in this area. Most workers (e.g., Cotter, 1975a; Ryer, 1981; Gardner, 1995a, b; Barton, 1994; and Garrison and van den Bergh, 2004) agree that this portion of the Ferron records the progradation of a river-dominated system of deltas. The early upper Ferron is dominated by seaward stepping parasequence sets. The middle portion consists of vertically aggrading sets; the upper Ferron is interpreted as a series of back-stepping cycles with a final deepening and deposition of the overlying marine shale (i.e., Lower Blue Gate Member of the Mancos Shale, Hintze and Kowallis, 2009). Terminology and divisions of these cycles of sedimentation vary considerably. However the majority of the framework of the Ferron in the Last Chance area is built around transgressive-regressive or regressive-transgressive sequences. The transgressive-regressive stratigraphic terminology of Anderson and Ryer (2004) will be followed in this paper (Figure 2.2), and is similar to the regional framework established by other authors (Barton et al., 2004; Gardner et al., 2004; and Garrison and van den Bergh, 2004).

The general regional framework of the Last Chance area consists of regressive dominated, approximate 4th order, cycles loosely defined by deltaic progradation followed by abandonment and flooding. Each deltaic, progradational sandstone bodies is grouped into parasequence sets. Parasequence sets are typically paired with associated coal zones (Ryer, 2004). In the naming of these parasequence sets, the abbreviated notation for the regressive sandstones includes: (K) for Cretaceous-aged and (f) Ferron Sandstone, the number of the parasequence set that it represents, followed by the area in which each subset (parasequence) is best developed (Anderson and Ryer, 2004). In this study we focused on Kf-4-MI (Figure 2.2), which is the Miller Canyon (MI) parasequence of the 4th parasequence set, between the “C” to “G” Coals (Figure 2.3; Ryer, 2004)).

2.2.2 Study Area

In the Bear Gulch study area the Kf-4 (or parasequence sets 4a and 4b of Garrison and van den Bergh, 2004; Figure 2.3) is over-thickened in the landward portion (Kf-4-MI) relative to other parasequences in the Ferron. The transgression over the “C” coal represents one of the largest landward shifts within this area (as seen in regional cross sections of Garrison and van den Bergh, 2004). This is followed by renewed progradation

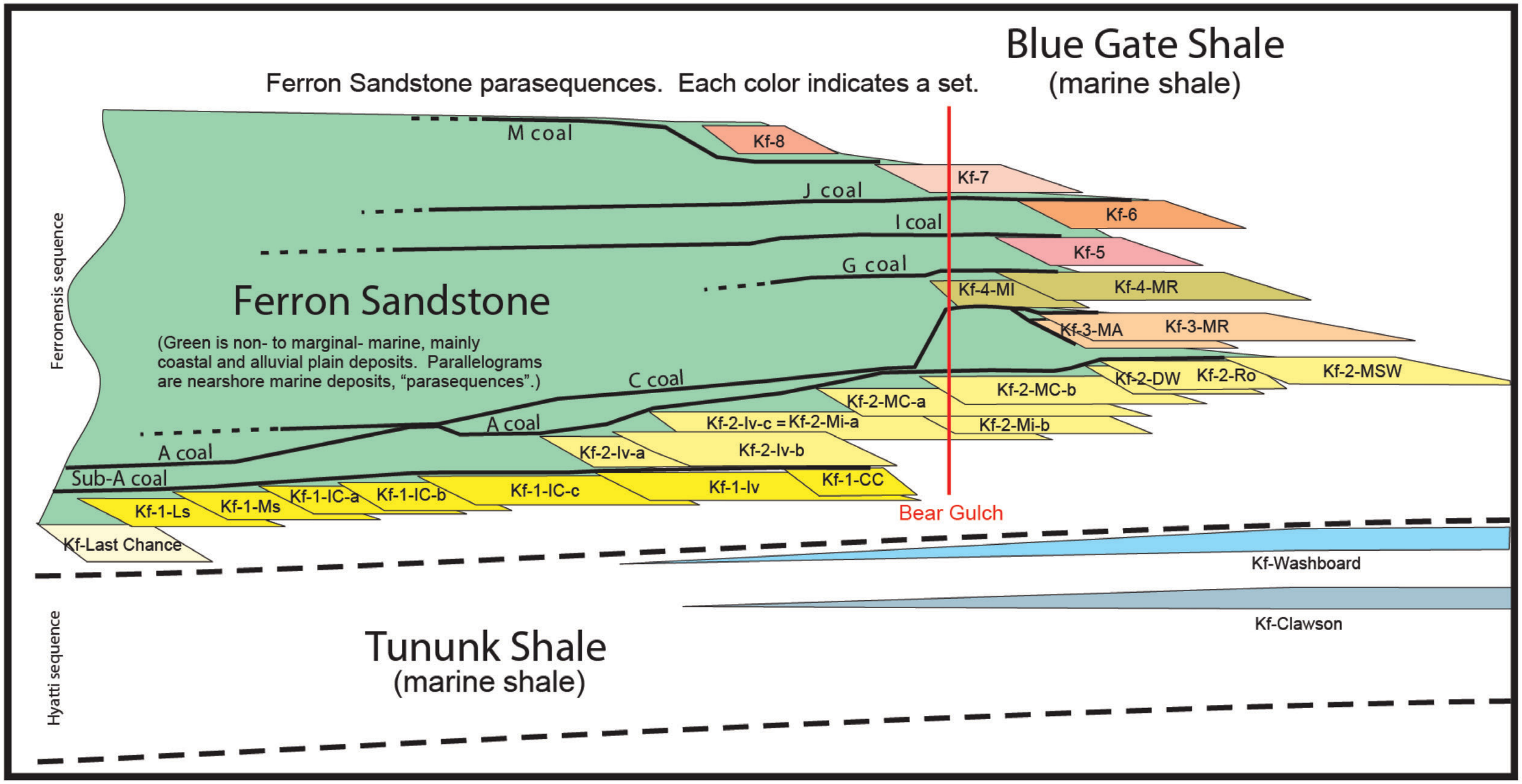

Figure 2.2: Diagrammatic representation of the Ferron Sandstone "wedge" as exposed in the region near the study area (figure provided by P. Anderson, 2013, pers. comm.). Each parallelogram represents a parasequence with its abbreviated name. Parasequence sets are represented by a common color fill of the parallelograms and the only numeric in the name. "Lower Ferron" consists of the Washboard and Clawson units.

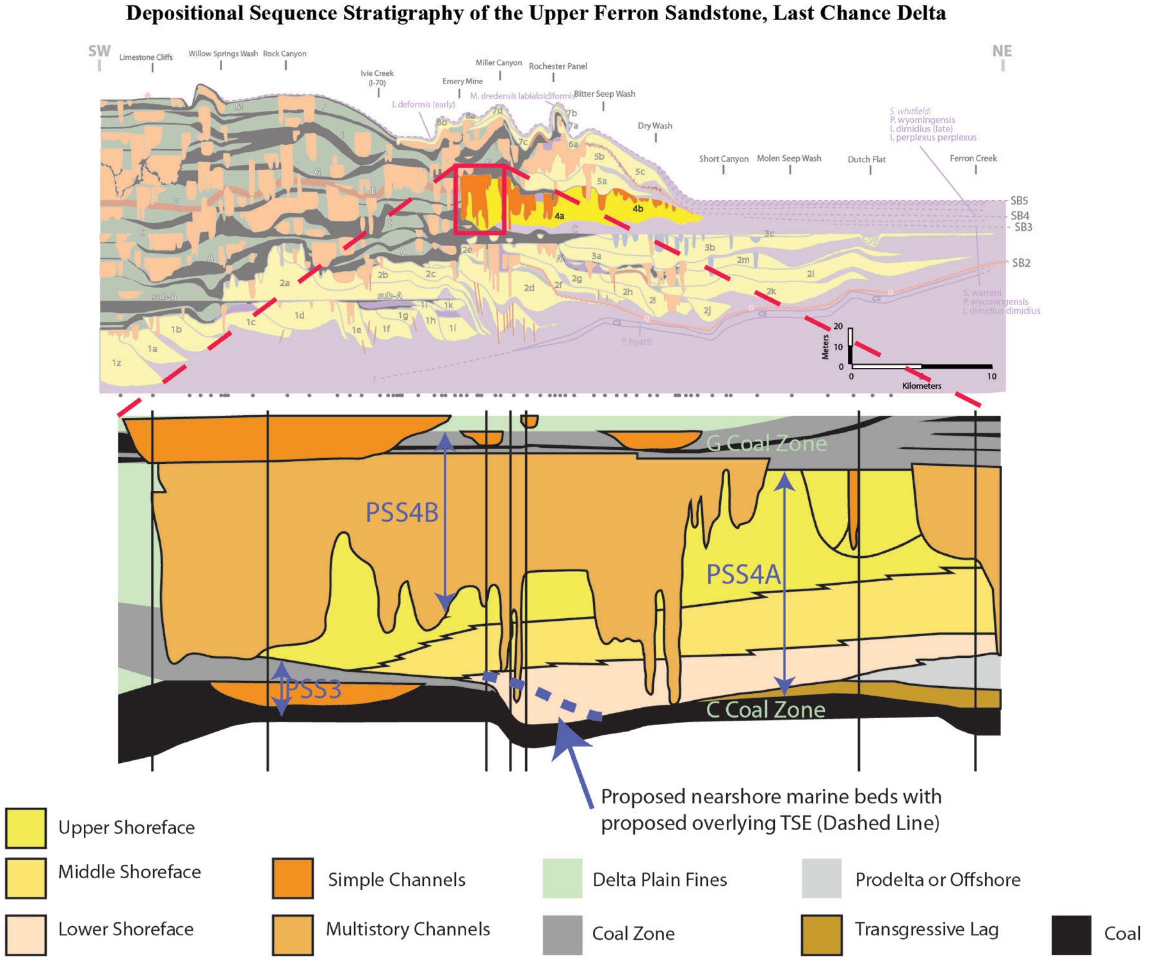

Figure 2.3: Cross-sections with depositional environment interpretations illustrating the lateral and vertical relationships to the study area of Bear Gulch (modified from Garrison and van den Bergh, 2004). Vertical black lines represent where their sections were measured and the morphology of the overly thickened sandstone. Two of the three close black lines in the middle were measured in the Bear Gulch area. Dashed purple line indicates the proposed location of the transgressive surface of erosion from this study.

of the Kf-4-MI (parasequence set 4a, Figure 2.3) and subsequent removal associated with channels (i.e., parasequence set 4b of Garrison and van den Bergh, 2004, Figure 2.3). The outcrop studied here is near the landward pinch out of all marine sandstone associated with the Kf-4 parasequence set (Anderson and Ryer, 2004). The regional shoreline trend of the Ferron Sandstone is a few tens of degrees west of north, with land to the southwest and sea to the northeast during time of deposition (Anderson and Ryer, 2004). The orientation of the Bear Gulch drainage is shoreline-normal (P. Anderson, personal communication, 2012).

Facies of the Kf-4 in Bear Gulch have been described as consisting of upper shoreface deposits (Anderson and Ryer, 2004), shoreface and subordinate interdistributary bay deposits (Gardner et al., 2004), and lower to upper shoreface deposits (Garrison and van den Bergh, 2004). These studies, however, focused on larger scale features and therefore had sparse detail in some areas.

2.3 FACIES ASSOCIATIONS

This study denotes two distinctive sandstone facies associations in the Kf-4-MI sandstone of the Bear Gulch study area: 1) a lower landward portion of nearshore facies (Facies Association 1), and 2) overlying more marine shoreface deposits (facies associations 2a and 2b) that shallow upward overall (Figure 2.4). The distribution of facies and traces are listed in Table 1 according to facies association.

2.3.1 Facies Association 1 (FA1)

2.3.1.1 Description of Facies Association 1 (FA1)

Facies Association 1 (FA1) is composed of four major facies: planar laminated sandstone [Sp], cross-bedded sandstone [St], cross-bedded sandstone with bioturbation [Sti], and rippled sandstone [Sr]. Two minor facies were also observed: massive sandstone [Sm and Smi] and mudstones with evidence of subaerial exposure [Fb](Figure 2.4). FA1 dominantly lies over laminated mudstone, which may contain bioturbation (can be absent or abundant in the forms of *Thalassinoides* and *Planolites*), lenticular sandstone, and local sulfur. This underlying laminated mudstone is interpreted as weakly developed coastal plain or muddy bay fill deposits. The contact between FA1 and the underlying mudstone

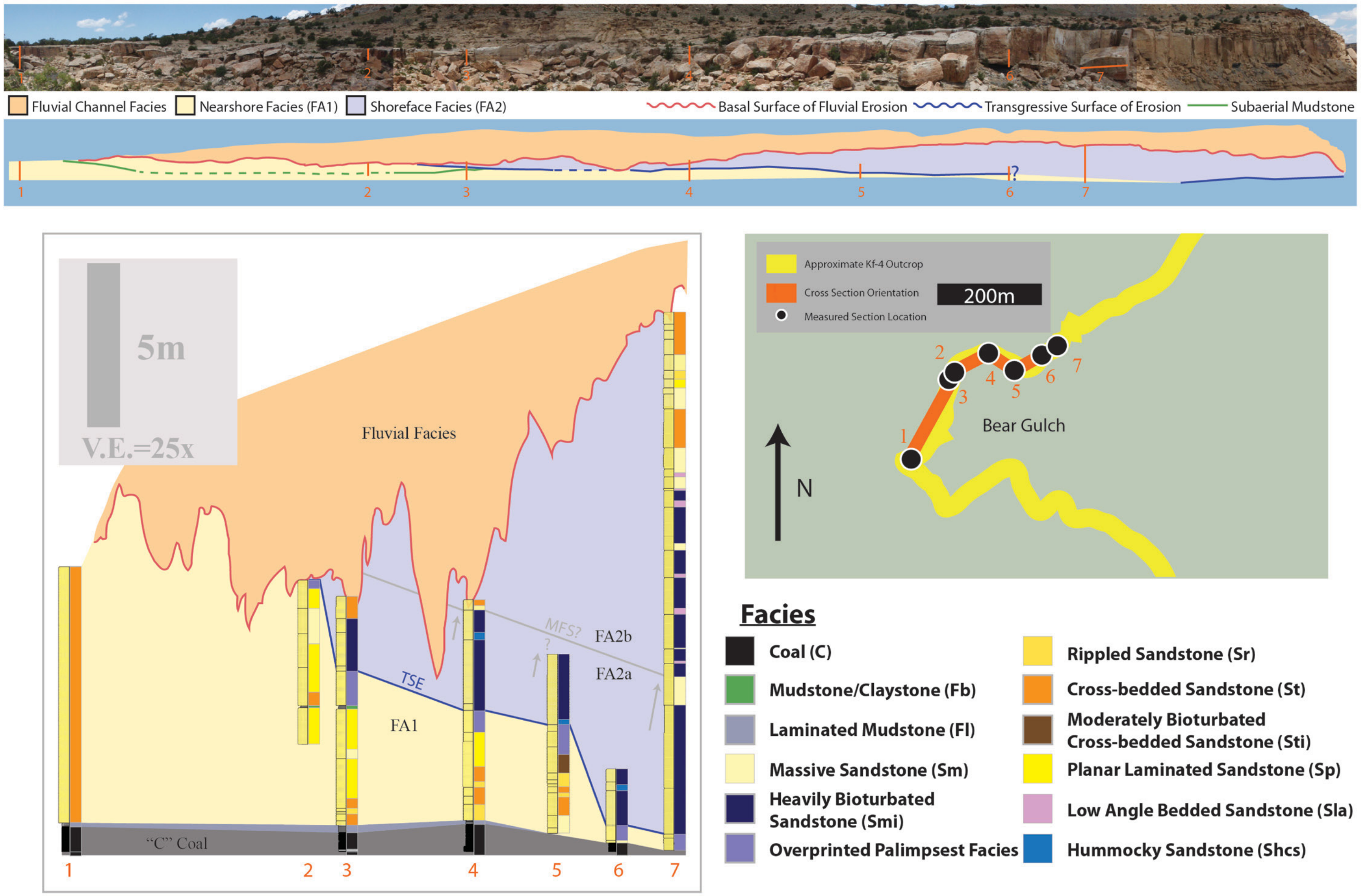

Figure 2.4: Measured sections (1-7) in Bear Gulch illustrating the relationship between the nearshore facies of Facies Association 1 (FA1), and that of overlying more seaward shoreface facies of Facies Association 2 (FA2a and FA2b) which all combined comprise the Kf-4-MI sandstone body (Parasequence set 4a of Garrison and van den Bergh, 2004). Erosive based fluvial facies of Garrison and van den Bergh (2004), named parasequence set 4b (PSS4b), replace the tops of these two facies associations in Bear Gulch.

	Facies Association 1 (FA1) Nearshore Environment	Facies Association 2a (FA2a) Shoreface	Facies Association 3 (FA2b) Shoreface
Facies			
Mudstone-Subaerial Exposure (Fb)	m		
Rippled Sandstone (Sr)	X		
Cross-bedded Sandstone (St)	X		X
Bioturbated Cross-bedded Sandstone (Sti)	X	m, X (updip)	
Planar Laminated Sandstone (Sp)	X		
Massive Sandstone (Sm)	m	m	m
Bioturbated Massive Sandstone (Smi)	m	X	X
Hummocky Cross Strat. Sandstone (Shcs)		X	
Low Angle Bedded Sandstone (Sla)			X

X=prominent facies m=minor facies

Trace Fossils	**Facies Ocurrence in FA1**	**Facies Ocurrence in FA2a**	**Facies Ocurrence in FA2b**
Tree trunks/roots	Fb, St		
Dinosaur Tracks	Sr, Sp, Smi, Fb		
Insect Traces	Sp		
Planolites	Smi, along mudstone lamina, or at base of FA1		
Thalassinoides		Smi-fine grained lamina	Smi-fine grained lamina
Psilonichnus	Sp, Sti		
Equilibrichnia (other than Diplocraterion)	Sp, minor Sti		
Teredolites	All except Fb	All, except Sm	All, except Sm
Ophiomorpha	All except Fb	All, except Sm	All, except Sm
Rosselia		X	
Diplocraterion		X	
Zoophycos		X	

Table 2.1: A comparison of facies, facies associations, and trace fossils in the study area. Note that abbreviation of each facies, indicated in the lower set of columns, corresponds with those abbreviations in parenthesis next to each facies in the upper left column.

varies from sharp, to gradational, grading upwards from these laminated mudstones into the current rippled sandstone facies of FA1 or sharp erosive trough cross-bedded facies. Frequently the base of FA1 may show subtle undulations due to loading (Figure 2.5a), however some of this deformation is attributable to downward deformation of the sands by dinosaur tracks.

The sandstone (FA1) is up to 7.8 meters thick in the western portion of the study area, but easterly is either completely removed and/or is overprinted by heavy bioturbation (Figure 2.4). This facies association can be observed onlapping to the south (Figure 2.5b). To the east, the bottom portion (up to one-third of the sandstone) is composed of yellow (sulfur-rich?), rapidly alternating Sr, St, Sti, Sm, Smi, and Sp facies (Figure 2.6a). The base of this association starts out as very fine upper to fine lower sandstone, but coarsens upward overall (in this lower portion) to upper fine to lower medium grained. There are small alternations in grain size between bedsets, but there is not a significant difference in grain size between facies. Cross-beds are on a scale from 2-55 cm thick. Organics can be observed and range from small millimeter to centimeter scale subround to subangular clasts or sparse to moderately *Teredolites* bored logs (Figure 2.6b). These organics can comprise up to 70% of some bedsets, and often appear at the bottom of St, Sti, or Sp, or associated in large quantities with Sr (Figure 2.6a). Facies St, Sti, and Sr can contain double mud or organic drapes. Flaser bedding is locally present. Facies laterally may pass from one into the other (sigmoidal cross-beds (St) into planar sandstone (Sp)) (Figure 2.6c). Some facies are observed offlapping towards the west locally (Figure 2.6a).

Bioturbation occurs along small mudstone interbeds near the base and as Facies Smi. Abundant *Thalassinoide*s and *Planolites*, with rare *Teichichnus* dominate these mudstone/former mudstone interbeds, which often contain dinosaur tracks. The sandstone facies contains equilibrichnia (*Siphonichnus*, and *?Lingulichnus* or *?Rosselia*)(Figure 2.6d), *Psilonichnus* (Figure 2.6e), and *Ophiomorpha* (some iron or siderite cemented) (Figure 2.6f).

These lower, sulfur-rich(?), facies disappears towards the west. A rapid transition occurs above the sulfur-rich facies to a well-cemented lower visual sulfur content facies that typically occupies the upper two-thirds of FA1. This transition is typically marked by large (up to 60 cm) cross-beds (St). Cross-beds in this interval can occasionally be observed dipping at high angles, some greater than 35 degrees (Figure 2.7a). This upper two-thirds of FA1 is dominated by facies Sp and St, with minor Sm and one Fb bed (Figure 2.4). *Teredolites*–bored logs can be seen floating in the sandstone, or as part of organic lags

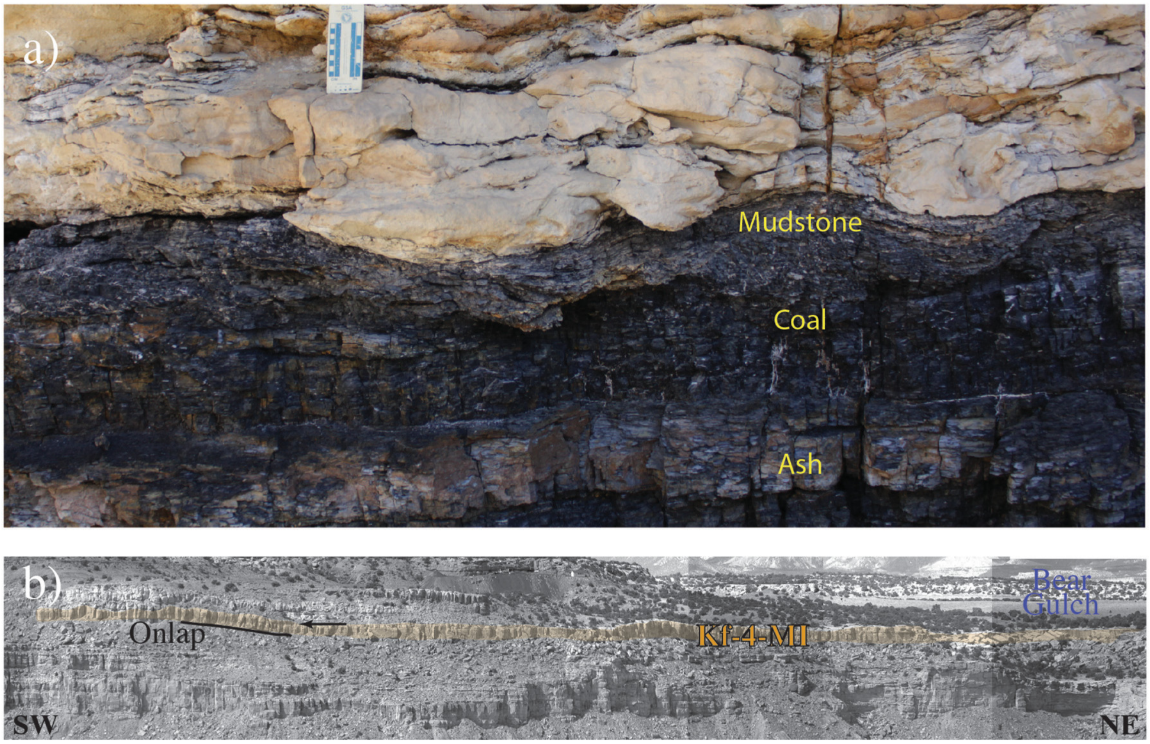

Figure 2.5: The base of Kf-4-MI: a) Base of Facies Association 1 (FA1) in Bear Gulch showing loading of the sandstone base (ash in coal at the bottom of photo used as datum to help correlate sections), b) a photomosaic (modified from Anderson et al., 2003) showing the onlapping of Kf-4-MI onto the mudstones above the “C” coal to the southwest of Bear Gulch.

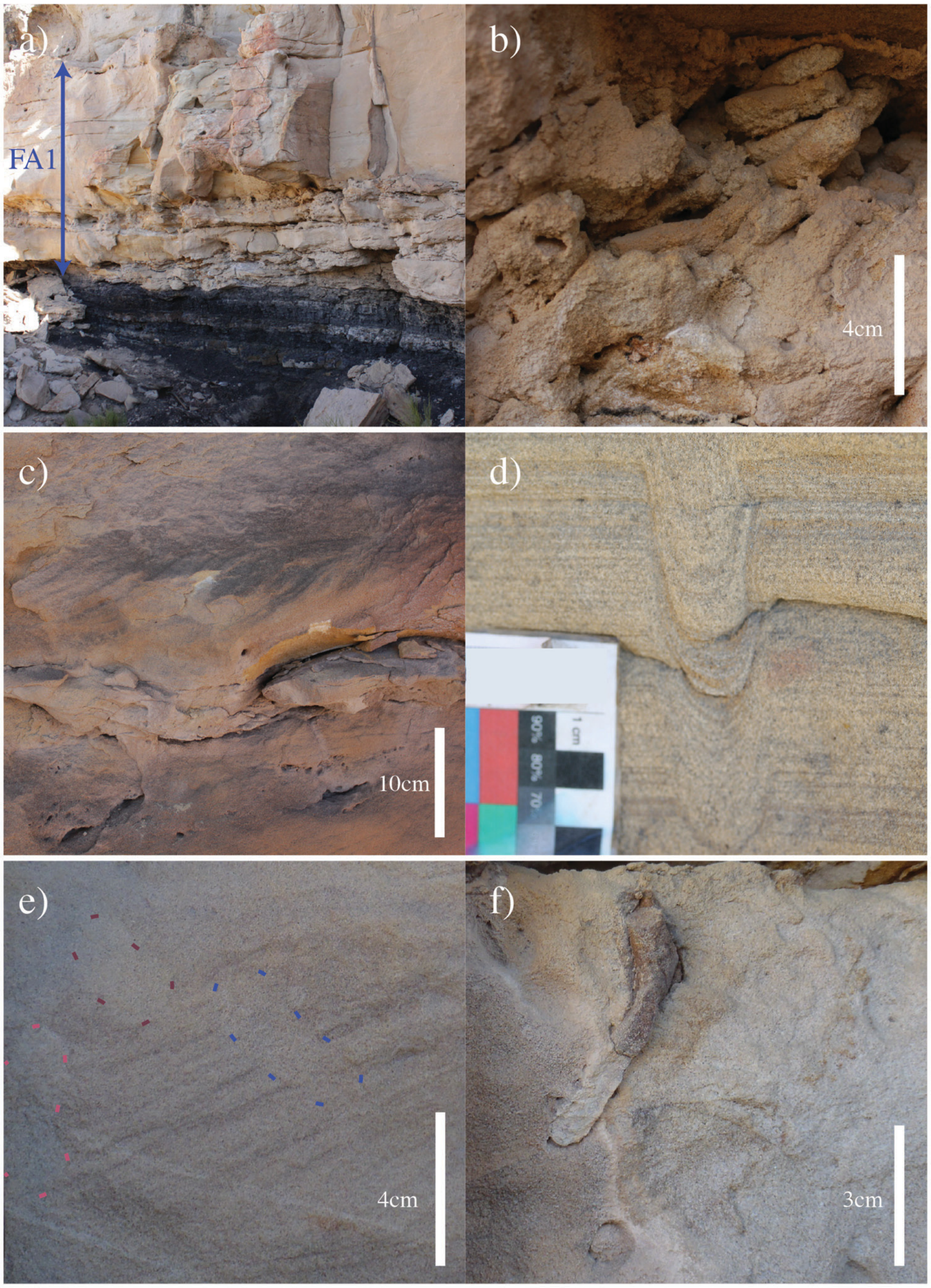

Figure 2.6: Facies, bedforms, and traces of the lower portion of Facies Association 1 (FA1): a) FA1 with high amount of organic, and a wide variety of facies variation in the basal portion, b) an example of the organic material weathering out leaving only the sand-filled *Teredolites longissima* tubes preserved, c) facies St showing sigmoidal cross-bedding, d) facies Sp with a *Siphonichnus* trace representing a bivalve's adjustment upward (equilbrichnia) to keep pace with sedimentation, e) facies Sti with large ovate traces (outlined with dashes) interpreted as the cross-sectional view of *Psilonichnus*, and f) a sideritized or iron-stained *Ophiomorpha*.

along planar surfaces. Facies Sp has parting lineations, often in the form of rhomboidal rill marks (Figure 2.7b). Along some lineation breaks, *Psilonichnus* is observed in cross-section with convex hyporelief traces similar to *Haplotichnus* (Figure 2.7c; Maples and Archer, 1987) and some traces that exhibits meniscate and pustulose textures (Figure 2.7d) that are commonly associated with modern insect burrows (Hasiotis, 2006). Dinosaur tracks are additionally exposed on fallen blocks in rippled, lineated, and thin non-descript surfaces. Grain size alternates between lower fine to lower medium, but no overall trend is observed. Laterally within FA1 there is some minor variation with the outer FA1 sections (section 1 and 5) containing some coarser medium-grained intervals (Figure 2.4).

Facies Fb are mudstone beds distorted by dinosaur tracks, that have large downward branching structures in the top, with vertical remnants into the overlying sandstone (interpreted as tree casts with diameters close to 20 cm)(Figure 2.7e, f). This facies occurs along a thin (10 cm or less) concave up bed that is traceable around the Bear Gulch amphitheater. The geometry is asymmetrical with the steepest side to the west (8.5 degree dip). The overlying cross-beds rarely contain mudstone clasts along the foresets, but onlap and climb the surface towards the west.

The top of this facies association is consistently marked by the trace *Ophiomorpha* regardless of which sand-dominated facies are present (unless overlain by erosional fluvial facies). These *Ophiomorpha* traces decrease in abundance downward from the overlying, eastward-dipping easily erodible centimeter scale interval (Figure 2.8). This easily erodible interval is visible as a surface when looking from the opposite side of the amphitheater, but becomes harder to recognize as it drops closer to the base in the northwestern part of the Bear Gulch amphitheater.

2.3.1.2 Interpretation of Facies Association 1 (FA1)

Facies Association 1 represents nearshore sediments that were deposited at paleo sea-level. The lateral relationships between the facies in this association are complex. Further research is currently underway to evaluate these spatial relationships, paleocurrents, and cryptic sandstone on sandstone erosional surfaces within FA1. However, the environment of deposition was likely dominated by intertidal conditions fluctuating throughout deposition between shallow subaqueous and subaerial settings. The sedimentological and ichnological data suggest the environments could be related to a wide range of settings such as backshore/backbarrier, washover fan, foreshore, distributary channel/mouthbar, and possible aeolian deposits.

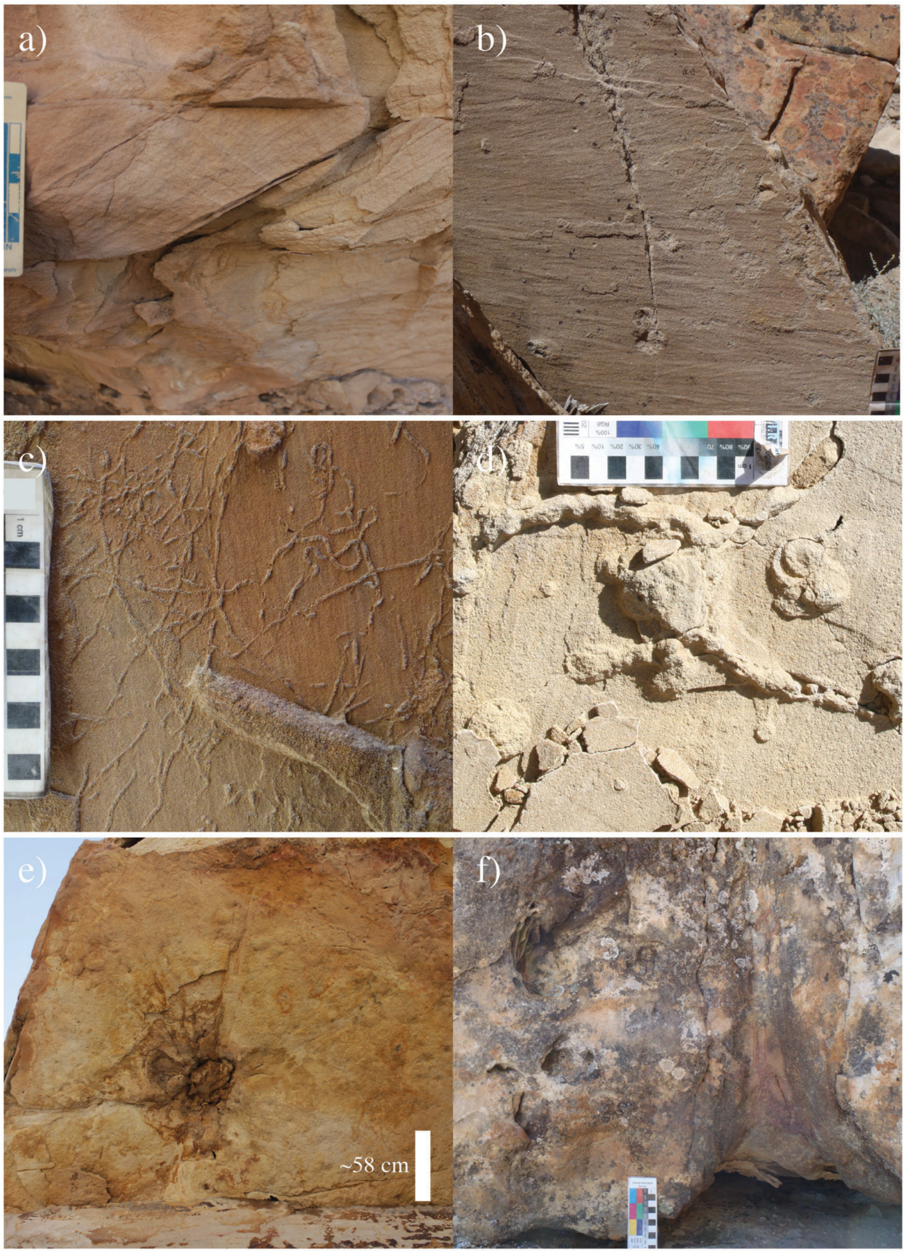

Figure 2.7: Facies, bedforms, and traces of the upper portion of Facies Association 1 (FA1): a) High angle cross-beds (inch scale), b) Surface with parting lineations (rhomboidal rill marks), c) probable insect traces and parting lineations, d) probable insect traces (some may be meniscate backfilled), e) tree casts and root system, and f) vertical cross-section of tree cast, base of stump greater than 20 cm across.

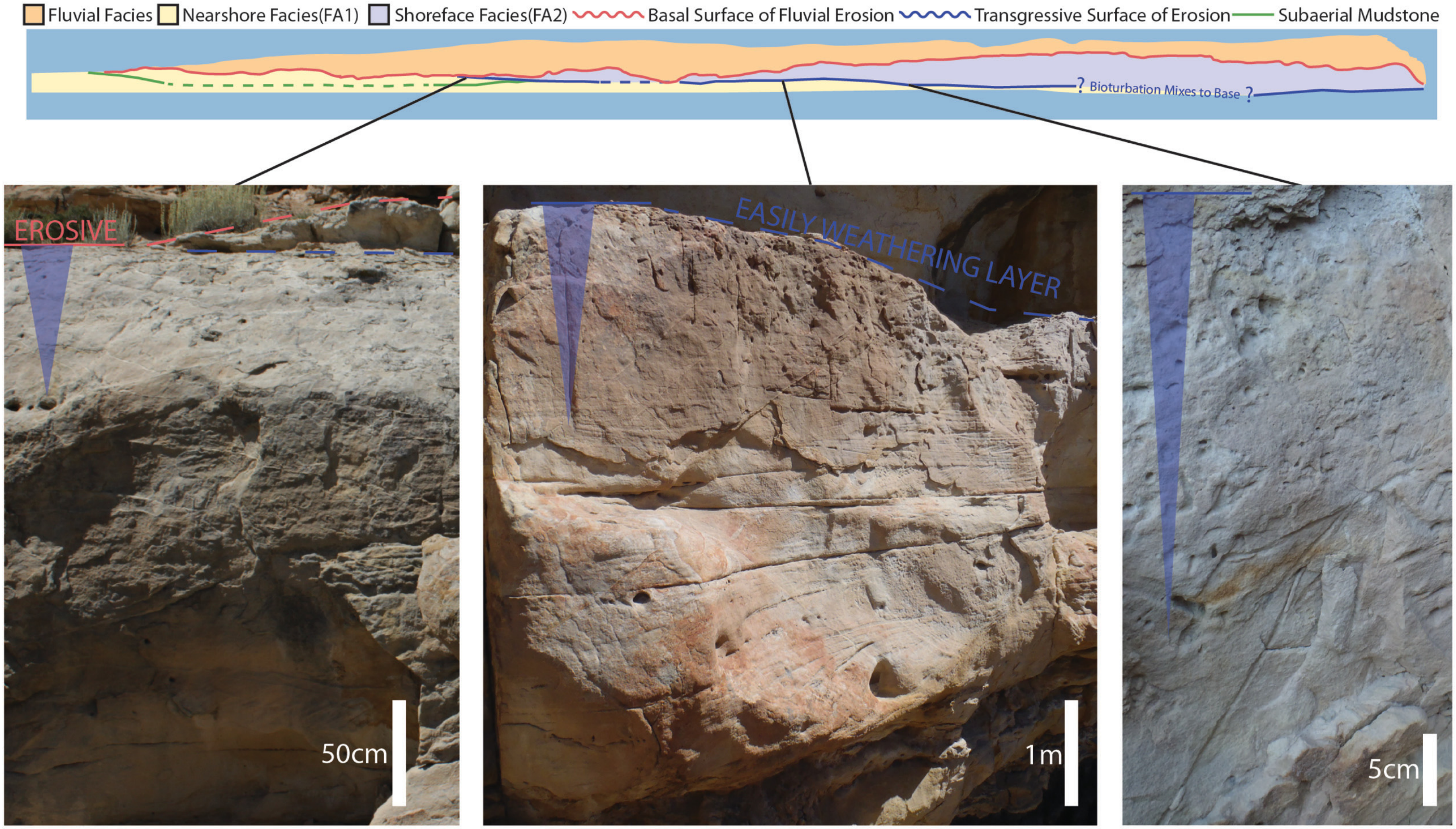

Figure 2.8: Three examples laterally of Facies Association 1 (FA1) being overprinted by *Ophiomorpha* from depositional environments associated with the overlying Facies Association 2 (FA2). Purple triangles help to illustrate the decrease in bioturbation downward from the easily erodible surface that lies between FA1 and FA2.

Initial filling of the accommodation space may be in a west-southwesterly direction as it onlaps the southern mudstone high (P. Anderson, personal communication, 2009; Figure 2.5b). The overall upward coarsening trend in this lower FA1 suggests progradation of the sand body, but not necessarily in a seaward direction. Rapid facies shifts in the base show periodic alternation between high (St, Sti, and Sp) and low flow conditions (Sr). Whereas in some places the organics suggest reworking, the high proportion of organics associated with Sr facies suggest either the organics were baffling flow, or were deposited during times of low flow. The *Teredolites* borings suggest these organics were likely deposited in an environment close to marine conditions (Gingras et al., 2004).

Equilibrichnia indicates upward movement of an animal in response to rapid or increased sedimentation (Gingras et al., 2009; Zonneveld and Gingras, 2013). *Psilonichnus* is typically associated with backshore conditions (Frey and Pemberton, 1987). The *Ophiomorpha* have often been linked to nearshore environments (Pollard et al., 1993). The thin, highly abundant interbeds of *Thalassinoides* suggest frequently changing, highly stressed conditions (Pemberton and Wightman, 1992). The occurrences of these *Thalassinoides* with dinosaur tracks suggest either shallow water or periods of exposure. Flasers and sigmoidal cross-beds may indicate tidal influence.

The fluctuations of high influx of sediment and organics may represent washover fan conditions. Washover fans are often dominated by planar laminated sandstone, tabular cross-bedding, *Psilonichnus*, and organics (Frey and Howard, 1988). The planar laminated sands are also common to swash zones of high energy beaches (Clifton et al., 1971) or the apex of mouth bars and levees adjacent to distributary channels (Tye and Hickey, 2001). The flasers may be part of a local backbarrier tidal channel with a cryptic sandstone on sandstone contact. More paleocurrents must be collected to discern if these are separate features and in which direction the sandstone body is prograding initially.

In some areas, a rapid shift to high-energy facies (Sp and St), about 1/3 of the way up section, could be related to a shoreline/environment shift, or a part of the bay filling. If related to a landward shift of the shoreline, the high-energy facies suggest foreshore/upper shoreface conditions. Evidence for this includes rhomboidal rill marks, which have been described from modern foreshore environments (Otvos, 1964; 1965; Stauffer et al., 1976). However, high angled cross-sets suggest aeolian backshore (e.g. Frey and Howard, 1988) or terminal washover fan deposition (Sedgwick and Davis, 2003; Wang and Horwitz, 2007). *Psilonichnus* and insect traces observed on some lineation surfaces are more indicative of backshore conditions or overprinting those of the upper shoreface (Frey and Pemberton, 1987; MacEachern et al., 2009). Additionally, dinosaur tracks are present on some of these lineation surfaces, as well as in the thin mudstone layer (Fb), suggesting periodic subaerial exposure or shallow water conditions. Vertical tree casts at the upper portion of the mudstone indicate that subaerial/shallow water conditions existed for at least scores of years. *Ophiomorpha* characteristically observed at the very top of Facies Association 1, originates from marine environments overlying the surface, overprinting the top of FA1. Facies Association 1 is otherwise sharply overlain by deposits that have been established fluvial channels (i.e., Anderson and Ryer, 2004).

2.3.2 Facies Association 2 (FA2)

Facies Association 2 is broken into two parts: a lower FA2a portion and an upper FA2b. Both have similar features, but the two vary in vertical profile, with FA2a generally fining upwards, and FA2b overall coarsening upwards.

2.3.2.1 Description of Facies Association 2a

Facies Association 2a is composed of three main facies: massive sandstone with heavy bioturbation (Smi; Figure 2.9a), trough cross-bedded sandstone with bioturbation (Sti) (Figure 2.9b), and hummocky cross-stratified sandstone with various degrees of bioturbation (Shcs; Figure 2.9c). The base of FA2 is often marked by an eastward-dipping, white, easily-weathered boundary that is typically less than 10 cm thick. This boundary is sandwiched between consolidated sandstones (Figure 2.8). Cut samples have revealed a low abundance of sub-centimeter rounded grey mud clasts at this boundary. The first 5-15 centimeters below this boundary are typically heavily bioturbated by *Ophiomorpha irregulari*, with large vertical, but slightly inclined *traces* extending further down from this surface. Lenses of organic debris are often prevalent in the synforms above the basal contact, and can be recognized in the preferential weathering of the outcrop face (Figure 2.9d).

Facies Association 2a is up to 4 m thick, however to the west the top is removed by the fluvial channel facies (Figure 2.4). Where preserved to the east, the upper contact of FA2a is represented by a change in grain size trends. FA2a is fining upward, whereas FA2b is coarsening upward (Figure 2.10). An increase in mud content and decrease in organic content upward is observed in FA2a.

Figure 2.9: Facies, bedforms, and traces of Facies Association 2a (FA2a): a) Massive bioturbated sandstone facies (Smi), dipping features that weather out are due to post depositional compression, b) bioturbated cross-bedded sandstone facies (Sti), c) hummocky cross-stratified sandstone facies (Shcs) between Smi facies, d) distinctive organic lenses that weather out at the base of FA2a.

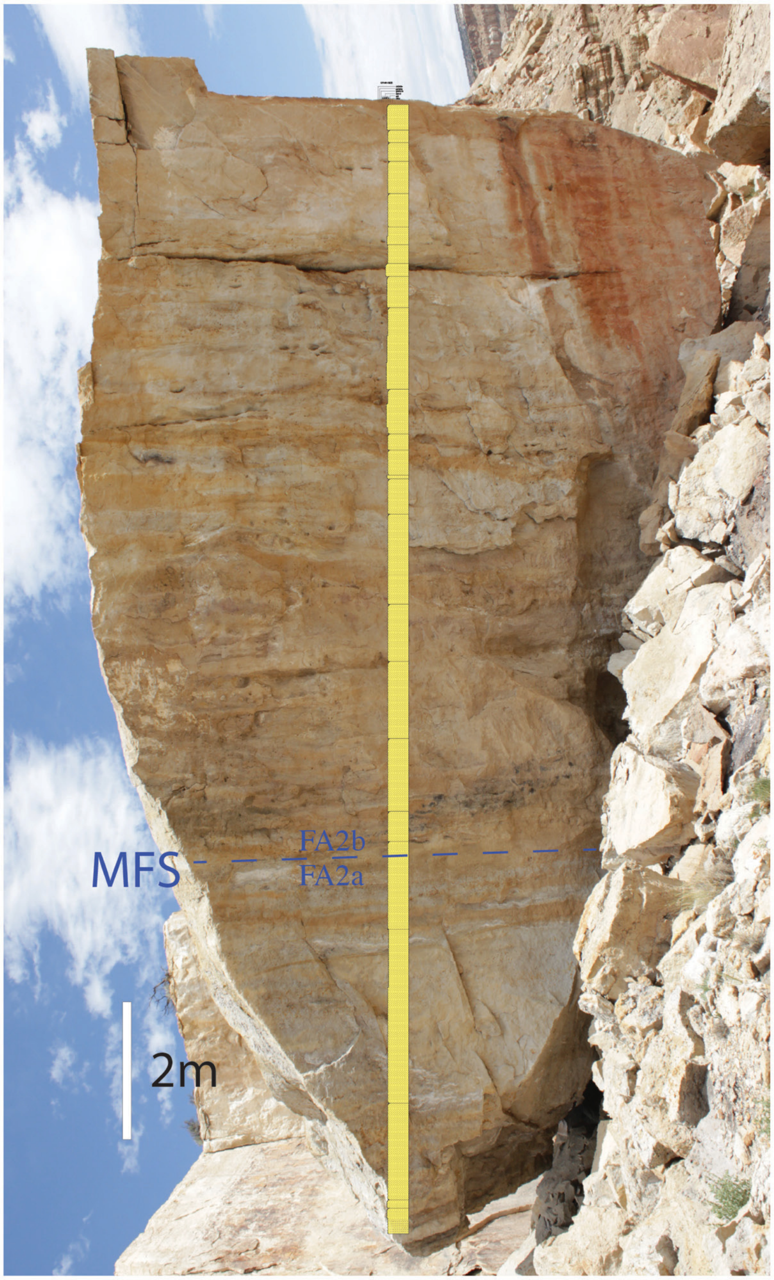

Figure 2.10: Inflection point of grain size (Section 7) denoting the probable maximum flooding surface (MFS) between Facies Association 2a (FA2a) and 2b (FA2b).

A marked change in bedforms is observed up depositional dip from east to west in FA2a. In the east, the bioturbation is quite abundant and diverse with forms such as *Rosselia*, *Ophiomorpha*, *Diplocraterion*, *Teredolites*, and rare *Zoophycos*. These intervals of facies Smi, have some minor interbeds of facies Shcs. Westward (up depositional dip), bedform-dominated intervals become thicker and more abundant and transition into trough cross-bedding (facies Sti). The bioturbation is less diverse, with *Ophiomorpha* being the main trace fossil. The trough cross-beds typically contain thin horizons of intense bioturbation. Grain size is fairly consistent laterally.

2.3.2.2 Interpretation of Facies Association 2a

Facies Association 2a represents shoreface conditions with the more westerly facies representing the upper shoreface, and easterly facies representing the upper portion of the lower shoreface. The lower shoreface of the eastern portion is evidenced by the high diversity and abundance of cross cutting traces, which compares to that of the *Cruziana* ichnofacies (MacEachern et al., 2009). Rare occurrences of the Shcs facies suggest that these sediments were above storm wave base (Hunter and Clifton, 1982; Dumas and Arnott, 2006). This environment was dominated by long periods where the sediment could be reworked by organisms interrupted by the erosion and rapid deposition by storm event beds (e.g., Pemberton and MacEachern, 1997).

In the westerly portion, the change in bedforms laterally and up depositional dip represent a change from the lower shoreface to a shallower upper shoreface environment. The troughs in this environment represent a change to wave-forced currents. This change is observed in modern environments such as in the surf zone of the upper shoreface (Clifton et al., 1971; Hunter et al., 1979). The presence of bioturbation suggests the environment was not one of constant high energy.

The two vertical trends observed in FA2a, the decrease in organics, and the decrease in grain size may both be the results of a transgressing shoreface. The organics at the base may be attributable to erosion of the underlying coal. Additionally a decrease in grain size, although not fully diagnostic, has often been linked with increasing depth of the shoreface (Catuneanu, 2006).

2.3.2.3 Description of Facies Association 2b

Facies Association 2b is similar to FA2a in the basal portion, having massive heavily bioturbated sandstone (facies Smi) interbedded with low angle sandstone beds (facies Sla, interpreted as low amplitude hummocks and swales). Up section, facies Smi disappears, and the hummocks are preserved as swales. Above this, trough cross-bedded sandstone (facies St) display no or little bioturbation. In Bear Gulch, the overlying fluvial channel facies cut out much of the planar bedded sandstone (facies Sp) observed overlying the trough cross-bedded facies in the wash to the north. Additionally, these younger fluvial channels cut out FA2b in western portions of Bear Gulch.

The base of FA2b is defined by a change in grain size trends from the fining up succession (with upper very fine grains to a coarsening upward succession containing upper medium grains). Facies Association 2b has been observed to be as thick as 12m in Bear Gulch, but has been seen to be 18.3m thick where more fully preserved in the drainage north of Bear Gulch.

2.3.2.4 Interpretation of Facies Association 2b

Facies 2b is consistent with the interpretation of Garrison and van den Bergh (2004) as a prograding shoreface succession, from that of upper lower shoreface to foreshore. The interpretation of lower shoreface is for the same reasons as discussed for FA2a. However, the lack of persistent bioturbation upward suggests that this was a higher energy and/or more erosive environment than FA2a. The upward progression from swales, to trough cross-beds, to foreshore deposits is a typical succession for a prograding shoreface (e.g., Clifton et al., 1971; Hunter et al., 1979). However, since this interval (FA2b) is about 3 times thicker than a typical modern shoreface succession (e.g., Clifton et al., 1971; Hunter et al., 1979) and one of the thickest in the Ferron Sandstone (Garrison and van den Bergh, 2004; Ryer and Anderson, 2004), the depositional history of this succession may encompass more than just simple progradation.

2.4 STRATIGRAPHIC DISCUSSION

A backstepping succession of deposits from peat marsh to intertidally dominated nearshore to that of fully marine shoreface accounts for the thicker Kf-4-MI sandstone in the Bear Gulch study area. The thicker transgressive deposits bring forward an interesting conversation to current and future stratigraphic approach in the Ferron Sandstone of the Last Chance Delta. Much of the Ferron stratigraphic architecture of this area was original built off of parasequence concepts of Van Wagoner et al. (1990) and Van Wagoner (1995).

It has been suggested that parasequences are regressive cycles with little preserved in the way of transgressive sediment (Van Wagoner et al., 1990; Zecchin, 2007). Arnott (1995) indicated that parasequences did not address all types of sedimentary successions, but to preserve the usefulness of the terminology, he suggested that the flooding surface be placed at the base of transgressive deposits. Placing the flooding surface at the base of the parasequence's transgressive deposits parasequence would define a transgressive-regressive cycle. Conversely, Catuneanu (2002) illustrated that since flooding surfaces can be maximum flooding surfaces, maximum regressive surfaces, ravinement surfaces, or facies contacts, and that these surfaces could define different types of cycles (T-R, genetic R , or allostratigraphic). This is represented as well in the Ferron where the overall makeup of the large-scale stratigraphic architecture is the same, but the cyclicity is defined differently (T-R cycle of Ryer and Anderson, 2004; versus the genetic-based cycles of Gardner et al., 2004). It is really personal preference as which to use, but which classification is used also has some implications for numbering of the transgressive packages (briefly discussed below). In accordance with the rest of the article, this chapter will use nomenclature focused on transgressive-regressive cycles from which Ryer and Anderson (2004) based their parasequence definition. This discussion is visually summarized in Figure 2.11.

The transition from the “C“ coal to the base of the thin mudstone underlying FA1 could be termed a flooding surface, but it is probably more appropriately titled a transgressive surface/maximum regressive surface. Transgressive Surface (TS) will be used here since the emphasis is on transgression, in accordance with the suggestion of Catuneanu et al. (2011). The Transgressive Surface is a primarily conformable surface marking the change from progradation (tentatively the top of the coal, explained subsequently) to that of retrogradation (Zecchin, 2007). The base of coals have been used in paralic to continental successions in the Cretaceous Book Cliffs of Utah to mark the basal flooding surface of parasequences using the logic that transgression creates the raised water table and limits clastic input allowing peats to thrive (Kamola and Van Wagoner, 1995; Howell and Flint, 2003). Conversely, Garrison and van den Bergh (2004) suggest the Ferron coals are not like the Book Cliff coals of Kamola and Van Wagoner (1995), because the Ferron coals are the product of progradational stacking and additionally are difficult to divide into individual parasequences. The authors herein have no evidence to currently dispute a progradational origin for the coal nor a transgressive origin, nor a combination of the two. Therefore, this study tentatively defers to Garrison and van den Bergh's (2004) progradational hypothesis and place the transgressive surface at the top of the coal along the base of the thin mudstone

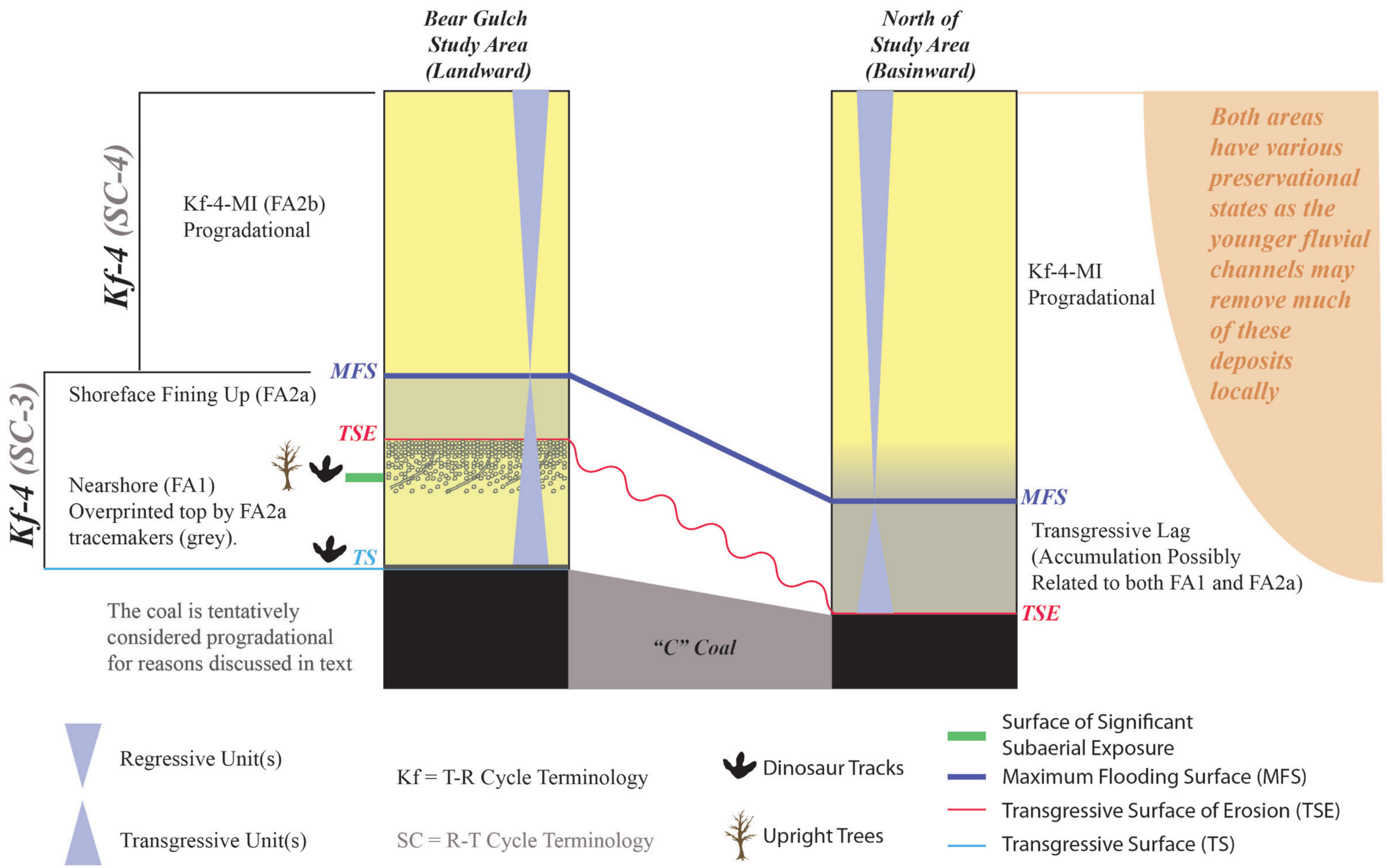

Figure 2.11: A generalized schematic of how the strata of the Bear Gulch study area ties into the transgressive-regressive cycles and stratigraphic surfaces that are observed basinward. Additionally the nomenclatures of both transgressive-regressive (Kf terminology) and genetic sequence (SC terminology) are illustrated in order to show how it affects the numerical assignment in the Ferron Sandstone.

under FA1.

Within FA1 there is likely some higher frequency cycles, as previously evidenced by the disparity between trace fossils and sedimentary structures. Dinosaur tracks are found in FA1 along multiple surfaces primarily in two zones (Figure 2.11). The upper zone may represent a significant period of exposure based on the association with large upright trees.

The top of FA1, where not scoured out with fluvial channels, is marked by a transgressive surface of erosion (TSE). This transgressive ravinement surface dips down to the north and becomes hard to trace as it approaches the base sandstone unit/top of the coal. This ravinement surface is correlated to the base of the transgressive lag, defined by previous authors, north of the study area (Figure 2.3 and 2.11). The transgressive ravinement surface is diachronous (Cattaneo and Steel, 2003; Zecchin, 2007) and therefore the deposits overlying the surface could be chronostratigraphically related to either FA1 or FA2 or both. Additionally, there could be palimpsest facies included in the lag, but these issues can not be resolved with the current data set. The maximum flooding surface, the change from transgressive to regressive, is tentatively distinguished by the transition from fining upward FA2a to coarsening upward FA2b. This surface is difficult to observe in the sandstone, but it is more evident in the interbedded mudstone sandstone interval to the north where the full regressive succession can be viewed (Figure 2.3).

The crosscutting behavior of the transgressive surface erosion across that of the transgressive surface/maximum regressive surface results in the transgressive-regressive cycle having a relatively conformable base in the landward portion and an unconformable base in the more seaward portion (Figure 2.11). The Transgressive Surface (TS) at the base the transgressive package is consistent with the surface's use as the boundary of T-R cycles (Catuneanu et al., 2009). The concurrence of this surface, with that of the ravinement surface is noted by Zecchin (2007). Additionally, this conforms to how Arnott (1995) uses the transgressive ravinement to define the base of the T-R parasequences. By these standards, it was elected to keep the entire package both the transgressive and already established regressive facies as it's original parasequence name Kf-4-MI, representing the transgressive-regressive cycles of Ryer and Anderson (2004). It should be noted for future work in the Ferron Sandstone that applying genetic (regressive-transgressive) cycles (Gardner et al., 2004), while just as relevant, will result in a different cycle assignment for the transgressive facies (i.e., the 3rd cycle; SC-3). This could become a point of contention in future nomenclatural assignment.

2.5 CONCLUSIONS

This study identifies transgressive nearshore conditions of deposition (dominantly intertidal) in the base of the overly thickened landward portion of the dominantly regressive Kf-4-MI. Additionally, a succession of landward stepping deposits, comprising up to several meters of sandstone, are observed within the base of this transgressive-regressive (T-R) cycle. Near the top of the backstepping deposits is a cryptic, sandstone on sandstone, transgressive ravinement surface. This transgressive surface of erosion is manifested as a subtly inclined palimpsest surface. This surface overlies nearshore deposits that are overprinted by abundant *Ophiomorpha*, produced post-erosion from the overlying fully marine environment. Some could misinterpret the *Ophiomorpha* and planar bedding to be representative of the shoreface rather than a cross cutting trace fossil assemblage. The diachronous ravinement surface dips down to the north and is linked to the base of the basinward transgressive lag, which overlies the coal north of the study area. The base of the transgressive-regressive cycle in the study area (landward portion) is represented by a relatively conformable initial transgressive surface with the later transgressive ravinement surface lying above (over the nearshore sandstone). The base of the T-R cycle in the north is unconformably marked by this ravinement surface.

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CHAPTER 3: *RHIZOCORALLIUM* AND TURTLE TRACKS: A LATE CRETACEOUS FLUVIAL CHANNEL TRACE ASSEMBLAGE

3.1 INTRODUCTION

Turtles and mayflies (*Rhizocorallium* producer) are often observed in modern freshwater environments, and originate prior to or during the Triassic (Edmunds, 1972; Carpenter, 1979; Rieppel and Reisz, 1999; Sinitshenkova et al., 2005; Lyson et al., 2010, 2013), however the preserved activity of these organisms are rarely observed in the fossil record (Lockley and Meyer, 2000; Boyd and Lillegraven, 2011). Additionally, reports of trace fossil assemblages in channelized fluvial deposits are rare and believed to have low preservation potential in the fossil record (Melchor et al., 2012). This study examines several bedding planes, comprising a trace fossil assemblage, in a Cretaceous channelized sandstone body by examining the traces, types of preservation, and the proposed tracemakers, thus allowing for discussion on fluvial ichnofacies as well as problems with identification and preservation of these traces.

The investigation focuses on an interval in the Turonian-Coniacian Ferron Sandstone of central Utah, which is noted to contain a wealth of invertebrate traces, but the reports of vertebrate traces and body fossils are rare. Jones (2001) and King and Anderson (2013) have reported occurrences of dinosaur tracks within the Ferron Sandstone, but no other terrestrial vertebrate traces are described thus far. In the study area, Last Chance Delta, the Upper Ferron Sandstone is up to 150 meters thick and lies between the Tununk Shale and the Blue Gate Shale (Ryer, 2004)(Figure 3.1a). These deposits are dominantly the result of fluvial and deltaic sedimentation along the western margin of the Western Interior Seaway (Garrison and van den Bergh, 2004).

3.2 SEDIMENTOLOGY

3.2.1 Description

The channelized sandstone of interest in this study is located near the Ivie Creek area in the Last Chance Delta of the Upper Ferron Sandstone (Figure 3.1b). This sandstone

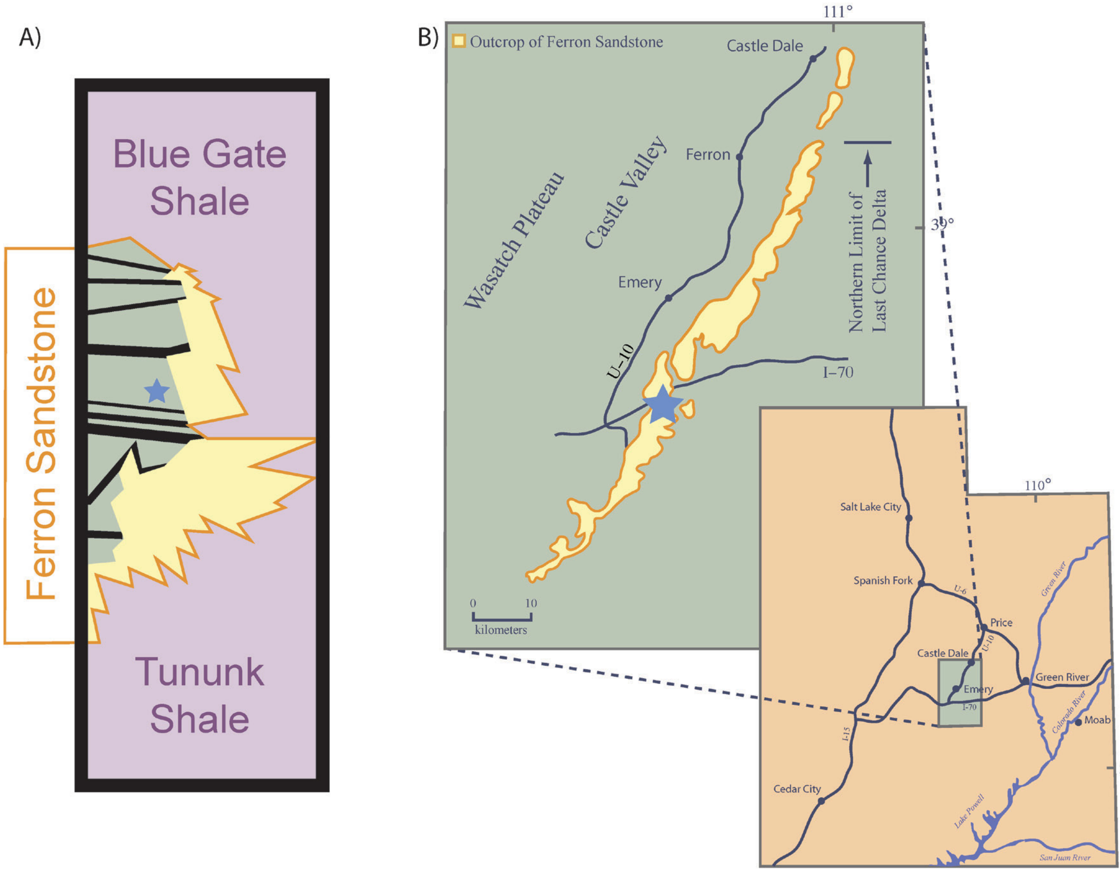

Figure 3.1: Location of the study area. a) Generalized stratigraphic section with blue star indicating stratigraphic location of the trace assemblage within Last Chance Delta. The section represents a rough outline (modified from Garrison and van den Bergh, 2004) of the southwest to northeast distribution of the marine/nearshore sandstone (yellow), coastal plain deposits (green), and coal zones (black). b) Geographic location of the study area indicated by the blue star (modified from Garrison and van den Bergh, 2004; after Cotter, 1975).

body (Figure 3.2) lies 1.6 meters over what appears to be the uppermost coal in the "C" coal zone in this area. The sandstone has a sharp dipping basal contact with blocky, rooted mudstone. Large wood debris can be seen in the underlying mudstone extending up into the sandstone at moderate to almost vertical angles. Some wood debris was observed completely within the sandstone at various levels. Additionally, centimeter scale angular to subrounded grey mudstone clasts are seen in the base of the sand body, and within the sandstone at the base of cross-beds, or overlying undulatory contacts.

The sand body appears ribbon-shaped (*sensu* Friend, 1983) and at one level is observed with an extension and thinning into the laterally equivalent mudstone. Numerous dipping undulatory contacts occur within the sand body (Figure 3.2, top). The sandstone is composed mainly of very fine to fine grains with cross-beds typically in decimeter scaled sets. The cross-beds dip toward almost due east. The preservation of the biogenically modified surfaces are present about 73 centimeters up from the base of the sandstone in a rare interval of relatively straight crested 2-D rippled sandstone interbedded with thin mudstone beds and lamina. Typically, less than ten centimeters of this rippled unit is preserved and it is replaced laterally on several meters of either side as cross-beds with undulatory bases drop and replace the interval. This interval tops a small overall fining upward succession. Ripples in the interval appear to maintain the same orientation over multiple surfaces with the strike of the crest ranging from 340 to 4 degrees.

3.2.2 Interpretation

This sandstone body is interpreted as deposits of suspended to mixed load meandering systems that appears to represent limited lateral migration and reoccupation by small channels. An event marking a decrease in flow allowed for the preservation of the trace fossil assemblage. Re-initiation of higher velocity flow in the channel removed much of the previously deposited lower flow regime facies.

Ribbon shaped sand bodies are relatively fixed channels, which are often characteristic of suspended and mixed load river systems (Miall, 1985; Miall, 1996). This is further supported by the wing-like extension into floodplain mudstones, which is indicative of the levee deposits, or the product of the channel exceeding bankfull stage (Stear, 1983; Nadon, 1994). While the roots and blocky texture of the mudstones indicate paleosol development, the grey color of the adjacent mudstones is often linked with gleying or prolonged saturation due to a high water table (Retallack, 1988; Kraus, 1999; Retallack,

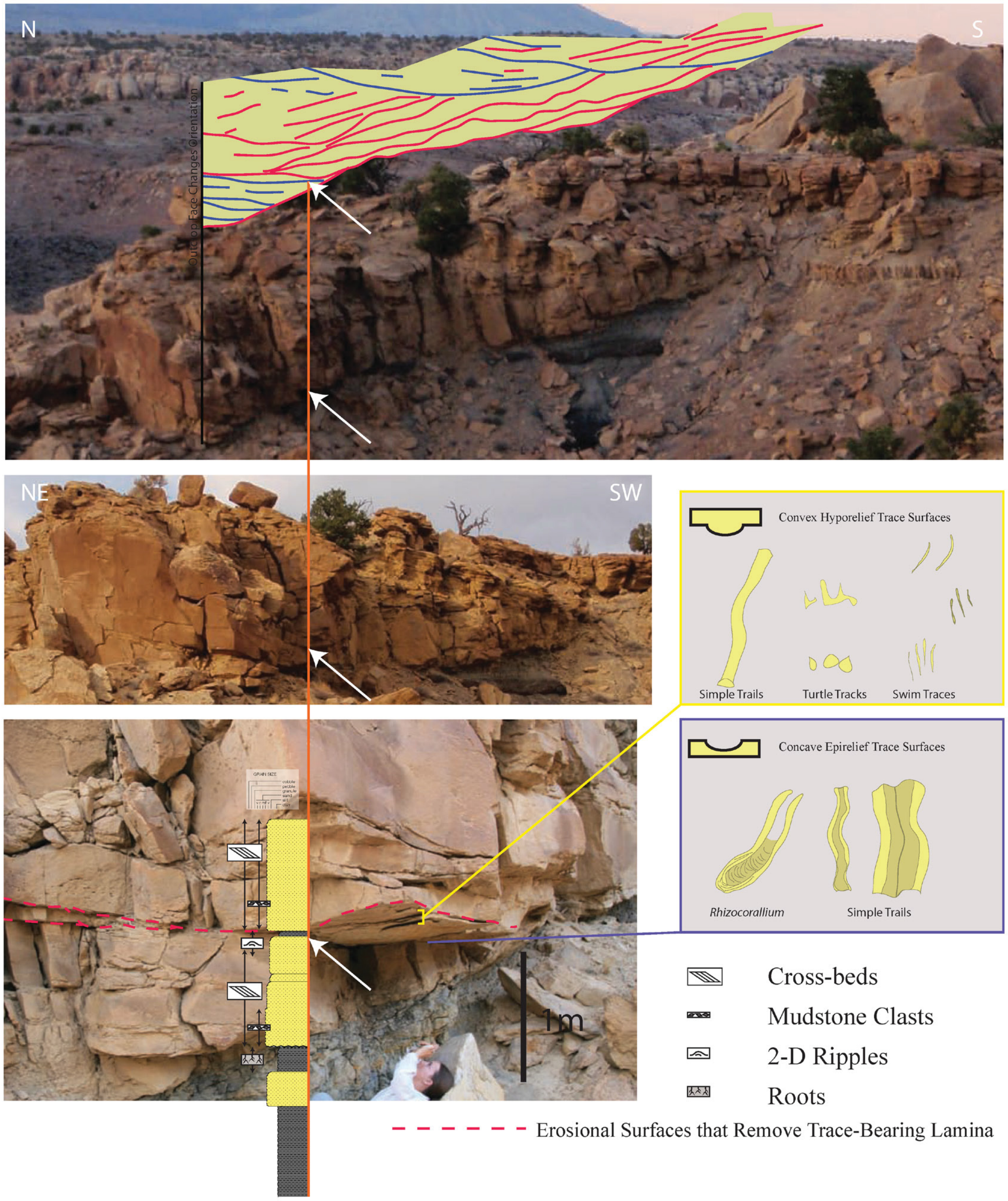

Figure 3.2: Different views of the channelized sandstone with the location of the trace assemblage in measured section. At top is a graphic representation of the bounding surfaces in the lenticular sandstone body. Right dipping bounding surfaces are denoted by blue lines whereas left dipping surfaces are in red. Notice the change in the direction of bounding surfaces from blue to red right about the trace assemblage likely indicating a different generation of channel occupation.

2001). The dipping surfaces within the sand are likely the product of lateral migration of the point bar (e.g., Allen, 1970). The dominance by cross-beds and erosional bounding surfaces suggest a system that regularly achieved higher energy. The directions of the cross-beds are similar to regional northeastern direction of progradation of the deltaics (e.g., Garrison and van den Bergh, 2004). Additionally, the grey mudstone clasts appear to be ripped up from the underlying and adjacent floodplain deposits.

The 2-D rippled interval that contains the trace fossils represents a period of hydrodynamic energy decrease, which is evident from the decrease in grain size upward to the surface as well as the decrease from cross-beds to that of ripples that become interbedded with mudstone. Possible causes for the decrease could have been the result of seasonal or climatic fluctuations in the volume of water, the result from an upstream avulsion, or may simply represent point bar shift resulting in a sheltered downstream position. Symmetry and continuity in ripple crests is largely the product of one of three processes: waves, winds, or migration along a slope (Rubin, 2012). Edwards et al. (1983) documented straight crested and continuous ripples that were produced oblique to transport along the slope of Permian point bars. Similar ripples are also seen along the downstream end of modern bar documented by Martin (2010), however, he noted some of the small ripples are produced by wind in shallowly ponded bar top depressions during low water levels. Possible similar ripples are seen in the photos of Pryor (1967) in slough (abandoned chute on the downstream side) ponding during water level drops.

The 2-D ripple directions are roughly perpendicular to that of the noted general cross-bed orientation, but as noted above may provide a tangential indication of flow direction, or actually represent prevalent wind direction. Although, the common orientation of the ripples does suggest a rather continuous flow orientation during deposition. The mud drapes and interbeds suggest that this was not a singular rapid sedimentation event, and may have been separated temporarily by more stagnant conditions. Regardless of the mechanism that led to the lower flow condition that allowed the deposition of the ripples, this is followed by later reoccupation, rejuvenation, or shifting of the point bar which is indicated by the change in directional dip of erosional forms and bounding surfaces (on the outcrop face) above the 2-D rippled interval from right dipping to left dipping (Figure 3.2, top).

3.3 TRACE FOSSILS

The trace fossils in this study are present along bedding planes in two semirelief forms: one dominated by concave epirelief and one dominated by convex hyporelief (Figure 3.2, 3.3). The concave epirelief surfaces occur as trails cutting across the 2-D rippled surface and the weathered out remnants of *Rhizocorallium* traces that extended down to allow their horizontal component to rework this surface. Above this surface is 2-D rippled sandstone with interlaminated/interbedded mudstone that contains several surfaces with convex hyporelief expressions of turtle tracks and a few simple, possibly branching trails. Additionally, *Teredolites* is present in the channel sandstone, however, evidence is present that these are not associated with the depositional environment, but are being reworked from the underlying sediment.

3.3.1 Simple Trails

There are three types of simple trails exhibited within the 2-D rippled sandstone and interbedded mudstone. These types are small simple furrows, large simple bipartite furrows, and traces exhibiting chevron type morphologies.

3.3.1.1 Description

The small simple furrows are epichnial or hypichnal surface trails that are shallow, small, generally u-shaped, simple furrows that are typically between 1.5 to 3 millimeters wide (Figure 3.4, 3.5a). Subtle ridges are often present along the margin of the trace, but the prominence or occurrence of these ridges may change along the length of the trace. These trails are straight to broadly meandering. The meander of the trail is not regular. They do not loop or cross their prior path. They may cut other traces. These trails are often discontinuous, but can be as long as 19 centimeters in some segments. The longer preservation of trails appears to be parallel to the ripples and dominantly in the troughs between the ripples, conversely, many of the shortest trails are perpendicular cutting the crest of ripples. There appears to be three major orientations of the trace in relation to the crest of the ripples: parallel, perpendicular, and left tangential (Figure 3.4).

The large furrows are observed as bipartite epichnial surface trails that are 1.5 to 2.5 centimeters wide and contain two sloped walls meeting in the median, forming a shallow v-shaped cross-section (Figure 3.4, Figure 3.5a). The walls are very roughly symmetrical

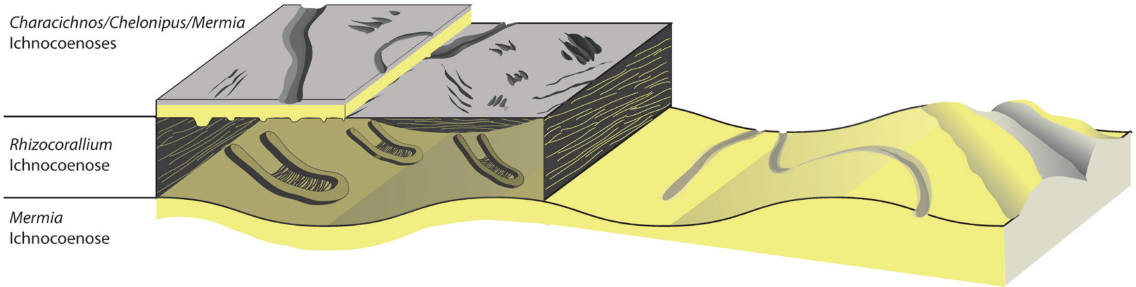

Figure 3.3: General relationship of traces and ichnocoenoses. Not to scale.

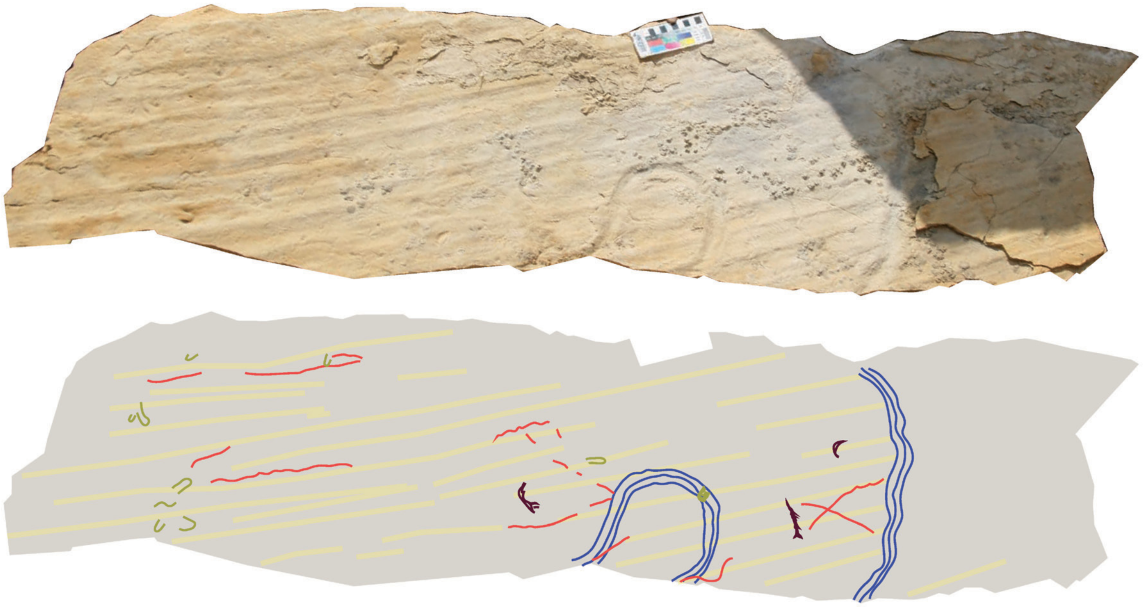

Figure 3.4: Epichnal traces on the 2-D rippled surface: ripple crest (yellow), small simple trails (*Helminthoidichnites*; red), large simple bipartite trails (blue), *Chevronichnus* (maroon), and *Rhizocorallium* (green).

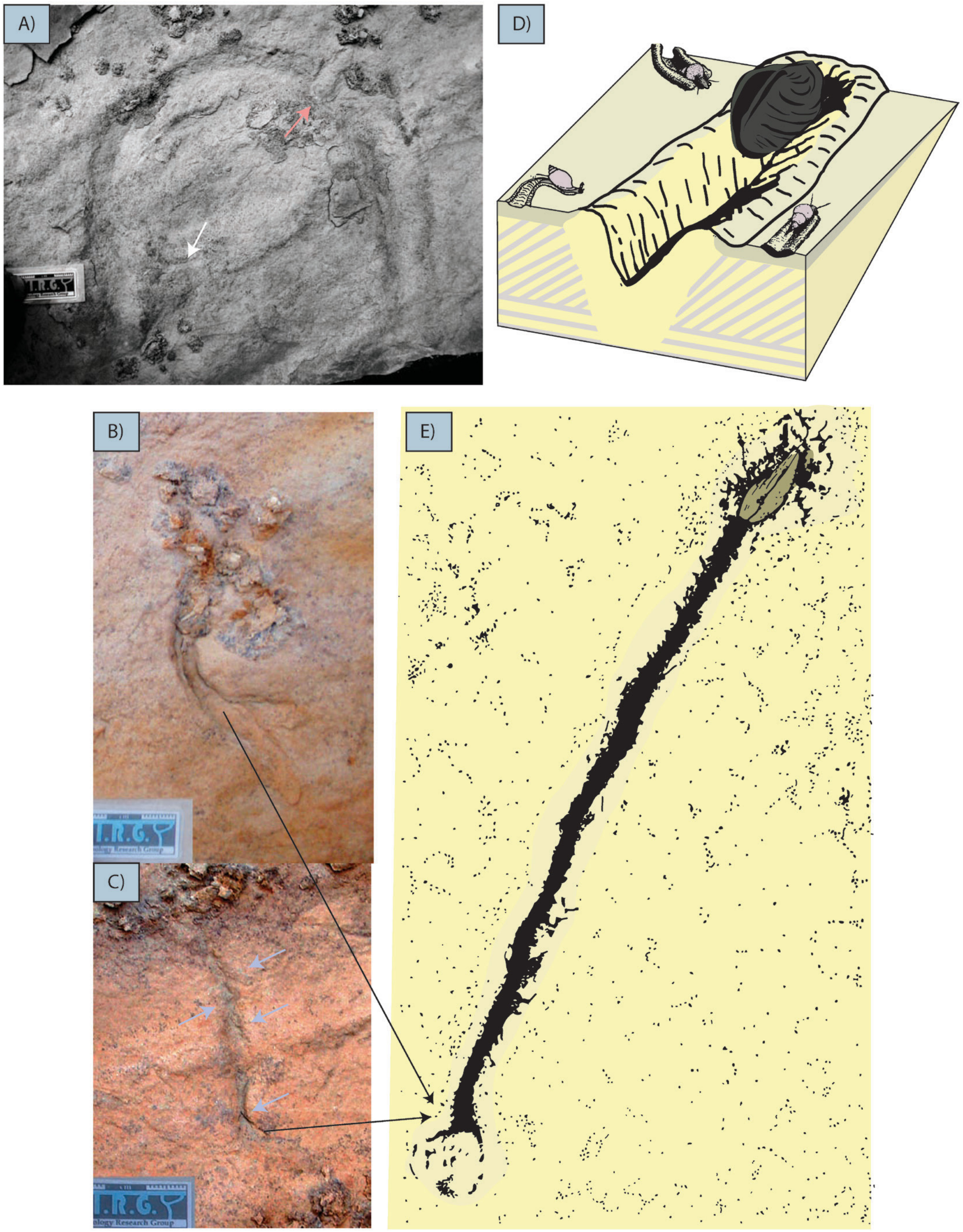

Figure 3.5: Epichnal trace expressions: a) Large bipartite trail cut by simple trail (*Helminthoidichnites*; white arrow) and *Rhizocorallium* (pink arrow), b, c) *Chevronichnus* traces d) simple U- and V-shaped trails produced by mollusks (modified after Pryor, 1967; Baldwin, 1974; Chamberlain, 1975), and e) bivalve uprighting/entry structure produced at the end of a plowed trail (Heezen and Hollister, 1971).

in cross-section. Small ridges are typically present along the margin of the furrow. These traces exhibit relatively straight to meandering paths with lengths (limited by the edge of the exposed surface) of up to 43 centimeters.

The chevron structures are epichnial structures that are 1 to 1.5 centimeters wide and meet at a central furrow (Figure 3.5b, c). These structures are up to 6 centimeters in length and are straight to arcuate in plan view. The furrow can sometimes start from another one of the smaller furrows or have a distal horn shaped feature. These generally appear perpendicular to and cross-cutting the ripple crests.

3.3.1.2 Taxonomic Interpretation

The small relatively straight u-shaped epichnial and hypichnal trails are probably best assigned to *Helminthoidichnites* since they do not meander like *Cochlichnus* or *Helminthoida*, and do not cross over themselves like *Gordia* (Buatois et al., 1997; Wang et al., 2009). Some authors may refer to these as *Scolicia*, however those traces are generally reported at a slightly larger scale than those in this study (e.g., Hasiotis, 2006). Simple traces like *Helminthoidichnites* produced in modern environments by the locomotion and grazing activity of organisms such as nematodes, oligochaetes, insects, or in larger instances molluscs (Baldwin, 1974; Chamberlain, 1975a; Buatois et al., 1997; Hasiotis, 2004; Martin, 2010). Similar sedimentary structures (i.e. tool marks) may also be produced by fluid transport of dragging clasts across the surface (e.g., Allen, 1982). However, this may be ruled out for many of these since the traces are at odds with the direction of the ripples on the surfaces.

The large simple bipartate epichnial structures (surface trails) like the one in this study have been taxonomically described in the modern as "*Gordia*-like" (Lawfield and Pickerill, 2006) and as the trace of "*Scolicia*?" by Turner (1978). However *Scolicia* is a transversally U-shaped and consists of a tripartite arrangement (a floor and two lateral walls)(Smith and Crimes, 1983; Fillion and Pickerill, 1990). The trace in this study as well as the modern examples does not fit the description of *Gordia* because the furrow comes to a medial low (as a v), not a simple cylinder-like shape, and *Gordia* is generally an order of magnitude smaller (on the millimeter scale) and cross-cuts itself (Buatois et al., 1997; Wang et al., 2009). There does not currently appear be a proper ichnotaxonomic name for this type of trace preservation. Conversely, there is an abundance of modern examples of molluscs (gastropods and bivalves) producing similar traces as they plow through the sediment (Figure 3.5d). The repichnia (locomotion) traces of bivalves are split into two categories according to foot morphology by Seilacher and Seilacher (1994): a) *Lockea* representing the locomotion of wedge-footed bivalves and b) *Protovirgularia* represented the movement of cleft-footed bivalves (Protobranchia). However, the trace in this study does not show either the distinct ovoid or chevron shapes associated with either of these. As Seilacher and Seilacher (1994) noted, *Lockea* and *Protovirgularia* traces are generally produced as under tracks, which may lie under a surficial trail. Since no under tracks can be observed from the relief presented in the outcrop, it makes it unwise to try to attribute a previously defined bivalve repichnical trace genera. While *Protovirgularia* are often traces exhibiting a continuous long medial furrow, and some authors use *Chevronichnus* as a taphonomic modifier on the trace (e.g., Buatois et al., 2009), it is worth noting that the freshwater producers (Unionoidea) of strikingly similar (to this study) modern examples (e.g. Pryor, 1967; Chamberlain, 1975a; Lawfield and Pickerill, 2006) are produced by the wedge-footed bivalves. Assigning it to *Protovirgularia* would only convolute the usefulness in the current genus ethological relationships.

Conversely, the fourth type of furrow described that contains the chevron ornamentation would fall into the classification as *Chevronichnus*. *Chevronichnus* is the product of an organism (e.g. bivalve) plowing through the sediment during locomotion (Hakes, 1976). Additionally, the similar horn shaped epichnal grooves that are produced at the end of the trace is similar to modern bivalve entry/uprighting structures of Heezen and Hollister (1971)(Figure 3.5e). Although the location of these horn shapes in relation to the ripples may also indicate that they are the product of the organism's initial plowing through the microtopographic highs (ripple crests).

3.3.1.3 Depositional Environments

These simple trails are fairly nondescript, representing a water saturated or subaqueous surface on which the traces were produced. There is no implication about the water salinity, nor depth, that can be currently teased out of these behaviors. These behaviors and resulting biogenic structures are widespread through modern subaqueous environments and are reported from freshwater lakes and rivers, brackish lagoons and tidal flats, beaches, all the way to the depths of the ocean floor (e.g., Abel, 1935; Pryor, 1967, Heezen and Hollister, 1971; Chamberlain, 1975a, b; Lawfield and Pickerill, 2006; White and Miller, 2010), all be it they occur in different assemblage groups.

These traces are similar to the constituents of the archetypal *Mermia* trace fossil suite with a dominance of grazing traces (*Helminthoidichnites*) and lesser occurrence of locomotion traces (Large bipartite trails, and *Chevronichnus*). Melchor et al. (2012) suggests fluvial *Mermia* suites are permanently subaqueous, low energy environments that are restricted to "floodbasin ponds" in fluvial settings. Conversely, the simple horizontal trails in this study occur within the channel, which could be the conversion of the channel to more lentic conditions during abandonment, but also studies on modern fluvial bars (Pryor, 1967; Lawfield and Pickerill, 2006; Martin, 2010) have shown abundance of these small simple traces in sheltered areas along the bars (e.g., chute channel sloughs and the downstream ends). Melchor et al. (2012) does assert that there are currently not many ancient fluvial *Mermia* assemblages known (seven in his thorough review).

3.3.2 U-Shaped Traces (*Rhizocorallium*)

3.3.2.1 Description

The traces weather out as an organized series of small epichnial grooves (Figure 3.6a, b) along the top a 2-D rippled sandstone surface, associated with all three of the epichnial types of simple trails described above (Figure 3.4). These traces appear to have no distinct unimodal orientation, are sparsely to moderately distributed across the surface, don't appear to cut themselves, and are rarely crossed by any other forms. These traces contain a 1−3mm u-shaped groove bounding the trace, with spreite running between the arms of the larger "U". The spreite appear to be in fairly regular sets. The large groove is always present on the outside of these spreite making the traces protrusive along the horizontal axis (e.g. Seilacher, 1967). Small linear features run parallel with the larger tubes in some places suggesting vertical axis shifting, but since the trace is only present as an epichnal feature, it is difficult to determine the overall direction. Poorly definied, small oblique to transverse grooves may also be observed at the trace fossil margin. Overall the trace is roughly bisymmetrical along a central axis. The outer arms of the large bound "U" are mainly straight, but may have a bowed appearance. The bowed appearance, when observed, is accompanied with a flaring of the trace width and the parallel linear spreite. This might indicate a false bowing or flaring that is representative of a preservation bias of vertical movement than the synonymous relationship of horizontal structure. These traces are always longer, 11-31 mm, in respect to the arms of the outer "U" than the total width across, 6-19mm. The length to width ratio is roughly 2:1 for the portion of the traces that were observed (Table 1). However true length is likely not preserved on this surface, and the level to which the traces extend upward could not be observed at the outcrop. No

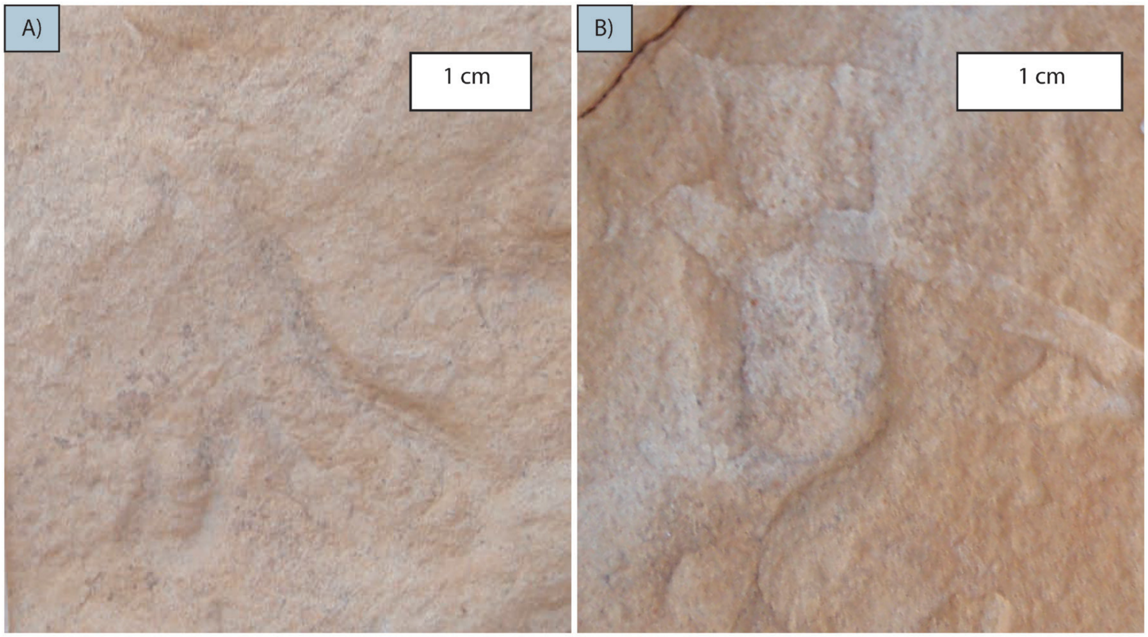

Figure 3.6: *Rhizocorallium* traces: a) *Rhizocorallium* traces with false branching and b) rare example of trace cross-cutting *Rhizocorallium*.

Outer Tube Diameter	Length of Tube Preserved	Widest Outer Portion
2	>17	10
2	26	10
2	18	8
2.5	43	11
2	14	7.5
2.5	>26	13
3	31	19
3	34	15
2	18	11
1	11	6

Table 3.1: Measurements of *Rhizocorallium* burrows in the study area.

fill was present within the traces either, but is assumed to be mainly a mudstone or silty mudstone fill based on the capping lithology.

3.3.2.2 Taxonomic Assignment

These traces are interpreted to represent the weathered endichnal expression produced along the bases of *Rhizocorallium* traces. A thorough review and revision of *Rhizocorallium* taxonomy can be found in Knaust (2013). Species identification is hindered by the inability to access the full trace length, cross-sectional geometry, the trace fill (passive or active), or the inclination angle in relation to the surface. However, these traces are probably best tentatively described as *Rhizocorallium jenense* (Zenker, 1836; revision of Knaust, 2013) rather than *Rhizocorallium commune* due to the small size of the traces and relatively straight arms with a general lack of sinuosity. The small groove marks in the traces from this study do show evidence of some scratching in the tubes (bioglyph; Bromley, 1996), but the taphonomic preservation of the trace as well as the small scale hinder the ability to tease out the overall orientation and cross-cutting relationship of the scratches. These traces are morphologically similar to the protrusive *Rhizocorallium jenense* described by Fursich and Mayr (1981), however the traces in this study have slightly smaller average widths and tube diameters. It is worth noting that the description of the traces in this study do not conform to the similar continental trace, *Fursichinus commune*, which was differentiated from *R. jenense* by Bromley and Asgaard (1979) as a retrusive trace, that is not as organized, and typically have J-shapes that do not exhibit parallel legs.

3.3.2.3 Ethological Assessment

Rhizocorallium jenense is the domicile of a suspension-feeding organism (Knaust, 2013). Three modern animals were identified by Seilacher (1967) to produce small rhizocorallid burrows with parallel arms: ephemerid larvae (mayflies), *Corophium volutator*, and *Polydora ciliata*. However, the term was used in terms of the morphofamily Rhizocorallidae (which includes vertical forms), and modern examples of *Corophium* and *Polydora* burrows in tidal channels are typically shown to be vertical *Arenicolites* or *Diplocraterion*-like traces (e.g., Gingras et al., 1999; Gingras et al., 2000; Gingras et al., 2001). Ephermerid (mayfly) larvae are known to produce horizontal *Rhizocorallium*-like burrows in the modern (Abel, 1935; Ilies, 1968; Scott et al., 1959; Chamberlain, 1975a). Nevertheless, most of these studies have focused on description of the high-density occurrences along the cutbanks leaving interpretation fairly open as to whether these are also capable of being produced in other subaqueous areas that do not exhibit near vertical surface-water interfaces. In general, more neoichnological work is needed to determine the burrow orientation reliance on the slope of the sediment-water interface of these organisms, since the orientation often appears perpendicular to the surface slope. It is important to know which organisms or factors can produce/result in *Rhizocorallium* that are not sediment-water contact slope mediated (i.e., relatively horizontal surfaces).

With the present understanding, mayfly larvae are suggested to be the most likely *Rhizocorallium* trace producer. However, at the face of this outcrop there is no indication of a near vertical inclined bounding surface (cutbank). Additionally, the problem with this study lies in the sporadic orientation of the *R. jenense* which is contrary to what is seen in the previously mentioned modern studies, where the u-shape is dominantly directed toward the sediment-water interface. The varied orientation could be the response to multiple factors such as the shallowness of the mud (e.g., cohesiveness of walls, inability or avoidance of moving the underlying larger sand particles), lack of strong unimodal currents or separate emplacements during disparate currents, or microtopographic mediated flows patterns created by the mud armored underlying ripples, let alone the microtopography itself.

3.3.2.4 Depositional Environment

All of three Rhizocorallid tracemakers listed above share the occupation of a similar environment with highly turbulent subaqueous conditions and a prerequisite stiffness of the substrate (Seilacher, 1967). This may suggest that, prior to colonization, the substrate cohesiveness was greater, and that could be a result of dessication or compaction. Due to the size and placement of the *Rhizocorallium*, it seems unlikely that they are related to the overlying erosion, but since the tube apertures cannot be located this cannot be ruled out all together. The *Rhizocorallium* alone, with the current understanding of channel-produced biogenic structures, cannot necessarily assess salinity. Mayflies in modern settings are known to construct burrows in freshwater lotic environments, which are often meandering rivers (Abel, 1935; Wesenberg-Lund, 1943; Edmunds and McCafferty, 1996; Scott et al., 1959; Chamberlain, 1975a; Staniczek, 2003; Tittizer et al., 2008). The rare reports (Fursich and Mayr, 1981; De, 2002; Sinitshenkova et al., 2005) of *Rhizocorallium* in ancient fluvial deposits have suggested mayfly biogenic sedimentary structure production as far back as the Triassic.

3.3.3 Turtle Tracks and Swim Marks

3.3.3.1 Description

The traces are represented by various convex hyporelief traces (natural casts) at the bases of very fine-grained sandstone beds that overlay thin mudstone lamina or beds. These traces are typically grouped into tracks composed of three, sometimes four hyporeliefs, more rarely two and possibly, yet inconclusively five. These tracks show a multitude of morphotypes across the surface, which are additionally marred by high density and hence trace overprinting on many of these surfaces. The tracks range from elongate linear features to that of subrounded natural casts. The casts appear to mainly parallel the ripple crests (Figure 3.7)

At one end of the spectrum the traces are represented by elongate linear features (Figure 3.8a), which are most often observed as three realitively equal spaced features. The trace fossils are roughly symmetrical with the middle feature typically being the largest. These features can be connected at one end by a slightly arcuate hyporelief depression (Figure 3.8b). The features all taper away from this depression. Variations on this theme include: a) additional features present on either side of these, as shorter elements, b) only two linear features prominently represented in the track c) exhibition of a more arcuate nature, and d) length of and spacing between the features in each track. The individual marks are typically only a few millimeters in width and depth, and range from 0.75 to 4.5 cm long. The tracks can be up to 4 cm wide.

The second type, subrounded natural casts (Figure 3.8b,c, f, g), are typically in groups of three, but may exhibit a faint fourth feature. These natural casts are often elongate tear drop or comma shaped. These are grouped into tracks in parallel to arcuate arrangements. The individual features can be up to 2 cm long, and typically less than 1 cm wide. The track as a whole is always wider than the length. The width typically ranges between 2-3cm.

3.3.3.2 Taxonomic Assignment

The trace morphologies describe above represent a continuum between more ambiguous, simple expressions (*Characichnos*) and more detailed morphological preservations (*Chelonipus*). The elongate features described are consistent with the formal description of *Characichnos* from Whyte and Romano (2001) in that the trace consists of 2-4 parallel hypichnal ridges that can be defined as reoccurring sets of features along the surface.

The second morphology of shorter, more rounded features representing the other end of

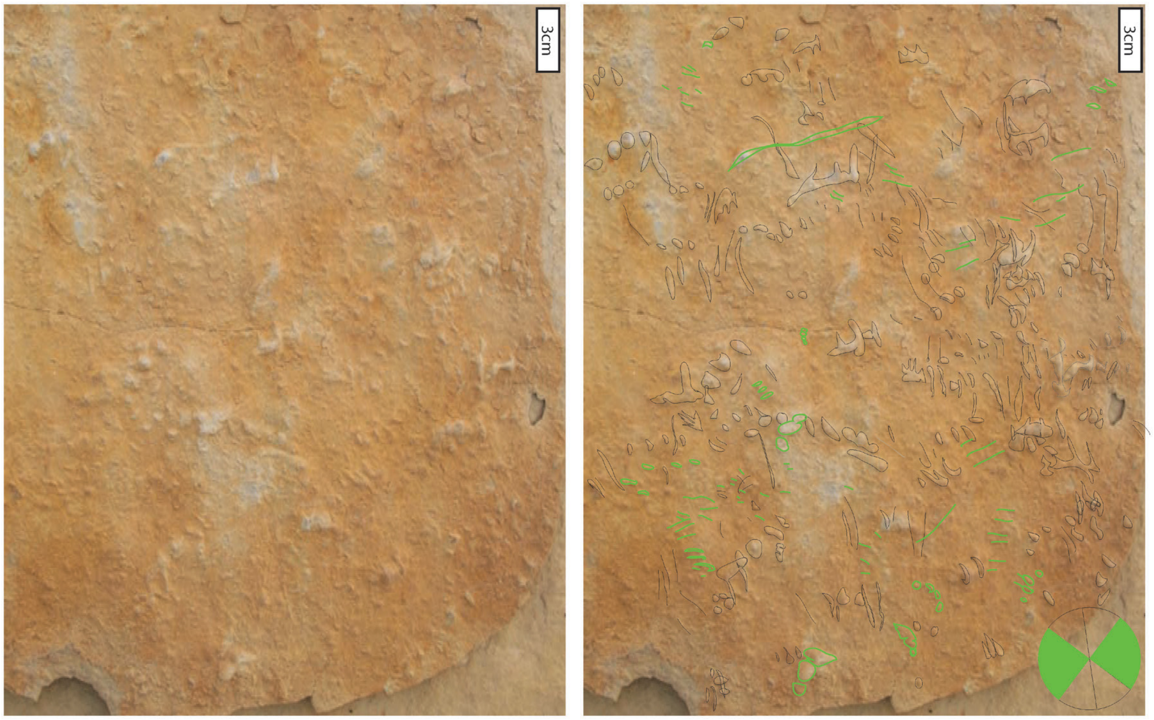

Figure 3.7: Orientation of *Chelonipus* and *Characichnos* traces. Green represents perpendicular orientations to 2-D ripples hence probable traces related to movement with flow. Note, most orientations are in black, hence contradictory to flow.

Figure 3.8: Examples of vertebrate traces in the study area compared to other reports of turtle tracks: a) *Characichnos*, b) *Chelonipus,* c) Possible five-toed trace, although difficult to completely dismiss overprinting, d) tridactyl *Chelonipus* of Foster and Lockley (2006), e) *Chelonipus* of Lockley et al. (2010), f) pentadactyl *Chelonipus* of Lockley and Foster (2006), g,h) *Chelonipus*, possible manus/pes sets.

the morphological spectrum are interpreted as *Chelonipus* (turtle tracks). These traces fit the description of *Chelonipus* in Lockley and Foster (2006): traces are often sets of three (up to five) tapered (anteriorly) features, with the middle feature most often being the longest and the set having a greater width than length. The features in an individual *Chelonipus* track are typically fairly symmetrical in appearance (Foster et al., 1999). Additionally, some of these traces (this study) display an arching connection of these features that have been used as a characteristic by others to describe *Chelonipus* (e.g., Lovelace and Lovelace, 2012) as well as other tracks attributable to turtles (e.g., Avanzini et al. 2005; Belvedere et al. 2013).

Another trace that belongs in the morphofamily Chelonipedidae (*sensu* Sarjeant and Langston, 1994) named *Emydhipus* exhibits similar morphologies, but is considered a separate valid ichnogenera based on the parallel relationship of the toes in the manus, and the relative orientation of the manus to the pes (Avanzini et al., 2005). However, the authors assert that the manus morphology of individual prints from both ichnogenera (*Chelonipus* and *Emydhipus*) may look similar in certain substrate conditions. Therefore, being able to relate the manus and pes becomes a vital part of identification. The problem with the surfaces like the ones reported in this study are that the trackways are incomplete, often heavily overprinted, and the manus/pes sets are difficult to establish. The difficultly of establishing manus/pes sets in *Chelonipus* is thought to be an inherent result associated with the style of turtle locomotion (Foster et al., 1999; Lockley and Foster, 2006). Since manus/pes relationships cannot be consistently established for this study, these traces are referred to the senior of the two ichnogeneric terms, *Chelonipus*. Lockley and Foster (2006) additionally suggest that these *Emydhipus* (*sensu* revision of Avanzini et al., 2005) occur at a larger scale, and typically display four prominent elongate features. Notably depositional environment of *Chelonipus* are consistent with earlier reports (e.g., Lockley and Meyer, 2000; Lockley and Foster, 2006).

Some of these tracks could be attributable to crocodile manus prints since they can have similar morphologies, and often are associated with *Chelonipus* tracks (Lockley et al., 2010). Although at this time this is tentatively ruled out due to the small size of the tracks, there is no apparent indication of two distinctive sized tracks (manus/pes heteropody; Avanzini et al., 2005), and both crocodiles (and lizards) typically leave tail drag marks (Bernier et al., 1982), which were not evident on the trace surface. Additionally, lizards (e.g., *Rhynchosauroides*) also have more asymmetric track geometries with digit length increasing from digit I to IV and amphibians typically display rounded features instead of claw marks (Haubold, 1984; Avanzini et al., 2005).

3.3.3.3 Ethological Assessment

Characichnos is one of the few vertebrate ichnogenera named (*sensu* Whyte and Romano, 2001) based on organism behavior (swimming) with a morphology that could be attributable to multiple organisms (e.g., dinosaurs/avians, crocodilians, chelonians, amphibians). The *Characichnos* here are attributed to turtles,because of the similiar size and direct occurrence with *Chelonipus*, but it is not out of the question that any of the aforementioned other organisms may have produced some of the traces. Especially since *Hatcherichnus* and *Chelonipus* often occur together (Lockley et al., 2010). These traces do indicate a subaqueous behavior.

Chelonipus tracks are often interpreted to be associated with partially buoyant movement (with anterior dragging of the claws during withdrawal) of turtles in shallow waters when leaving inconsistent prints (Foster et al., 1999; Lockley and Foster, 2006). Variations in vertebrate track morphology (i.e., foot morphology vs. swim tracks) have been noted to change across single surfaces due to substrate variations or between layers due to changing conditions (i.e., subaqueous to subaerial) (e.g., Bernier et al., 1982; Avanzini et al., 2005; Mickelson et al., 2006; Milner et al., 2006; Lovelace and Lovelace, 2012).

Turtles (excluding fully marine forms) for the most part have trouble dealing with variations in salinity, and their presence in brackish environments usually suggests a close proximity to a freshwater source, or an adequate supply from rainfall (Dunson and Mazzotti, 1989). Turtles (*sans* fully marine forms) in the late Cretaceous preferred slow flowing rivers or dry land habitats (Figure 5.1 of Renous et al., 2007)

3.3.3.4 Depositional Environment

These tracks likely indicate dominantly subaqueous conditions in a freshwater channel. *Chelonipus* tracks have been generally described from freshwater fluvial channels (e.g., Foster et al., 1999; Foster and Lockley, 2006; Lockley and Foster, 2006; Lockley et al., 2010; Lovelace and Lovelace, 2012). The presence of both *Characichnos* and *Chelonipus* likely reflect variable saturation/firmness conditions during emplacement, or possibly just variations in the way the buoyant animal interacted with the surface.

3.3.4 Organism-Bored Wood

3.3.4.1 Description

The traces are contained within coal lenses and along weathered wood impressions

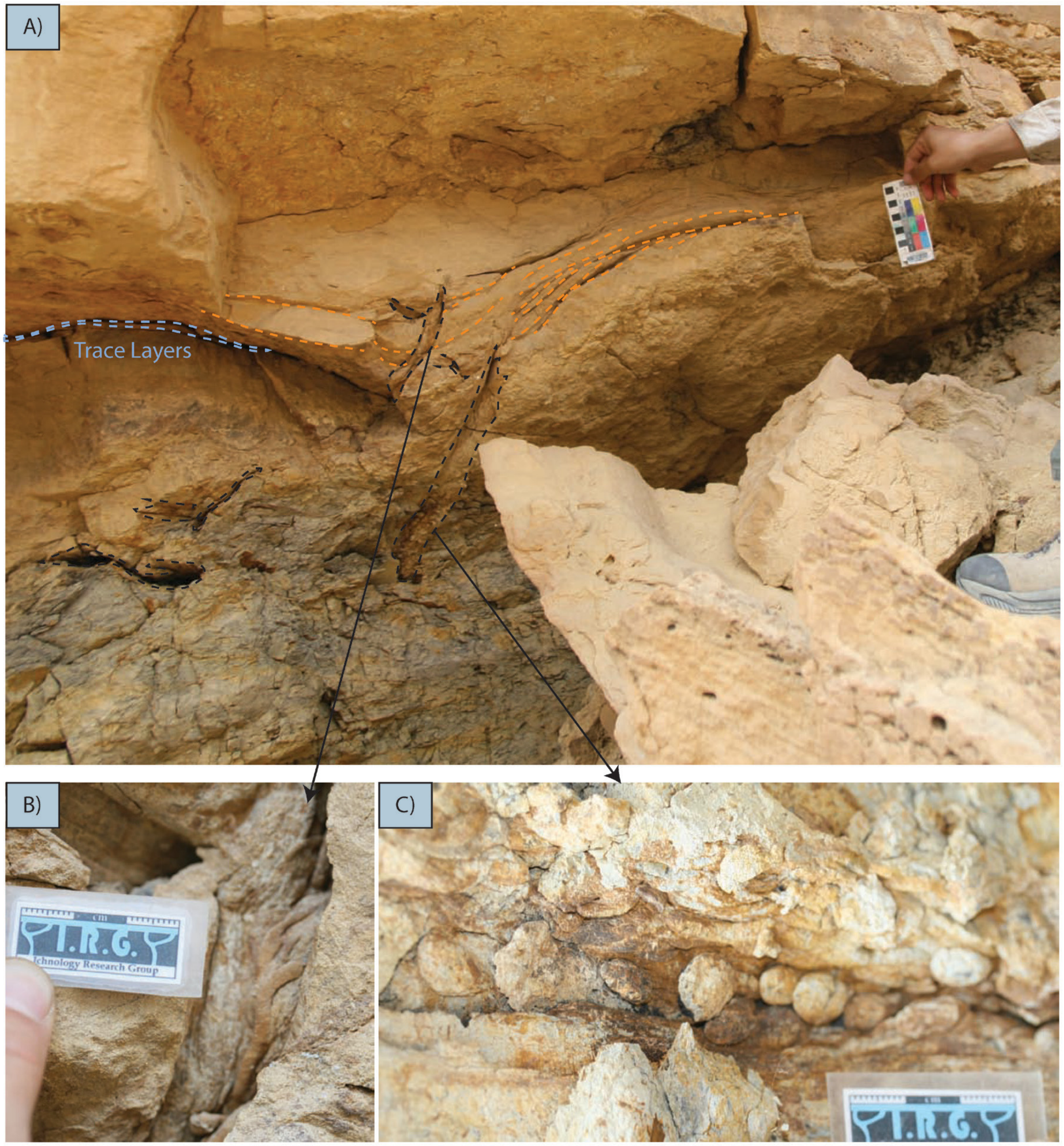

Figure 3.9: Stratal relationship and morphology of *Teredolites* bored clasts: a) Relationship of the 2-D rippled trace layers (blue dashed lines), wood remanents containing *Teredolites* (black dashed lines), and centroclinal cross-strata (orange dashed lines), b) *Teredolites longissimus,* and c) *Teredolites clavatus*.

within the underlying mudstone, the channel sandstone, and extending from the underlying mudstone into the sandstone (Figure 3.9a). Two morphologies are observed as elongate tubes (Figure 3.9b) and rounded sandstone casts (Figure 3.9c). The elongate tubes are up to 3 millimeters in diameter and can be up to 4.5 centimeters long. These tubes may have a hooked end. The rounded morphologies are up to 1 centimeter in diameter, and may be close to 1 centimeter in depth, but often exhibit a more button-like shape. The wood casts mainly contain the rounded traces. Centroclinal cross-strata (*sensu* Underwood and Lambert, 1974) dip down towards the trace riddled wood debris where it extends upwards into the sandstone.

3.3.4.2 Taxonomic Assignment

These traces are interpreted to be two forms of *Teredolites*. The elongate tubes represent *Teredolites longissimus* similar to hooked elongate shapes of Savrda and Smith (1996). The rounded casts are like *Teredolites clavatus* of Bromley et al. (1984) or Kelly and Bromley (1984) in cross-section, but are not the typical elongate club shape.

3.3.4.3 Ethological Assessment

Teredolites is associated with wood boring organisms. The producers of the *T. clavatus* and the *T. longissimus* forms are traditionally interpreted to made by shallow to marginal-marine bivalves (e.g., Bromley et al., 1984; Savrda and King, 1993; Savrda and Smith, 1996). The shortened length of *T. clavatus* could be the product of deterioration of the outer layers of wood upon exhumation.

3.3.4.4 Depositional Environment

Not much can be ascertained from these traces about the organism behavior within the channel because these traces have the potential to be transported, and show evidence that they are being reworked from the underlying and lateral mudstones. The centroclinal cross-strata around these bored logs (sticking up from the mudstone) has often been found as “vegetation-induced sedimentary structures” in relation to tree casts as in situ paleo-obstacles (Davies and Gibling, 2003; Rygel et al., 2004). Vegetation (including large allocthonous debris) in modern river channels have been documented as creating these obstacle produced scour and fill structures (Nakayama et al., 2002; Rodrigues et al., 2007). While these branches sticking up from the underlying floodplain deposits probably had an effect on deposition, and may help to create/preserve lower flow regime intervals (discussed later). The vegetation obstacles were likely not the reason for preservation of the trace assemblage due to migration of the cross-beds (underlying the assemblage) towards the logs and one might expected a more varied orientation of the ripples due to bending of flow around the obstructions.

3.4 ICHNOFACIES

The traces herein all appear to dominantly be the result of subaqueous activity of organisms of a shallow lotic environment with preservation in the localized lentic areas of this system. This environment may have been periodically exposed for short durations. There appears to be at least three ichnocoenose types in this small interval (Figure 3.3). An ichnocoenose is interpreted as traces that are members of the same community or a succession of similar communities (i.e., homogeneous ichnofabrics)(McIlroy, 2004). It should be noted that in this study that this trace assemblage composes a "suite" (sensu MacEachern et al., 2007). While the preservation and emplacement of the traces are a product of substrate variation, all of these traces can be produced by organisms (turtles, molluscs, and insects) of the same lotic habitat or community. These ichnocoenoses (ichnofabrics) more likely represent subtle preservation variations (taphocoenoses) within the same depositional system (suite) rather than ethological responses.

The first ichnocoenose is a *Chelonipus*/*Characichnos*/*Mermia* ichnocoenose that contains varying proportions of the trace elements (turtle traces, swim related traces, and shallow trails) between surfaces and laterally across individual surfaces. The other two ichnocoenoses are a *Mermia* ichnocoenose dominated by trails and an overprinting ichnocoenose dominated by *Rhizocorallium*. Some work in modern fluvial environments (Lawfield and Pickerill, 2006; Martin, 2010) have used the presence of vertebrate tracks as indication of an overprinting/associated *Scoyenia* ichnocoenose with that of a *Mermia* ichnocoenose. Therefore indicting a composite *Mermia*-*Scoyenia* ichnocoenose. Melchor et al. (2012) suggests that vertebrate tracks alone can not indicate *Scoyenia*, and that vertebrate traces are best compared to vertebrate ichnofacies.

Currently vertebrate and invertebrate ichnofacies analysis are done differently, but both in accordance with Keighley and Pickerill (2003) are exclusively reliant on trace morphology. The difference in analysis between the two is that invertebrate ichnofacies (ethoichnofacies) are dominantly based on using trace morphology to establish an organism’s behavioral response to environmental conditions, while vertebrate ichnofacies (biotaxonichnofacies) are mainly using morphological observations to infer the taxon of the producer (Hunt and Lucas, 2007). Archetypal (Seilacherian) ichnofacies are defined as globally extensive and reoccurring ethological groupings with long temporal range (Bromley, 1996; MacEachern et al., 2007). While the invertebrate ethologically defined ichnofacies conform to this term, vertebrate biotaxonichnofacies have limited time ranges (Buatois and Mangano, 2011). In this sense Hunt and Lucas (2007) suggested that vertebrate biotaxonichnofacies represent a mid level classification scheme that is not equivalent to archetypal ethologically defined ichnofacies, but a system that is defined as a parallel analysis. The trace fossil suite present in this study will be defined below in relation to both types of analysis.

3.4.1 Ethological Classification (Ethoichnofacies)

This interval is similar to the archetypal *Mermia* Ichnofacies (Buatois and Mangano, 1995, 2011) dominantly containing horizontal and subhorizontal traces. Additionally, under the assumption that *Helminthoidichnites* is a grazing trace, the grazing behaviors are, in accordance with the archetype, dominant to those of the locomotion traces. Conversely, there is not the requisite high abundance or diversity of the invertebrate trace on these surfaces and the *Rhizocorallium* indicate behaviors that are contrary to the norm (i.e., behaviors with a low degree of specialization).

Rhizocorallium does not fit within the *Mermia* model, and it represents a firmground behavior. The *Rhizocorallium* likely represents a short term, autocyclic expression of the *Glossifungites* Ichnofacies (Fürsich and Mayr, 1981; MacEachern et al., 2007). The autocyclic short term hiatus is supported by that the nature of the physical sedimentary structures and invertebrate traces do not drastically change on opposing sides of the *Rhizocorallium*’s occurrence. The presence of this semi-firmground may suggest temporary subaerial exposure, and therefore adverse to permanent subaqueous nature presumed from the archetypal *Mermia* Ichnofacies example. Although temporary exposure may have helped to compact the surface for inhabitation, the tracemaker’s likely constructed the burrows in the same subaqueous conditions present before exposure. Keighley and Pickerill (2003) have noted that this complex juxtaposition is a likely to be seen in continental environments and the alternating exposure conditions would result in overlapping ichnocoenoses creating “composite ichnofacies”. Composite ichnofacies are probably the norm in fluvial channels, which are subject to high frequency changes in environmental conditions, and therefore best approached by comparison to archetypal ichnofacies (e.g. methods of MacEachern et al., 2007) to gauge the variation in conditions.

Melchor et al. (2012) suggest that vertebrate swim tracks (vertebrate *Characichnos* Ichnofacies) overlap with the *Mermia* Ichnofacies. The interesting thing about this though is that the *Characichnos* Ichnofacies of Hunt and Lucas (2007) could be classified ethologically because it represents a behavior (swimming) that is different from the rest of the vertebrate track ichnofacies (dominantly terrestrial locomotion).

3.4.2 Vertebrate Trace Classification (biotaxonichnofacies)

The vertebrate traces herein are likely those of the *Chelonipus* Ichnofacies (Foster et al., 1999) or lesser so that of *Characichnos* Ichnofacies (Hunt and Lucas, 2007). The current state of morphological description/understanding of *Chelonipus* suggests that *Chelonipus* may sometimes be (when indicative of subaqueous locomotion), a chelonian subdivision of *Characichnos*, like *Hatcherichnus* (e.g. Hunt and Lucas, 2007) is a crocodilomorphic subdivision (e.g., Lockley et al., 2010). Additionally it is likely that many vertebrate morphotypes, including *Chelonipus* may quickly grade into *Characichnos* along the narrow margins of paleo water bodies, or may represent a surface that contains tracks of varying water level fluctuations (subaerial vs. subaqueous).

Melchor et al. (2012) suggests that *Chelonipus* and *Characichnos* should be regarded as ichnocoenoses due to their lack of temporal and spatial reoccurrence. While this is likely advisable for now until morphological revision and more examples are described, it would be naive to ignore the potential of these as vertebrate ichnofacies, due to the long temporal ranges of turtles (*Chelonipus* and *Emydiphipus?Chelonichnium?* ichnocoenoses) and crocodilomorphs (*Characichnos* Ichnofacies or *Hatcherichnus* Ichnocoenoses). These reptiles are limited to similar restrictions as invertebrates (e.g., salinity, temperature, etc.), have less environmental tracking ability than many vertebrates, and the preservational distinctness of their tracks are likely more depositional environmentally restricted than the simple trail morphologies that often compose the *Mermia* Ichnofacies. Additionally, the traces of swimming vertebrates (*Characichnos*) should have the longest temporal range of any vertebrate because it is based on behavior regardless of the animal type (e.g., fish, crocodile, turtle, pterosaur, dinosaur, etc.). Even though these individual ichnocoenoses may have a long range, the problem lies in that they are not globally extensive due to climate restrictions, as may be the problem with other vertebrate ichnofacies.

3.5 DISCUSSION: FLUVIAL TRACE PRESERVATION WITHIN CHANNEL

This discussion focuses on zonation and the potential of trace preservation in freshwater suspended or mixed load meandering channels (Figure 3.10a). There are probably climate restrictions as well to niche filling in modern channels (e.g., Martin, 2010), as well as bias in subaqueous trace recognition due to most modern studies being conducted of exposed subaqueous settings during low water levels rather than an actual observations of subaqueous behavior in the system. These modern channels in a general simplified cross-section can be broken down into the deposition-dominated point bar, and across the thalweg, the erosion-dominated cut bank, and will be addressed in these terms below. Additionally, trace recognition will be discussed as one of the potential biases.

3.5.1 Point Bar

Chamberlain (1975a) divided sloped surfaces bordering freshwater river channels (e.g., point bar) into four zones based on saturation (Figure 3.10a), but in a more general sense there are two zones: zones with traces made by subaqueous organism (e.g., oligochaetes, bivalves, gastropods, mayfly nymphs) and a zone influenced by animals in subaerial conditions (insects and crayfish). This is not to understate that many of the subaerial tracemakers still rely on a close proximity to water and wet vs. dry substrate, but that the traces made by the organisms in the subaqueous zone provide an important indicator of environment at the time of construction. Vertebrate locomotion traces are some of the few traces that bridge the gap between the two zones, especially with animals who split time between the two, but may change morphology from one zone to the other (e.g. *Chelonipus* or *Hatcherichnus* to *Characichnos*). When one extrapolates this to ancient conditions these assemblages can be an indicator of high frequency changes (Melchor et al., 2012). Thus, one may observe multiple conditions overprinting one surface. Therefore, each preserved fluvial trace assemblage represents an amalgamation of the continuum between these processes, and when considered may be more of a gauge of the extremity to which the conditions lie. Preservation of these deposits are mainly depended on subsequent hydrodynamic reworking, subaerial processes, or biogenic modification.

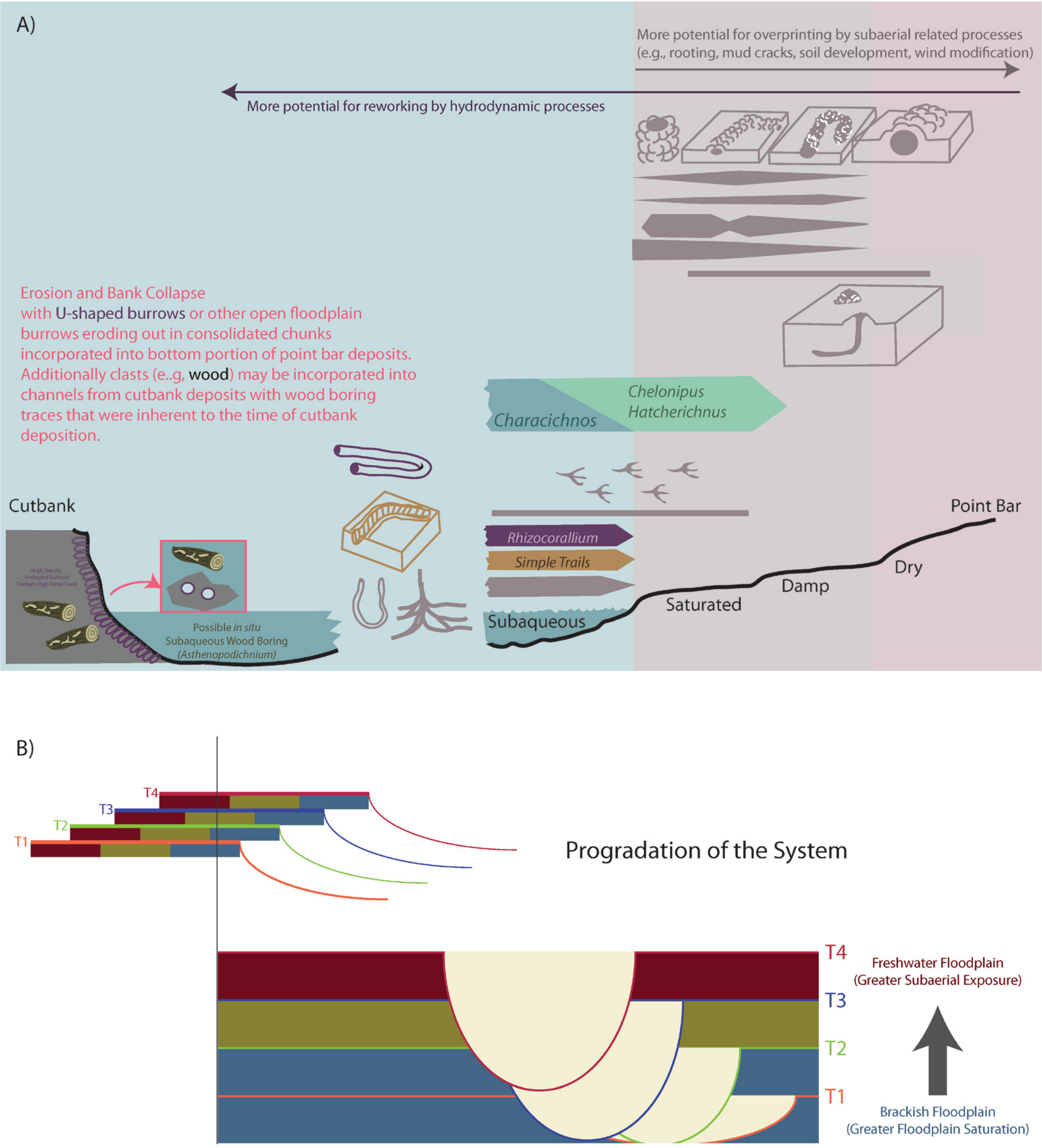

Figure 3.10: Freshwater trace location and preservation potential: a) Lateral relationships in sloped freshwater settings modified from Chamberlain (1975a) and hypothetical preservation in the cutbank. The traces (*Rhizocorallium*, simple trails, *Characichnos*, and *Chelonipus*) from the suite in this study all overlap in initiation in the subaqueous setting. b) A hypothetical model of channel and floodplain relationships. Successive environments related through a vertical sections illustrating how freshwater floodplains could likely cannibalize brackish water floodplains.

Local sheltered areas perhaps have great potential for within channel preservation of surface or near surface emplaced traces of subaqueous regimes during normal channel migration, whereas channel abandonment or aggradation of the system may drive overall preservation of the surfaces. The downstream portions of bars are typically finer grained and more protected (e.g. Pryor, 1967; Martin, 2010). However, dynamic scouring during high volume events creates space that may be left as sheltered environments, as in the case with chute channels. Alternatively, objects such as large wood debris or vegetation, creates sheltered areas downstream of the object.

3.5.2 Cutbank

The cutbank is the erosive side of the river, so preservation potential along this surface is mainly dependent on aggradation of the system. This presents a problem for the preservation of mayfly larvae burrows (*Rhizocorallium*), since most records indicate that these burrows are abundantly constructed steep compacted substrates, a niche which can not be utilized by many of the other subaqueous organisms. Therefore, the lack of these burrows in the continental fossil record is probably a preservational norm, and *in situ* preservation would likely require special conditions (e.g., rapid aggradation or channel abandonment).

On the other hand, these burrows may be more likely to preserve in bottom part of channels during bank collapse as the channel migrates (Figure 3.10a). The high density of burrows actually promotes bank collapses as the channel migrates (Scott et al., 1959). Theoretically, not only do these *Rhizocorallium* burrows have potential to preserve in the base of the channel, but any burrow (even those not subaqueously constructed) that lies in the cutbank deposits. Additionally, wood debris (and inherent burrows) may be reworked from the adjacent floodplain into the channel. This could result in a channel containing wood borings from other systems (e.g., *Paleobuprestis*, *Paleoscolytus*, *Teredolites*, etc.), or possibly the borings of the freshwater fluvial channel (*Asthenopodichnium*) overprinting them. With the Ferron Sandstone largely representing progradational deltaic systems, one would expect the floodplain to go from brackish floodplains to those of freshwater overtime. Thus allowing the reworking of traces in wood from older brackish floodplains (i.e., *Teredolites*) into that of the overlying freshwater channels (Figure 3.10b).

3.5.3 Appearance Bias

In terms of why turtle tracks are not greatly documented in the literature, as within channel traces, is probably as much as an observational bias as it is a taphonomically bias. While it is greatly limited by the fact that turtle tracks (excluding lagoonal forms) likely only really preserve in narrow bands along the channel, where the substrate is soft (saturated) enough to deform, but rigid (cohesion or compaction) enough to hold form, the tracks are often small in scale, and represented by scratch-like morphologies. In high-density occurrences, these could easily be mistaken for physical structure produced hydrodynamically, which are inline with the erosive nature of fluvial channel deposits. To complicate distinguishing between the superficially similar hydrodynamic and biogenic produced structures,*Chelonipus* (even *Characichnos* and *Hatcherichnus*) typically have rather unimodal distributions with the current direction (e.g., Foster et al., 1999; Lockley et al., 2006; Lockley et al., 2010) due to many of their nature as swim tracks. These similarities in appearance may play a role in the sparse reports of these vertebrate traces from channel deposits, outside the paleontologists who study them.

3.6 CONCLUSIONS

This study presents a Cretaceous trace fossil assemblage that was deposited within a fluvial channel. The assemblage contains rarely noted trace ethologies that may be attributed to mayfly larvae and turtles. The variation in a suite containing *Mermia*-like traces, *Rhizocorallium*, *Characichnos*, and *Chelonipus,* suggest that the ichnocoenoses (ichnofabrics) in this suite represent variations in substrate conditions and taphonomic preservation rather than a change in community, since all of these traces may be subaqueous produced in modern freshwater channel environments. Allochthonous traces (e.g. *Teredolites*) may be present within a trace assemblage, but do not necessarily indicate the conditions within the channel, nor belong as part of the suite. Caution must be exercised in using bored clasts or debris, seeing as adjacent deposits of stratigraphically older and potentially disparate environments can be reworked into the channel, and lateral strata must be accessed before proceeding with interpretation.

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CHAPTER 4: PRESERVATION OF TURONIAN VERTEBRATE ICHNITES IN THE FERRON SANDSTONE AND THE RELATIONSHIP BETWEEN MORPHOLOGY AND DEPOSITIONAL ENVIRONMENT

4.1 INTRODUCTION

Vertebrate ichnites in western North America are well know from Aptian-Cenomanian coastal strata (e.g., Glen Rose Formation of Texas and Dakota Group of Utah, New Mexico, Colorado, Oklahoma, and Kansas) and the Campanian Blackhawk Formation (Mesa Verde Group of Utah, New Mexico, Arizona, Colorado, and Wyoming), but during the Cenomanian-Campanian time much of the Western Interior Seaway (WIS) basinal accumulation lacked terrestrial environments for vertebrate ichnite preservation (Figure 4.1a)(Lockley and Hunt, 1995). More recently, vertebrate ichnites have been described from the middle-Coniacian Toreva Formation (Irby and Albright, 2002) and upper Santonian-lower Campanian Iron Springs Formation (Milner et al., 2006) filling in the upper portion of this gap. Vertebrate fossils of mid-Turonian to early Coniacian age are sparse in the WIS, and increase the value of vertebrate ichnites of this age (Currie, 1989; Lockley and Conrad, 1989; Hamblin et al., 2000; Jones, 2001; Irby and Albright, 2002).

A few authors have noted ichnites elsewhere during this period of WIS deposition. The closest geographically (to this study) is from the Frontier Formation (likely middle-late Turonian) of northeastern Utah consisting of a few undescribed tridactyl tracks and one possible tetradactyl track (i.e., Hamblin et al., 2000). To the south, in the Turonian Moreno Hill Formation of New Mexico, Wolfe (2006) has described 13 mid-sized to large theropod ichnites resembling *Irenesauripus* (*sensu* Sternberg, 1932) from a fallen sandstone block. Along the northwestern shore of the western WIS, in western Alberta, three theropod tracks were noted by Currie (1989) in the Turonian Cardium Formation. Rylaarsdam et al. (2006) suggest in excess of 50 unpublished traces (largest trackway length is four tracks) have been located in British Columbia comprising tracks of small theropods, large ornithopods, and possible ankylosaurs. These authors review the terrestrial vertebrate fossil record (both body and trace) from the Turonian, and note how few published examples of Turonian vertebrate ichnites exist globally.

The study herein focuses on the Last Chance Delta area of the upper Ferron Sandstone, more specifically the extensive outcrops from Interstate 70 to Muddy Creek Canyon, in Emery County, Utah (Figure 4.1b). This area of the upper Ferron was deposited

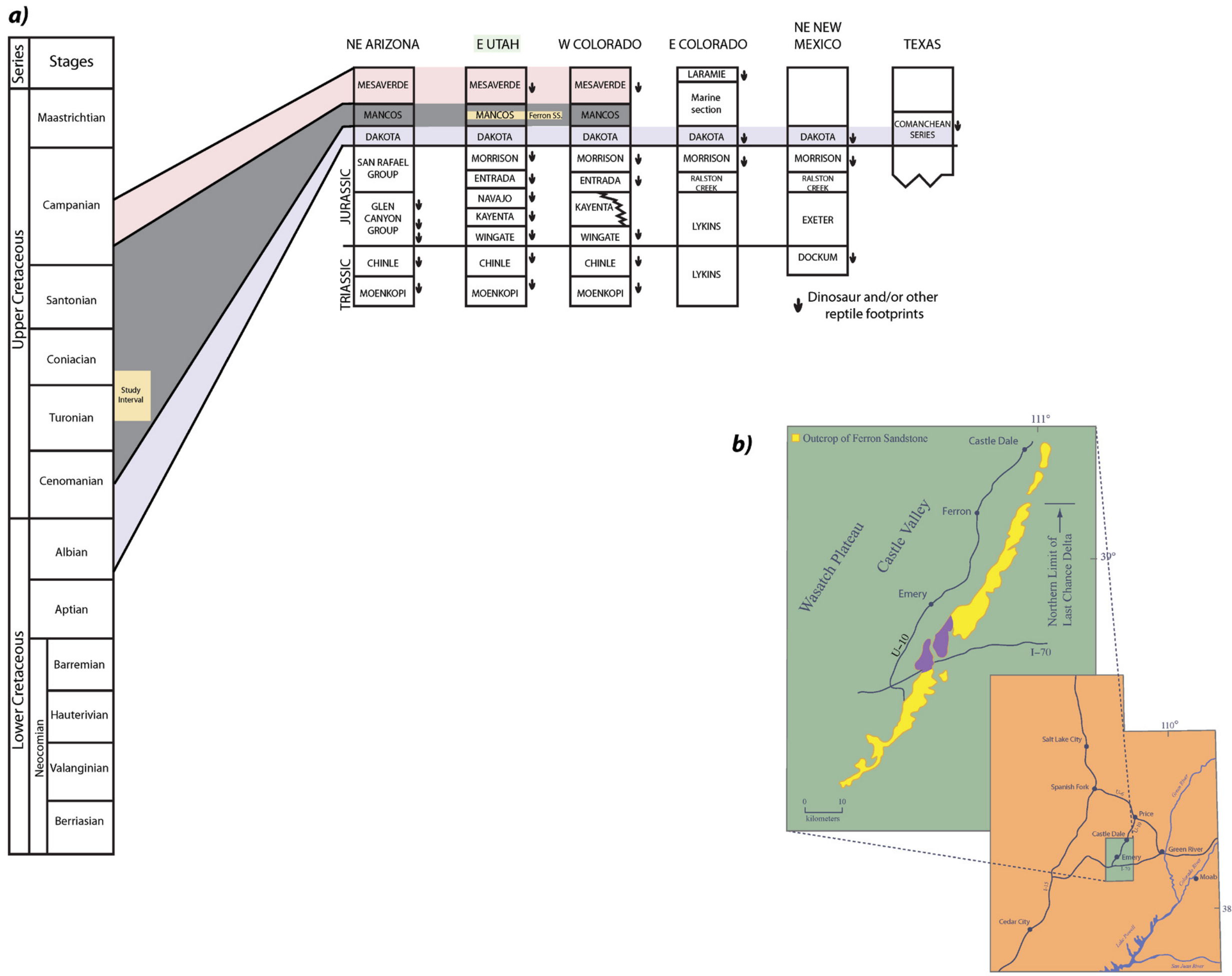

Figure 4.1: Study Area Locations: a) Cenomanian-Campanian vertebrate ichnite gap of the Western Interior Seaway (modified from Lockley and Conrad 1989, Lockley and Hunt 1995). b) Area of upper Ferron Sandstone outcrop in Emery County (modified from Garrison and van den Bergh, 2004, after Cotter, 1975). Study area shown in purple.

during the late Turonian-upper Coniacian (Garrison and van den Bergh, 2004). Therefore providing additional information to the sparse data available on this time period (Figure 4.1a).

The Ferron Sandstone was deposited along the western margin of the WIS (Garrison, 2003; Garrison and van den Bergh, 2004). The Ferron Sandstone overlies and grades basinward into the Tununk Shale and is capped by the Blue Gate Shale. All three are part of the Mancos Shale (Ryer, 1983; Ryer, 2004; Garrison and van den Bergh, 2004) (Figure 4.1a). The upper Ferron Sandstone lithostratigraphically (*sensu* Davis, 1954) represents the shallow-marine and fluvial sandstone-dominated portion of the Ferron (up to 150 m thick); whereas the lower lithostratigraphic division is dominated by finer lithologies (Ryer, 2004). The coal horizons of the upper Ferron form the basis for correlation, as each is associated with the transgressive-regressive (delta-front) cycles (Ryer, 1980, 1981, and 1983). A sequence stratigraphic framework (Figure 4.2) has been established in which eight of these cycles are generally recognized (e.g., Anderson et al., 1997; Garrison and van den Bergh, 1997; Gardner et al., 2004; Ryer, 2004). This study aims to incorporate these vertebrate ichnite locations into their proper stratigraphic position as well as provide insight into the taphonomy of these traces.

Only one trackway has been previously formally described from the Ferron Sandstone (the Moore Tracksite, Jones, 2001). The trackway on this fallen block is composed of nine rather amorphous tracks that are interpreted to be tridactyl traces of a bipedal ornithopod. Other than this report, known vertebrate material from this area of the Ferron Sandstone is sparse: composed of two vertebrate ichnites at the Museum of the San Rafael, and track horizons briefly discussed in Chapter 1 that are further expanded upon in this chapter.

4.2 VERTEBRATE ICHNITE TOPONOMY IN THE FERRON

Multiple factors contribute to the sparse record of vertebrate ichnites in the Ferron Sandstone. Identification of vertebrate ichnites within this area is difficult due to several factors. Steep cliff faces make it prohibitive to access surfaces and do not provide much in terms of plan view exposure of horizons. Therefore, trackways (consisting of 3 or more prints) are rare. Fallen sandstone blocks do provide a much better plan view of surfaces, but often times, vertebrate ichnites appear to have been removed as the block rolled down

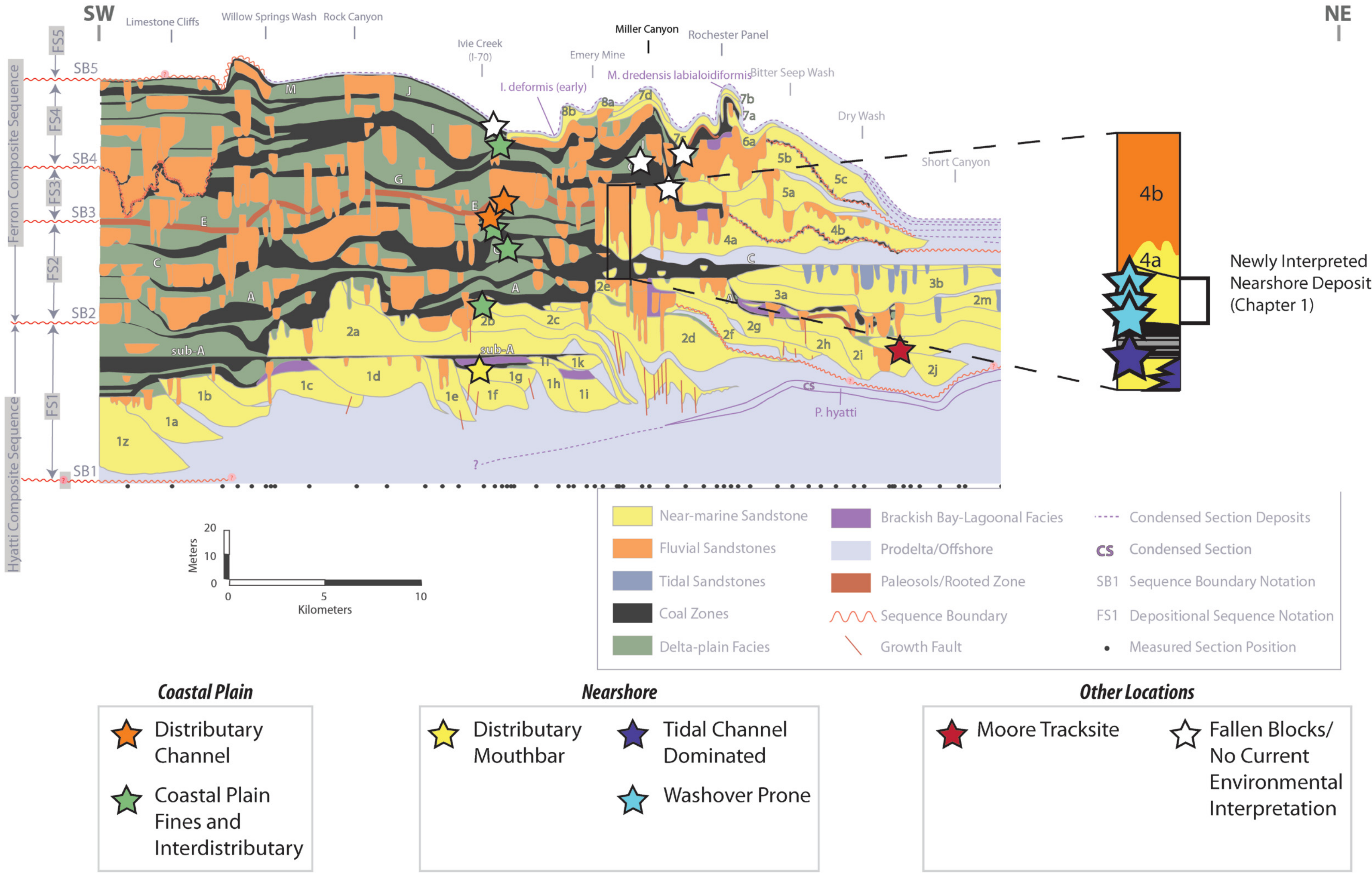

Figure 4.2: Generalized regional cross-section of the upper Ferron Sandstone, Last Chance Delta (modified from Garrison and van den Bergh, 2004). Colored stars indicate stratigraphic positions of tracksites identified by this study. The red star indicates the probable stratigraphic location (based on field observation) from which the fallen block described by Jones (2001) originated.

the hill. In addition, rapid weathering of natural casts is evidenced on the upper exposed surface of many upended fallen blocks. Soupy substrate conditions associated with the coastal/paralic environments may make it difficult to distinguish vertebrate ichnites from loading features, which are also common. Overprinting and logs (organics) are also seen obscuring, otherwise easily identifiable morphologies. Additionally, cross-cutting burrows can modify the morphology, or in the case of small ichnites, may destroy much of the evidence of an ichnite even being present. Vertebrate ichnites preserve in the Ferron Sandstone as weathering out sandstone casts or molds in sandstone, and in cross-section have been identified with various forms of transmitted deformation, and bulb displacement. It should be noted that this chapter is biased towards ichnites with definitive morphologies or exemplary expressions of transmitted or displaced forms.

4.2.1 Sandstone Casts (Convex Hyporelief)

Vertebrate ichnites in the Ferron Sandstone mainly preserve as sandstone casts within a mudstone dominated lithology. In one location, a few vertebrate sandstone casts were present in a coal split, but the tracks themselves were emplaced into a thin mudstone overlying the coal. Dinosaurian natural casts primarily preserve the outline of the trace; pad impressions are rare. The pad impressions are only evident on the shallowest track found, <1cm depth, which agrees with Thulborn's (1990) assertion that many of the finer details of foot morphology are lost as the foot impresses deeper. Some deeper tracks display completely flat tilted bases, which may represent the indenter reaching some sort of compressive maximum during rapid compression, or may be the result of basal lamina peel up (along planes) during sand filling. Mainly digits II-IV are preserved (digit I, rarely). Depth can vary greatly, by tens of centimeters, between tracksites and along the same horizon. Natural casts may display mechanically produced linear features (striations) along the margins.

4.2.1.1 Tubercle Striations

Long, linear features (Figure 4.3a-d) running parallel to the casts of digits, along the sidewalls of the ichnites, representing what has been interpreted as tubercles along the feet as they moved through the substrate (Currie et al., 1991). Nadon (1993) and Difley and Ekdale (2002) have noted these striations along the edges of deeply impressed tracks. Similar striations have been reported in the neoichnological substrate variability

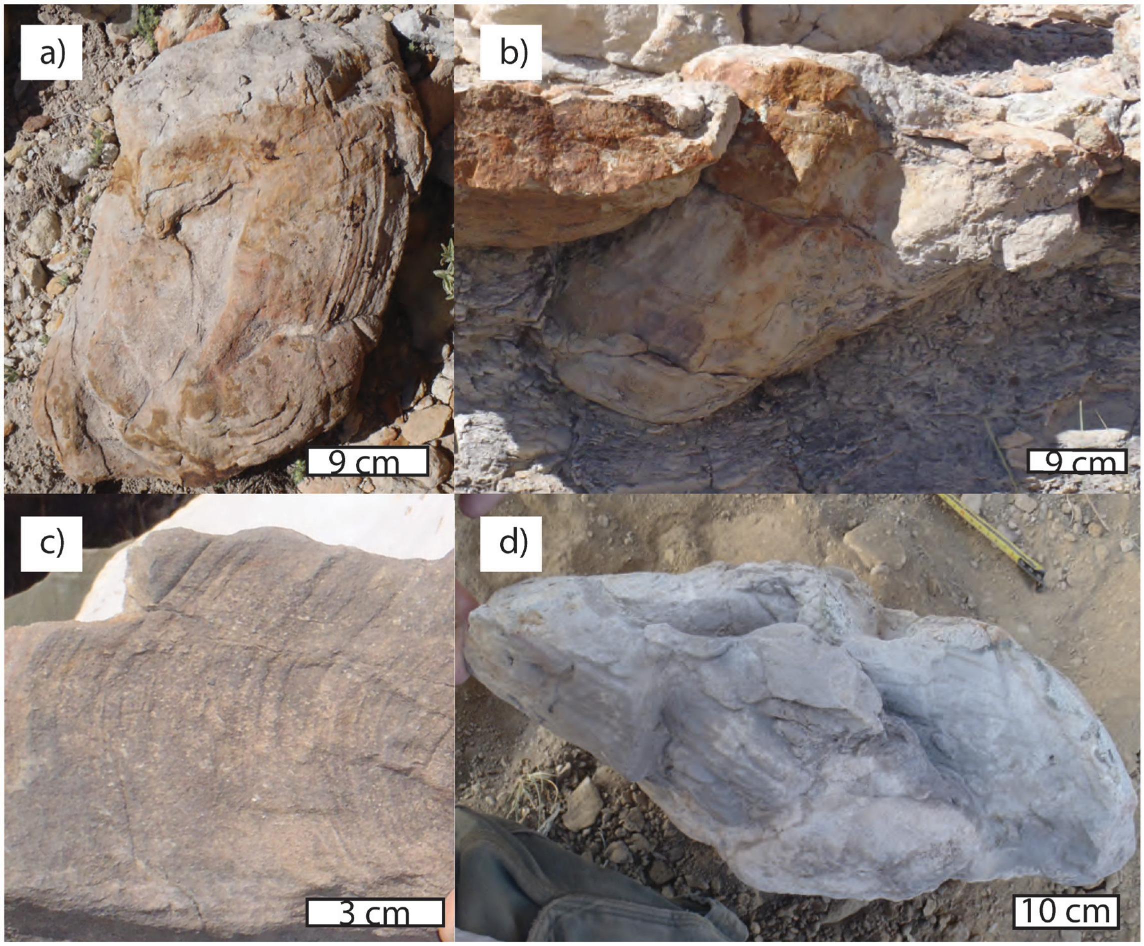

Figure 4.3: Linear striations along the margins of vertebrate ichnites in the study area. The best developed striations do not necessarily occur in the same position along margins each time: a) an example of well -developed posterior striations, b) well developed anterior striations. The striations vary in frequency width from track to track: c) millimeter scale spacings, d) centimeter scale spacings.

experiments of Milan (2006) resulting from movement along the tubercle-sediment contact at the margins of emu (*Dromaius novaehollandiae*) feet in deep firm to semi-firm muds. The same is true in the Ferron where these grooves are dominantly noted in deeply impressed tracks in excess of 20 cm depth.

The striations in the study area can occur along any portion of the outer track wall (Figure 4.3a,b), but are never seen developed on the floor of the track. The striations in the study area exhibit two vastly different width frequencies, one on a millimeter scale (Figure 4.3c), and one on a centimeter scale (Figure 4.3d). Similar disparities in striation widths are noted by Difley and Ekdale (2002) in their vertebrate ichnites.

4.2.2 Sandstone Molds (Concave Epirelief)

While natural casts dominate preservation, morphologically distinctive, plan view, footprint impressions (molds) are only observed at three locations. All three sites contain vertebrate ichnites impressed into sand with a mudstone infill. The key to preservation appears to be having a mechanism to bind the normally cohesionless sand grains, and likely a change to reduced energy conditions (deposition with little to no erosion, or flooding) directly above the surface. The well-defined tracks at all three sites are all shallow (<3cm deep), and two of the three are represented by gracile morphologies.

The first two sites are each represented by an individual track that is in close or direct association with either natural casts, or transmitted reliefs (discussed below). Each of these lies on top of sandstones that have mud drapes along ripples and are typically heavily bioturbated by mud-lined or mud-backfilled structures that may have aided in the cohesion necessary for preservation. Additionally they both represent intervals going from low energy sedimentary structures, up to bioturbation, and capping what is likely flooding and slack water deposition.

The last site containing impressions is represented by a single fallen block, contains two vertebrate ichnites. The impressions are relatively shallow (up to 2.8 cm deep), but one print appears to have preservation of digit I (Figure 4.4a,b) While the infill is not present; it was likely a mudstone due to the clean weathering nature of the upper surface. Small, typically 1 to 3 cm long, wavy ridges (Figure 4.4b) cover the surface. These ridges are interpreted to be adhesion ripples (*haftrippeln*; *sensu* Reineck, 1955) due to their asymmetric cross-sectional and erratic plan view profiles, and the faint preservation of cross lamina. While van Straaten (1953) originally described these sedimentary structures

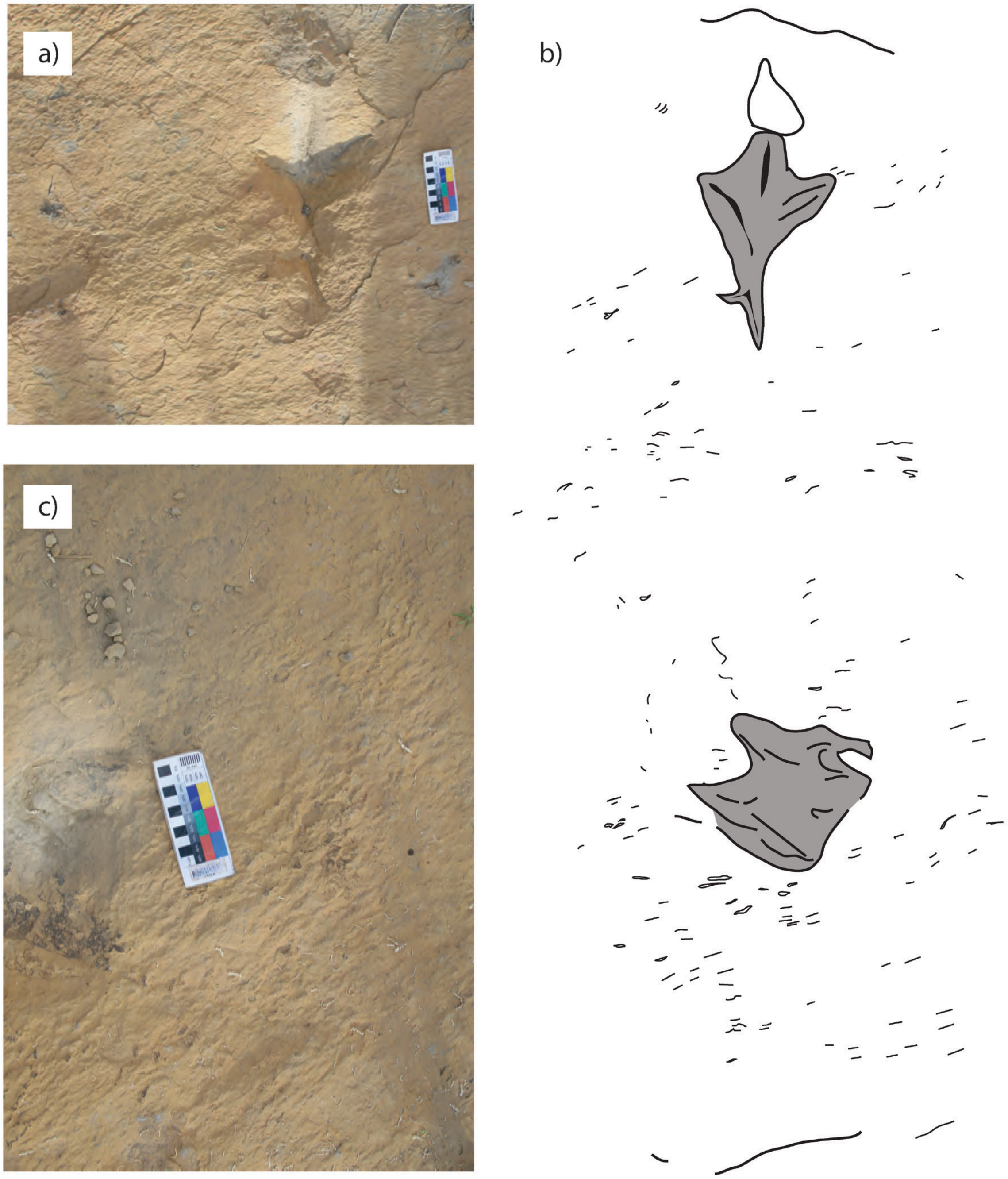

Figure 4.4: Vertebrate ichnite impression associated with small linear ridges. a) Plantigrade trace with preservation of digit I. b) Field tracing of tracks and orientation relative to prominent associated ridges. c) Close up view of ridge structures.

as “anti-ripplets”, Reineck’s term, adhesion ripples, is favored due to its nominal indication of conditions required to construct the bedform (Hunter, 1973). Adhesion ripples form when wind blows dry silt to fine sand-sized grains onto a wet (>80% saturation; Kocurek and Fielder, 1982) to shallowly covered (<1cm water; Hunter, 1973) surface, resulting in the saltating grains preferential adherence onto the stoss side of ripples. Adhesion ripples must form close to a dry source of sand (Kocurek and Fielder, 1982). The high water table conditions proximal to a dry sand source is likely why many of the modern examples of adhesion ripples are dominantly reported noted from modern coastal environments (e.g., van Straaten, 1953; Reineck, 1955; Hunter, 1973).

The adhesion ripples on the track surface provide evidence that the sand substrate was water saturated. The water saturation in the sand was the cohesive element needed to preserve the impressions on the surface. This is further evidence by Milan (2006), whose modern emu substrate interaction work suggests very low preservational potential in dry sands, but that additional water content greatly adds to the sand substrate cohesiveness and resultant track preservation. Since the tracks are preserved on a fallen block with no remaining overlying lithologies, it is hard to ascertain what the final resulting deposition was that preserved this surface, but it likely could be a continuation in the water table rise resulting in interdune ponding, and a suspended sediment cap. In terms of the preservation of digit I, in such a shallow track, there does appear to be some collapse along the margins of the track helping to fill it in, but it probably should be noted that the tracks have a perpendicular orientation to the ripple crest (parallel to the paleowind direction). While it is impossible to tell in such a short series of tracks, the plantigrade stance in the track could suggest the animal foundering in strong wind conditions. Similar plantigrade impression have been reported in Kuban (1989), Gatesy (2003), and Marsicano et al (2010), but often these are a result of a deep impression into a muddy substrate which is not the case in this Ferron track.

4.2.3 Displaced Media Under Ichnite Surface

Displacement of strata underneath the surface that was the indented contact (print) is most easily recognized in cross-sectional views of vertebrate ichnites in the Ferron Sandstone. However, it can be seen in plan view, as deformational outlines in heterolithic strata, and more rarely as topographic features along sandstone bed tops. Two expressions of vertebrate displaced media are present: one which exhibits minor folding and faulting as transmitted deformed media, and a more rare, faulted expression, showing rapid and significant stratal failure, resulting in displaced bulbs.

4.2.3.1 Transmitted Deformed Media

Deformation of sediment under the primary surface of vertebrate contact (print) are prevalent in the Ferron Sandstone, but dominantly only recognizable in their original context. Historically, these deformational processes that lessen away from the track have been referred to by a variety of names (summarized in Allen, 1989; 1997; Thulborn, 1990) such as transmitted prints, ghost prints, or undertraces. For this study, the term "transmitted reliefs" (*sensu* Thulborn, 2012) will be used to refer to all reliefs, produced by a vertebrate, that does not represent the print or primary surface of contact. This term is used in place of how Allen (1989; 1997) utilized the term undertrace zone, as well as, features in the marginal zone. The purpose of this section is not to argue about the true nature of the identifiable cast or mold, as whether as primary or secondary points of contact, but to describe and discuss what types of sediment preserve transmitted reliefs in the Ferron Sandstone and the unique expressions of these reliefs that may provide more insight.

Nadon (2001) alluded to two major factors in transmitted relief preservation: heterogeneous substrate, to facilitate recognition, and the strength of the substrate, which influences dispersal of deformation. The preservation/ recognition of transmitted relief in the Ferron Sandstone is dominantly reliant on heterogeneous substrate. In one case, this dispersal manifests as prominent topographic highs.

4.2.3.1.1 Heterogeneous character:

The heterogeneous deposits recognized in the Ferron Sandstone as media subject to producing recognizable transmitted relief appear to mainly be the product of at least one of these three factors: 1. interbedding of subdecimeter beds, 2. variability of grainsize along sedimentary structures, or 3. passive and active fill of burrows.

Deformation of thin beds and sedimentary structures is commonly associated with vertebrate ichnites in the Ferron Sandstone. This is most apparent in the interbedded sandstone and mudstone beds. However, cryptic expressions of this can occasionally be seen within sand bed (coset) activity, where heterogeneous sedimentary structures (e.g., draped or differentially weathered ripples) are deformed and then filled by a similar sand medium. In these cases the ichnite surface would likely not be preserved in plan view, but the activity of mechanical deformation (transmitted relief) is still seen in cross-section.

Transmitted relief is normally described in deposits that are resultant from fluctuations in modes of sediment deposition, however in the Ferron Sandstone there are several examples of the deformation of bioturbation-generated heterogeneity (Figure 4.5a-e). These intervals are mudstones that have been almost completely bioturbated with the dominant expression being the sandstone tubes of *Thalassinoides* and *Planolites*. Vertebrate ichnites are often sand filled showing deformation along the margins (Figure 4.5a), but can also be filled with similar sediment only weathering as preserved fabrics of burrow deformation (Figure 4.5b). This is similar to the concentric patterns seen in Allen (1997) or the "onion-ring effect" of Thulborn (2012) that results from the deformation of heterogeneous bedding around the indenter. Deformation of the burrows behaves similarly to the deformation of beds in that the deformation of the burrows mimics the shape of the track and decreases away from the point of impact (Figure 4.5c). In this toponomic expression, it is difficult to truly discount the role that concentric fracturing may play. Each new implacement imparts a new deformational fabric on the surface. By looking at these fabrics of ichnites in close proximity, the timing of implacement relative to one another can be observed in the cross-cutting relationships (Figure 4.5d,e).

4.2.3.1.2 Topographic dispersal:

The most prominent plan view display of transmitted relief in the Ferron is observed as a series of large antiform features (Figure 4.6a). The features at their highest points can be between 8-20 cm above the surface of the tracksite. Depressions associated with these antiforms can give the structures heights up to 28.5 cm from the base of the pit to the peak of the antiform. The crest of the antiform generally varies in height with a central peak dipping towards the edges. The crest often has a slightly curved planar view profile. The antiforms are asymmetrical, usually displaying one gently dipping side and one steep dipping side with dips between 22 and 87 degrees. Although loading and soft sediment deformation are key elements in river-dominated deltaic environments, these structures are more likely the products of mechanical loading and shearing due to animal movement.

Similar features, on a smaller scale, of ovate rather amorphous depressions with raised rims were described as squelch marks by Tucker and Burchette (1977). The rather amorphous nature likely comes from sediment collapse once the indenter was removed from the sediment (Scrivner and Bottjer, 1986). Raised rims along the depressed area are known as marginal rims when following the outline of the foot (Allen, 1997). However, fully enclosed marginal rims are the product of the indenter's motion in a vertical direction,

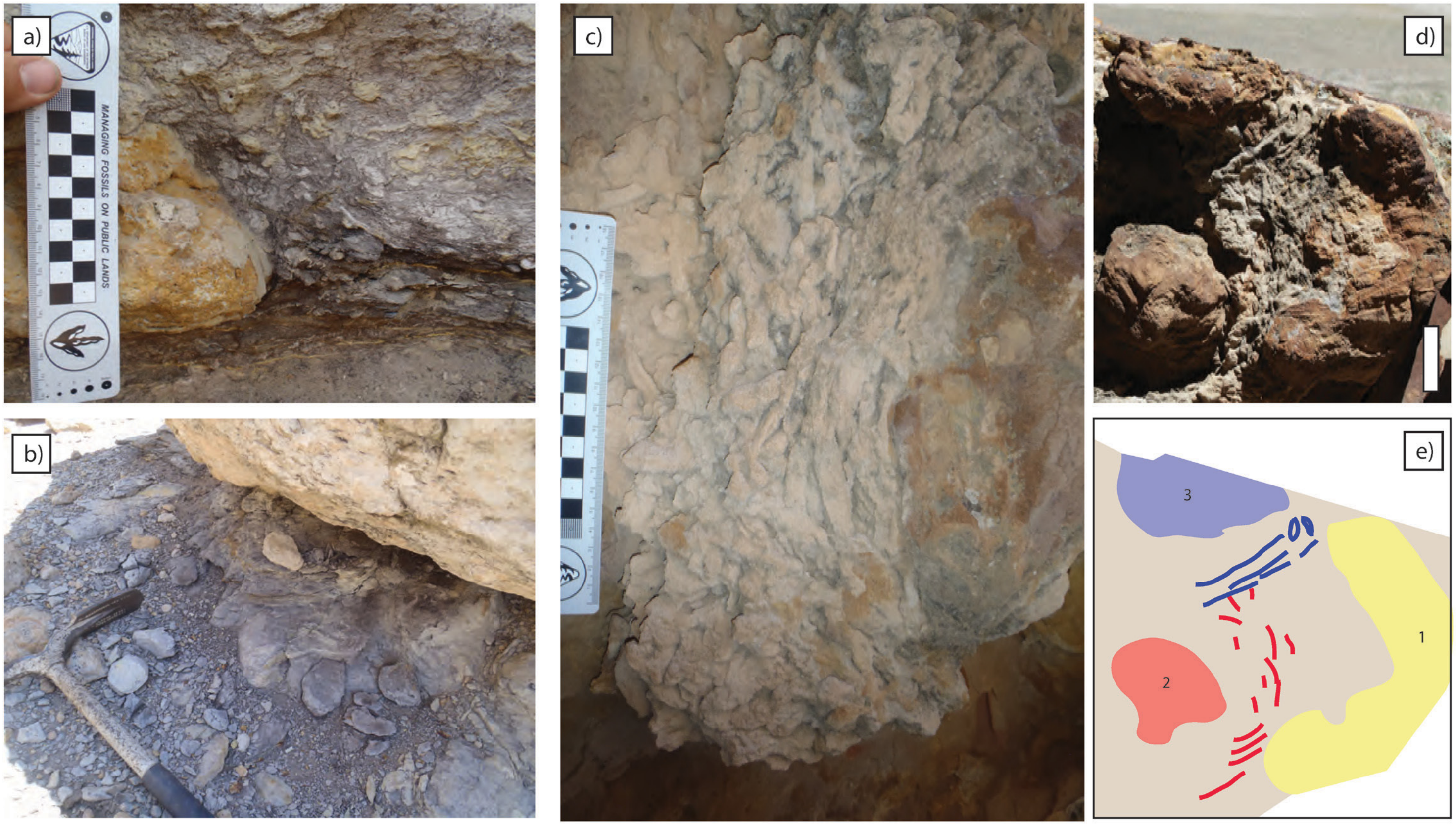

Figure 4.5: Transmitted relief of bioturbation generated heterogeneity: a) Deformation of *Thalassinoides* and *Planolites* burrows along the margin of a natural cast. Notice the deformation of the fabric has a largely horizontal nature likely representing the forward movement as the foot withdrew. b) Concentric fabrics with no related natural cast suggesting deformation, but that the infill may have been by mud, or by the collapse of the adjacent strata. c) Deformation of *Thalassinoides* burrows illustrating the decrease of impact related fabric away from the ichnite. It is difficult to access in this toponomy the magnitude to which microfaulting played a role. d) Cross-cutting deformational fabrics e) illustrate the order by which the ichnites of the overlying photo were emplaces with 1 (yellow) bordered by the fabrics of 2 (red) and with the fabrics of 2 (red) being overprinted by 3 (blue). Shaded objects are ichnites (natural casts) with the colored lines representing deformational reliefs.

Figure 4.6: Antiform structures formed by vertebrate disturbance of sediment. a) View from above of surface containing large antiforms and associated pits. Rock hammer for scale. b) Cross-section of antiform illustrating the shearing cross-cutting relationship.

and the magnitude is probably limited by substrate type. The antiforms in the Ferron do not outline the entire depression, and are actually more related to Allen's (1997) marginal thrust that were seen in damp sands by Frey and Pemberton (1986). Thulborn (1990) referred to the raised rims as a bourrelet, which suggested larger trackmakers, and implicated the dependence on substrate by which mud folded upwards around the track, whereas damp sand was faulted to the surface. It is also of interest to note the plan view morphological asymmetry of the rims he illustrates, particularly the human footprint because the rim begins laterally on inside front of the foot continuing down and rounding across the arch, covering the arch portion and separating the footprint into two depressions. This is important because it suggest that in damp sand, the motion of the foot may be the dominant control on rim shape and may not necessarily represent the true foot morphology, and the concavity of the axis may be tangential to the direction of travel. Additionally, Cretaceous quadrapeds (sauropods) have shown positive ridges that form as the sediment in front of the pes is pushed forward into the unoccupied manus depression (e.g., Pittman and Gillette, 1989; Thulborn, 2012).

In cross-section, a dynamic movement is suggested more than the load dominated effect that is associated with deposits containing continuous marginal rims dues to the asymmetrical deformation and faulting (Figure 4.6B). In this figure you can clearly see that the left side of the cross-section contains subdued relief and downward bending from loading, whereas the left side shows faulting of layers above the equivalent adjacent strata. The asymmetrical displacement suggests a lateral component, however it is plausible that the asymmetry may also represent asymmetric pressure of the indenter forcing more sediment to one side. The sedimentary fabric appears to indicate that the sediment faulted (décollement) along the weak plane of the mudstone lithology. This is comparable to the large-scale décollement that occurs along less competent lithologies that are sandwiched between more competent deposits (e.g., Gwinn, 1964; Milici and Leamon, 1975).

4.2.3.2 Displacement Bulbs

A displacement bulb (*sensu* Jackson et al., 2009) is the relatively undeformed package of sediment that may occur under the footprint, also known as the "dead zone" of Allen (1997) (Figure 4.7a). Displacement bulbs in the Ferron Sandstone are the other end of the spectrum from the dominantly ductile deformation associated with transmitted reliefs. They represent brittle dominated behavior of rapid failure along the margins where a bulb of sediment is punched down by the foot like a cookie cutter. This is not to say no

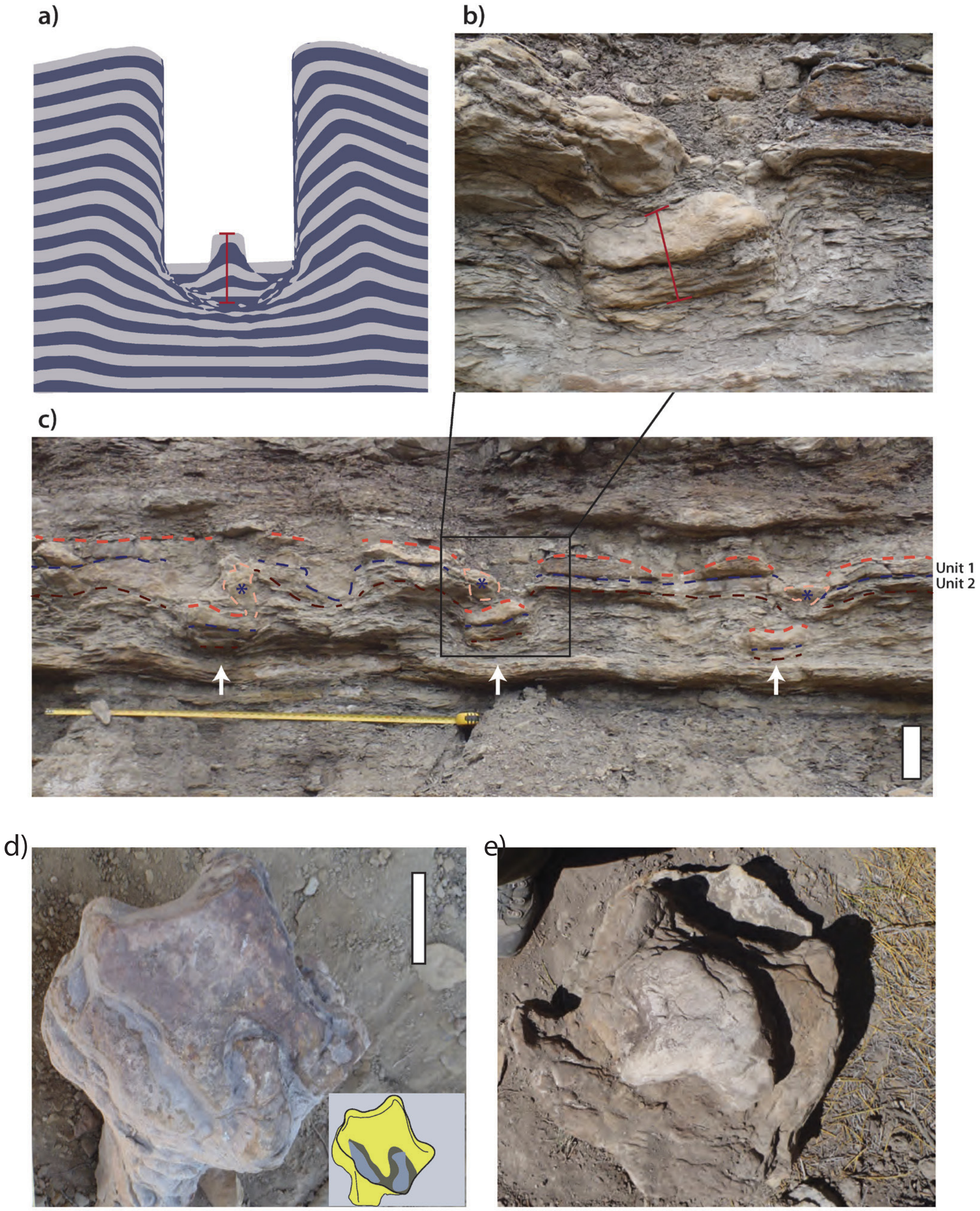

Figure 4.7: Displaced bulbs: a). Indention into a cohesive medium (plasticine) by the downward force of a circular grooved punch (modified from Allen, 1997). The indicated interval red marks the approximate zone known as the displacement bulb (discussed in text). b) Illustrates a similar interpreted behavior from the Ferron Sandstone of displacement of a semi-cohesive sand (with mud-draped ripples) bulb into more cohesive muddy sediments. c) The inferred relationship from the parent units to that of the vertebrate displaced units (bulbs) with the upper unit 1 being the coarsest unit in the interval. Dashed lines are interpreted equivalent surfaces. Fleshes colored dashed lines with asterisks are interpreted to be either the product of collapse or liquefaction. d) Part of a cross-cut track (grey inset) that is incorporated as a displaced bulb into the new tracks base. e) Another possible example of a smaller underlying track becoming a displaced bulb.

deformation occurs, but primary displacement appears more as a brittle material behavior. This occurs only in the deepest tracks of the Ferron Sandstone, and likely within highly saturated sediments; comparably a high moisture parameter has also been suggested by the lab work of Jackson et al., (2010). Similar depositional behavior is seen in the prodelta/delta front deposits of the Ferron Sandstone where rapid loading of watered sediments produces growth faults.

There are two expressions of bulb displacement in the Ferron. The first is likely only preserved in transmitted relief, however, there is no ability to see the preserved plan-view of the punched sediments, though some casts were found nearby. The displacement bulb is composed dominantly of two rippled sandstones with the lower unit being more heavily mud draped (Figure 4.7b, c). Part of the top of the bulb may be sediment related to collapse. Marginal folding can be seen up through the sandier units, suggesting that this was dominantly the result of downward displacement rather than a passive sandy infilling of the base. Additionally, blocks of sandstone are seen faulting down into the shaft, suggesting collapse after displacement, and possible associated margin liquification.

The second bulb displacement involves the incorporation of an underlying ichnite, as the displacement bulb, into the underlying portion of a natural cast (Figure 4.7d). While other casts at the same site, contain smaller ichnites on their bases (Figure 4.7e), it would be hard to justify, with current recorded data, that the tracks on the base were not emplaced after the larger tracks. However, the preservation of a partial track on the base (Figure 4.7d) shows that the underlying ichnite was sheared prior to infilling. Otherwise, the unfilled track should have been compressed flat. It begs the question: how do rigid media (sand) within a cohesive media (mud) act in the dead zone (displacement bulb), and what are incorporated traces on the base of ichnites? It is interesting to note that this track (Figure 4.7d) has a flat base like many of the other tracks, which could suggest development of a displacement bulb (sheared dead zone) is the reason for the rather flat preserved bases.

4.3 VERTEBRATE ICHNITE MORPHOLOGY

In the study area, ten morphotypes were differentiated based on variations in interdigital angles (II-III, III-IV), total divarication (II-IV), interdigital toponomy, digit definition, digit shape, and the presence of digit I. Distinguishing related morphologies based on the prominent features were determined by comparing individual morphologies from different sites. Trackways are rare, resulting in little data that could be accessed in terms of track relationships (e.g., pace angle, stride, morphological variations of a single animal). Ten distinct morphotypes were identified from the compiled data. This evaluation was based on the best seventy-four examples taken from over one hundred acetate traces that were collected from 16 sites in the field area and two taken from the Museum of the San Rafael. These 10 distinct morphologies fall into four general categories: morphotypes with appreciable interdigital connection, two types of well-defined digit morphologies with various total divarication between digit II-IV (either 63-85°, or equal to or greater than 90°), and small (<10cm) morphotypes that have little to no divarication.

The interdigital angles and total divarication measurement were taken in relation to where they intersected the midline of the axis of digit III at a single point, often at the posterior margin. Lockley, Wright, and Makusawa (2001) suggest this is incorrect procedure since it often relies on how much of the heel is impressed, and that a more correct methodology is that of Leonardi et al. (1987) where the axis of each digit is used for measurement regardless of where it intersects. However, in some of the morphologies in the study area there is no individual digits by which to properly access the axis, and most of the time the axis still appear to be inline with the line connected to the convergence point, regardless of using a less accurate method. Additionally, Thulborn (1990) has outlined the many methods by which these measures have been taken over the years in literature, and the individual bias that is introduced when using the axial method (e.g., Leonardi et al., 1987) to determine the divarication of curved digits (as are also present in this study). Sarjeant (1989) is a proponent of using a standardize method such as Leonardi et al. (1987) for description when possible, but maintains that the most important aspect is to illustrate how the measurements were obtained (regardless of method). In such accord, all of the morphologies have schematic representation of the digital axes from where the angles were measured. Additionally, emphasis was placed, in this section, on comparison to known morphologies, instead of just relying on the quantitative measure, which could vary, dependent on the method.

4.3.1 Morphotypes With Appreciable Interdigital Connection

There are two tridactyl morphotypes in the area that show interdigit connectivity (Figure 4.8a). The first morphotype (M1) is defined by a rather symmetrical appearance due to similar divarication between digits II-III and III-IV. Conversely, morphotype 2

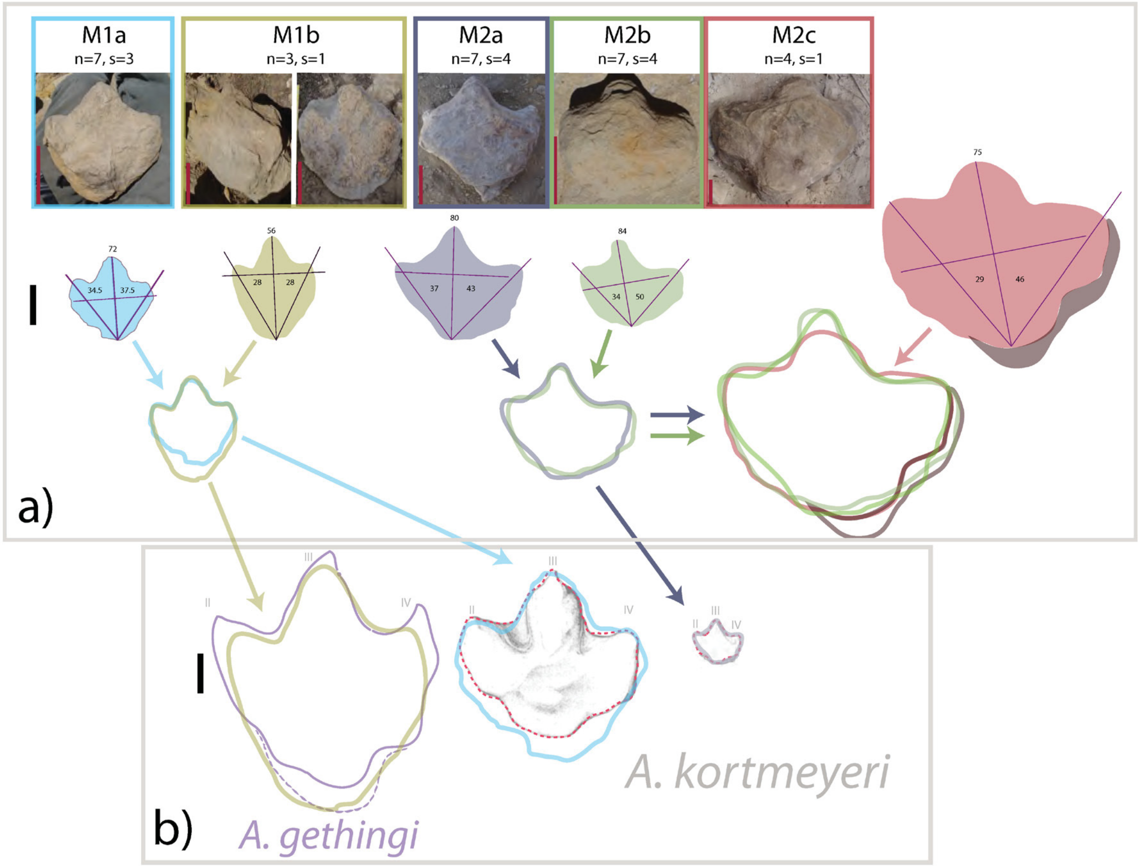

Figure 4.8: Morphotypes with interdigital connection: a) Morphologies from the study area with prominent interdigital connection. Top row: M1=symmetrical morphologies, M2=asymmetrical morphologies, associated letters represent further subdivision, n=number of tracks used to compile morphology, s=number of sites the tracks came from. Middle row: Compiled morphological outlines (at typical size) for each morphotype with interdigital angles, and total divarication (above digit III). The four lines on each track are equidistant representations of digit III used to visually illustrate the length relationship to the other digits, as well as the length to that of the width (perpendicular and centered to the midline of digit III). Many of these symbols and abbreviations are repeated on subsequent diagrams, but will not be restated on the subsequent figure captions. Scale is 10 cm. Bottom row: Morphotype outlines as scaled overlays respectfully represented by the same colored outline. b) Scaled comparisons of morphotype 1b to that of *Amblydactylus gethingi* modified from Sternberg (1932), and the holotype (middle) and paratype III (right) of *Amblydactylus kortmeyeri* modified from Currie and Sarjeant (1979) compared to scaled versions of M1a and M2a. The 10 cm scale is in relation to the tracks of these other authors, and not the scaled morphotype overlays. The morphotype size can be directly compared using Figure 4.8a (middle).

(M2) is asymmetric with divarication between III-IV being 5-17 degrees larger than II-III. Additionally, M2 is wider than it is long, whereas M1 has than a width that is less than or equal to the length.

4.3.1.1 Morphotype 1 (symmetrical connected)

Morphotype 1 (Figure 4.8a) is subdivided, with M1a being as wide as it is long and having a total divarication of 72; M1b is longer than wide with a resultant smaller divarication of 56. M1a is 21 cm long to 47 cm. M2 is around 25-28 cm long. Both morphologies are present as shallow (2 cm) and as deep (over 20 centimeters) natural casts. In deep tracks, M1a can have elongate attachments that taper towards the surface. The relief on the base can be both rather 2-D (flat) or 3-D. Overlay of the digits (Figure 4.8a) shows that the two morphologies are similar, differing mostly in the posterior end.

M1a and M1b are analogous to *Amblydactylus kortmeyeri* (*sensu* Currie and Sarjeant, 1979)(Figure 4.8b) in that both are tridactyl, comparable in size, the digits barely extending beyond the webbing (interdigital connection), and both have a similar outline in the distal portion of the ichnite. Additionally, M1a total divarication is comparable. However, the posterior margin is longer in both M1a and M1b than is seen in *A. kortmeyeri*. The longer length to width ratio and lower divarication (56 degrees) of M1b is more comparable to *Amblydactylus gethingi* of Sternberg (1932). Conversely, *A. gethingi* is represented by a morphology that is typically twice the size of M1b, and the shape and length of digits II and IV are proportionally different. Both M1a and M1b both appear to be *Amblydactylus*, but at this time it would be difficult to justify these as falling definitively under either of these species. Some may represent a more plantigrade expression of *A. kortmeyeri*.

4.3.1.2 Morphotype 2 (asymmetrical connected)

Morphotype 2 (Figure 4.8a) can be divided into three types based on the outline of the track. The outline of M2a consists of many relatively straight vectors and the digital tips appear sharp. M2b appears similar in shape to M2a, but has a more subtle rounded outline, especially in regards to the heel. M2c has a more rounded outline like M2b, but the expression of digit III is much shorter and there is a prominent recess in the heel on the digit IV side. Total divarication corresponds more in M2a (80) and M2b (84), than it is in M2c (75). However, the ratio of the divarication between II-III and III-IV is more equivalent between M2b and M2c.

M2b are the smallest ranging from 10 to 24 cm in length. M2a is the next largest mainly ranging from 23 to 31 cm, but one example has been documented (without environmental context) that was 57 cm. The largest morphology is M2c that ranges between 48 and 52 cm. In accordance with the sizes, M2b is also consistently the shallowest (3 to 9 cm). M2a can be shallow (2 cm) or deep (over 22 cm), however track size does not equate to depth since the largest track can be impressed at the same depth as many of the mid-sized tracks. The M2c tracks are typically less than 20cm deep. The largest (M2c) and smallest (M2b) have a comparable toponomic expression of a rather bulbous appearance to the margins, whereas M2a has a flat base and very sharp abrupt edges. Elongate heels may occasionally preserve in the deeper tracks of M2b.

M2a and M2b are referable to *A. kortmeyeri* (*sensu* Currie and Sarjeant, 1979) both in size, total divarication near 70-80 degrees, and shape (Figure 4.8b). M2b has a slightly more rounded outline, a slightly greater width to length ratio, and average smaller size, which could suggest a juvenile (M2b) to elder (M2c) relationship. Currie and Sarjeant (1979) previously noted the likelihood of this relationship with the smaller (more juvenile) ichnites having greater proportional widths. This relationship could extend up to the larger morphology of M2c. However, while the general outline, distal roundness of digits, greater width than length, and divarication of M2c resemble that of *A. kortmeyeri* (*sensu* Currie and Sarjeant, 1979); the size of M2c and the prominent posterolateral recess related to digit IV are more akin to *A. gethingi* (*sensu* Sternberg, 1932)(Figure 4.8b). The shortness of digit III is divergent from the prominent examples of either of these species, and could be an adult characteristic. There is evidence that M2c might belong to a quadraped, but at this time there is not enough justification or data to prove this.

4.3.2 Well-defined Digit Morphologies (Total Divarication 63-85°)

There are four morphologies (M3-M6) that have well defined digital expressions (i.e., lack substantial connection in the interdigit regions). All are tridactyl expression, and are mainly natural casts. M3 are tracks that are wider than long with the outer digits often having a triangular outline. M4 has at least two digits with bulbous terminal margins. M5 is similar to M3, but the digits are thinner, and there is a large stride observed. M6 is significantly longer than wide, and has a prominent pointed posterior margin (i.e., heel).

4.3.2.1 Morphology 3

Morphotype 3 (Figure 4.9a) is represented by tridactyl morphologies that typically

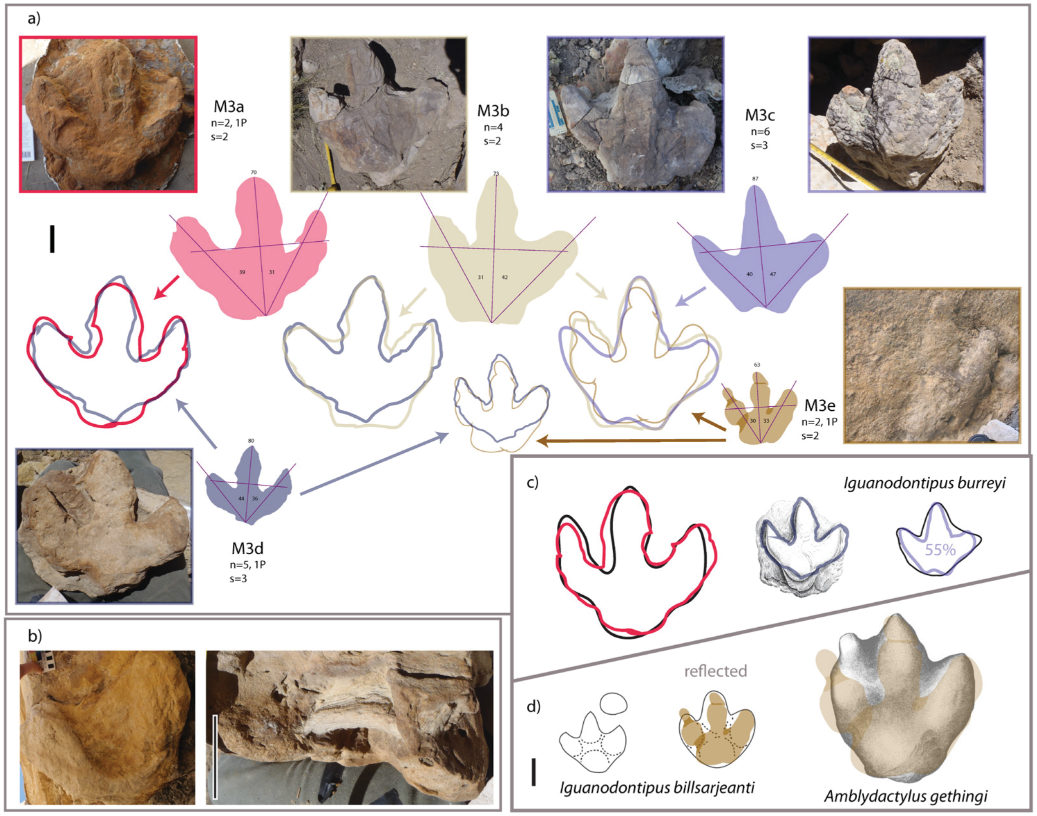

Figure 4.9: Morphotypes that are wider than long with little prominent interdigital connection: a). Morphotype 3, and examples the subtypes. Scale bar equals 10 cm. b) Left: example of interdigital connection sloping to center of track, and likely the result of indenter related stresses. Right: horizontal view of interdigital connection that expands overall downward, and more likely the expression of webbing between the toes. c) Ichnites synonymous with *Iguanodontipus burreyi* according to Sarjeant et al., (1998) compared to some of the subtypes of M3. Black or shaded representations are pes track after Thulborn (1990)(left), Beckles (1854)(middle), and modified from Sarjeant et al., (1998)(right). All are from the from the Lower Cretaceous of England, and the track on the right is Holotype D, which the authors claimed was not illustrated to scale, and for that reason was trued using the measurements the authors provided as well as the photograph. Neither M3a nor M3d are scaled, and are true size-to-size comparisons to the other authors' illustrations, whereas M3c is scaled down to 55%. d) Scaled comparison of M3e to the morphology of *Iguanodontipus billsarjeanti* (Meyer and Thuring, 2003) and *Amblydactylus gethingi* (Currie, 1983). Black scales equal 10 cm, white scale in the right photo of B equals 5 cm.

exhibit separation in the digits by the halfway point in the length of digit III, and is wider than it is long. The three digits are of unequal size, with each being slightly smaller, and digit III being the largest. Morphotype 3 is divided based on digit shape, heel shape, and length/width. M3a and M3d have relatively narrow heels, display a crescent shape in the connection of digits II and IV, and are wider than long. Digit III in M3a is more round, and the heel is more defined. M3b and 3c are pretty similar, but M3c can show higher divarication, may sometimes have a bilobed heel, and always have triangular digit III that has straight margins. M3e has well defined digital nodes, and has a smaller total divarication (63). M3a-c are all relatively the same size, a few half-sized and one possible quarter-sized ichnite. The large ones all impressed to the same depth of around 12-18 cm. M3d typically impressed between 6 and 9 cm. M3e is shallow, <3.5 cm deep, and the only subtype that may occur as shallow casts and as impressions. Morphology 3 is dominantly expressed with three-dimensional bases.

While almost all of these tracks display clearly differentiated digits, morphotypes 3a and 3e sometimes exhibit shallow connecting structures. The connecting structures do not always appear, and when they do it may just be in the interdigital area on one side. Thulborn (1990) suggested that while many of these structures are assumed to be interdigital webs, that there is a general lack of evidence to prove this. An experimental study by Falkingham et al. (2009) has suggested that many of these structures may be the result of sediment failure between the toes during emplacement. This may be a viable interpretation for some of the structures seen in M3a, e (Figure 4.9b, left) where the interdigital structures get thicker in the direction of the track, much like what was produced in the modern experiments. However, one track in M3d (Figure 4.9b, right) has an interdigital structure with an asymmetrical v-shaped cross-section, which would imply, at least for this track, a structure (webbing) that cross-cut the sediment rather than an inward collapse.

While the implication of webbing would be that some tracks of M3a and M3d could be argued to be *Amblydactylus*, but not all of them display this feature, the digits are well preserved, and it would be difficult to discern the taphonomic bias in preservation. The tracks of morphotype 3 are tentatively attributed to *Iguanodontipus* (sensu Sarjeant et al., 1998) due to the lack of prominent interdigital connection. Lucas et al. (2011) suggests that *Amblydactylus* and *Iguanodontipus* are synonymous, with *Amblydactylus* constituting the valid genus. This study will not follow this synonymizing of the terms, because even though the traces may illustrate similar characteristics, the one fundamental difference lies in the connection of the digits. *Amblydactylus* digits do not extend as far past the interdigital structure (e.g., webbing) as those of Iguanodont prints (i.e., *Iguanodontipus*). Regardless of if these expressions are prints from the same animal, morphologically these genera are vastly different in outline, and should be referred to as separate genera.

There are slight variations in the interdigital angles and shape/width of the heel in M3a-M3d, but they all are assignable to *Iguanodontipus burreyi* (*sensu* Sarjeant et al., 1998). This species have comparable shape, divarication, and triangular-shaped expressions at the distal portion of digits with the holotypes. There are some pretty large discrepancies with the description of I*guanodontipus* as a genus in the 1998 paper, namely the similar length of all digits, and the equilateral triangle-like shape of digit III. Hornung et al., (2012) has suggested that *Iguanodontipus* is largely being misused too include to many morphologies of Lower Cretaceous tracks, and that it represents a specific morphology, not a place to assign all iguanodont tracks. While these morphologies (M3a-d) do not adhere to the specific description of *Iguanodontipus* in Sarjeant et al. (1998), they do adhere to how the authors defined *Iguanodontipus burreyi*. The 1998 paper provides measures of digit length illustrating as much as 9 cm of disparity between digits, as well as many illustrated examples and synonymous examples where digit III is elongate and not an equilateral triangle-like expression. The examples of Lower Cretaceous *Iguanodontipus burreyi* are strikingly conformable to the Upper Cretaceous morphologies seen in this study (Figure 4.9c).

Morphology 3e is very different from the others with the low divarication and the presence of distinct digital nodes. The narrow divarication of M3e may just result from the firmness of the substrate. A firmer substrate for this subtype than the others in M3 is suggested by the shallowness of the track. A change in divarication due to substrate consistency has been mention in the modern experiments of Milan (2006). Currie and Sarjeant (1979) suggested that softer substrates might lead to wider spreading of the toes, or greater divarication. Besides the low divarication, digit II appears closer in size to digit III than that seen in M3a-d. While the divarication and general pad placement and shape of M3e are similar to *Iguanodontipus billsarjeanti* (*sensu* Meyer and Thuring, 2004), the one digit is still larger (Figure 4.9d). The general morphology of the track is more comparable to the *Amblydactylus gethingi* track of Currie (1983). The interdigital connection is not readily apparent, but this could also be due to the shallowness of the track.

4.3.2.2 Morphology 4 (bulbous, robust digits)

Morphotype 4 (Figure 4.10a) is differentiated from the previous morphotypes by

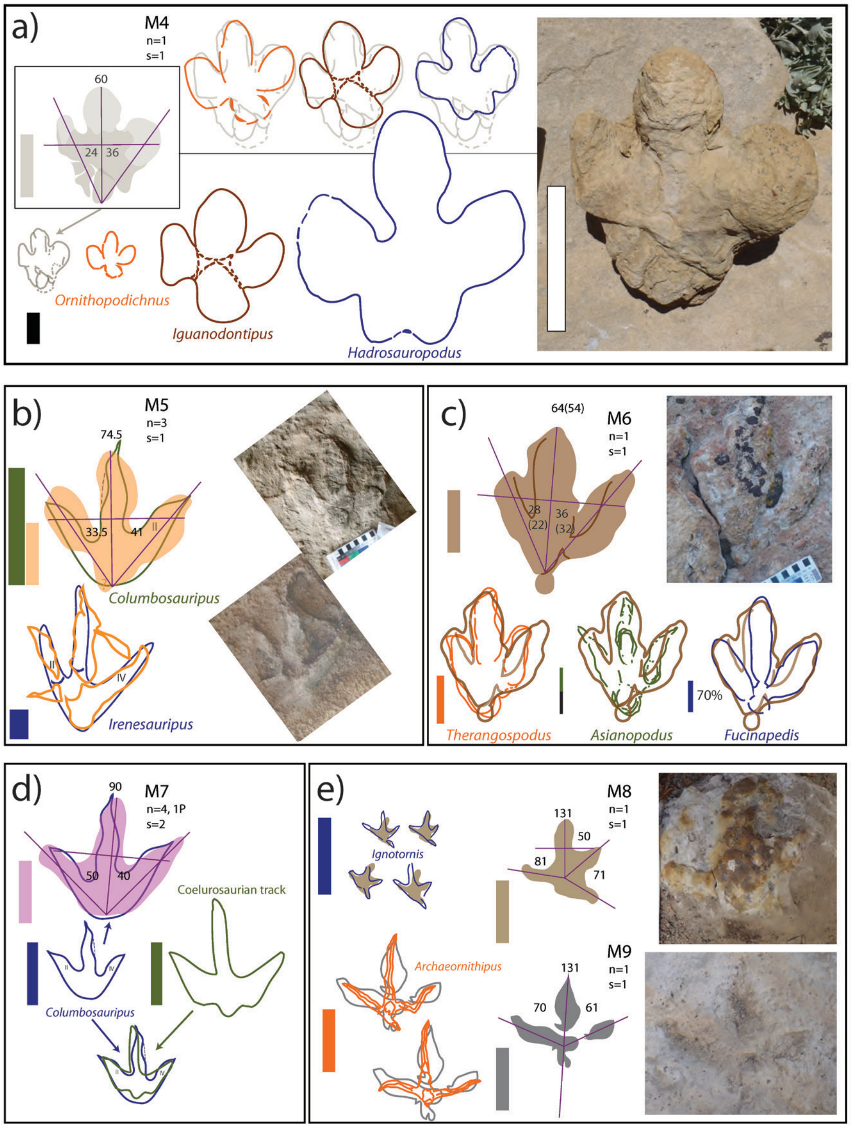

Figure 4.10: Small to medium tridactyl morphotypes lacking significant interdigital connection: a) Morphotype 4 compared to scaled morphologies (top) and true to size examples of *Ornithopodichnus* (after Lockley et al. 2012), shallow taphonomic variation of *Iguanodontipus* (after Diedrich, 2004), and an ichnite tentatively assigned to *Hadrosauropodus* (after Lockley et al., 2004). b) M5 compared to scaled theropod ichnites of *Columbosauripus ungulatus* and *Irenesauripus acutus* (after Sternberg, 1932). c) M6 compared to theropod ichnites of *Therangospodus pandemicus* (after Lockley et al., 1998), *Asianopodus pulvinicalx* (after Matsukawa et al., 2005), and *Fucinapedis woodbinensis* (after Lee, 1997). d) Top: M7 compared to scaled *Columbosauripus ungulatus* after Sternberg (1932), middle: true to scale *Columbosauripus ungulatus* and unnamed Coelurosaurian track after Lockley et al. (1985), bottom: scaled comparison showing the similarity between the morphology of the two tracks. e) Scaled comparison of M8 to examples after the paratypes of *Ignotornis mcconnelli* from Lockley et al., (2009) and true comparison of M9 to *Archaeornithipus meijidei* after Fuentes Vidarte (1996).

the bulbous outline of the toes. M4 has a low divarication around 60 degrees, is longer than wide, and digit III is longer than the other two digits. This track is 17cm long and 7cm deep. The heel is elongate, inclining towards the surface. Additionally, there is potentially a sharp bilobate morphology preserved within the heel. Only one specimen can be clearly attributed to this morphotype, but there is evidence of other similar tracks, of which heavily burrowing has masked the full morphology.

This morphotype (M4) is similar in size and morphology to the Korean Cretaceous (Campanian; Paik et al., 2012) tracks assigned to *Ornithopodichnus* by Lockley et al. (2012) (Figure 4.10a). M4 also shares the same morphology with the ornithopod pes prints from the Lower Cretaceous (Berriasian) of Germany that were referred to *Iguanodontipus* by Diedrich (2004) and the much larger Late Cretaceous (Maastrichtian) pes traces from Wyoming that were precautionarily assigned to *Hadrosauropodus langstoni* by Lockley et al. (2004). All of these forms exist as shallow imprints, which Diedrich (2004) suggested was a taphonomic variation of *Iguanodontipus* on drier sediment. However, M4 is a fully impressed natural cast, with similar depth to *Iguanodontipus* ichnites (M3) that occur at the same site as M4, and that shows no indication of the sharp distal ends that should be present upon deeper penetration. The rounded nature of the distal ends is more akin to those seen in some of the *Amblydactylus*-like forms (e.g., M2b, c), but M4 does not have evidence of connected digits. The smaller size of M4 compared to the *Iguanodontipus* ichnites (M3) could indicate a different juvenile morphology (e.g., Currie and Sarjeant, 1979), but the aforementioned studies show evidence of recurrence and often larger large size of similar morphologies suggesting that this belongs in a different ichnogenus than *Iguanodontipus* (*sensu* Sarjeant 1998). Additionally, even though *Ornithopodichnus* is a probable assignment, it is really only comparable to the unnamed species in this ichnotaxa of Lockley et al. (2012), and not those of the more robust, type ichnospecies of *O. masanensis* (i.e., Kim et al., 2009).

4.3.2.3 Morphology 5

Morphotype 5 (Figure 4.10b) is similar to the aforementioned morphologies in divarication, length/width ratio, and digit length relative to one another. However, the heel is narrow and prominent, and there is a high pace length (4.7 times track length). One digit often appears unattached at the base, but since it occurs on the same side of two consecutive tracks it is likely unrelated to the foot morphology. Additionally, there are many wood impressions on the surface, and at least one of these features appears to be related to wood disrupting the preservation. The ends of the digits may curl outwards and may come to sharp points, but it is difficult to access from the various states of preservation. The tracks are around 18-22 cm in length and less than 2.5 cm in depth.

It is hard to access the morphology on this track in terms of the true shape, heel shape, and length of digit III. From what can be accessed, the heel is narrow dimensionally, and the stride is long; it appears to be of an unascribable theropod affinity. The narrow heel is more akin to preservation in the much larger Lower Cretaceous *Irenesauripus acutus* (Sternberg, 1932), but digit ratios appear more like *Columbosauripus ungulatus* (Sternberg 1932). Both ichnogenera of Sternberg are likely produced by theropods (Thulborn, 1990). Additionally, long step (pace) lengths, as seen in M5, are typical of theropods (Lockley et al., 2001).

4.3.2.4 Morphology 6

Morphotype 6 (Figure 4.10c) only consists of a single track, but the morphology is vastly different from any of the other morphologies in the shape of the heel, which is axially elongate and has a small round structure at the most posterior portion. Additionally, the divarication is lower than almost all of the others, and the length/width ratio, from the posterior of the rounded structure to tip of digit III, is 1.2 (1.19). The track is 26 cm long and less than 2 cm deep.

Morphotype 6 heel shape is comparable to theropod morphologies, but the length/width ratios are slightly smaller than the 1.25 length/width ratio minimum that is suggested (e.g., Moratalla et al., 1988; Thulborn, 1990; Castanera et al., 2013 (180)). Common comparable theropod morphologies are those of *Eubrontes* and *Megalosauripus*, but normally smaller (<30 cm) tracks with a general lack of phalangeal pads (as seen in M6) are referred to as *Therangospodus* (Lockley et al., 1998a). However, M6 shows greater divarication, a less robust heel, and a smaller digit II than is seen in *Therangospodus* (sp. *pandemicus*) (Figure 4.10c; e.g., Lockley et al., 1998b). *Hispanosauropus* (sp. *hauboldi*) has similar divarication, but the ratio digit II relative to the overall size appears shorter in the tracks described by Mensink and Mertmann (1984). Additionally *Hispanosauropus* is another genus that is normally reserved for much larger tracks (e.g., Avanzini et al., 2012). The two examples that most resemble M6 in overall morphology are *Fucinapedis woodbinensis* (Lee, 1997) and *Asianopodus pulvinicalx* (Matsukawa et al., 2005). However, heel morphologies of both vary, with *Asianopodus* having a more robust heel than M6 and more defined distal portions of the digits, while *Fucinapedis* has a comparably sized heel and similar distal roundness, but the heel is more medially directed than M6. The authors suggested that theropods likely produced both ichnotaxa. Therefore much like M5, M6 is of an unascribable, but different, theropod affinity.

4.3.3 Well-defined digit Morphologies (Total Divarication 90° or greater)

4.3.3.1 Morphotype 7

Morphotype 7 is wider than long, and has a divarication of 90. It is 17-20 cm long and less than 2.5 cm deep. Digit I is not apparent. M7 is similar to M5, but with a wider heel.

Morphotype 7 appears to be a coelurosaurian-like theropod track (Figure 4.10d). The wide rounded heel and general digit ratios are comparable to the Lower Cretaceous *Columbosauripus ungulatus* of Sternberg (1932), which is likely produced by a coelurosaur (Thulborn 1990). *C. ungulatus* digits have sharper ends and the tracks are slightly smaller than M7. Larger *C. ungulatus* (16.5 cm long) have been reported from Alaska by Gangloff et al. (2004). An even larger (up to 25 cm long) unnamed coelurosaurian tracks (Lockley et al., 1985) from the Lower Cretaceous Dakota Group share similar morphology, but the digits tips are more rounded. M7 falls between these sizes. The heel of the Dakota and Alaskan track does appear shortened and has a tripartite shape (Figure 4.10d). However, most of the tracks illustrated in the trackway from the Dakota (Lockley et al., 1985; Lockley and Gillette, 1989) show a larger rounded heel that is similar to M7 and *C. ungulatus* of Sternberg (1932).

4.3.3.2 Morphotype 8 and 9

Morphotype 8 and 9 each consists of a single ichnite with a large total divarication between digits II-IV (131 degrees). The preservation in these tracks is rather poor, but they appear to be tetradactyl. Digit I is present divaricating from digit III at 121 degrees in M8, and close to 180 degrees in M9. Both are close to 15 cm in length.

An avian producer is suggested for M8 and M9 because divarication in dinosaurs between digit II and IV generally does not exceed 100 degrees (Currie, 1981). While M8 might have slightly more webbing and a slightly longer digit I than M9, the poor preservation and diminutive sample size, makes it impossible to discount the possibility that these two similar sized morphologies are taphonomic variations. In the assumption that both morphologies have a fourth toe (digit I), both tracks would be similar in outline to *Ignotornis mcconnelli* (Mehl, 1931). The interdigital angles fall outside of the original parameters set by Mehl (1931), but do fall within the divarication angles, of more recent examples from the same area, that were documented by Lockley, Chin, Houck, et al. (2009). However, their data shows *Ignotornis mcconnelli* is typically half the size of the tracks seen in this study. Most Cretaceous bird tracks are usually 2 to 7.5 cm in length, with a rare exception being *Magnoavipes lowei*, which is around 20 cm in length (Lee, 1997). However *Magnoavipes* is larger than the tracks seen in this study, has no webbing, a slightly lower divarication, and a heel but no prominent hallux (digit I). Lockley, Wright, and Matsukawa (2001) suggest that *Magnoavipes* is actually a small theropod since the divarication is less than 105 degrees, averaging 85 degrees, and that there is no prominent hallux (digit I). *Archaeornithipus meijidei* of Fuentes Vidarte (1996) is closer (12 cm) to the true size of M8 and M9, may have a short or prominent hallux (digit I), and has similar total divarication values.

As stated earlier, with the poor preservation and lack of repetitive examples, while not much in terms of true taxonomy can be taken away from these samples, M8 appears like a larger representative of *I. mcconnelli*, with possible webbing between the digits, while M9 more resembles *A. meijidei*. Both of these ichnogenera are considered to be the product of large wading birds (e.g., heron-like or crane-like)(Lee, 1997; Fuentes Vidarte, 1996).

4.3.4 Small Morphologies (Little to No Total Divarication)

4.3.4.1 Morphotype 10

Morphotype 10 is represented by several morphotype variations that occur together (Figure 4.11). This morphotype (10) is wider than long, and composed of 3-5 linear to tear drop shaped hyporelief structures, that are generally less than 2.5 cm long, 0.5 cm wide, and 1.5 cm deep. Usually the central feature is the longest. Each feature is relatively symmetrical laterally from the central digit to its corresponding opposite. However, the anterior placement of the digits vary slightly, giving the ichnite a slightly asymmetrical appearance. The linear features are dominantly parallel, having very little or no interdigital divergence or total divarication. The linear features are fairly evenly spaced, except for digit I on the five digit examples, in which digits I and II are slightly closer than the others. These features are commonly connected posteriorly by an arcuate hyporelief structure. The arcuate hyporelief is positive (deeper impressed) may be accompanied by

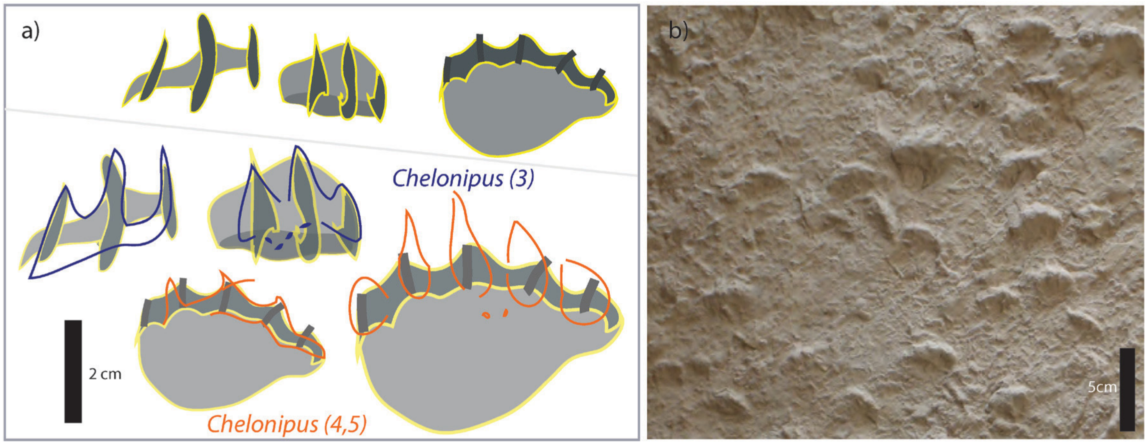

Figure 4.11: Tracks attributable to *Chelonipus*: a) Examples of variations (tridactyl and pentadactyl) seen in Morphotype 10, with faded M10 examples scaled to examples of *Chelonipus* of Lockley et al. (2010) (tridactyl) and Lockley and Foster (2006)(pentadactyl). b) Examples of *Chelonipus* positive hyporeliefs (natural casts) from site 2 that show tridactyl and pentadactyl morphologies that are connected by an arcuate structure. Darker oval negative hyporeliefs posterior to the *Chelonipus* tracks likely represent posterior displacement rims that were produced during terrestrial locomotion.

an adjoining negative hyporelief structure (raised above the depositional surface). The negative structure is roughly ovate, and loosely symmetrical along an axis running between the most posterolateral expressions of the positive arch. The positive arch has a shallow anterior slope, and a steeper posterior slope. In some instances, the linear features may extend down (depositionally up) the steep posterior slope, drawing closer in proximity posteriorly. Additionally, sometimes the positive arch can be divided into individual lobes. The arch structures and related ovate structures dominantly preserve in the deeper ichnite expressions, whereas the shallowest ichnites may show no arch. Related to this, the linear features often do not extend much past the arch in deeper ichnites, whereas shallow ichnites often show the longest linear features.

Morphotype 10 represents the quadrapedal locomotion of a turtle. This morphology fits the key criteria of the ichnotaxon, *Chelonipus* (amended from Rühle von Lilienstern, 1939), which is a fairly symmetrical, wider than long ichnite composed of 3-5 elongate, anteriorly tapered, features (or digits), which are often connected by posteriorly-directed arcuate structures (e.g., Foster et al., 1999; Lockley and Foster, 2006; Lovelace and Lovelace, 2012). Some of the *Chelonipus* traces in the study area probably grade into the swim traces (*Characichnos, sensu* White and Romano, 2001). The gradational relationship between these ichnotaxa is discussed in more detail in chapter 2, as well as, a more thorough explanation for the morphological assignments. A morphological relationship likely exists between the variations in morphology to represent a continuum related to substrate firmness and behavior. In general observation, one site is dominated by shallow longer linear features, with less interdigital connection and arch expression, and predominantly three digit forms. Whereas, the other site displays at least an equal number of five digit forms, with shorter linear features, and deeper impressed arches with attached ovate structures. The first site likely is more representative of the swimming, or subaqueous bottom walking behavior that is often interpreted from *Chelonipus* (e.g., Foster et al., 1999; Lockley and Foster, 2006). The second site is most likely a terrestrial walking behavior.

While, a terrestrial nature might be thought to produce more continuous trackways in site two, than seen in what is likely a buoyancy-aided behavior in site 1, the data is inconclusive at this time since the mapping of the surfaces is still underway. Figure 4.11b does show some of the continuous nature of the tracks at site 2, but site 1 does have a trackway consistency to it as well, that is marred by overprinting. One major difference though is the negative ovals associated with the arcuate structures in site 2. Positive structures behind the ichnite of *Chelonipus* (likely different species) have been noted in late Eocene of Texas by Sarjeant and Langston (1994). The creation of these was attributed to mud sticking to the foot as the animal moved forward, resulting in a crescent structure, mainly positioned posterior to the track. However, these tracks create a sharp posterior raised lip, which is different than the ones in site 2, where the elevation appears to peak closer to the track. The structure is more consistent with the posterior displacement rims, seen in the modern experiments of Avanzini et al. (2005), which were created by turtles walking (terrestrial) on firm sands.

An alternate explanation could be that these two sites represent different species. More work is underway to ascertain whether the greater number of tridactyl forms at site 1 is due to partial preservation of pentadactyl morphologies. It appears likely that the pentadactyl forms represent manus prints, and that the lesser forms may represent pes prints. However, true manus/pes relationships still need to be established, as documented in chapter 2. The difficulty in establishing these in *Chelonipus* has been documented by Foster et al. (1999), and illustrated by Avanzini et al. (2005) in modern turtles showing high variations in manus/pes spatial relationships, as well as, manus divarication related to the midline.

4.3.5 Morphotype Conclusion

Morphotypes 1-4 all represent small to large tracks of bipedal ornithopods, M1-3 are referable to *Amblydactylus gethingi* and *kortmeyeri*, as well as, *Iguanodontipus burreyi*. The argument between whether these ichnotaxa are attributable Hadrosaurs or Iguanodonts is beyond the scope of this paper, although the robustness of the digits of Morphotype 4 leans more towards Hadrosaurine affinities. Conversely, morphotypes 5-7 are ichnites produced by small to medium theropods. Morphotypes 8 and 9 are likely the product of large wadding birds. Morphotype 10 is the product of turtle movement (*Chelonipus*) that could result from walking or swimming or a combination of the two.

4.4 THE OBSERVABLE RELATIONSHIPS BETWEEN ICHNITES, ICHNOLOGY, AND ENVIRONMENT

In this section the ten previously defined ichnite morphotypes will be addressed in the context of what depositional environments they occur in, and how the ichnites relate to the facies and invertebrate ichnology. In order to discuss the depositional environment interpretations, the facies and facies associations must first be addressed.

4.4.1 Facies

Facies in the study area are denoted in the simplest terms possible due to the high variability in some facies (e.g., rippled sandstones) that would result in either lumping, which would still only produce consensus of the hydrodynamic conditions, or would result in splitting to the point in which the other facies were overshadowed. Therefore, the facies are referred to in a style comparable to Miall (1985), in which the first letter (capitalized) represents the lithology, and any proceeding letter(s) represent the observable sedimentary fabric. Therefore, "S" represents sandstone, "F" is mudstone, and "C" is coal. The modifier "l" refers to lamina or planar bedding. The parallel lamina may be horizontally deposited or inclined in unison, in extreme cases up to 28 degrees. The descriptors of "b" and "p" are referable to the blocky and platy textures described by Retallack (1988). The labels of "r" and "t" designate the physical sedimentary structures of ripples and cross-beds respectively. Facies displaying an overall lack of organized texture are described with "m" or massive.

The laminated or planar-bedded facies of the sandstones (Sl) represents upper flow regime conditions, possibly related to shallow water depth (Clifton et al., 1971, Harms et al., 1982). Whereas this laminated texture in mudstone (Fl) equates to suspension settling in more quiescence conditions (Harms and Fahnestock, 1965) with minimal modification due to subaerial exposure. Increased subaerial exposure leads to platy texture (Fp), and with longer durations to blocky texture (Fb)(Retallack, 1988). The rippled facies (Sr) typify low energy conditions of variable geometry and mud content based on factors such as the rate of sedimentation, slope, depth, oscillatory or unidirectional current, and grain size (Dumas et al., 2005, Rubin, 2012). Conversely, trough cross-bedding forms at higher velocities than ripples at comparable grain sizes, or at similar velocities with grain size increase (Southard and Boguchwal, 1990). Massive facies (Fm, Sm), observed in the study area, typically delineate intense post depositional modification processes of plants or animals. In rare cases, the massive appearance is related to weathering of the outcrop.

4.4.2 Facies Associations

There are eight facies associations present within the studied sites. These can be grouped into coastal plain (distributary channels, source distal coastal plain of moderately drained or poorly drained conditions, and interdistributary) as well as nearshore environments (distributary mouthbar, brackish bay, washover prone, and tidal channel dominated).

4.4.2.1 Coastal Plain

Most of the sites in this study (Figure 4.2) appear to be less than 10 km from the paleoshorelines of Garrison and van den Bergh (2004). The term coastal plain is used in this study rather than delta plain due to the possibility that some of these deposits may not represent the deposits accumulated during delta progradation. However, it is likely that most of the deposits related to the coastal plain facies associations are delta plain deposits. In deltas, the greatest variance in deposition environments is established in the delta plain (Scott and Fisher, 1969). Therefore, the facies successions are likely highly-variable, and thus some facies associations show greater variability.

Three subdivision are made, with four representative facies associations. The first subdivision is the Distributary Channel Facies Association that is typified by the domination of high-energy structures (facies St, Sl) and contains some portion of medium-sized grains. The base, where observable, is highly irregular, generally concave up, with centimeter scaled subangular to angular mud clasts overlying it. The second subdivision refers to deposits that have no appreciable coarse clastic (sand-sized) facies, and are inferred to have deposited away from the source (i.e., channel). The data available allows no priority to be placed on the single mechanism responsible (e.g., lobe abandonment vs. distance from channel). This subdivision of distal deposits is divided into two facies associations: a Moderately Drained Facies Association chiefly composed of facies Fp and Fb; and a Poorly Drained Facies Association predominantly represented by Facies C, with minor Facies Fl.

The third subdivision of the coastal plain deposits, the Interdistributary Facies Association, represents the wide variety of vertical successions that may occur in the same area with close proximity to the source. This association is dominated by Facies Sr, but in some cases may contain almost as much Facies Fl. Various proportions of facies St, Sl, and Sm can be present. The Interdistributary Association can typically be differentiated from the poorly drained source distal association, in the regular interbedding of the Sr with the Fl facies, as well as the thickness of the Fl facies; but there are some contacts between the two that are gradational and therefore, within a few centimeters, reflect a bias of the author. The Interdistributary Association is different from the Distributary Channel Association by the proportion of facies, but additionally is normally dominated by finer grain sizes.

Additionally, where the bases of the Interdistributary Association are sharp, the bases are more subdued in nature, and there is no sizable amount of mudstone clasts directly above mudstone contacts.

4.4.2.1.1 Distributary Channel Description:

The Distributary Channel Facies Association is a channelized association (Figure 4.12). These geobodies are composed of fining upward cycles of moderately to poorly sorted sandstone of facies St, Sr, Sl. Facies Sr maybe represented by 2D or 3D ripples. The grain size within the sandstone ranges from medium upper to fine lower. Mudstone and organic clasts are present at the base and along sharp dipping surfaces that may be slightly undulatory, and often associated with a abrupt increase in grain size over the dipping surface. The surfaces may dip up to 28 degrees. Thin mudstone beds or lamina are sometimes present, but usually only extend a few meters. The Distributary Channel Association lies above the source distal, poorly or moderately drained coastal plain associations.

Vertebrate ichnites of Morphology 10 (*Chelonipus*) are present as natural casts along the thin mud lamina, beds, or breaks in the sandstone as groupings of 3-5 scratch marks in often arcuate patterns. These breaks occur along rather flat, dipping surfaces within Facies Sr (Figure 4.12). At the site in Figure 4.12a, the tracks appear to be related to terrestrial movement, as discussed earlier. Associated traces within the Sr facies at this site are tiny vertical mud structures that are 1-2 cm long, which could be attributable to either plants or *Skolithos*. Conversely, the other site (Figure 4.12b) contains *Chelonipus* more relatable to swimming behaviors. *Rhizocorallium*, *Helminthoidichnites*, larger surface plowing traces, and *Teredolites* (likely allochthonous) are associated with these traces in facies Sr. Rare *Planolites* may be related to these surfaces, but exposure did not allow confirmation. Most of these traces are not directly associated with the surface, but do exist in the same facies, and within several centimeters of these track surfaces.

4.4.2.1.2 Distributary Channel Interpretation:

The track bearing facies associations (distributary channel) represent point bar deposits, preserving the tracks in a sheltered or lower flow interval (e.g., abandonment). Channelized fining upward cycles of sand with basal mudstone clasts are often common in fluvial channels (e.g., Miall, 1985). Large dipping surfaces within the sandstone geobody are characteristic of the lateral migration surfaces seen in point bars of meandering river systems (Allen, 1970). A more detailed justification is present in Chapter 2. *Chelonipus* has

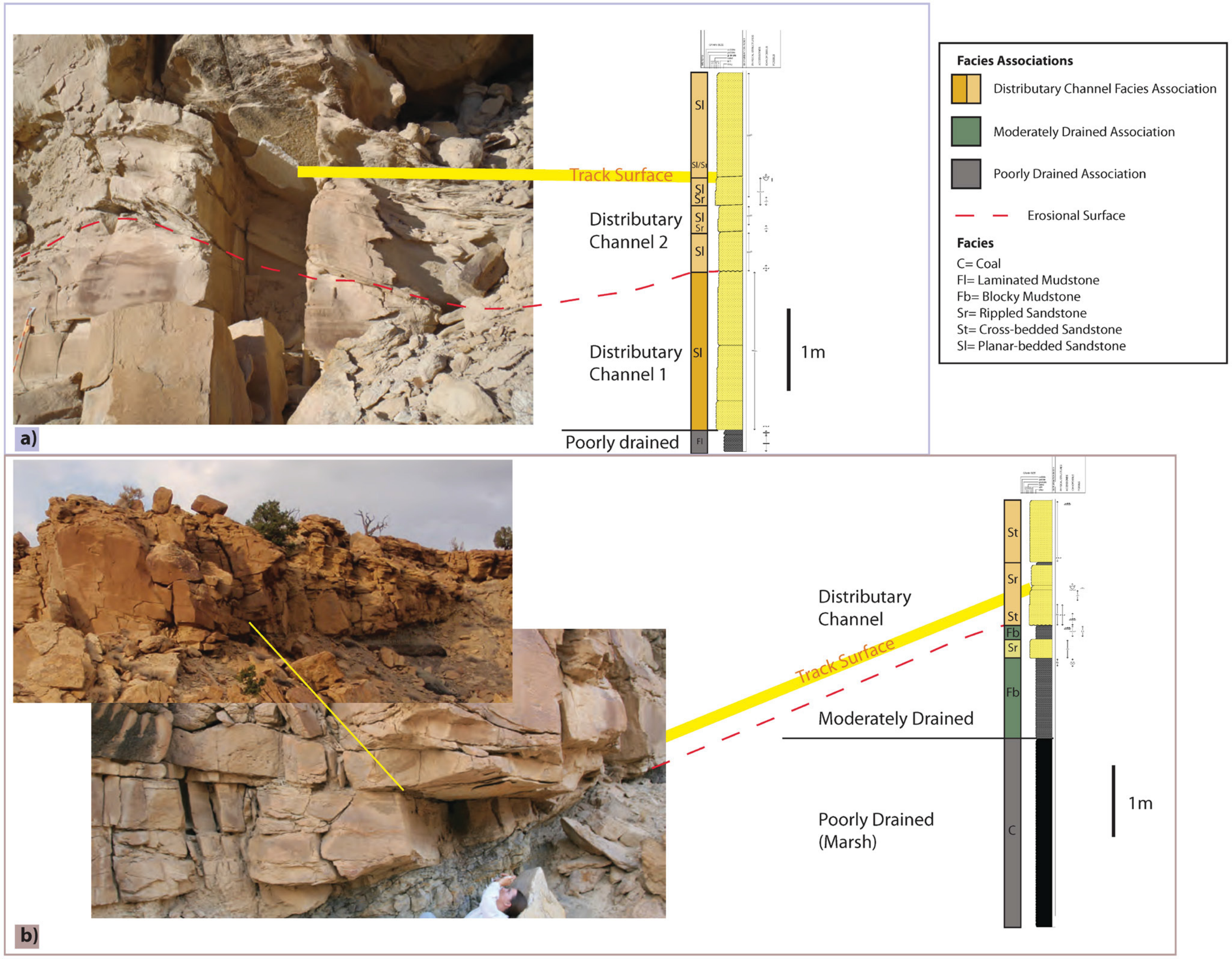

Figure 4.12: Distributary Channel Facies Association with track surface locations along dipping bar surfaces: a) measured section showing dominance by Facies Sl, b) measured section example with dominance by Facies St.

almost exclusively been found in channel deposits in the Mesozoic (e.g., Foster et al., 1999, Lockley and Foster, 2006, Lockley et al., 2010, Lovelace and Lovelace, 2012), which agrees with this assessment. The two studied sites in the Ferron Sandstone do seem to represent different exposure conditions. The terrestrial *Chelonipus* is linked with small vertical mud structures that could represent either rooting, or *Skolithos*. Meniscule *Skolithos* have often been linked to insect-generated structures in subaerial fluvial environments (Ratcliffe and Fagerstrom, 1980). Conversely, the assemblage of traces at the other site, that are associated with the swimming behavior of *Chelonipus*, are products of the subaqueous behaviors of insects and mollusks, as detailed in Chapter 2.

In the third location where this facies association is observed does not contain tracks, and does not represent point bar deposits (Figure 4.13c). Garrison and van den Bergh (2004) interpreted this sandstone as distributary mouthbar deposits. It is hard to dispute their interpretation for this third location. In order to maintain the simplicity of facies associations this unit was placed within the Distributary Channel Facies Association due to the dominance of medium grain sizes and by Facies St. These characteristics are very disparate from what is likely a more distal mouthbar expression closer to the terminal end of the distributary channel, which is expressed in the Distributary Mouthbar Facies Association as defined later in this section.

4.4.2.1.3 Moderately Drained Coastal Plain (Source Distal) Description:

The Moderately Drained Facies Association (e.g., Figure 4.13a) is composed of 0.15 to 2 meter thick (typically between 0.3-0.75m) mudstone with blocky texture (facies Fb) and/or platy texture (facies Fp). The mudstone may be sandy with up to vfL grain. Sand lamina may be present, but sand beds are rare (facies Sm, Sr). Both coarsening and fining upwards trends may be present. The mudstone facies are typically various shades of grey, but may also be a reddish brown color. Color mottling is often apparent. Iron and sulfur staining is common. Iron occasionally may be present as nodules.

Carbonaceous material is often seen downward branching (i.e., roots), but may also be recognized as larger, more horizontal structures (logs). Rarely these horizontal structures show *Teredolites* expression. Passively infilled (sand) tiny *Skolithos* are rarely preserved in the top. Vertebrate ichnites (Morphology 3a, *Iguanodontipus burreyi*) were only noted as passively filled casts (shallow <15cm) at the top of this association in one location (Figure 4.12a). Passive infill was from the Interdistributary Facies Association. *Teredolites* in carbonaceous debris are rare, and was not associated with the footprint surface.

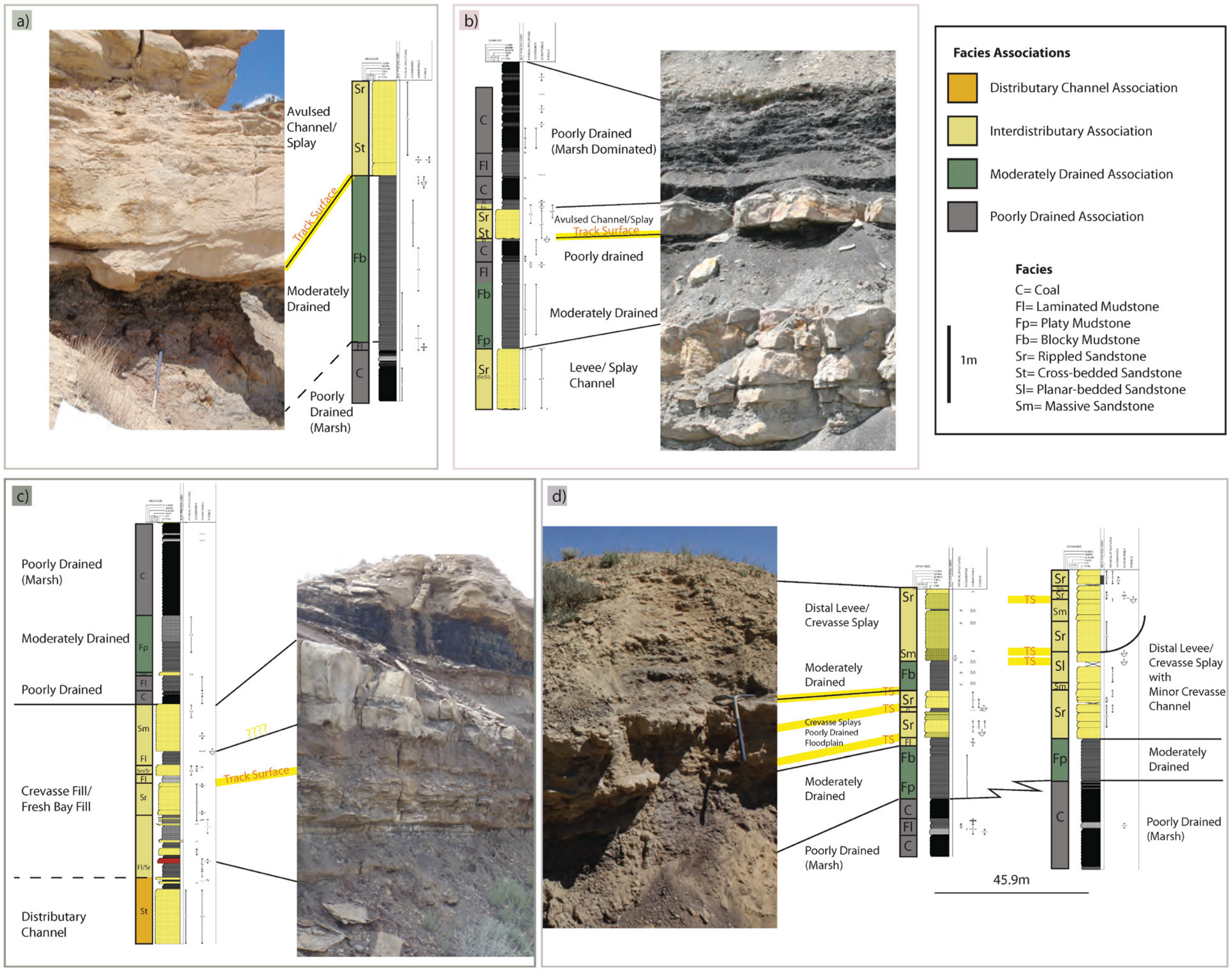

Figure 4.13: Coastal Plain Facies Associations: a) Track surface along top of moderately drained coastal plain, b) tracks along base of sandstone in the Interdistributary Facies Association, c) muddier and likely more subaqueous deposition represented in the Interdistributary Facies Association, d) multiple track horizons associated with meniscate backfilled burrows (*Beaconites*) in the Interdistributary Facies Association.

This association can be over or underlain (typically gradationally) by the Poorly Drained or Interdistributary Facies Associations. The Moderately Drained Facies Association overlies Interdistributary (channel), Distributary Channel and Tidal Channel Dominated Facies Associations sharply, with varying degrees of relief.

4.4.2.1.4 Moderately Drained Coastal Plain (Source Distal) Interpretation:

The Moderately Drained Facies Association represents moderately drained floodplain (coastal plain) deposits. The dominance by finer grained lithologies indicates a distal nature to the sediment source. Blocky to platy textures are indicative ped creation during soil development (Retallack, 1988). The creation of these textures in paleosols is reliant on exposure of the surface. Exposure is dictated by how well the soil is drained and how rapidly sedimentation buries the horizon (Kraus, 1999). Rooting also indicates exposure. The iron stain may indicate oxidation, but the dominance of grey color suggests gleying or iron reduction due to water saturated conditions (Retallack, 2001). These textures likely indicate a range of B horizon development from weaker textures (e.g., paleo-inceptisols associated with prolonged wetness) to that of better-developed blocky Bt horizons (e.g., paleo-vertisol). Paleo-vertisols have been identified in the rock record and are often interpreted to indicate seasonally high water table fluctuations in floodplain environments (Kraus, 1999, Nadon, 1994, Makaske, 2001).

Teredolites may indicate some of these deposits accumulated in close proximity to the shoreline where they are normally produced (Bromley et al., 1984; Savrda and King, 1993; Savrda and Smith, 1996). Conversely, the unlined *Skolithos*, that occur on the same surface as the ichnites, is made in modern floodplain deposits by various types of insects (Ratcliffe and Fagerstrom, 1980), and this behavior has been observed as vertical shafts in Jurassic floodplain deposits (Hasiotis, 2004). The preservation of the vertebrate traces (M3a) is a result of the overbank avulsion of coarser deposits passively infilling tracks emplaced in the floodplain.

4.4.2.1.5 Poorly Drained Coastal Plain (Source Distal) Description:

The Poorly Drained Facies Association (e.g., Figure 4.13) is dominantly or entirely composed of blocky or laminated coal (Facies C). Laminated mudstone (Facies Fl) is a secondary facies that almost always lies between coal and any other facies. Additional mudstone is present in the form of several centimeter ash beds as coal splits. This association ranges between 0.25 and 1.5m thick.

There is generally very little coarse grain content within this association. Facies Fl is rarely even silty. The ashes however are coarser, silt to very fine sand, and contain abundant micaceous material. Carbonaceous material is often abundant in facies Fl, often as lamina or lenses, that can account for over half the deposited material. Facies Fl is often a brownish color when associated with the organic lenses, otherwise, it is various shades of gray. Small vertical carbonaceous material (roots) are sometimes seen in facies Fl, but are typically more associated with the ash splits, or overlying coal. Generally, there is no animal bioturbation recognized within this association.

No tracks are found within this facies association, however it should be noted that vertebrate ichnites are common in Facies Fl, which is also often grouped into the base of track-bearing Interdistributary Facies Association due to the often gradational contact with overlying Facies Sr. In one place (Figure 4.13b), vertebrate ichnites push down through Facies Fl to make contact with Facies C of the Poorly Drained Association.

This facies association typically lies under the Moderately Drained Facies Association, but may also underlie Facies Fl of the Washover Prone Association and the Interdistributary Association. The Poorly Drained Association dominantly overly Facies Fp, of the Moderately Drained Coastal Plain or Tidal Channel Dominated Association.

4.4.2.1.6 Poorly Drained Coastal Plain (Source Distal) Interpretation:

The Poorly Drained Facies Association represents coastal areas that have a high water table and allow for the accumulation of large quantities of organics. The generation of thick coals such as these require a long period of time with low clastic influx and waterlogged conditions (McCabe, 1987). Coals commonly occur in the delta plain as abandonment fills (lakes, bays, channels, or behind barrier islands) on both local and large scales (e.g., lobe abandonment)(Fielding, 1985). These facies dominantly represent organic rich A horizons of paleo-histosols, that are deposited in dominantly waterlogged conditions. The succession of gleyed paleo-vertisols, then paleo-histosols, topped with laminated mudstone is a common pattern that is noted within Paleozoic delta plain and fluvio-lacustrine cyclothems (Driese and Ober, 2005, Cecil, 2013).

4.4.2.1.7 Interdistributary (source proximal) Description:

The Interdistributary Facies Association (e.g., Figure 4.13) is 0.38 to 2.3 meter thick, with the dominant component being facies tan to white Sr. Facies Sr is typical mud draped, and often is rapidly gradational along the top and base. Minor sandstone facies are St, Sm, Sr, and Sl. Facies St is only occasionally seen, and only in the basal part of the sandstone. The grain size ranges from silt to vfU grains, and less commonly up to fine upper grains. Fine upper grains are only associated with the two thickest sandstone beds seen. Mudstone clasts are conspicuously absent, and only abundant near the middle of one of the thick sand beds. Alternatively organic debris, both as angular-subangular clast, and as leafy material is fairly common. Iron staining is a common feature, as well as rooted tops. In some intervals, iron occurs as nodules or beds. The sandstone in this facies rapidly thin laterally or grade into mudstone facies. Small convex up based sandstones may appear and disappear over 10's of meters.

Mudstones occur as thin deposit intervals of Fl or Fp. The mudstones are often silty or sandy, and may contain sand lamina. Vertebrate ichnites are present in three places: along the base of the thick sandstones, in Facies Fl in this association, or as mudstone or cryptic sandstone filled depressions along the tops of the deformed Sr, Sm, and Sl facies. The depth of penetration was typically 2.5-9.5 cm, but in one location the sediment was displaced (as bulbs) greater than 20 cm. Tiny *Skolithos* may be present along the base of the thicker sandstone intervals (Figure 4.13a), whereas rare *Planolite*s may be present along the thin bedsets. Meniscate backfilled burrows (*Beaconites antarticus sensu* Bradshaw, 1981, after Vialov, 1962) are often present in the Sr, Sm, or Sl facies (Figure 4.13d). These burrows in the study area are similar in their relatively small size (0.5-3 cm) and their relative straightness. However, many of them are vertical, which is disparate from the description, and often these burrows appear as weathered out *Skolithos* tubes. Toponomic *Skolithos* expressions of *Beaconites* are noted in the Lower Cretaceous of England by Goldring et al. (2005). In many cases, the massive appearance of facies Sm appears to be due to reworking by the meniscate burrows or by heavy rooting. A heavily nodose burrow possibly attributable to *Camborgyma* (Hasiotis, 2004) may be present in the example with heavy interbedding by facies Fl (Figure 4.13c). Ichnites of Morphologies 1-4 (ornithopods) are often seen being cross-cut by *Beaconites antarticus* after the cast is filled, or deforming the underlying sandstones that contain *B. antarcticus*. Some vertebrate natural casts may have *Planolites* on the base.

4.4.2.1.8 Interdistributary (source proximal) Interpretation:

The Interdistributary Facies Association represents the wide variety of clastic successions that Elliott (1974) described from the area of a delta that lies between the distributary channels. This applies to both open and closed bays of varying salinity. There are no observable indicators of brackish conditions that were seen in this association. The fining upward, and decrease upward of bedforms (facies St to Sr) towards rooted tops (Figure 4.13a, b) are reminiscent of Elliott's (1974) channel avulsion facies. Whereas, Figure 4.13b and d are comparable to the overbank flooding and crevasse splay deposits with rooting, lateral thinning, domination by ripples (current and climbing), and occasional small channels. The Interdistributary Association succession that likely represents the most subaqueous conditions is represented in Figure 4.13c, where wave modification of ripples, heavy mud draping, and significant mudstone interbeds are present, and the impressed ichnites (displacement bulbs) are the deepest (out of this association). This is comparable to the minor sand split of Elliott (1974) or a smaller version of the bay mouth sequence.

As discussed above, the Morphotype 3a is observed with tiny *Skolithos* on the base of the avulsion channel (Figure 4.13a). It was not confirmed, in plan view, but ichnites are likely to occur along breaks in these channels where they are resultant of periodic filling. The more inundated setting (Figure 4.13c) had the web-like morphologies of 2a and b as rare fallen blocks, and prominent displacement bulbs in cross-section. The only notable trace was that of *?Camborgyma.* The overbank/splay types (Figure 4.13d) were dominated by sub-decimeter natural casts of small to medium ornithopods of Morphotypes 1 and 2 (*Amblydactylus*), rare incomplete M3a, several preservations of M3d (*Iguanodontipus burreyi*), a mostly complete impression of M3e, and M4. More impression were seen along the tops of beds in cross-section, but not in plan view. Additionally, many forms were subsequently heavily burrowed to the hindrance of identifying smaller forms (<10 cm) that appeared theropod-like. A few large gracile forms (>30cm) were also seen, but due to the thin nature of toes, were often broken. The small roots, meniscate backfilled burrows (*Beaconites*), and Iguanodon natural casts (*Iguanodontipus burreyi*) are commonly seen associated with the seasonally wet overbank deposits of Lower Cretaceous Wealden Strata in England (e.g., Graham and Pollard, 1982, Woodhams and Hines, 1989, Parkes, 1993, Sarjeant et al., 1998, Goldring et al., 2005, Radley and Allen, 2012). Ornithopod tracks are also commonly seen associated with these bioturbation signatures in anastomosing fluvial deposits of the Upper Cretaceous North Horn Formation (Bracken and Picard, 1984, Difley and Ekdale, 2002). Modern insects in moist (subaerial exposed) fluvio-lacustrine environments produce the meniscate burrows, where the resulting sediments are "softgrounds" with no indications of scratch marks (Buatois and Mangano, 2004).

4.4.2.2 Nearshore

The four nearshore facies associations (Distributary Mouthbar, Brackish Bay, Tidal Channel Nearshore Complex, and Washover Prone Nearshore Complex) are characterized by fossils (trace or body) that indicate a close proximity to marine conditions. The Distributary Mouthbar Facies Assocation is defined by small lenticular bodies that dip laterally into Facies Sl, which furthers transitions laterally into Facies Sr. The Brackish Bay Facies Association contains brackish water mollusks. The Tidal Channel Dominated Facies Association is dominated by facies St and Sl that transitions to more facies Sr, Fm, and Fl upwards. The Washover Prone Facies Association has many of the same facies as the previous association except the vertical transition is largely reversed, and Facies Sl often shows rhomboidal parting lineations.

4.4.2.2.1 Distributary Mouth Bar Description:

The Distributary Mouthbar Facies Association (Figure 4.14) is 2.4 meters thick composed of two packages of dominantly subdecimeter beds of facies Sr and Sl. Facies Sr is normally vfU-fL sandstone that contains a wide variety of ripple forms (e.g., 2-D, climbing, wave modified, catunary, or linear to straight crested) and mud draping or flaser bedding (Figure 4.14c). Facies Sl is composed of planar bedding, that may be dipping or graded, and is usually a little coarser, ranging from fL-fU. These two facies grade laterally and vertically into one another. The contacts can be gradational rippled surfaces, or load-cast bases. Facies Sr and Sl are interbedded with minor facies Fl, which may be moderately bioturbated by *Thalassinoides* or *Planolites*, or facies Fm which is heavily bioturbated. The two sandstone facies are sparsely to moderately bioturbated by *Skolithos* or *Monocraterion*-like vertical burrows.

Architecturally small orange channels can be seen with facies Sl beds dipping away from them, which laterally become a muddier facies Sr (Figure 4.14a). Onlap is seen between the two sand packages. Beds appear to become flatter upwards, and the channel form near the top in this outcrop is much smaller in the upper than the one seen in the lower package. This facies association is located under the Brackish Bay Facies Association.

The vertebrate ichnites occur at the very top of this association marking the transition between the two facies associations. The overlying beds do not appear deformed in relation to the antiform structures on this surface, and therefore these are not believed to be transmitted reliefs from the overlying association (Figure 4.14e). Ichnite impact often results in the collapse and soft sediment deformation of the underlying layers (Figure 4.15a),

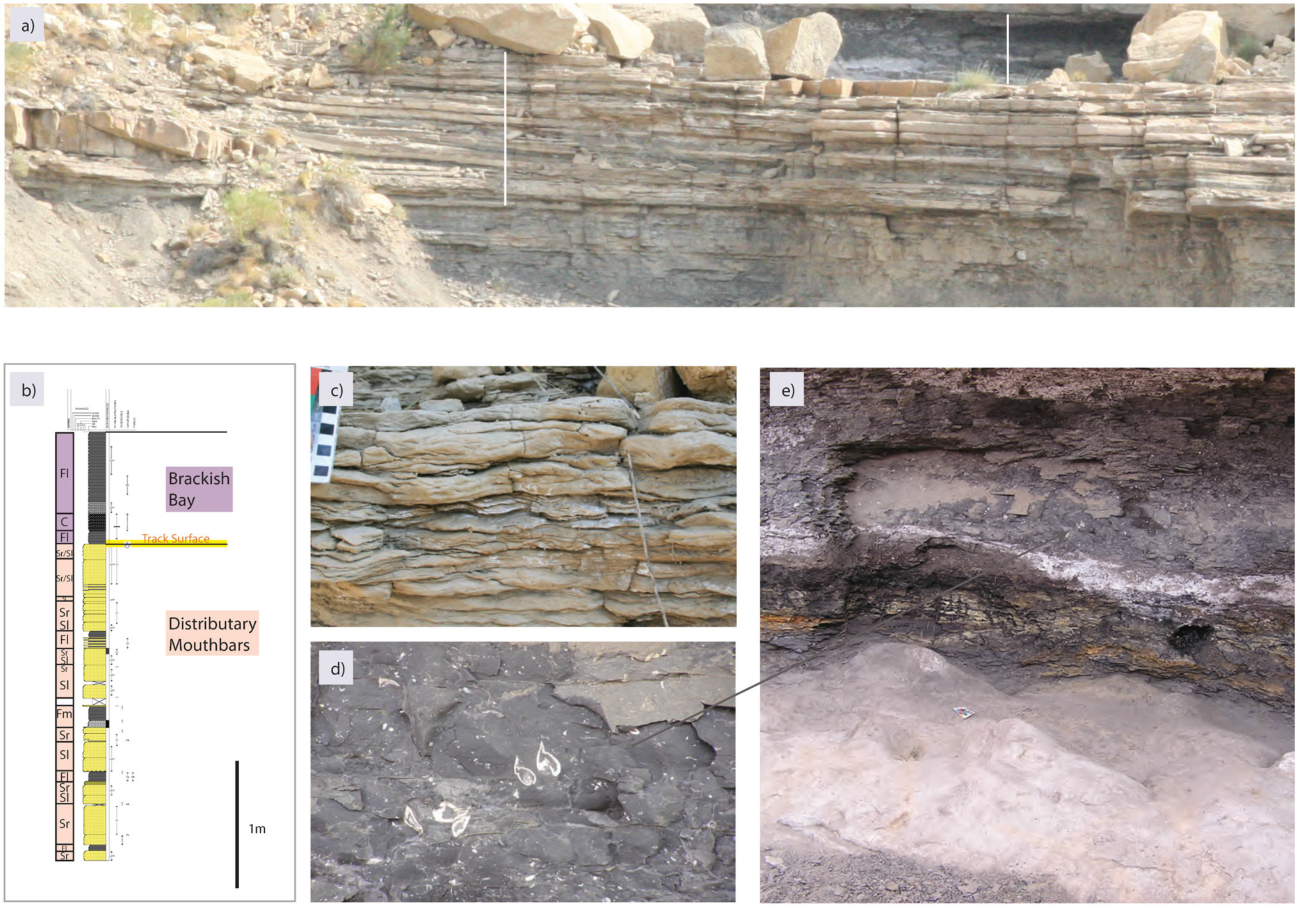

Figure 4.14: The Distributary Mouthbar Facies Association overlain by the Brackish Bay Association: a) Small lenticular channels (orange color) with beds of facies Sl and Sr dipping away. Initially the beds dip from right to left, and are subsequently onlapped from a left dipping interbeds. b) Measured section showing the location of the track surface between the two associations (measured section locations are white lines on 14a). c) A photo showing the variability in a single bed of mud draped and flaser bedded ripples. d). Vertically oriented bivalves which suggest *in situ* preservation. e) Overlying coal's relationship to a marginal fold (antiform) along the top of the sandstone is rather flat making it unlikely that the antiforms are undertracks. Additionally it shows initial appearance of *in situ* shells above the tracks surface.

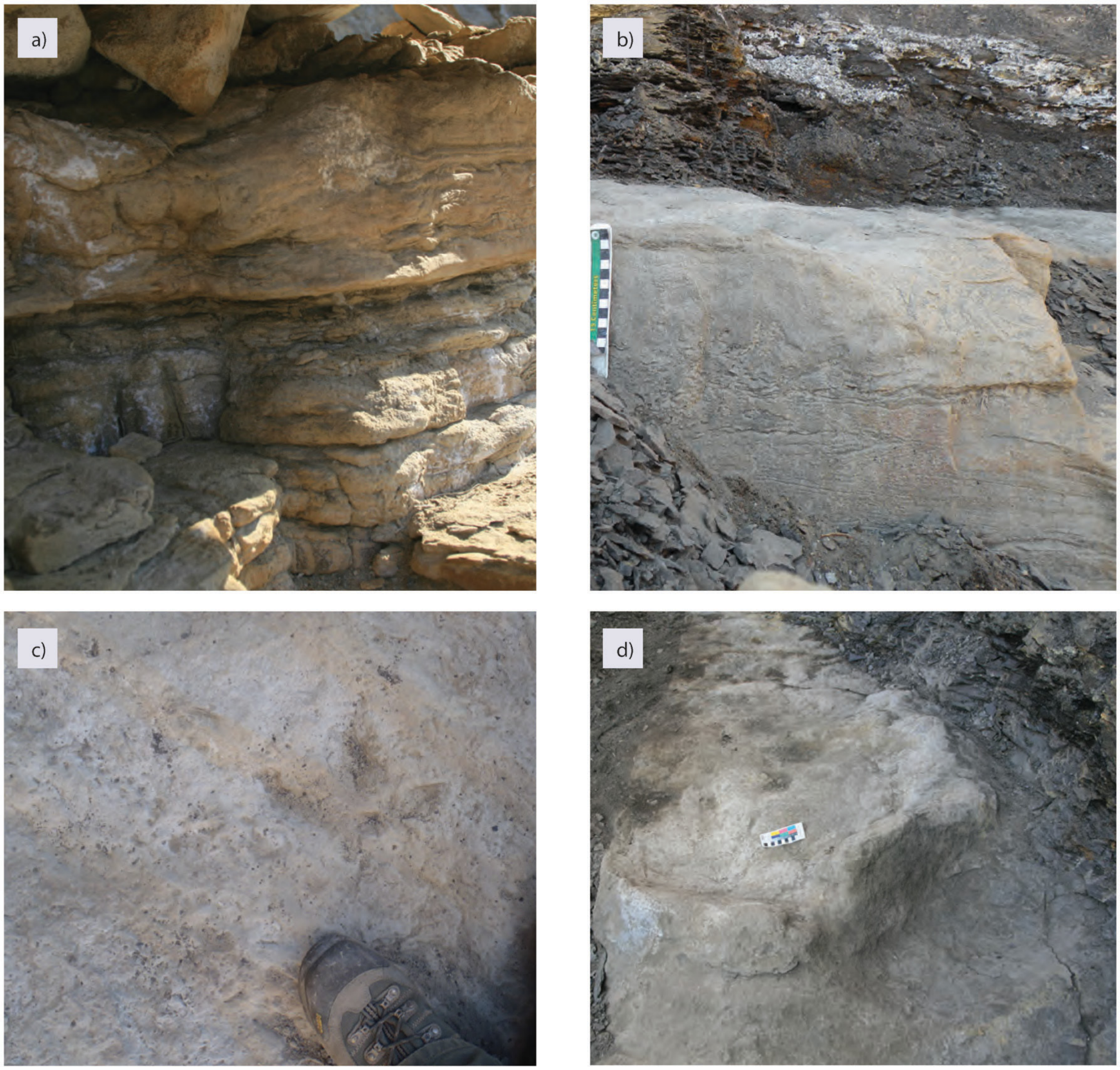

Figure 4.15: Sedimentary features of Distributary Mouthbar Association: a) Sediment collapse associated with vertebrate ichnites, b) Emplacement may result in convolution of the upper part of facies Sr beds even when ichnite can not be morphologically distinguished above the convolution. c) The divot or pock marked surface with impression of an ichnite likely attributable to a wading bird. d) Possibly manus/pes set of large quadraped along surface. Manus (lower left), pes (circular raised rim with scale within).

and even when tracks are not visible as ichnites often convolutes more than 10 cm of the facies Sr at the top of this association (Figure 4.15b). This makes it difficult to truly assess the nature of the small divots thar are abundant along the track surface (Figure 4.15c). Vertebrate ichnites occur along this surface as rare small tridactyl prints (Morphotype 9; Figure 4.15c), or as large transmitted reliefs, some that may be attributable to large quadrapeds (Figure 4.15d). Some surfaces below this may contain regularly progressing small circular pits (<15cm), which are likely small biped tracks, on rather straight-crested and linear-rippled surfaces. The amorphous nature of the impressions, leads towards the inability to make a conclusion on their genesis at this time.

4.4.2.2.2 Distributary Mouth Bar Interpretation:

The Distributary Mouthbar Facies Association represents terminal deltaic mouthbar deposits. Similar, but slightly coarser mouthbar deposits that contain small channels and low to moderate bioturbation by vertical forms (e.g. *Skolithos*) were described from the Ferron Sandstone by Fielding (2010). He suggested some of the planar bedding near the top may be due to wave reworking of the bar into beaches. This could be a possibility for the top surface where the tracks lie, but there were no swash marks seen on preserved surfaces. While the vertebrate generated convolution at the top makes it difficult to tell if the sandstone is bioturbated, similar pock marked surfaces have been seen in the modern bar top surface of Kanes (1970) which is riddled by probable annelid worms burrows. The preservation of the large vertebrate generated antiforms on the upper surface suggests that the sediments were likely fairly firm, possibly indicating compaction during temporary exposure. However, the tracks may have been deposited during shallow subaqueous conditions due to their poor preservation of the track morphology, as well as the only definable morphotype (M9) likely being produced by a wading bird. The preservation of the antiforms suggest little in the way of reworking of this surface, suggesting rapid burial or relatively quiescent conditions during subsequent deposition. The quiescent flooding conditions that led to the preservation of the ichnites is further evidenced by the direct draping by the Brackish Bay Association.

4.4.2.2.3 Brackish Bay:

The Brackish Bay Facies Association (Figure 4.14b, d, e) is composed dominantly of Facies Fl. Facies Fl is a grey mudstone, often organic rich, which contains shell material in the upper two-thirds of the association. Common shells are *Crassostrea* and axial elongate gastropods. Shells are broken in some intervals, but in others may be articulated in vertical positions (Figure 4.14d). Coal is a minor facies (Facies C), near the bottom of this association. Facies C is sulfur and iron stained. No vertebrate ichnite emplacement horizons were noted within this association. The lack of observable ichnites within this association could be the result of the largely homogeneous nature of the deposits. The Brackish Bay Association drapes the track surface at the top of the Distributary Mouthbar Facies Association (Figure 4.14).

4.4.2.2.4 Brackish Bay Interpretation:

Dense accumulation of shells containing *Crassostrea* and often containing abundant carbonaceous debris from the Ferron Sandstone have been described as brackish bay facies by Anderson et al. (2004). *Crassostrea* is a filter-feeding oyster that thrives in stressed environments, such as estuaries, that have variable salinity fluctuations and are often very turbulent (Nelson, 1960; Yonge, 1960; Galtsoff, 1964; and Kotmatsu et al., 2002). *Crassostrea* and elongate gastropod forms (e.g., Pseudomelania) are indicative of mesohaline (brackish) conditions (0.5-1.8%) in the Upper Cretaceous (Fürsich, 1993). This suggests that these deposits had a significant freshwater influx into the system. The vertical position of some of the bivalves lend to the interpretation *in situ* deposition of the shells. The lower few decimeters of the association may be more akin to the conditions present during deposition of the Poorly Drained Facies Association due to the similarity in facies. This may suggest the association represents an initial sequence of flooding of coastal facies by brackish facies.

4.4.2.2.5 Nearshore Complex (Tidal Channel Migration) Description:

The Tidal Channel Dominated Facies Association (Figure 4.16) is dominated by basal fine-grained sandstone of the St and Sl facies interbedded with facies Sm. The thickness of the St and Sl beds generally decrease upwards whereas the thickness of Facies Sm (related to bioturbation) increases (Figure 4.16a, f). Mudstone and organic clasts may be present as lags. This association becomes finer grained upwards with these basal facies being replaced dominantly by facies Sr and Fl. These upper sandstones often thin and disappear laterally. Additionally, the percentage and thickness of massive to bedded facies may change from east to west (Figure 4.16). The basal sandstone weathers tan in color, but the sandstone near the top is iron stained red, with a white interior (Figure 4.12e). The top of this association is gradationally overlain by the Poorly Drained Facies Association.

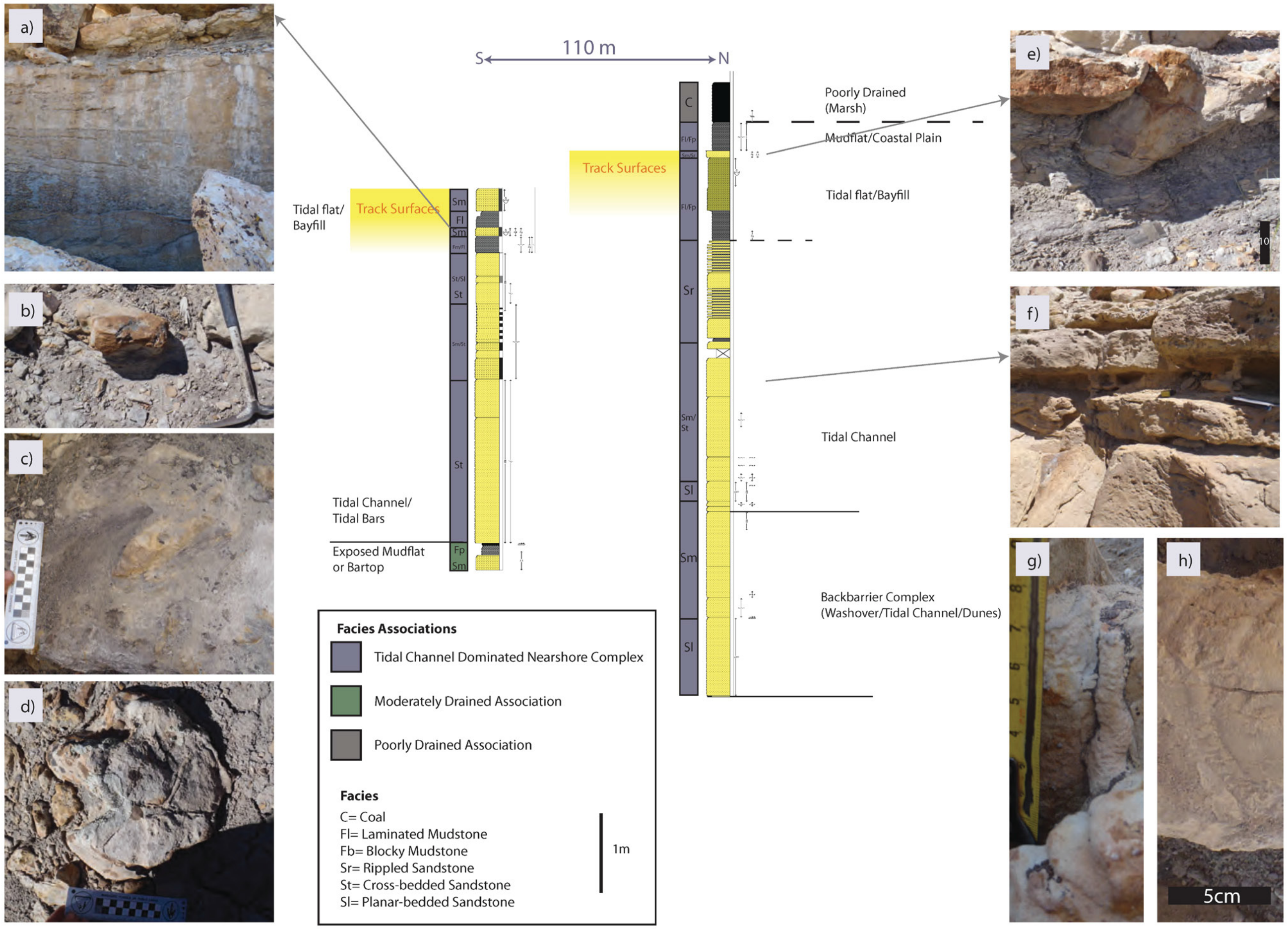

Figure 4.16: Tidal Channel Dominated Facies Association: a) Example of the interbedding between Facies St and the highly bioturbated Facies Sm. b) Iron stained ichnite weathering out of Facies Sm. c) An muddier example of an ichnite weathering out with the iron staining. d) A natural cast that has weather out of the matrix in place and shows cross-cutting *Thalassinoides*. e) Ichnite cutting through heavily rooted iron stained facies Sm/Sr near the top of the succession. f) Interbedded facies of St, Sl, and Sm closer to the base of the succession with preferentially weathered *Ophiomorpha*. g) Burrow of *?Camborygma* along the margin of a track near the top of the association. h) Pseudo-meniscate backfilled burrow (*?Beaconites*) along track margin.

Vertebrate ichnites are present mainly as ornithopods (M1,M2, and M3b, c), and one possible wading bird (M8). Although with the way these weather out the gracile forms often lose digits hindering their classification. Some of the deepest tracks (>20cm) observed in the study area are associated with M2 from this association.

The ichnites are often preserved in the heavily bioturbated interval (Sm, Fm) as either iron stained sandstone natural cast (Figure 4.16b, c) or as deformation of the bioturbated horizon. The tracks may also occur in facies Fl and Fp as sandstone bed attached structure (Figure 4.16e), or even as a weathered deflation lags that have maintain position as the matrix has eroded out from around them (Figure 4.16d).

The basal Sl and St facies contain rare to moderate bioturbation by *Siphonichnus*, equilibrichnia, and *Ophiomorpha*. The Sm interbeds are heavily bioturbated by mud-lined forms (*Ophiomorpha* and *Palaeophycus*), which are replaced upwards as facies Fm interbeds with *Thalassinoides*, *Planolites*, and *Ophiomorpha*. The bioturbation lessens upwards and becomes replaced more by small roots, rare linearly scratched vertical structures (*?Camborygma*; Figure 4.16g), and rare pseudo-meniscate backfill structures (*?Beaconites*; Figure 4.16h). Tracks can be cross-cut by most of the traces listed (e.g., Figure 4.16d, g, h).

4.4.2.2.6 Nearshore Complex (Tidal Channel Migration) Interpretation:

The Tidal Channel Dominated Facies Association represents the complex interrelationships of a nearshore (e.g., back-barrier) setting that is dominated by successions representing tidal channel migration. Many back-barrier subenvironments may be present in this association, but the dominant process is comparable to the tidal creek point bar sequence of Barwis (1978) and Barwis and Hayes (1979). The study area example is around half the height of their model, but displays a similar trend of upward decrease in grain and cross-stratified bed size; and increase in rooting. This model represents an environmental change from incision and deposition of higher energy bedforms in the deep channel to deposition of smaller lower energy bed forms upwards as the channel moves laterally. As the migration of the channel continues, muddier burrowed sediment of the intertidal flat drape on top followed by more rooting associated with marshes. Heavy bioturbated intervals with cross-cutting crustacean dwellings (e.g., *Ophiomorpha* and *Thalassinoides*) have been noted in intertidal flat deposits by Gingras et al. (1999). Additionally, *Ophiomorpha* are present across many brackish to marine deposits from the Cretaceous Western Interior Seaway, from marginal marine to proximal offshore (Mieras et al., 1993). Conversely, the ichnogenera of *Siphonichnus*, *Planolites*, and *Thalassinoides* are characteristic of tidal flat settings (Gingras et al., 2012). Track preservation appears to be limited in this setting to the upper zones of the heavily bioturbated intervals (intertidal flat), where subsequent invertebrate activity was not sufficient to destroy the ichnites; and to a point upwards where there is still sufficient enough influx to result in depositional heterogeneity (below marsh) to allow recognition of the ichnites.

4.4.2.2.7 Nearshore Complex (Washover Prone) Description:

The Washover Prone Facies Association (Figure 4.17) is different than the previously described facies association in that it is essentially a reversed vertical succession with Fl on the base overlain by an often loaded surface that in turn is covered by facies Sr, Sl, and St. This sandstone is dominated overall by facies Sl. The grain size is vfU-fL at the base coarsening up slightly (within the first meter) to fU-mL. Often, the largest cross-beds lie in this area around a meter up. Small breaks (surfaces; Figure 4.18) show evidence of swash marks (rhomboidal rill marks), catunary and straight crested ripples, and possible adhesion ripples. Much of the details regarding sedimentary structures have been addressed in Chapter 1. This association overlies the Poorly Drained Association.

The organic rich mudstone (facies Fl) underlying the base of the sandstone may contain burrows of *Thalassinoides*, *Planolites*, *Teichichnus*, and *?Gyrolithes* (Figure 4.16d, e) and small interbeds of Fm at the base can be completely bioturbated, whereas one Fm surface near the top contains large downward branching shafts (trees). The sandstone facies near the base contain *Ophiomorpha*, *Siphonichnus*, *Psilonichnus,* and equilibrichnia (e.g., Figure 4.17c).

Vertebrate ichnites (M1-3, M5-7) typically occur along these small interbeds or intersurfaces that can be heavily burrowed, flat, rippled, or slightly deformed. The deepest tracks occur as casts in the mudstones at the base of the sandstone (Figure 4.17b, c, 4.18b, d), or within a broadly concave upward interbed (original discovered by P. Anderson) of mudstone that contains vertical tree casts. The only tracks seen to exceed 20 cm in depth were also some of the largest tracks (M2c), occurring in the mudstone at the base of the sandstone. Most of the intersurfaces appear as small breaks or completely bioturbated beds (Figure 4.18a), and the tracks are often shallow casts (Figure 4.18e-h). The molds may preserve as reliefs in the sandstone on the opposite sandstone face, but typically they are amorphous. In some cases, when tracks are present as filled features (natural casts), they can be much thicker than the underlying bed (Figure 4.18a). These intersurfaces with

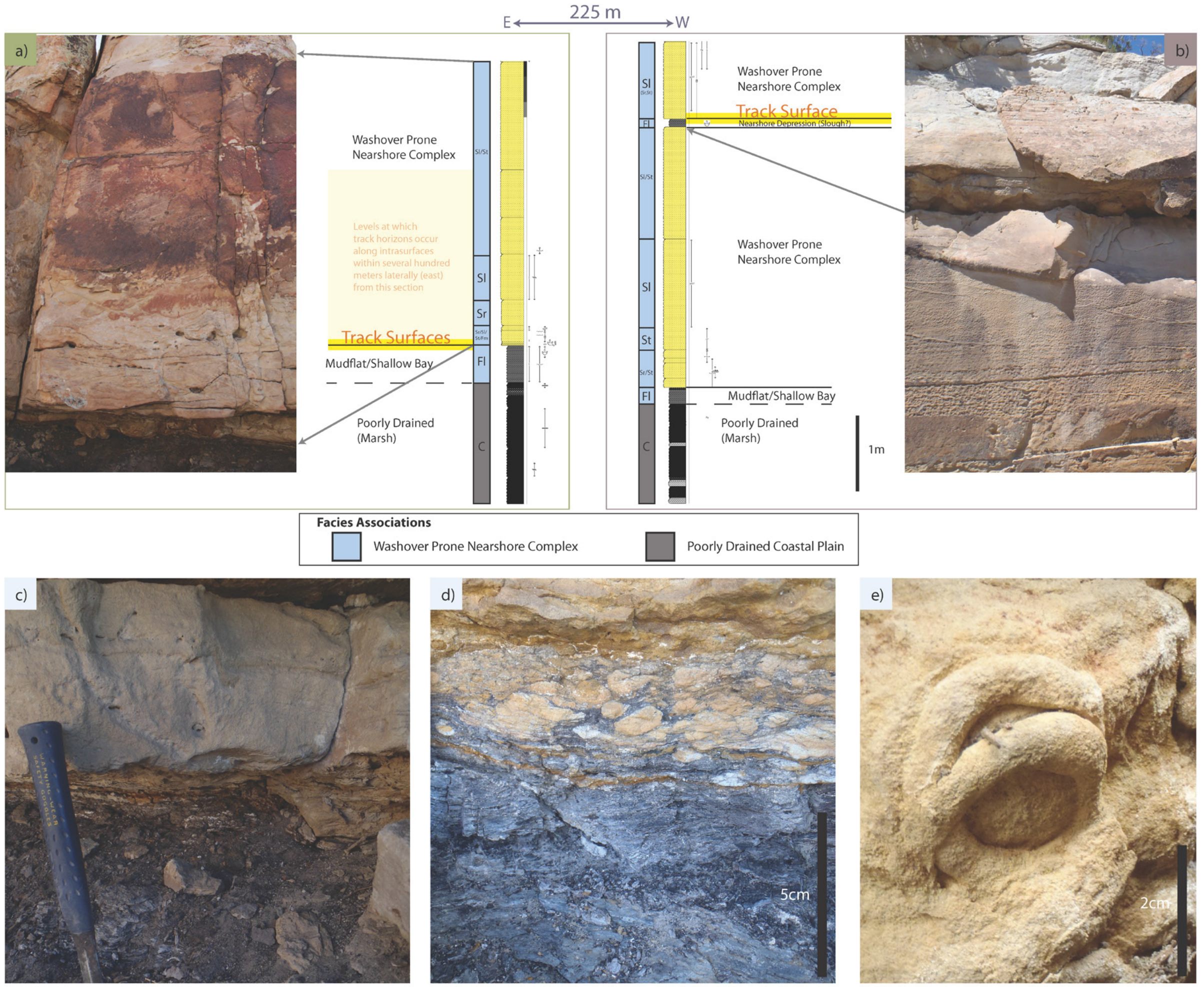

Figure 4.17: Washover Prone Association: a) Section with track surfaces more along the base. b) Measured section with a concave up mudstone track surface bed that contains upright tree casts. c) *Ophiomorpha* in sandstone bed that has tracks along the base (in photo represented by depressed portion of sandstone). d) The burrowed organic rich mudstone at the base of the sandstone, which contains *Thalassinoides*, *Planolites*, and *Teichichnus*. e) Possibly *Gyrolithes* burrow from the base of the sandstone.

Figure 4.18: The nature of ichnite containing interbeds and intersurfaces within the Washover Prone Association: a) the numerous intersurfaces that can occur in the basal portion of the sandstone. A track (black arrow) can be seen depressed much farther than the completely bioturbated bed that it is cutting. b) The mudstone ichnite surface near the top that contains tree casts showing vertebrate induced deformation and dewatering of the sandstone below the mudstone. c) A track that has almost been wiped from existence by the subsequent bioturbation (*Thalassinoides*). d) Radiating root casts (black arrow) along the base of the sandstone with the upright tree casts. The surface also contains various preservations of ornithopod tracks. e) Partial tridactyl track preserved on the base of an intersurface cross-cutting rhomboidal rill marks. f) Adhesion ripples along the base of an intersurface that turn laterally (to the right) into catunary ripples. Tracks are slightly larger 20 cm and the picture is taken obliquely to the surface. g,h) Intersurfaces at two different horizons displaying a similar pock mark nature that may be related to microbial matting.

shallowly preserved tracks provide large surfaces to study when they fall away from the cliff, and could be a bias as to why the theropod tracks (M5-7) are only identified from this association. Tracks may be difficult to recognize in some of these intervals due to the biogenic overprinting of invertebrates (Figure 4.18c). Tracks are seen in these intersurfaces associated with the rhomboidal rill marks (Figure 4.18e), linear and catunary ripples, adhesion ripples (parallel to crest of other types)(Figure 4.18f), and are often pock marked (Figure 4.18g,h).

4.4.2.2.8 Nearshore Complex (Washover Prone) Interpretation:

The Washover Prone Association is a nearshore complex (back-barrier) much like that of the Tidal Channel Dominated Association, except it contains evidence of foreshore or washover conditions, and the base is more conformable than the base seen in the Tidal Channel Association. These two associations likely share some of the same subenvironments, due to the overall similarity in facies. However, the successions are much different. Essentially the succession in this association is the opposite, with the marsh (poorly drained) grading upwards into more subaqueous and brackish conditions of the intertidal flat or shallow bay. This is evident by the ichnological signature of heavy bioturbation by *Thalassinoides* and *Planolites* with *Siphonichnus*, equilbrichnia, and cross-cutting *Ophiomorpha* seen in this association as comparable to that of the tidal flat facies of the previous association. The additional traces of *Teichichnus* and *Gyrolithes* are also commonly associated with these tidal flat environments (Gingras et al., 1999, Gingras et al., 2011). The coarsening upwards may represent some form of washover due to storms or landward migration of the barrier. Much of this interpretation was discussed in Chapter 1.

The preservation of the ichnites appears similar in the base and in the lower interbeds of this association to what is seen in the Tidal Channel Association. However, the preservation along the intersurfaces, or the concave up mudstone interbed appears inherent to the Washover Prone Association. The intrasurfaces are related to intertidal areas, whether it is high-energy facies of a foreshore or washover, or that of low energy ripples along a tidal flat. Microbial mats may potentially play a role in preservation, and may be the reason for the often pock marked surfaces. Microbial mats provide cohesion to the sediment and are common in modern windy back-barrier supratidal-intertidal flats, where they are often buried by washover sediments (Davis, 2011) The origin of the concave up mudstone bed with the trees may indicate a long period of exposure, as discussed in Chapter 1, but also may have maintained a high moisture content as evidenced by the dewatering of the sandstone underneath (Figure 4.18b). This hollow may represent a nearshore environment, such as a slough or interdune area along the coast. The tracks of this surface and the root casts of trees appear similar to fallen blocks that can be seen near the Moore Trackway that was described by Jones (2001).

4.5 DISCUSSION

Of the ten morphotypes there is clearly some definable patterns observed, such as, the theropod morphologies only occur in the Washover Prone Association, that the probable wading bird ichnites only occur in the nearshore settings, and that the turtle traces are only evident in the Distributary Channel Association (Figure 4.19). There are probably strong biases that are present due to the lack of large track surface exposure, and this may also be why so many morphotypes are seen in the Washover Prone Association, which has the largest exposed surfaces. Additionally, bioturbation plays a role in the preservation potential of smaller morphologies, and large gracile forms in both the Tidal Channel Dominated and Interdistributary Associations lose digits easily when weathering out and were therefore unable to provide a complete morphotype for these forms. Also, it is more difficult to identify quadrapeds from weathered out natural casts, and the exposure of the outcrop may limit morphological observation, as is the case in the Moderately Drained Association. Track taphonomy plays a vital role in the assessment, as can be seen in the Distributary Mouthbar Association, which appears to have no other forms, but there is a lot of evidence for larger animals in this association, there is just no definable morphology associated with the transmitted reliefs. While these factors greatly limit the potential of using this work to set definitive vertebrate-defined ichnofacies for the Ferron Sandstone, the *Chelonipus* (M10) associations within channels do appear to be a reoccurring theme in the Mesozoic (further discussed in Chapter 2).

The greater utility of this study is the association of the ichnite preservation with the depositional environments and associated ichnologic fabrics (Figure 4.19, right side). In the coastal plain, tracks preserve as depositional hiatuses within the channel, or often as either natural casts at the base of avulsion facies, or as molds along flooding surfaces. Displacement bulbs may form in more saturated heterolithics providing evidence of vertebrate passage in cross-section. Within the channel, there appears to be two assemblages, one terrestrial and one subaqueous. The terrestrial channel assemblage has *Chelonipus* with

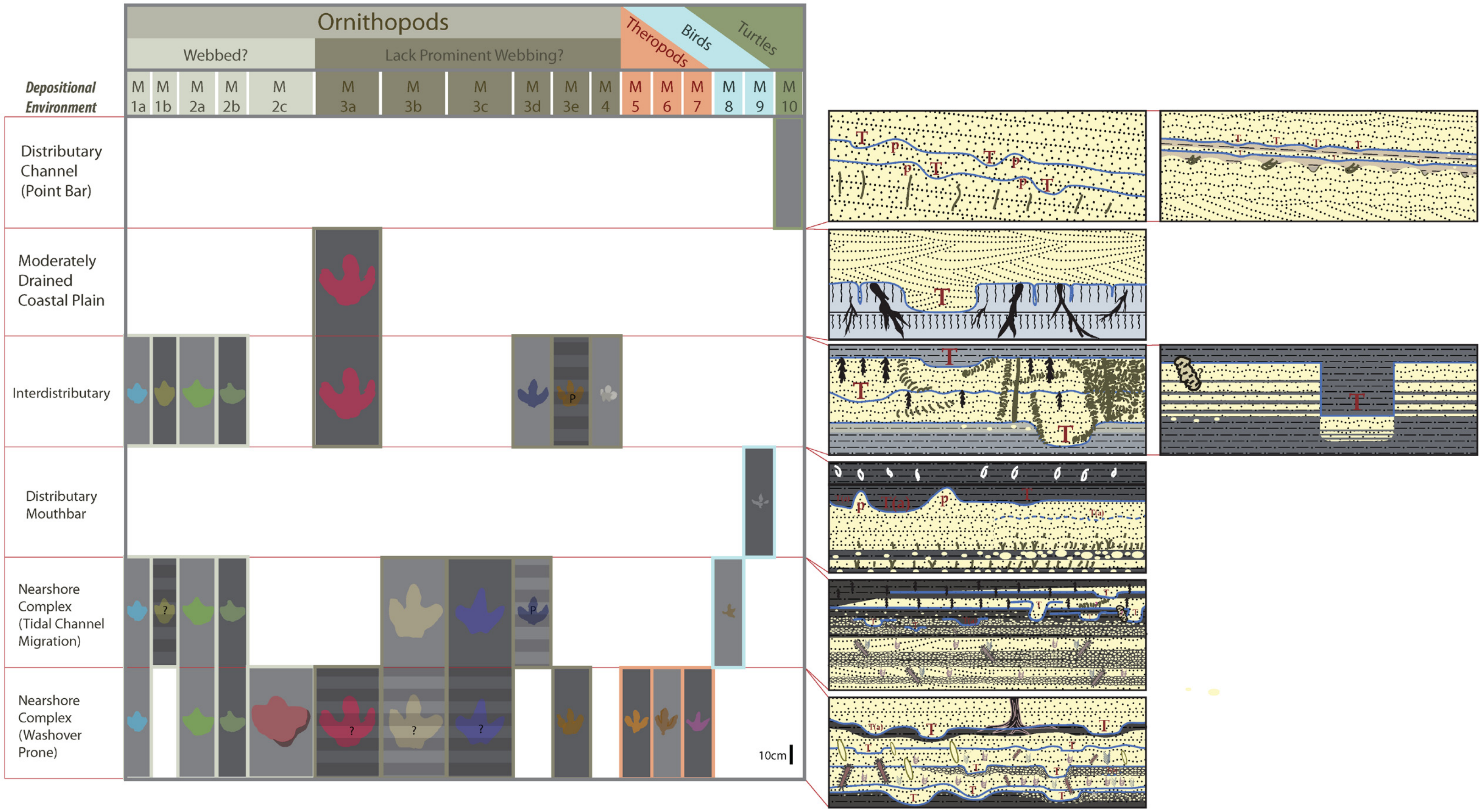

Figure 4.19: Comparison of morphology to the Facies Associations in which they are emplaced. Morphotype outline represents to scale comparison of the size between morphologies. Morphology 10 (Turtles; *Chelonipus*) is too small to be represented to scale. On the right side of the diagram is general (not to scale) cross-sectional (schematics) showing the relationships between the vertebrate and invertebrate traces and the lithologies of each association. This is addressed in more detail in the text. T=track, P=pushed up margin, (a)=amorphous representation, and (x)=mostly or completely removed by subsequent bioturbation.

pushups (posterior displacement relief) and small vertical mud structures. The subaqueous channel assemblage has *Chelonipus*, *Characichnos*, *Rhizocorallium*, *Helminthoidichnites*, mollusk plowing traces, and possibly *Planolites*. There may be a continuum for the coastal plain strata outside of the channel, with passively filled unlined *Skolithos* in texturally mature mudstone with large roots being a more expose/better drained end member, and with laminated mudstone with *Planolites* being the poorly drained end of the spectrum. The meniscate backfilled (*Beaconites*) assemblage with small roots is an important indicator of exposed areas with softground (moist) conditions, and can have a high abundance of traces, which might lead some to mistake it as a more nearshore environment. It is uncertain the true taxonomic identity of *?Camborygma*, or the level from which the trace distends from, therefore making it hard to use as an ecological assessment tool.

In the nearshore environment, the tracks in the Distributary Mouthbar appear to be preserved on flooding surfaces near the top, with the largest animals occurring at the terminal flooding surface of the start of the Brackish Bay Association. Most of these tracks are amorphous, likely due to the saturated nature of the sediment, and therefore do not lend much in terms of morphotype comparison. However, the large transmitted reliefs (antiforms) may be more useful in indicating a taphonomic/toponomic bias that is limited to these types of settings. The Tidal Channel Dominated and Washover Prone Associations are the only associations that contain the assemblage of dinosaur tracks with *Thalassinoides*, and often overprinting by *Ophiomorpha*. Although these occur at different places in the two successions, they both appear to represent tidal flat environments. The preservation of the tracks requires there to be little subsequent reworking by invertebrates. Laterally, this can result in the track horizons disappearing into heavily bioturbated textures. Additionally, this relationship is present in vertical succession as well. The heavy bioturbation in these environments provides a media for preservation of transmitted reliefs in cross-section, even in the absence of a sandstone fill. Conversely, most of the distinguishable morphologies in these environments are natural casts. Natural casts are preserved with the deepest appreciable specimens in the mudstone lithologies, whereas they are the shallowest when emplaced in close proximity to an underlying sandstone, such as in the intersurface of the Washover Prone Association. The upper portion of the Tidal Channel Dominated Association may contain forms closer to that of the coastal plain associations, but cannot be verified due to the limited number of traces preserved in the heavily rooted sections.

In general overview, the ichnites are preserved either along flooding surfaces or hiatal surfaces, or in areas that provide rapid sediment fluctuations such as coastal plain interdistributaries and intertidal flats in the Ferron Sandstone. While the interdistributary and channel deposits are likely to occur with delta progradation, the tidal flat preservations are more likely linked to the abandonment or transgressive cycles of the delta.

4.6 CONCLUSIONS

Vertebrate traces are fairly common in the Ferron Sandstone, but are not abundantly recognized mainly because they do not normally occur in direct contact with a minable resource (coal) and because there is very few plan view exposures of track bearing surfaces in outcrop. Ten morphotypes are identified from the Ferron Sandstone of small to large ornithopods (*Amblydactylus*, *Iguanodontipus burreyi,* and a small morphology with robust digits), small to medium theropods, turtles (*Chelonipus*), and possible wading birds. The expression of tracks occurs in numerous toponomic expression such as natural casts, molds, displacement bulbs, marginal displacement, and transmitted reliefs (e.g., burrow fabric alteration). Preservation of an ichnite as a mold relies on flooding of the environment. Hence, the molds are often found in interdistributary area (coastal floodplain and brackish bay flooding). Conversely, the preservation of the natural casts relies on sediment influx and heterogeneity. Heterogeneity may come from physical impartment or created by biogenetic reworking. Natural casts are found in distributary channel point bars, coastal plain overbank, and back-barrier intertidal areas (e.g., tidal flats). While the significance is undetermined, it should be noted that the definitive morphologies of the theropods and wading birds were only found in the intertidal environments. A more meaningful observation comes in the examination of the *Chelonipus* tracks, and the *I. burreyi* tracks in relation to the invertebrate traces and depositional environment. *Chelonipus* is only seen in channel point bars deposits of the Ferron, which is consistent with the other Mesozoic occurrences, and there appears to be two different behaviors (terrestrial walking vs. bottom walking) present at the different sites. The more aquatic behavior is associated with subaqueous traces (*Rhizocorallum*, *Helminthoidichnites*, and mollusk plowing trace) that can be produced in modern fluvial environments. The *I. burreyi* occurrence in the Ferron with meniscate backfill (*Beaconites*) and small roots is significant because of the agreement of this association with the fluvio-lacustrine deposits of the Lower Cretaceous of England.

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CHAPTER 5: FUNNEL APERTURE ICHNOTAXA AS INDICATION OF STOPE FEEDING BEHAVIOR IN THE ROCK RECORD

5.1 INTRODUCTION

In modern intertidal and shallow subtidal settings, funnel-feeding is a common sustenance mechanism used by prolific deposit feeding vermiform organisms, such as Arenicolid polychaetes (*Arenicola*; Richter, 1924; Thamdrup, 1935; Linke, 1939; Wells, 1945, 1966; *Abarenicola*; Hylleberg, 1975; Healy and Wells, 1959) and enteropneusts (*Balanoglossus*; Frey and Howard, 1969, 1972; Dörjes and Hertweck, 1975; Duncan, 1987; *Pytchodera;* Dobbs and Guckert, 1988). The suspension feeding or domicile forms of arenicolid polychate burrows have been used as a modern analog for the simple U-shaped burrows, *Arenicolites*, and identified as far back as the Cambrian (Binney, 1852; Salter, 1856, 1857; Fürsich, 1974; Brasier and Hewitt, 1979; Droser et al., 1994) However, there is little of the morphological equivalents (i.e. biogenic structures) to funnel-feeding behavior described from the rock record. Most ichnogenera with funnel or "V"-shaped cross-sectional morphologies nucleating from a central shaft (e.g., *Cylindrichnus*, *Rosselia*, *Lingulichnus*, *Monocraterion*, and *Altichnus*) are attributed to the domichnia or equilibrichnia of suspension feeding or selective surface feeding organisms (e.g., Howard, 1966; Chamberlain, 1971; Hakes, 1976; Szmuc et al., 1976; Crimes, 1977; Frey and Howard, 1985; Nara, 1995; Bromley and Hanken, 1991; Zonneveld and Pemberton, 2003; Gaillard and Racheboeuf, 2006). There are likely several different reasons for the scarcity of funnel-feeding biogenic structures recognized in the rock record. Notably, the toponomic expression requires ambient sediment heterogeneity and the time of occupation must be relatively short to avoid total mixing of the sediment. Additionally, these structures are often lumped into other ichnotaxa, or misinterpreted as retrusive structures. In order to identify these structures in ancient deposits, the commonalities of biogenic structures between modern funnel-feeding organisms must first be established. Comparison also allows for evaluation of expected key, recurrent morphological characters, in order to determine which components are taxonomically important for systematic classification. Note that the term "burrow" will be used interchangeably with biogenic structure, even though it can be argued that parts of the biogenic structures discussed in this study may not entirely conform to the definition of a "burrow" *sensu* Frey (1973).

5.2 MODERN ETHOLOGY: FUNNEL FEEDING (STOPE FEEDING)

Funnel feeding is a deposit feeding method utilized in nutrient poor sandy sediment by which an organism intakes large quantities of material through undermining the sediment at the anterior end of the burrow, thus creating a funnel shape due to the downward flow of the sediment from the surface (Powell, 1977). The synonymous term, stope feeding, is probably more appropriate for this deposit feeding behavior since the animal essentially mines and collapses (stopes) the sediment from below (e.g., Frey and Howard, 1972; Frey, 1973; Gingras et al., 1999). A funnel-shaped aperture is used by various modern crustaceans to passively trap organics (e.g., Botto et al., 2006) and are a common component of predatory trapping behaviors (irretichnia) noted in modern predators and inferred behaviors from trace fossil morphology (Lehane and Ekdale, 2013). While modern funnel-feeders are noted to trap nutrients using the surficial depression, rapid draw down, or suspended material pumped forward against the sand (e.g., Figure 5.1b), such processes are not necessarily predatory, and funnel-feeders conversely ingest large quantities of stoped material, which is ethologically different and not as focused as the other funnel aperture constructors.

Modern organisms that create roughly U-shaped biogenic structures to utilize the stoping method of deposit feeding include Arenicolid polychaetes (e.g., lugworms of *Arenicola* and *Abarenicola*; Richter, 1924; Thamdrup, 1935; Linke, 1939; Wells, 1945; 1966; Healy and Wells, 1959; Hylleberg, 1975; Cadée, 1976; Rijken, 1979; Riisgård and Banta, 1998; Andresen and Kristensen, 2002), enteropneusts (e.g., acorn worms of *Balanoglossus* and *Pytchodera*; Frey and Howard, 1969, 1972; Dörjes and Hertweck, 1975; Duncan, 1987; Dobbs and Guckert, 1988*),* possibly holothorodians (e.g., *Leptosynapta*; Powell, 1977), and some specialized Maldanid polychaetes (e.g., *Axiothella*; Kudenov, 1978) are known to funnel-feed and have the capability to create U-shaped biogenic structures. *Balanoglossus* and the Arenicolid polychaetes are commonly investigated in the modern due to their large size, which contributes to the deepest tiering and sediment disturbing capacities of modern deposit-feeding organisms. Powell (1977) suggests that funnel feeders live in U-shaped tubes with the deposit-feeding funnel at one end and fecal casts at the other end. However, U-shaped tubes are an uncommon form in the modern funnel-feeders, such as *Arenicola*, which are mostly L- or J-shaped tubes that end anteriorly in a vertical funnel (not an open tube; completing a U-shaped constructional scheme) and whose reports may be biased by

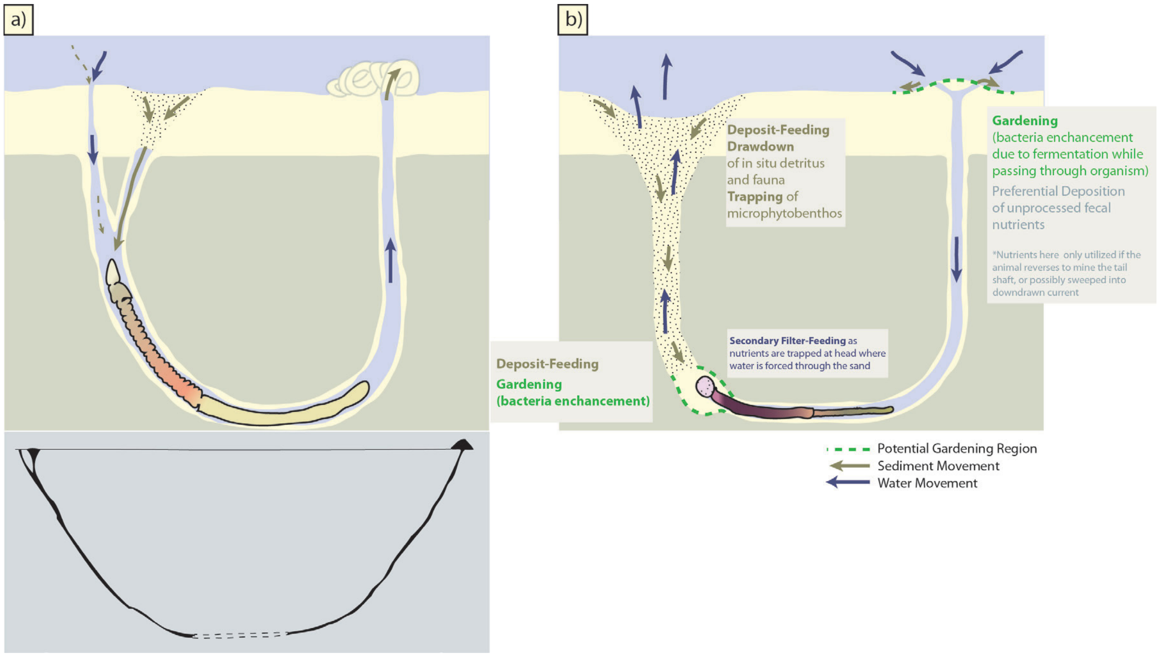


Figure 5.1: Generalized simplified schematic comparing feeding methods, water circulation, and biogenic structure between two of the largest stope (funnel-type) feeding organisms: a) schematic (top) of the burrow of *Balanoglossus gigas* showing the posterior transfer of water through the burrow from a non-flared aperture with the feeding funnel being roughly interior to that (modified from Howard and Dorjes, 1972; Duncan, 1987; Ruppert and Fox, 1988); and an outline (bottom) of the true cross-sectional form (modified from Duncan, 1987). It should be noted that the funnel (perpendicular to surface) and non-flaring incurrent branch (tangential to surface) are often angled to one another resulting in the skewing of the perspective of their relationship in cross-section. b) schematic of the burrow of an Arenicolid lugworm illustrating the anterior water circulation into the stoping structure, which suggest many feeding methods may be utilized secondarily besides the resources initially present in the sediment (modified from figures and text of Wells, 1945; 1966; Krüger, 1959; Hylleberg, 1975; Reise, 1981; Plante et al., 1989; Riisgård and Banta, 1998).

where the burrows are commonly excavated (e.g., drier substrates) (Wells, 1945; 1966). The U-shaped constructional program has a vertical anterior segment representing feeding behaviors (e.g., typically drawing sediment downward to the proboscis), and the posterior vertical segment is a tube for movement (backward movement of the animal) of fecal material to the surface (Schäfer, 1972). Furthermore, it is often overlooked that funnel-feeders, such as *Balanoglossus* and lugworms often circulate water through their burrows in opposing flow directions (Figure 5.1). *Balanoglossus* utilizes an anterior tube, not associated with the funnel, to pump to the posterior region of the burrow, whereas lugworms circulate water from the anterior region of the burrow into the funnel (Duncan, 1987). This leads to a fundamental morphological difference between the two funnel-feeders in that *Balanoglossus* needs an anterior tube to the surface established for circulation purposes, whereas head-forward pumping polychaetes do not. This distinguishing functional characteristic is later used, and discussed, as a key morphologic character for ichnotaxonomic subdivision in the rock record, but first we must evaluate the key criteria for establishing morphological character priority. This will be done by examining the variability in the burrows of organisms from the family Arenicolidae (mainly using a single species *Arenicola marina*). This species is used as an example because it is one of the most thoroughly described in terms of funnel-feeder burrowing in current literature.

5.2.1 Modern Biogenic Structure Morphology

The burrow morphology of all modern stope funnel-feeding forms can be distilled down to the three subdivisions of *Arenicola marina* burrows from Wells (1945; 1966) (Figure 5.2a): the tail shaft, the gallery, and the head shaft. These three form a simple continuum, which can be expanded to all funnel-feeding forms. The head shaft is the anterior region of the burrow dominantly shaped by the funnel-feeding mechanism. The gallery is attached to the head shaft and is the region where the animal lives and moves back and forth between feeding and defecation. The gallery connects posteriorly to the tail shaft where the animal's tail rests during defecation. It is important to recognize that the term "shaft" in these regional designations does not necessarily imply straight sided or open structure, but rather a biogenically modified area that is vertical in nature (e.g., funnel). Additionally, the gallery always represents a greater vertical reach than the tail shaft, and may constitute more of the vertical anterior segment than the head shaft. Each region of the tripartite subdivision shows numerous variations in shape and branching, which result from

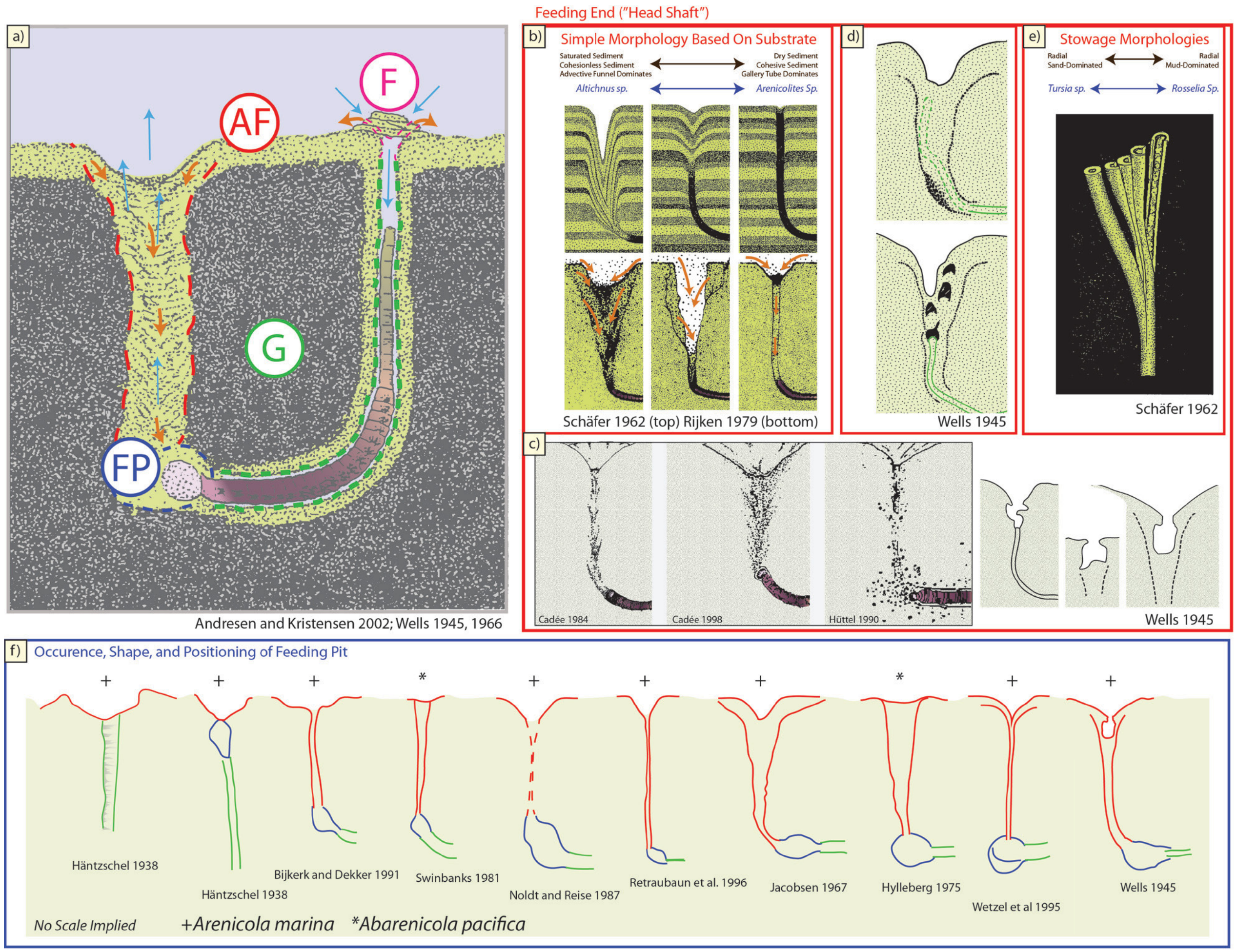


Figure 5.2: Overall shape and anterior variability in lugworm burrow morphology: a) general subdivision of a simple lugworm burrow with the advective funnel (AF, red lines) and feeding pocket (FP, purple lines) comprising the head shaft, the gallery (G, green), and the tail shaft/fecal pile (F, pink lines). b) variability of the head shaft (advective funnel) in relation to substrate cohesion. c) variation in the stoped lamina in the advective funnel as well as the shape of the funnel. d) tube structures created within the advective funnel. e) radial structures created by stowage in the tube. f) the location and shape of the feeding pocket. (all figures are modified from the authors listed).

numerous environmental variables, animal residence time, and for use as analogues to the ancient, preservation potential. The morphology of each region is subsequently discussed in more detail.

5.2.1.1 Head Shaft (Feeding Region)

The head shaft is the area of the burrow where the animal feeds as well as the overlying region that has been biogenically modified as a result (Wells, 1945; 1966). It is important to note that these vermiforms can have various feeding strategies (Figure 5.1b), and in the more cohesive sediments that are not conducive to stope feeding may feed along the sediment-water interface (Schäfer, 1972). This review focuses on the deposit feeding strategies. There are two regional subdivisions within the head shaft that are often present: the feeding pit (pocket) and the advective funnel (Hylleberg, 1975; Boaden, 1980; Hüttel, 1990; Timmerman et al., 2002, 2006; Meysman et al., 2005).

The advective funnel is largely the result of the stoping feeding method, which makes the morphology dependent on the substrate (Figure 5.2b)(Thamdrup, 1935; Linke, 1939). More cohesive or drier sediments result in less sediment collapse, and hence a smaller funnel. In very cohesive sediment, the animal has to switch to a different type of deposit feeding (e.g., surficial) method to survive (Wells, 1945; 1966; Schäfer, 1972; Rijken, 1979). With a wetter or less cohesive sediment, the funnel can reach to a greater depth, and stoping is often resultant in radial microfaulting along the margins (e.g., Wells, 1945; Rijken, 1979). In even wetter, or dominantly cohesionless sediment, grain-flow dominates and the advective funnel may distend the entire depth of the burrow. The pumping of water through the funnel by the animal is a secondary modification process (selected homogenization) in these pipes that can loosen the sediments or induce liquefaction and flush out finer particles (usually silts, in rare cases sand) between the larger particles (e.g., Wells, 1945; 1966; Trevor, 1977; Foster-Smith, 1978; Swinbanks, 1981; Jones and Jago, 1993). This cleans the fines out of the sands in the advective funnel, and may, in low energy conditions, preferentially deposit these fines as a layer at the top of the funnel (e.g., Swinbanks, 1981). The resultant "clean" texture is important for recognizing these features in the rock record. Recognition of biogenic sorting (grading) in the rock record is addressed in more detail in King et al. (2015).

Even though these organisms have long been studied, little work detailing the biogenic texture created in these funnels has been completed. Typically, only the outlines of the advective funnel features are documented. Cadée (1984, 1998), Hüttel (1990), and

Wells (1945; 1966) have shown that these features are often not a simple funnel (Figure 5.2c), but may pinch and swell, or as Andresen and Kristensen (2002) (Figure 5.2a) show may even be nearly consistent in diameter throughout. Wells (1945) has illustrated that large objects (shells) may change the funnel shape, or that the funnels may decrease in diameter near the top, which may result in a more fusiform cross-section (Figure 5.2c). Additionally, mucus-cemented tube-like features may be created in the advective funnel (Figure 5.2d) when the animal moves up to either mechanically aid in the collapse of sediment or move larger particles of which Wells (1945) has referred to as the drag cycle. Theoretically, these mucus-cemented tubes could be created from a process described whereby the animals create an opening at the surface from which their egg sacs are anchored (*Arenicola brasiliensis* of Okada, 1941; modified by Read, 1984), or which may force usage of a single aperture temporarily for both feeding and defecating (*Axiothella*; Bookhout and Horn, 1949). Additionally, Schäfer (1972) noted that sediment may be stowed laterally by these animals when there is a lot of fine sediments present or in suspension (Figure 5.2e). The common unifying feature in all of the advective funnels appears to be the biogenic production of collapsed sedimentary features, and in the case of head-forward pumpers, perhaps, better sorting within the burrow than in the matrix (i.e., less fines).

The feeding pit (or feeding pocket), lies below the advective funnel, and to the anterior of the gallery (Figure 5.2a). The feeding pocket is a bulbous-shaped open cavity where the organism feeds mainly on the stoped sediment loosened from the base of overlying advective funnel through pumping and gravity (Jacobsen, 1967; Hylleberg, 1975). The feeding pit may vary in size shape and position (Figure 5.2f), and has been noted to be very difficult to assess when cross-sectioning burrows due to the fissile/porous nature of the sediment (e.g., Andresen and Kristensen, 2002). It has been observed that the feeding pocket may result in the accumulation of coarser sand grains due to the inability, or preferential ability to keep lighter grains in suspension while pumping water (Hylleberg, 1975). The modern head forward pumping vermiforms, such as lugworms, were originally described to be non-selective deposit feeders (Thamdrup, 1935; Linke, 1939), but Cadée (1976) noted a grain size preference in what material was passed through the body. Baumfalk (1979) attributed some of this to the ability of the grain to stick to the mucus-coated proboscis, hence, coarser grains are believed to accumulate in the feeding pocket due to a passive selection. Mechanical sorting is additionally suggested by Wells (1945; 1966) for moving larger debris, such as shells, out of the way.

5.2.1.2 The Gallery

The gallery represents the mucus-coated area in which the vermiform pass back and forth from the feeding area (head shaft) to the defecation site (tail shaft) (Figure 5.2a). The gallery usually represents the largest part of the burrow, but the morphology is highly variable between similar species (*Arenicola marina* and *Abarenicola pacifica*) and even within the same species (Figure 5.3a). The gallery may comprise vertical portions of both the anterior and posterior, representing more of a "U"-shape, but as Well (1945) stated this form is rare, and a "J"-shaped gallery is the more typical form. The gallery does not have to be in a smoothed form but may have sharp kinks in the open passage (e.g., Wells, 1945; Grossmann and Reichardt, 1991). The gallery is an open tube structure that may have annulated ornamentation (e.g., Häntzschel, 1938; Linke, 1939). These annulations can differentiate the gallery from the tail shaft, which does not have annulations (Wells 1945; 1966). The mucus coating can result in the gallery (and potentially tail shaft) becoming iron-cemented along the margins (Häntzschel, 1938; Linke, 1939).

5.2.1.3 The Tail Shaft

The tail shaft (Figure 5.2a) is the smallest part of the burrow, and highly variable consisting of either a single open tube (straight or deflected) or multiple branching tubes (Figure 5.3b). The tail shaft is the top few centimeters of the posterior burrow, between the sediment-water interface and the gallery, where the final segments lacking neuropodia sit when the animal defecates (Wells, 1945). The tail shaft is the smallest part of the burrow.

5.2.1.4 Taphonomy

Richter (1924) noted that after a short period of time *Arenicola* burrows are no longer a simple form, but become a network of lateral branches. The posterior portion (posterior gallery and tail shaft) of these U-shaped burrows have often been noted to stay in a fixed location while the head shaft may migrate (e.g., Wells, 1945). This behavior may be similar to the mining method of Rijken (1979) (Figure 5.4a) where the posterior burrow stays relatively fixed and the animal works laterally from this point resulting in a circular pattern of head shaft structures. Given less time this head shaft pattern would likely appear more fan-shaped. Thamdrup (1935) suggest that the migration of the head shaft is dictated by sediment transport conditions (i.e., waves and tides) rather than time. Protected settings have stable head shaft locations, while in unprotected areas, new head shafts are constantly constructed. Sediment cohesiveness may play a role in determining

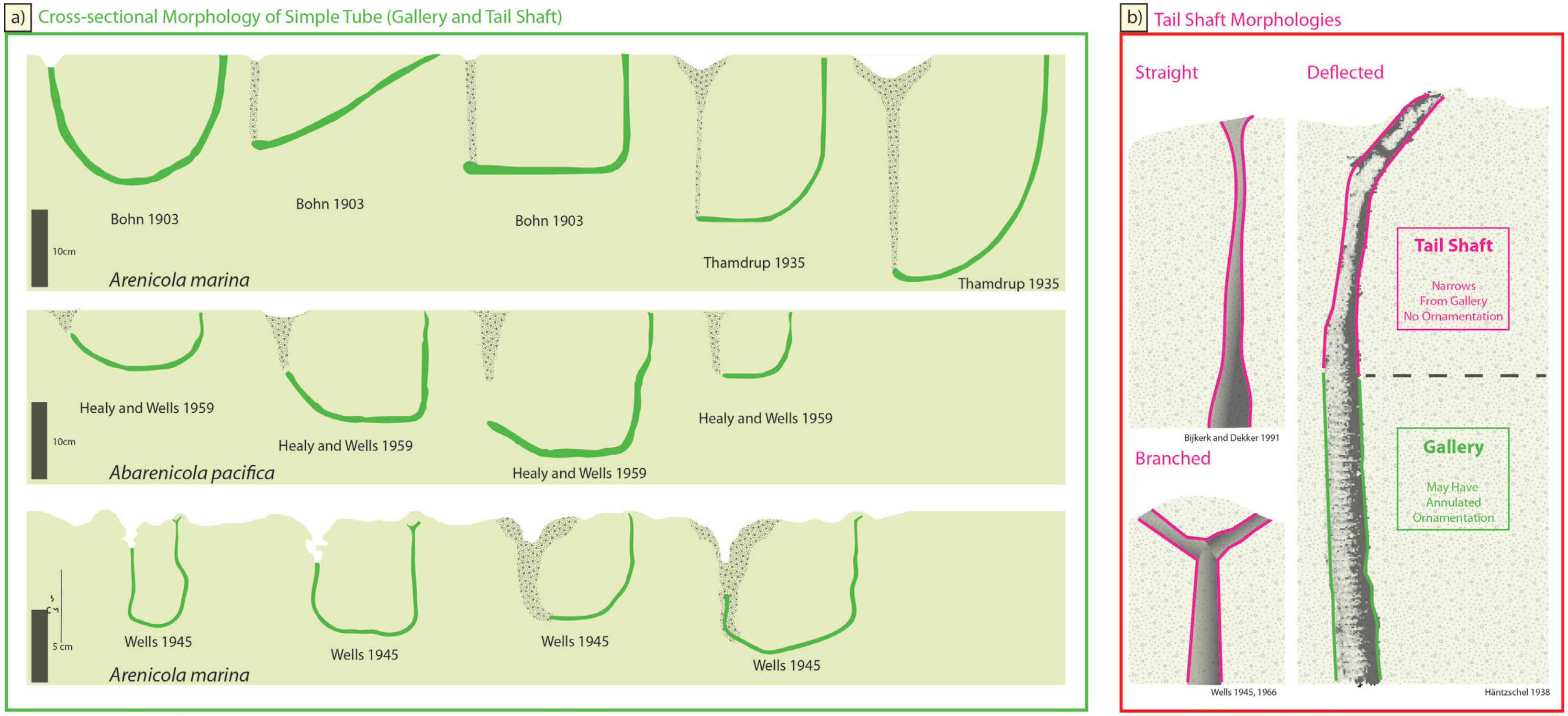


Figure 5.3: Variability of lugworm burrows in the gallery and tail shaft: a) cross-sectional morphology of the simple open tube structures in lugworm burrow. b) types of tail shaft morphologies. (all figures are modified from the authors listed).

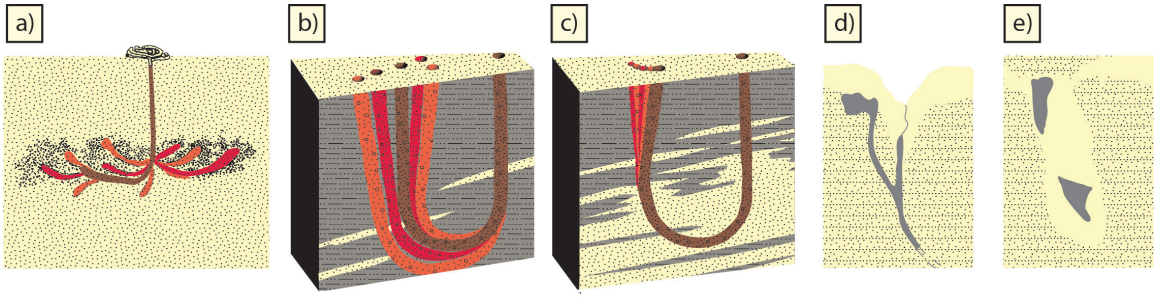


Figure 5.4: Examples of complex morphologies of lugworm burrows: a) deposit feeding with a fixed posterior region (modified from Rijken, 1979), b) lateral branching along the lowest part of the burrow while the posterior remains fixed (Schäfer, 1972), c) lateral branching along the anterior vertical reach of the burrow while the posterior remains relatively fixed (Schäfer, 1972), d) branching of the vertical anterior reach leading to a pocket (Wells, 1945), e) funnel pockets created with disturbed region (Wells, 1945).

where the animals construct their branches (Schäfer, 1972) (Figure 5.4b, c). Where as Wells (1945) has showed branching, as well as establishment of multiple chambers in one disturbed area (Figure 5.4d, e). The method of mining laterally with a stable posterior shaft results in the head shaft being the most abundant preserved biogenic feature over time. The amount of time required for the head shaft to dominate a texture is short, as the organisms move frequently, are often cited to occur in high abundances, and often overlap each others' burrows (Thamdrup,1935; Linke, 1939; Schäfer, 1972; Cadée, 1976). Additionally, many workers (Wells, 1945; summarized in Wells 1966) have shown that lugworms may occasionally reverse in their burrows to mine the posterior shaft and fecal pile, thus overprinting the evidence of a simple vertical tube structure. It is important to note that in some cases iron-cementation in the posterior of the burrow may result in greater potential of preservation of the resistant shafts (Linke, 1939; Schäfer, 1972). The tail shaft has the least preservation potential due to the close proximity to the surface, which may allow for easy reworking.

The morphology of the head shaft is influenced by many variables such as consistency of the sediment. We know these animals often live in areas where the sediment consistency changes on a daily basis (Linke, 1939), but know little about the resultant biogenic structures that signal substrate changes with time. Most studies have focused on the simple structures these animals produce, with less emphasis on how these features are generated over time. Little work has been completed to determine the feeding pit preservation potential and whether or not the head shaft collapses down into the feeding pit over time. Additionally, the advective funnel is a feature that can be reinitiated several times a day (Thamdrup, 1935), which may result in complexities, even in the most simple structures. Wells (1945) has noted that the funnels of a single animal can create multiple feeding pockets, as well as blind branches. This would result in complex morphologies, which may represent behavioral variations, environmental/substrate conditions, or may represent colonization durations. Even though these forms may be highly complex, the stoped, dipping lamina of the advective funnel represents a simple component of all of these biogenic structures and is relatively easily recognized. As well, it has greater preferential preservation potential, and the stoped structures versus the open portions present important ethological implications. Frey and Seilacher (1980) noted the potential of the stope feeding structures for use in identification of fossil specimens. The following is an attempt to rectify the taxonomy of trace fossils representing stoping deposit feeders by establishing end members with focus on biogenic stoping structures as key morphological characters.

Traces from the Ferron Sandstone are used to establish these new taxonomic variations.

5.3 GEOLOGIC BACKGROUND

The trace fossils described herein were collected from the Ferron Sandstone, of central Utah, or within 5 meters beneath the unit, in the mudstone dominated Tununk Shale (Figure 5.5a). The Tununk Shale gradationally underlies the Ferron Sandstone in this area, whereas the Blue Gate Shale lies above the Ferron Sandstone (Figure 5.5b). These *Altichnus* traces occur in the upper Ferron Sandstone of the Last Chance Delta area, which is dominantly Turonian (late Cretaceous) in age (Garrison and van den Bergh, 2004). All reference herein of the Ferron Sandstone will refer to this upper division and to this specific area. The Ferron Sandstone of this area is often broken up into transgressive-regressive cycles (approximately 4th order, Ryer, 2004). This paper will use the terminology of Ryer and Anderson (2004), which uses Kf to designate Cretaceous Ferron Sandstone, then a number for the parasequence set, and the final letters to designate the parasequence. The trace fossils come from Kf-1 (Kf-1-Iv[a] and Kf-1-Iv[c]) and the base of Kf-4 (Figure 5.5b). The *Altichnus*-bearing strata of Kf-1 in Ivie and southern Quitchupah Creeks are largely interpreted as prodelta to delta front facies of a river-dominated system (Ryer and Anderson, 2004, Garrison and van den Bergh, 2004). Whereas, the *Altichnus* traces in the Kf-4 of Bear Gulch are interpreted to lie in nearshore settings such as washover fans or sandy tidal flats (i.e., Chapter 2, Chapter 3). In all instances, *Altichnus* occurs in sandstone with planar or low angle laminated sandstones (often graded lamina) or graded silty-sandy mudstones. These features agree with the previously interpreted environmental settings as both are affected by periodic rapid influxes of sediment that could produce these beds. However, the organisms cited herein as the dominant producer of *Altichnus* are known to sort/grade the sediment over vast surficial areas, so the nature of the lithology in which the traces lie also becomes a question of biogenic versus physical processes, which will only be addressed briefly in this paper, and is addressed in detail in King et al. (2015).

5.4 INSTITUTIONAL ABBREVIATIONS

PMO, Palaeontological Museum, Oslo, Norway; TF, Earth and Atmospheric Sciences

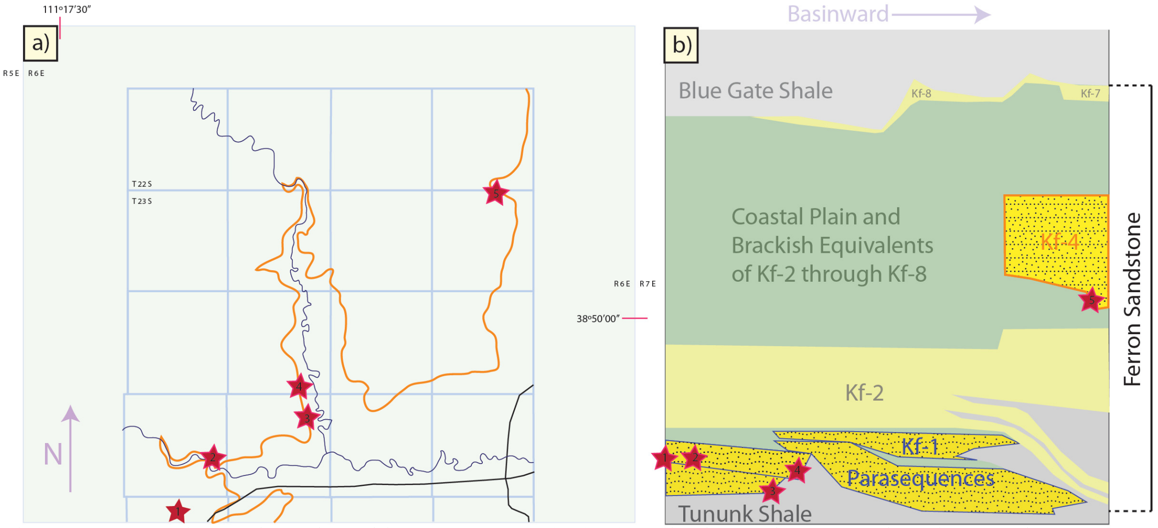


Figure 5.5: Location and stratigraphic occurrence of *Altichnus* in the study area: a) locations (red stars) from which the trace fossil in this paper are described (modified from Anderson et al. 2003), 1=Ivie Creek Core 11, 2=Ivie Creek Outcrop, 3=Southern Quitchupah Creek (Kf1-Iv-a Parasequence, two horizons), 4=, Southern Quitchupah Creek (Kf1-Iv-c Parasequence), and 5= Bear Gulch (Base of Kf-4). The orange line represents the westward extent of the Ferron Sandstone outcrop. b) A generalized stratigraphic schematic illustrating the gradational relationship of the Ferron Sandstone of the Last Chance Delta area to that of the underlying Tununk Shale, as well as the shoreline sandbodies (yellow) designations within the study area accompanied by the stratigraphic and geographic locations (directly comparable with left figure, except the first location should be slight more to the left on the schematic)(modified from Garrison and van den Bergh, 2004, Ryer and Anderson, 2004; Anderson et al., 2003).

Museum Collections, University of Alberta, Edmonton, Alberta Canada. All core photos are from half slabs between 418' to 425' in the Ivie Creek #11 Core stored at the Utah Core Research Center (UCRC), Salt Lake City, Utah.

5.5 SYSTEMATIC PALICHNOLOGY

5.5.1 Ichnogenus *Altichnus* Bromley and Hanken 1991

5.5.1.1 Type Ichnospecies

Altichnus foeyni Bromley and Hanken 1991, p. 268-270, Fig. 4a-d, 13a-e, 14

5.5.1.2 Emended Diagnosis

Vertical or subvertical shafts, perpendicular to the bedding plane, comprised of dominantly unwalled structures whose diameter generally increases upwards. These vertical shafts may take on funnel or bulb-like morphologies, especially at the terminal ends. Bulb-like morphologies may stack vertically. Both funnels and bulbs may branch laterally. Branches containing terminal bulbs or funnels will maintain elongate axis perpendicular to the surface. Whereas, branches of simple shafts axis's are oriented at an angle to the depositional surface, and may narrow in the terminal few centimeters. The vertical shaft often is connected to a J-, L-, or U-shaped structure. The branching of the vertical shaft can occur laterally off of the main shaft or secondary shafts, may branch at the base of the shaft where the burrow bends more horizontally, or the horizontal tunnel may branch from a similar position of the posterior vertical tube with each split tunnel terminating anteriorly in a vertical shaft. (Emended after Bromley and Hanken, 1991; Gaillard and Racheboeuf, 2006).

5.5.1.3 Discussion

The original description of *Altichnus* from the Lower Cambrian by Bromley and Hanken (1991) names an upward increasing unwalled structure (e.g., a funnel) as the primary characteristic with a J-shaped base likely resultant from tectonic related deformation. However, Gaillard and Racheboeuf (2006) believe that in their Devonian *Altichnus* examples the J-shape is the natural shape of the burrow. The J-shape is likely a key morphological criteria, and could actually be related to U-shaped biogenic structures, that may not be preserved or noted due to some factors as tunnel collapse, the high densities often associated with these traces, the toponomy, and the limited angle at which to view full reliefs. This J-shape is what helps to distinguish this structure from *Monocraterion* (Torell, 1870; Westergård, 1931). *Altichnus* can have a *Skolithos*-like tube at the base, which makes it resemble *Monocraterion* in some views, but the base of the *Skolithos*-like tube in *Altichnus* will round off (due to bending), bend, or even branch. Additionally, the fill and internal structures within the funnel portion of these two genera is notably different.

Gaillard and Racheboeuf (2006), additionally described multiple variations in the morphology of *Altichnus*, from that of the simple funnel to that of stacked bulb-like morphologies that terminate in a funnel. They interpreted the stacked bulb form as resultant from event deposition (i.e., an equilibrichnia variation of *Altichnus*). Even Bromley and Hanken's (1991) type series (Figure 13, p. 273) can be seen as composed of series of vertically stacked bulb-like morphologies. Although, Bromley and Hanken (1991) believe this is probably also resultant from deformation. Both sets of authors attribute the production of these traces to the work of suspension feeders over time. This likens *Altichnus* to forms of other vertical bulb-like traces attributed to suspension feeders such as *Rosselia* and *Polycylindrichnus*. Conversely, *Rosselia* and *Polycylindrichnus* are mudstone dominated, wall-lined, and possess near vertical spreite that are oriented in direct relation to the central bulb shaft(s) (e.g., Fournier et al., 1980; Nara, 1995; Nara, 2002). The same characteristic, vertical spreite, differentiates *Tursia* (D'Alessandro and Fürsich, 2005) from *Altichnus*. The interior of the funnel or bulb-like morphologies of the terminal vertical shaft are typically composed of concave up lamina containing dominantly organics, sand, or silt. These lamina can be low angled or may exist as steep chevrons. These traces often are composed of more homogenous accumulation of grains (e.g., organics or sand) than seen above or in the surrounding matrix. Large organic pieces of organic debris may be present near the bottom of funnels.

These concave upwards features are reminiscent of equilibrichnia traces (e.g., *Lingulichnus* , *Conichnus*, *Lockea*), escape traces (fugichnia), and collapse features. The lingulid shell is often still preserved in the *Lingulichnus* burrow (e.g., Zonneveld and Pemberton, 2003; Zonneveld et al., 2007). Additionally, many of the equilibrichnia or escape traces often show deflection in position over the vertical span, whereas *Altichnus* convex up lamina are mainly oriented in vertical packages. In cross-section, *Altichnus* can typically be differentiated from the other tube bearing form, *Lingulichnus*, because of *Lingulichnus*'s almond or oval shape (Hakes, 1976). *Altichnus* may appear to have oval shapes, but these shapes are resultant from having two tubes in close proximity, and care must by taken in accessing the two. Collapse features may share the closest morphology to *Altichnus*, due to the chevron shapes, and decrease in steepness of the convex up shapes upward. However, *Altichnus*, often may show several events or packages, may have lamina at steeper angles than would be produced by the collapse of a simple tube, may possess a central shaft(s) and may have a fill that is distinct in nature from that of the surrounding matrix.

Altichnus funnel shape and internal concave up structures is similar to the shape produced by stope feeding (or collapse mining of sediment) in modern organisms. This feeding ethology has yet to be attributed to this trace, but is suggested herein as the major method as biogenic construction. The funnel is the simplest stoped form made by the modern burrowers, thereby their burrows are often illustrated this way. A few authors have illustrated the internal lamina created in these "funnels" which often show that the internal lamina are more complex than a simple funnel, but may widen and offset or even produce structures that may show little upward tapering from the base. Additionally, the nature of the sediment dominates whether there is cohesionless grain-flow collapse or more cohesive microfaulting along the margins. Additionally, these animal move back and forth often and have to reinitiate these structures each time. These attributes make it more difficult to pigeonhole characteristics that can be used for trace morphology.

5.5.2 *Altichnus foeyni* Bromley and Hanken 1991

Figures 5.6d-g, h, 5.10d

5.5.2.1 Holotype

PMO 121.530, *Paratypes,* PMO 121.531 to 121.535; collected from the Lower Cambrian Dividal Group 132 meters above the base, 2km west of Voullenjoaski, Altaelv, Norway. (Bromley and Hanken, 1991, p. 268-269, 272, Fig. 4A-D, 13A-E, 14).

5.5.2.2 Diagnosis

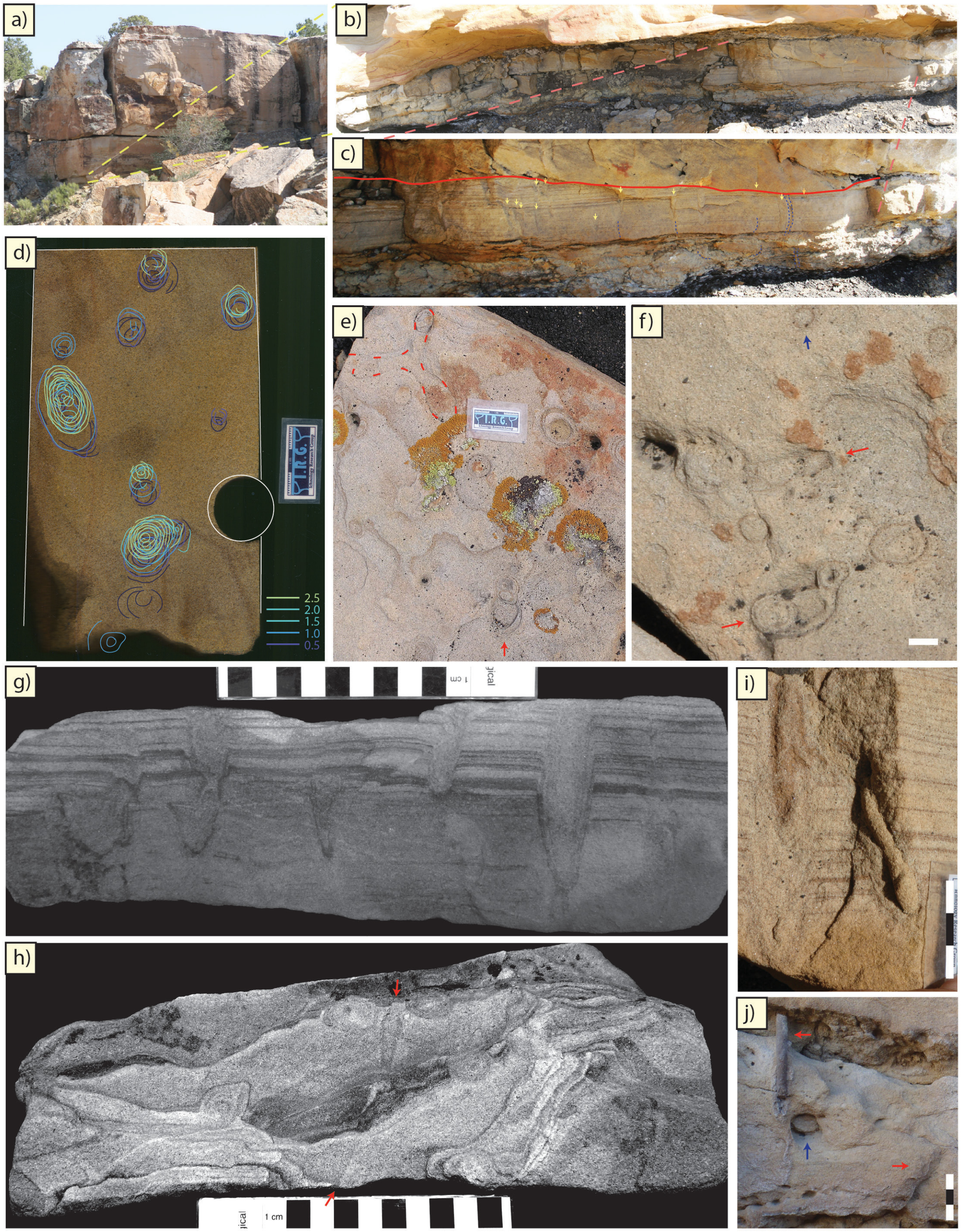
Clustered sand-filled shafts with vertical to near vertical orientation. The secondary shafts branch off of a parent shaft(s) and immediately curve upwards to vertical orientations. The diameter of each individual shaft (primary or secondary) increases upwards from the base. The upward expanding shaft(s) has no wall lining or ornamentation (bioglyphs).

5.5.2.3 Discussion

Altichnus foeyni is found in the landward pinchout of the basal portion of the Kf-4 sandstone (Figure 5.5b, 5.6a-c) in the Bear Gulch area, which is interpreted to be transgressive nearshore marine conditions with evidence for shallow high-energy conditions (washover; Chapter 2) and subaerial exposure (dinosaur tracks and tree casts; Chapter 2). *Altichnus foeyni* is found in dominantly planar laminated sub-decimeter very-fine to fine-grained sandstone beds with thin interbeds of heavily bioturbated organic-rich mudstone (Figure 5.6b, c), which are interpreted as tidal flat deposits in Chapter 3. The top of the beds are locally truncated by trough cross-bedding (Figure 5.6c). The main trace observed with *Altichnus foeyni*, besides other *Altichnus* species, is *Siphonichnus*. However, after cutting numerous specimens, it is difficult to quantify how many are *Siphonichnus* versus how many are toponomic variations of *Altichnus*. Some *Ophiomorpha* cross-cuts this unit locally. Overall, the beds show low diversity, and while the vertical cross-section shows moderate bioturbation and preserved planar bedding, the tops of the units can be completely covered in bulls-eye plan view cross-sections of *Altichnus* (Figure 5.6d-f).

The *Altichnus foeyni* of the Ferron Sandstone are preserved as branched funnels that are mainly noticeable with one primary funnel and an adjacent secondary funnel that together create an ovate ring pattern in plan view (Figure 5.6d-f). This could be mistaken for *Lingulichnus*, however, by creating closely spaced horizontal slices (Figure 5.6d) it can be seen that these ovate patterns contain two central structures, and may be the product of a slight inclination of the funnel to the bed top. Other complex relationships are noted in plan view such as tri-branching (Figure 5.6e) and possible lateral migration (Figure 5.6f; which also could be attributed to *Altichnus* isp. B, discussed below). The plan view ovate pattern is typically less than 4 cm along the maxim axis. In vertical cross-section, these traces are mostly chevron-shaped, but can be U-shaped in some cuts (Figure 5.6c, g). The chevrons may be terminated centrally, and can be over 9 cm in height. Small tapered shafts may be present near the base (Figure 5.6g) or within the funnels (Figure 5.6h). In addition to the tapered shafts, horizontal components are noted (Figure 5.6i), as well as iron-cemented vertical and inclined shafts locally (Figure 5.6j).

The tapered funnel base, horizontal shafts, and iron-cemented shafts are taken as indication that these funnel-shaped traces are connected to a J-shaped tube. As mentioned earlier, there is a taphonomic bias against preservation of the posterior tube. However, the iron-stained vertical shafts could represent the same posterior cementation seen in the modern *Arenicola* burrows (Häntzschel, 1938; Linke, 1939). The heavy bioturbation by


a)
b)
c)
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2.5
2.0
1.5
1.0
0.5
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1 cm
gical
i)
j)

Figure 5.6: Occurrences of *Altichnus foeyni:* a) the Kf-4 sandstone in Bear Gulch, b) interbedded *Altichnus* bearing laminated sandstone and heavily bioturbated organic rich mudstone that lies at the base of Kf-4 directly above coal, c) line traces of *Altichnus* and *Siphonichnus* with a locally erosional top (red line), d) line tracings of biogenic rings at intervals sliced ever 0.5 cm, which show the ovate ring patterns are composed of two structures lower down (*Altichnus foeyni*) whereas the circular rings appear to be related to a single structure (*Altichnus* isp. A), e) examples of burrow grouping, with a tri-branched example (dashed line) and a clustered example (above the red arrow), f) bundled examples that are potentially *A. foeyni*, but the linearity of the pattern may also suggest *Altichnus* isp. B, g) examples of lower branching (left of photo), and the presence of basal curving shafts (right of photo), h) central shaft extending upwards into stoped structure, i) top view of (g) showing central shaft in concentric rings of *Altichnus* as well as horizontal dipping tube (red arrow), j) iron-cemented vertical burrow reach and inclined reach (red arrow), with *Ophiomorpha* (blue arrow).

Thalassinoides and *Planolites* in the underlying organic mudstone to which the bottom of the J-structure would likely distend also plays a role in hindering recognition.

This varies from other known descriptions of *Altichnus* in terms of age, morphology, fill, and ethology. *Altichnus* has mainly been described in much older units of Lower Cambrian (Bromley and Hanken, 1991; Erdoğan et al., 2004), Devonian (Gaillard and Racheboue f, 2006) and Mississippian (Muszer and Uglik, 2013) ages. *Altichnus* has been noted in the Cretaceous (i.e., Pemberton and MacEachern, 1997), but has yet to be described. *Altichnus foeyni* of Bromley and Hanken (1991) was reconstructed as funnel forms, but in toponomic expression often appears more fusiform in nature; or club-shaped as noted by Knaust (2012). This differs from the toponomic funnel forms of the Ferron Sandstone, which is likely related to the differing lithology of the encasing matrix. The funnel forms of the Ferron are in a sandstone matrix, are closer to the muddy metasandstone examples of Erdoğan et al. (2004), than the club-shaped type specimens which are encased in silty shale. As such, the Ferron specimens are akin to the modern substrate cohesionless grain-flow type conditions, whereas the type specimens could represent the cohesive end of the spectrum. Although without seeing the type specimens in person, it is impossible to truly rule out the role of tectonic deformation, as well as, whether these are the passive fill of suspension feeders. Such is the case also with the *Altichnus* of Galliard and Rachebouef (2006), even though these specimens occur in a sandstone matrix. The question of the nature of the fill arises with these South American specimens and whether some of these are more comparable to *Polycylindrichnus* of Fournier et al. (1980), or do truly represent a suspension feeding form of *Altichnus*. Conversely, the Ferron example is the product of an active fill process interpreted to result from head down stope feeding of a forward pumping vermiform.

5.5.3 *Altichnus* isp. A

Figures 5.7a-g, 5.8b, d-h

5.5.3.1 Locality and Distribution

The described specimens of *Altichnus* ichnospecies A (isp. A) were collected from near the base of the Kf-4 sandstone (along the southern wall of Bear Gulch) and Kf-2-Iv[c] unit (Quitchupah and Ivie Creeks north of Interstate 70, and Ivie Creek Core #11) from Upper Cretaceous (Turonian) Ferron Sandstone of Ryer and Anderson (2004) to the southeast of Emery, Utah.

5.5.3.2 Diagnosis

A vertical, unlined upward expanding form that is funnel-shaped or fusiform in nature. The expanding upward outline is vertical to near vertical in relation to the bedding plane, and in some toponomic expressions is observed in association with a basal shaft. This basal shaft bends away from the vertical shaft and back up towards the surface, creating a general J-shape. The expanding upward form can appear massive, but mainly consists of chevron-like or concave up structures (lamina) that may often be laterally truncating underlying lamina. There can be multiple sets creating a quasi-vertical stacking of funnel-like morphologies and fusiforms. The basal tube may connect to an internal tube within the expanding form, in which the tube may be centralized, not present, or may be expressed as multiple partial tubes.

5.5.3.3 Preservation/Discussion

Altichnus isp. A is represented in the Ferron Sandstone by two basic forms: the funnel-like form (Figure 5.7a-f) and the bulb-like form (fusiform)(Figure 5.7g-i). The funnel forms are present in the same rock package as *Altichnus foeyni* (described above). *Altichnus* isp. A at this location externally appears to be a symmetrical funnel (Figure 5.7a), with a tree ring-like cross-section (Figure 5.7b). However, internally these features are often asymmetrical with cross-cutting down draped lamina (Figure 5.7c). Additionally, *Altichnus* isp. A can have a series of stacked funnels that lie in a similar vertical plane (Figure 5.7d). This differs from *Altichnus foeyni* in which each funnel distinctly branches off a parent funnel. Although, the two species likely form a continuum from unbranched (*Altichnus* isp. A*)* to branched (*Altichnus foeyni)*. The basal shafts can be difficult to recognize in the sandstone unless they are iron-cemented or filled with a contrasting lithology (Figure 5.7g). The posterior vertical shafts, may be iron-cemented as shown above (Figure 5.6j). Generally speaking, the *Altichnus* isp. A are round on the tops of beds (Figure 5.7f), whereas *Altichnus foeyni* is usually more ovate. Multiple small shafts are occasionally present in cross-section (Figure 5.7g). Some of the smaller circular features with only a few rings could be stowage in the posterior shaft, due to consistent overall diameter throughout, seen in cut samples.

The second form, the more bulbous or fusiform variations, are found in the Kf-2-Iv [c] of Quitchupah and Ivie Creek (Figure 5.5b, 5.8a-c), which are interpreted as distal delta front facies (e.g., Garrison and van den Bergh, 2004). These also occur in dominantly

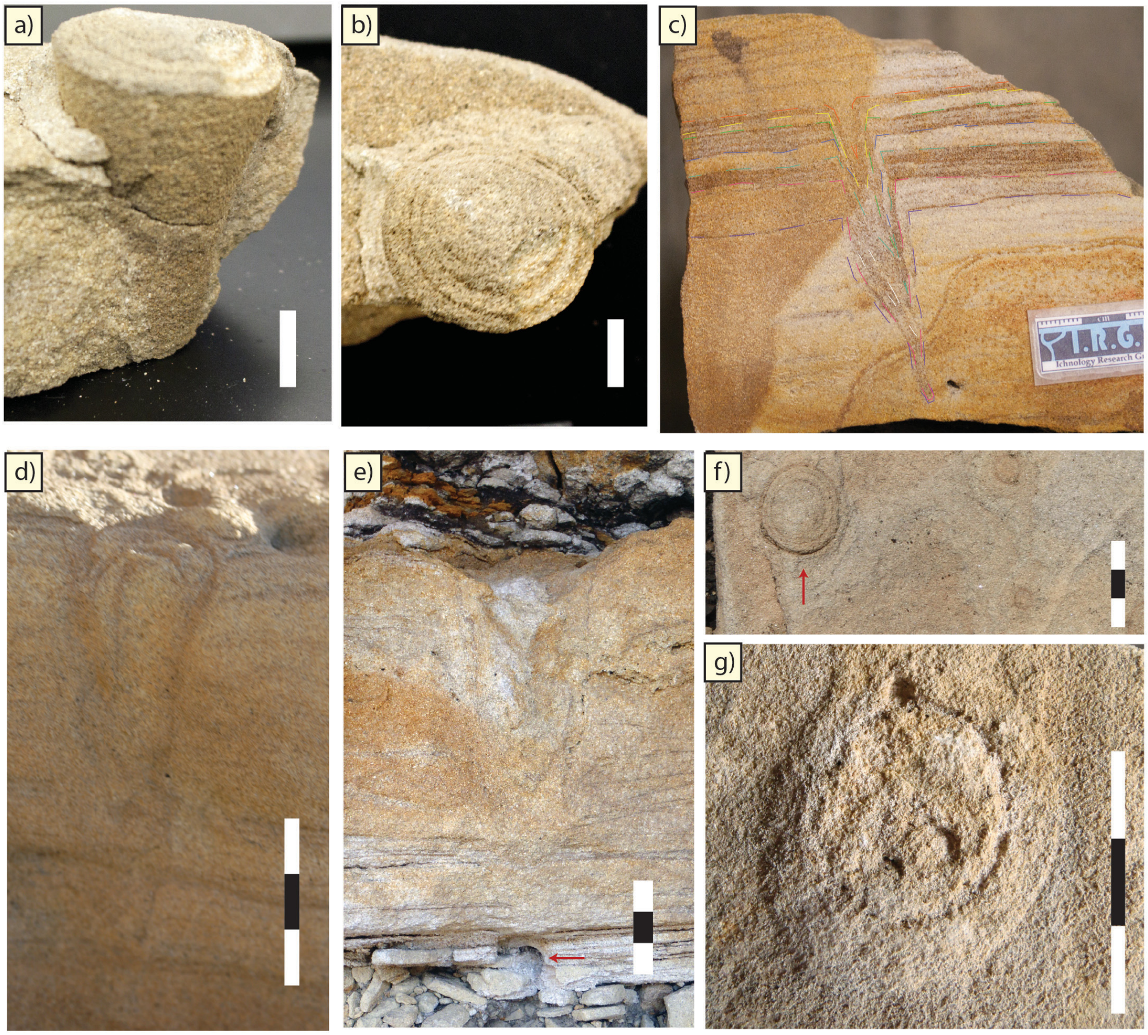


Figure 5.7: Variations of *Altichnus* isp. A: a) collected specimen, funnel variety, side view, b) top view of same specimen, c) another collected specimen showing chevron lamina pattern, d) more complex example illustrating several chevron co-sets, e) *Altichnus* isp. A displaying tube structure at the base, f) top view of *Altichnus* isp. A showing a rather symmetrical tree ring-like pattern with fainter preservations on the right, g) three tube structures within a plan view cross-section.

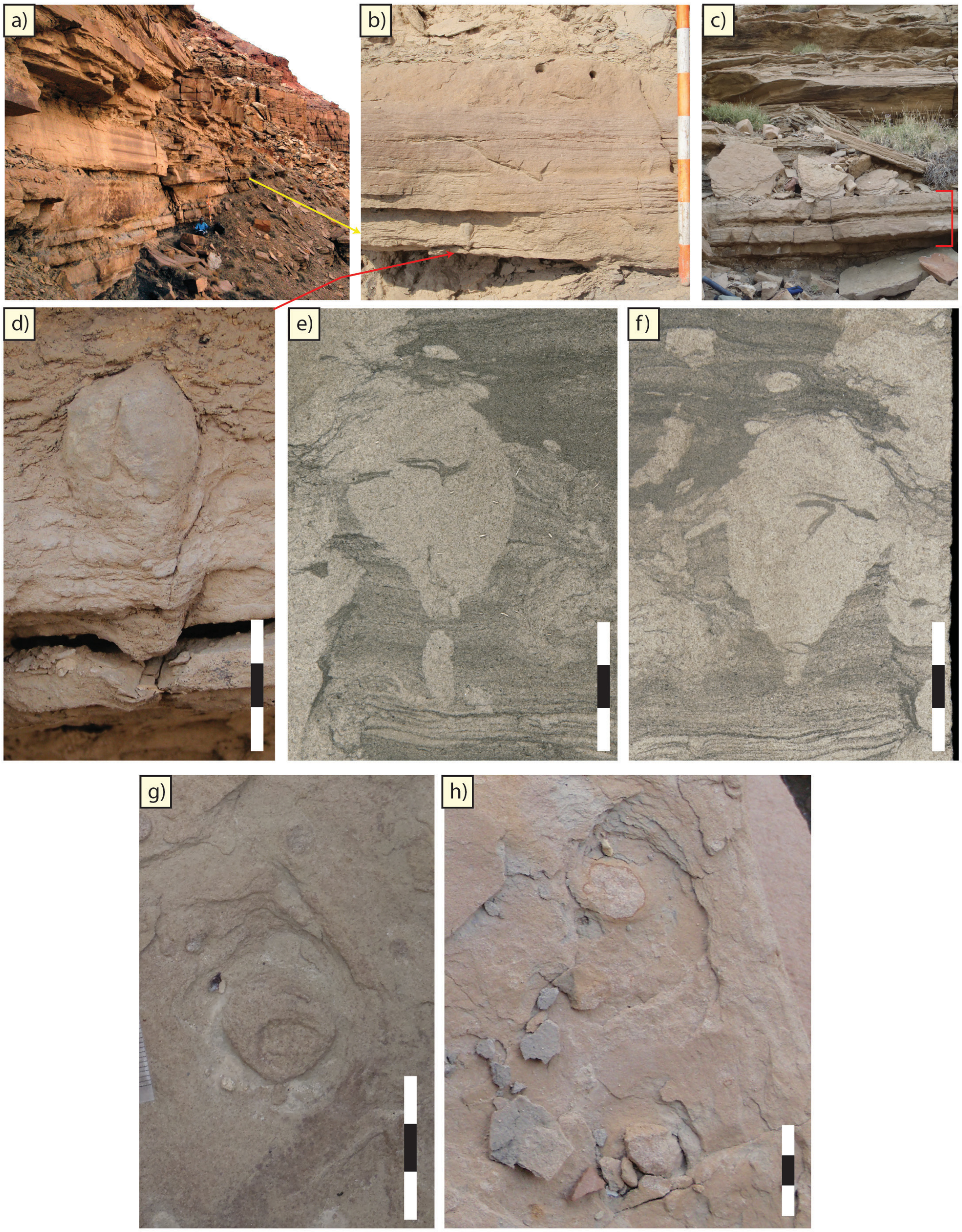


Figure 5.8: Locations where *Altichnus* isp. A and *Altichnus* isp. B were collected as well as fusiform varieties: a) Quitchupah Creek location at the base of the Ferron Sandstone in Kf-1-Iv[c] showing the interbedding of planar laminated sandstones with thin sparsely burrowed mudstones, b) bed from which *Altichnus* were noted, c) Ivie Creek location showing beds from which *Altichnus* was noted in Kf-1-Iv[c], d) fusiform variety of *Altichnus* isp. A, e, f) fusiform variety from slab and butt side of the core f) top view of bed showing sand rich *Altichnus* burrow with rather flat top and lowered surrounding rim in Ivie Creek, g) two more examples from Quitchupah Creek, the lower with a flat top and the upper with a more bulbous top.

planar-laminated sandstones, but the mudstone interbeds are more depauperate in terms of bioturbation. These fusiforms almost always occur with the concave down top in a muddier lithology (Figure 5.8d). Although, the top often appears flatter when observed on upper surface (Figure 5.8e, f), and have a lowered asymmetrical ring around them. The more bulbous tops are often seen with a central shaft, whereas the flatter examples have an asymmetrical divot in the top. It is difficult to access whether this is truly a funnel surrounding the sandier portion or is resultant of the up-warped lamina at the top of the burrow. The upwarped lamina at the top and bottom of the burrow may result from differential compaction. The microfaulting that typify the margins of these forms may result from this as well. Conversely, the microfaulting could be the result of radial fracturing that is seen in the modern creation of funnel structures by *Arenicola* by Wells (1945), and that typifies the more cohesive stoping structures of Rijken (1979). Such would be a reasonable assertion when looking at Figure 5.8d where the concave down laminae coincides with the muddier sediment. Thus the fusiforms represent *Altichnus* in more cohesive deposits and funnels typify cohesionless matrix variations. Alternatively, fusiforms may also represent an equilibrating form, as suggested by Gaillard and Rachebouef (2006), and as such would explain the shaft structures at the top of the burrow. Ethologically, both forms are interpreted to represent stope-feeding of vermiforms. However, the fusiforms also likely represent some degree of sorting by the animal (cf. King et al 2015) or may also relate to lateral stowage of the large grains.

An issue that needs to be addressed with these traces being interpreted as overall U-shaped constructions is the differentiation from similar forms such as *Arenicola* and *Catenarichnus*. This is an important distinction not only for morphological reasons, but also for ethological reasons. Ethologically Seilacher (2007) shows three types of simple U-form work schemes, those of suspension feeding organisms, those of surface-scraping deposit-feeding organisms, and those of sand-swallowing deposit-feeding organisms. The sand-swallowing organisms are fundamentally different because of the enlarged anterior structure (e.g., funnel) that they create by stope-feeding. As such, the presence of a prominent enlarged aperture with stoped lamina is distinctive. Therefore, the presence of this distinctive morphology on the end of an overall u-shaped tube should be referred to as an ichnotaxon that gives the funnel taxonomic priority rather than using the tube shape to name it *Arenicolites*. *Arenicolites* is a vertical U-tube without spreite (Fürsich, 1974). The limbs of the U-shape is roughly perpendicular to bedding with a sub-parallel relationship between the limbs; whereas arching tubes without distinctive limbs (perpendicular to bedding) are referred to the ichnogenus *Catenarichnus* (Bradshaw, 2002). Binney (1857) illustrates *Arenicolites carbonarius* (renamed by Salter, 1857) as having prominent funnel apertures. Eagar et al. (1985) describes *A. carbonarius* as having concentric retrusive upwards funnel infilling as well as have a "J" shaped appearance. It is suggested here that these retrusive J-shaped forms of *Arenicolites carbonarius* are synonymous with *Altichnus* isp. A because of the prominent funnel with downward converging lamina present, and thus it does not belong amongst the simple U-tubes that typify *Arenicolites*. The branched and Y-shaped morphologies of *A. carbonarius* from Eagar et al. (1985) may also need taxonomic emending, and could be a species of *Altichnus* but they do not belong in *Altichnus.* Another similar form that warrants investigation is that of *Monocraterion*, which may be distinguished by it's straight basal shaft, but has likely been a prior taxonomic catchall for misidentified stope-feeding structures.

5.5.4 *Altichnus* isp. B

Figures 5.9 and 5.10

5.5.4.1 Locality and Distribution

The specimens of *Altichnus* ichnospecies B (isp. B) were noted in the Upper Cretaceous (Turonian) Ferron Sandstone from Kf-2-Iv[c] at Quitchupah and Ivie Creeks, as well as Bear Gulch (Kf-4), north of Interstate 70.

5.5.4.2 Diagnosis

Vertical, unlined upward expanding forms that are funnel-shaped or fusiform in nature that are connected basally. The expanding upward outlines are vertical to near vertical in relation to the bedding plane, can overlap, are in relatively linear, or slightly curved, arrangements, and may occur at various heights. The funnel or fusiforms are connected basally by concave up tube like structures, or an amalgam of hypichnal linear structures. The tubes or linear structures are much longer than wide, and are often asymmetrical in orientation. The asymmetry results in the elongate axes of the tubes or linear structures converging in one general direction.

5.5.4.3 Preservation/Discussion

Altichnus isp. B is found in the same units as the *Altichnus* isp. A in Ivie and Quitchupah Creek, and possibly with the previously described *Altichnus* at Bear Gulch.

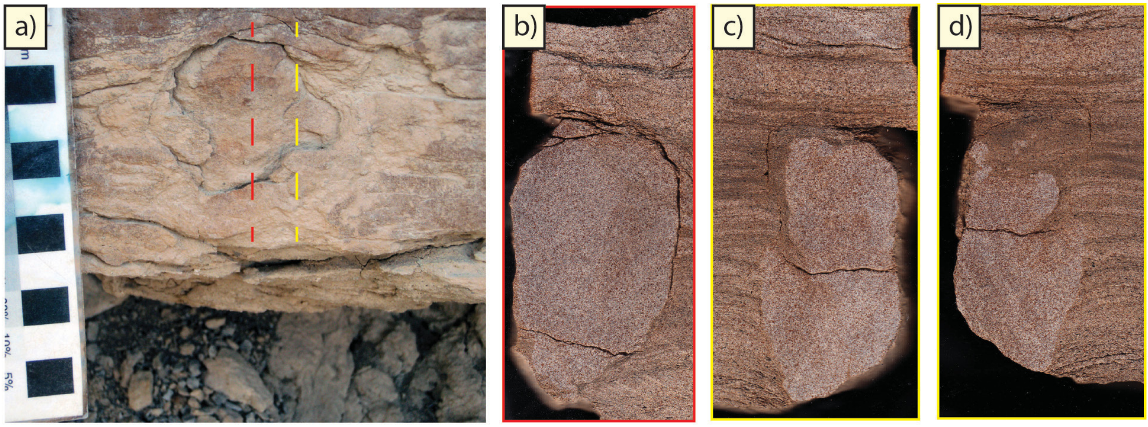


Figure 5.9: Type specimen of *Altichnus* isp. B: a) collected specimen, side view, b) cross-section along the red dashed line showing a singular expression with centrally downwarped lamina, c) cross-section along the left side of the yellow dashed line showing seperation of two features containing downwarped lamina, with the upper or left feature cross-cutting the lower feature, and d) cross-section along the right side of the yellow line showing the two features.

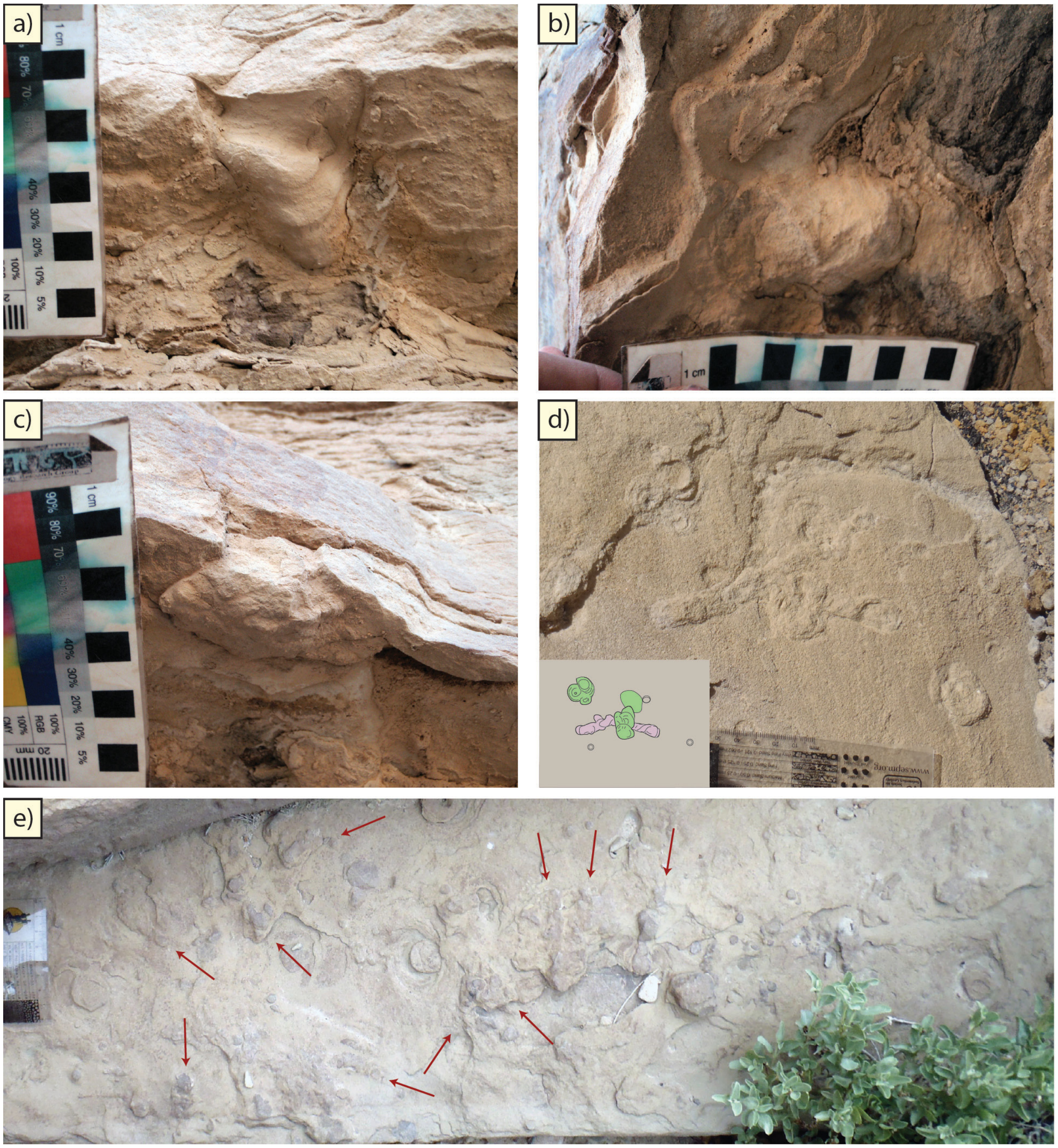


Figure 5.10: Plan view expression of *Altichnus* isp. B: a) basal expression seen under the trace in Figure 9a, representing a laterally migrating component, with b) and c) representing similar basal expressions along the same surface. d) a cross-sectional example from Bear Gulch showing a laterally moving funnel of *Altichnus* isp. B (inset pink) with species of *A. foeyni* (inset green). e) Top of a bedding plane in Ivie Creek with linear arrangements of the funnels (red arrows).

Altichnus isp. B is differentiated by the lateral grouping of burrow and connection or amalgamation of the basal concave up structures. While the individual stacking of the funnels is too often complex to be truly resolve at this point in vertical view (Figure 5.9a-d), they often show a lateral cross cutting of forms. This is coupled with basal hyporelief structures approximating a series of conjoined broad U-shapes, which often resemble a fist (Figure 5.10a-c). There is often an asymmetrical aspect to this where one side's tubes converge more than the other, or in a Bear Gulch example converge at a single point. Additionally, many of the tops in these areas show lateral groupings of the funnels (or fusiforms) (Figure 5.10d, e).

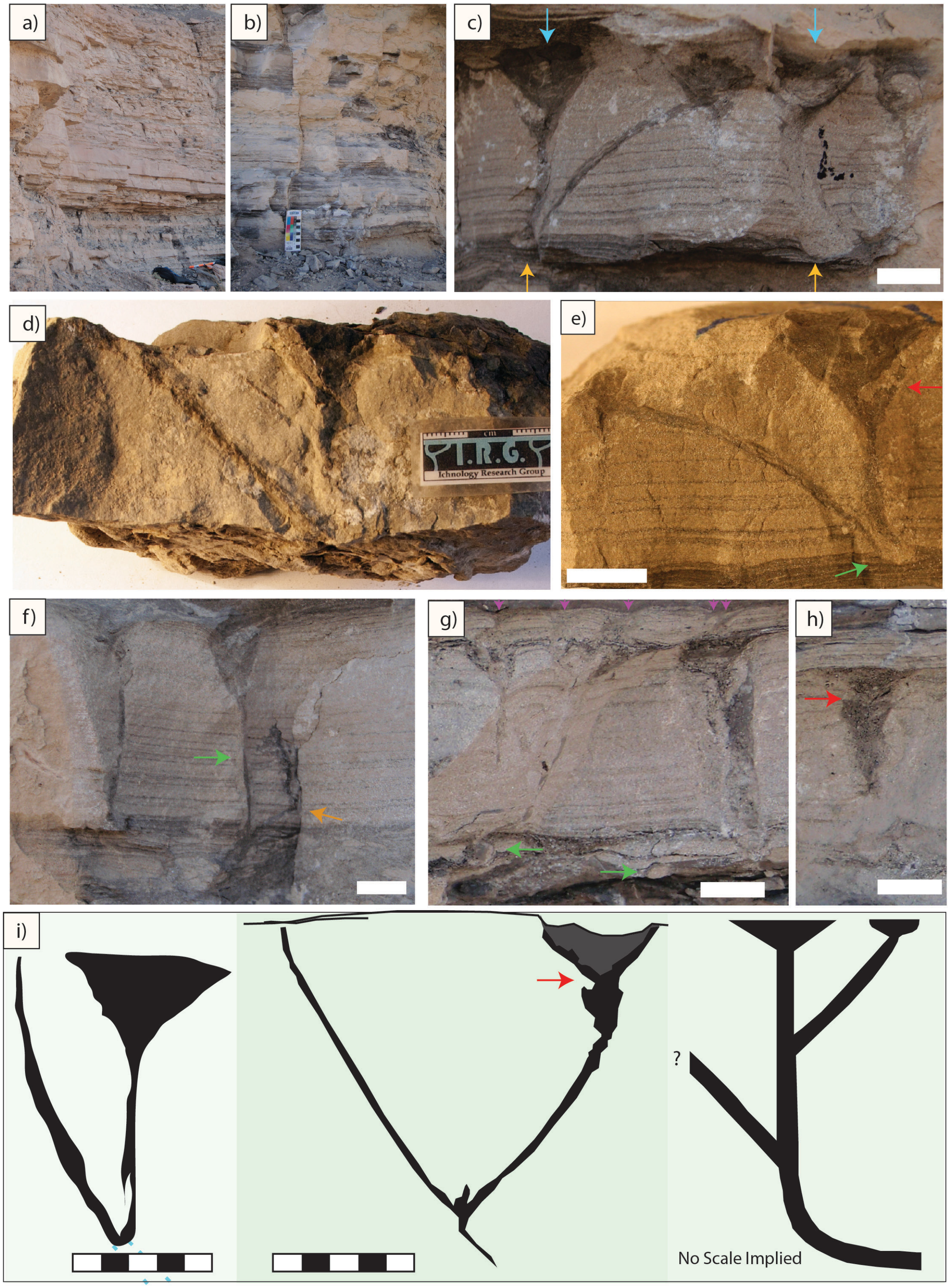
Altichnus isp. B is interpreted to represent the laterally migrating burrow of a stoping deposit-feeder. While alignment in *Arenicola* burrows (e.g. fecal mound alignments) have often been noted on modern shorelines in response to substrate depth preferences (e.g., Chapman and Newell, 1949), the basal hyporelief structures do indicate movement of a curved tube. The lateral movement of the curved tube over time is noted by Richter (1924) and Thamdrup (1935) in *Arenicola*. The asymmetry is consistent with what is noted from these burrows by Wells (1945); where the posterior portion remains more fixed resulting in more posterior conversion of the structure. Thamdrup (1935) suggested that the establishment of successive funnels in modern *Arenicola* is a result of the surficial sediments often being reworked. Whereas, Rijken (1979) showed that lugworms in nutrient-rich sediment may utilize migration of the anterior region for quasi-systematic deposit feeding instead of relying on down draw from the sediment surface. Establishment of the base of the structure all along a similar level during lateral movement is noted by Richter (1924) as a common theme among modern *Arenicola.* Conversely, the more cohesive substrate at this basal level may have played a role in where the branching occurred (e.g., Schäfer, 1972).

5.5.5 *Altichnus* isp. C

Figure 5.11

5.5.5.1 Type Locality and Distribution

The two specimens of *Altichnus* ichnospecies C (isp. C) were collected from near the base of the Kf-1 sandstone Upper Cretaceous (Turonian) Ferron Sandstone of Ryer and Anderson (2004) on the southwestern outcrop of Quitchupah Creek just north of Interstate 70, southeast of Emery, Utah. The two types were collected within a few hundred meters of each other, but along different horizons. One specimen was collected in the mudstone-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?
No Scale Implied

Figure 5.11: *Altichnus* isp. C: a) The interbeds of Kf-2-Iv[a] at the base of the Ferron Sandstone in the Quitchupah Creek area. b) A closer view of the base of the photo to the left showing the laminated and graded beds, with relatively low bioturbation abundance, in which *Altichnus* isp. C is found. c) The counter part of one of the collected specimens embedded in the outcrop. Comparison of adjacent burrows reveal different infilling (blue arrows), with the left infill being organic dominated and the right being sandier, suggesting the two operated differently (e.g., time or usage). The yellow arrow shows a characteristic asymmetrical enlargement, tilted medially, formed by the branching at the base of the funnel. d) collected specimen with vertical shaft topped by funnel structure branching from a low angle tube that continues towards the surface without flaring outward. e) a collected specimen showing the basal enlargement with crescent-like structure (green arrow). The low angle branch shows angled terminating lamina within, which could result from stowing, inhalant current, or possibly coughing behavior (noted in Duncan, 1987) to force collapsed sediment out of the tube. Conversely, the funnel is filled with concave up lamina that becomes steeper along the margins. The red arrow shows a lateral hook-like structure often seen along the sides of the funnel. f) Shows a funnel structure (right) with branching, and a vertical lining of sand (green arrow), suggesting lateral stowage, which is markedly different from the left burrow that does not have a significant expression of stowage. The orange arrow may represent additional branching, movement of the burrow, or just close proximity of two unrelated burrows. g) Funnels on left descend to a similar point which shows an asymmetrically distributed crescent infilling (stowage; green arrow) in the basal tube, whereas to the right (green arrow) displays an asymmetrical crescent of mud with a sand infill. These funnels display a more chaotic infill, than the adjacent systematic concave laminar infills. The chaotic fill is resultant from upward escape, as can recognized by the fugichnial structures (purple). This also suggests that at least one organism occupied each funnel. h) Similar structure (red arrow) as seen in E, where there is a distinct narrowing, such could result from the upward movement of the funnel, subsequent cross-cutting of the funnel, or a collapse event. i) Outlines of the cross-sections of modern *Balanoglossus* burrows (left and middle are modified from the photos of Duncan, 1987; right is modified from Stiasny, 1910). Cross-sectional views do not capture the way in which the branches are offset three-dimensionally (see discussion in text), and not all branches develop funnels, or in some cases multiple funnels are developed.

dominated portion around 4 meters below the base of the sand-dominated succession, and technically (lithostratigraphically) would be part of the Tununk Shale. The second specimen was collected in the basal part of Kf-1 of the Ferron Sandstone.

5.5.5.2 Diagnosis

Vertical or near vertical shafts that widen upwards, and are connected to a low angle branch (~45 degrees or greater) that does not significantly widen towards the aperture. The vertical to near vertical shaft is often seen in cross-section with an upper funnel portion, and a lower shaft (tube) portion, which bends away from the branch at the base, resembling a lowercase “y” in ideal cross-section. The tapering connects to a larger structure, as a continuation in the opposite direction of the branch. This continuation is inferred to be U-shaped, but the scale makes it impossible to resolve even in outcrop. The funnel(s?) always occurs on the inside of the non-expanding upwards branch which continues downward into the broad “U”. The fill of the funnel structures is often concave up in nature, but regularly has some degree of cross-sectional asymmetry, and may be steeper or truncated closer to the edges of the trace. There may be some wall material along the edge of the trace, but not as a continuous mudstone lining.

5.5.5.3 Preservation/Discussion

Altichnus isp. C was found in two locations along Quitchupah Creek. Both locations have sparsely bioturbated mudstones with interbedded graded or laminated very fine sandstones (Figure 5.11a, b). These deposits of Kf-1-Iv[a] have typically been interpreted as deposits of river-dominated delta fronts (Garrison and van den Bergh, 2004), of which these would lie in the distal delta-front or proximal prodelta.

The specimens of *Altichnus* isp. C differs from the other specimens of *Altichnus* due to the distinctive non-flared branch that has a medial axis oriented tangential to the bed (Figure 5.11c-e). In imperfect cross-sections, the funneled portion of these traces might be mistaken for *Rosselia*, or *Monocraterion.* However, *Altichnus* isp. C typically has convex up lamina within the funnel, unlike *Rosselia*, which has lamina that is oriented vertically. Additionally, *Rosselia* is mudstone-dominated, where as the fine material that appear to give the type series of *Altichnus* isp. C its grey appearance, is due to the large amounts of organics within the trace. *Altichnus* isp. B is differentiated from *Monocraterion* by the branching at the base of the vertical shaft, which is also denoted by an inward skewed enlargement at the base. Other features may be found later that help differentiate these two, such as the geometry of the fill and more specifically the hooked shape on one side of the funnel that is seen in some modern and ancient examples (Figure 5.11c, e, h, i, red arrow). Many of the burrows have a several millimeter homogeneous sand buffer (Figure 5.11c, e, f) along the vertical shaft under the funnel. It should be noted that this is more likely due to the collapse process and the passive mucus cementation of the walls, or sediment stowage, rather than an agglutinated tube. This can be evidence from the asymmetry in the homogeneous buffer on either side (Figure 5.11c, d), as well as in adjacent examples, the presence versus absence (Figure 5.11f).

Altichnus isp. C shows two forms of internal stratification within the funnel, one with concave up lamina in the center and steep lamina on the outer margins of the funnel; and the other which is a highly convoluted internally. The organized lamina represent the stope stratification due to feeding. It can be seen that these funnels likely operated at different times due to the difference in sand-size grains in adjacent funnels (Figure 5.11c). In regards to content, it should also be noted that a majority of the finer darker material is organic detritus, which is noncohesive in nature. This is a fundamental difference from stowage funnels (e.g. *Rosselia*, *Cylindrichnus,* and *Polycylindrichnus*), which are composed of cohesive materials. The funnels with convoluted internal structures are interpreted as feeding structures that represent escape of the animal upwards out of the feeding funnel. Evidence for escape can be seen above these burrow as tilted chevrons in the overlying sandstone (Figure 5.11g, purple arrows). This additionally shows that at least one organism occupied each funnel. There is potential evidence of multiple related funnels (Figure 5.10f), however it is difficult to ascertain, whether this is due to close proximity or communalism. In some cases funnels may appear stacked, which could be an equilibrating variety, in which the basal tube has also shifted up (Figure 5.11h).

The funnel structure and basal shaft is always a vertical to near vertical structure in *Altichnus* isp. C that connects basally to a low angle tube. This tube continues tangentially to the surface without flaring upward. This intersection is often represented at the base of the vertical shaft as a widening downward, with the base appearing rounded. The basal structure has one subtly rounded edge, and an opposite sharply curved inward flank (Figure 5.11c, e). The sharply curved flank is always on the inside of the burrow (i.e., opposite of the tangential branch). The basal structure also often contains crescent-like structures (Figure 5.11c, e), which are also present in some of the horizontal tubes (Figure 5.10g, green arrows). This could be for several reasons such as collapse from the vertical shaft, cross-sectional view of three-dimensional forking, or from asymmetrical sediment stowage. The low angle branch likely illustrates stowage as well, as noted in the stepped lamina within (Figure 5.11c, e), or could result from the passive infill of this branch.

Altichnus isp. C represent a disparate ethology from the other three due to the low angle branch. This provides a means by which to circulate water posteriorly. Overall, this interpreted to be a large U-shaped structure that is too large to be resolved even in outcrop. What distinctive morphology we do see is comparable to the anterior end of modern *Balanoglossus* burrows (Figure 5.11i, left, middle) with branching of a near vertical shaft containing a funnel aperture off the U-tube. The enormous length of *Balanoglossus* has made rectifying the entirety of these modern burrows next to impossible (e.g., Duncan, 1987). Such is the same issue with these burrows along the outcrop. The three dimensional relationship of the U-burrow and the near vertical fork, as described in Duncan (1987), likely skews the cross-sectional orientations at which the two lie in diagrams. It is rare to observe both the entirety of the low angle branch and the funneled branch in the same cross-section. It is more likely to see the funnel with the asymmetrical flaring at the base of the shaft, which represents the bifurcation. There is a possibility that multiple funnels may exist off of a single U-shape, but from what can be seen in outcrop, these funnels likely all initiate off of the U-burrow. This is vastly different from what is noted by Stiasny (1910) for burrowing in *Balanoglossus clavigerus* species where multiple funnels initiate off the vertical branch (Figure 5.11i, right). However, it seems like the vertical nature of the shaft would be preferred for stope-feeding, but this could also be a form of communalism.

5.6 DISCUSSION

All of the *Altichnus* species found in the Ferron Sandstone appear to be the product of stoping deposit feeders. *Altichnus foeyni*, *Altichnus* isp. A, and *Altichnus* isp. B are likely part of a continuum of forms created by head-forward pumping stoped sediment feeders. Conversely, *Altichnus* isp. C, appears to represents a stope-feeder that pumps water posteriorly (Figure 5.12). When identifying these taxa, the internal lamina and fill play equal roles in identification. These stoped lamina are one of the key indicators. However, the nature of the substrate is an important indicator, as well. The feeding mechanism works best in smaller sand sizes, however in homogeneous sandstone these would be hard to recognize. Heterogeneity in Bear Gulch is provided by the high amount of heavy minerals present in the sand. In poorer sorted lithologies (silts, clays, organic), head-forward

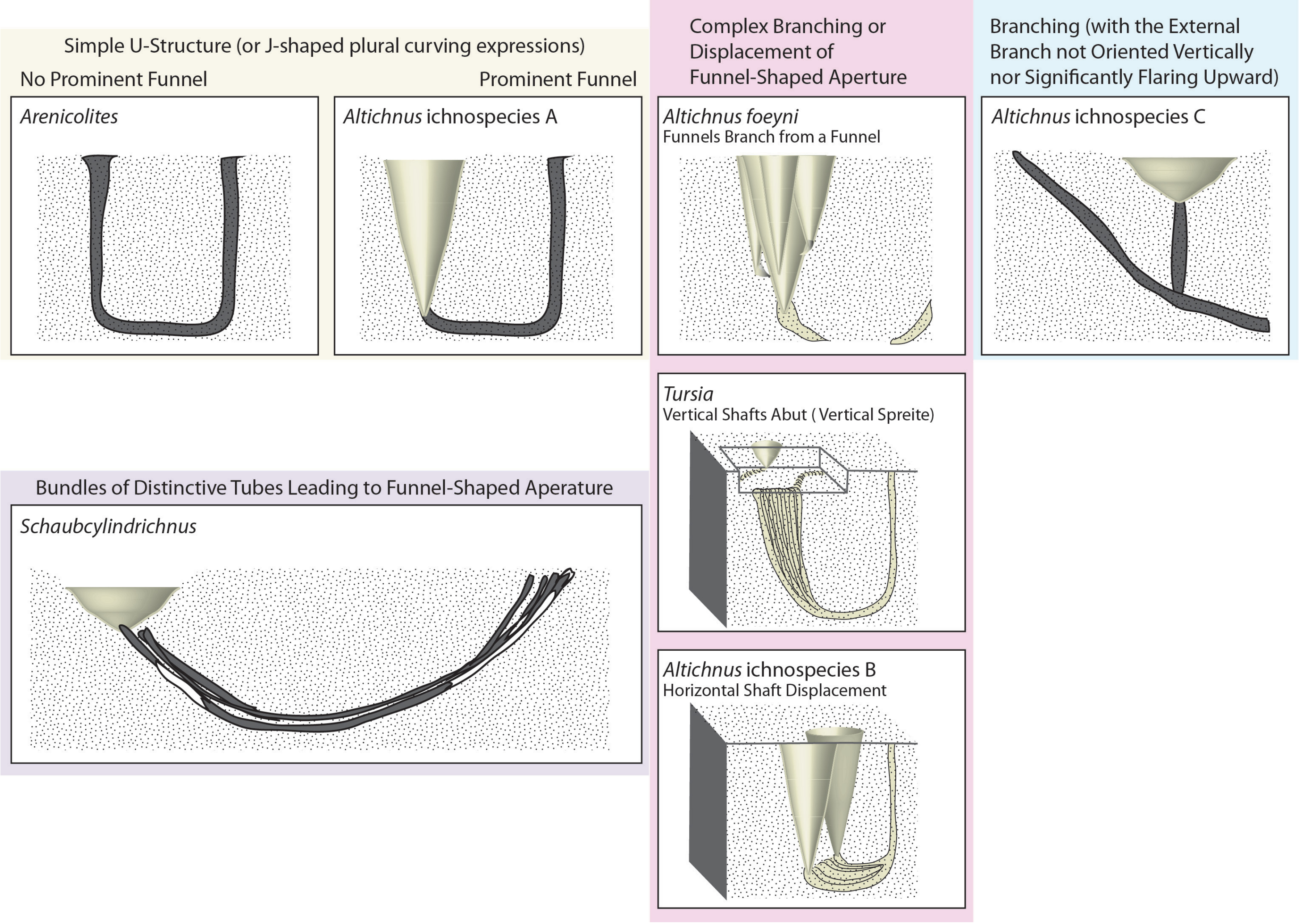

Figure 5.12: Ichnofamily Fundibulidae (minus *Arenicolites*), and how to differentiate the ichnotaxa. The drawing of *Tursia* is modified from D' Alessandro and Fürsich (2005), and the illustration of *Schaubcylindrichnus* is modified from Nara (2006).

pumpers would clean the finer/lighter sediment upward to the top of the funnel, where they have the potential to accumulate. In the Ferron, burrows with cleaner sand than the matrix or funnel-shaped accumulations of fines (e.g., organics in funnel-like structures) are observed. This is discussed in more detail in King et al. (2015; in prep). However, this appears to work differently in the funnels of *Altichnus* isp. C, where organics provide the heterogeneity. Since the organism is pumping backwards, the fines do not get cleaned out, instead surface material accumulates, and is subducted into the pipes. The funnel likely aids in the trapping of organics, and therefore, overtime, the accumulation is mainly that of organic material. The sand-rich fills of *Altichnus* isp. C may represent a different time of subduction. However, another explanation is that the old funnels are filled with sandy fecal material when abandoning them as seen in some funnel-feeding organisms (Myers, 1977; Powell, 1977). In the head-first pumping traces (e.g., *Altichnus* isp. A), there is often larger organic debris floating within the cleaner material, that is not observed in the matrix on that scale possibly representing immovable subducted material. Examples of immovable material in the modern have typically consisted of shells (e.g. Wells, 1945; Van Straaten, 1952).

While we propose *Altichnus* as a stoped funnel-feeding structure, herein, this is not the first trace attributed to funnel-feeding. Nara (2006) and Löwemark and Nara (2010) identify prominent funnel-shaped apertures in *Schaubcylindrichnus* attributed to funnel-feeding. The modern analog described for this *Schaubcylindrichnus* species by Nara (2006) is an enteropneust due to the large size and modern *Balanoglossus* ability to create new burrows and mucus coating the walls, which could line the burrow. However, the funnel-bearing *Schaubcylindrichnus* as described by these authors are lined tubes that terminate in what they illustrate as a singular large funnel-shaped aperture, which is not similar to the form of modern *Balanoglossus* burrow of Duncan (1987), and hence *Altichnus* isp. C. The genus of *Schaubcylindrichnus* should be maintained for the species of Nara (2006) and Löwemark and Nara (2010) because the bundled, lined tubes are a much easier toponomic expression to recognize than the funnel, and especially in such case that *Schaubcylindrichnus* represents domiciles of multiple ethologies. *Tursia* is another trace that is interpreted by D'Alessandro and Fürsich (2005) to potentially contain prominent funneled apertures. *Tursia* may be a transitional form to *Altichnus*. Although, *Tursia* is easily distinguished from the species described herein by the irregular folding and vertical spreite, which converge downward towards a central tube. As such, this is interpreted by D'Alessandro and Fürsich (2005) to represent the lateral movement of the vertical anterior shaft (tube structure) from a relatively fixed point. This is different from *Altichnus* isp. B, which represents dominantly a lateral movement of the burrow axis.

These morphologies are distinctive enough to maintain individual genera, but it is proposed that these separate genera be combined at a higher taxonomic level in the Ichnofamily Fundibulidae (Figure 5.12). The Ichnofamily Fundibulidae is tied together by the morphologic funnel-like apertures that show evidence of funnel-feeding (e.g., stoped lamina). This ties together the traces interpreted to represent the stope deposit-feeding ethological behavior of vermiforms. Grouping of vermiforms by feeding guild is a popular method of classification in the modern (i.e., Fauchald and Jumars, 1979). Others could choose to adapt the classification methods of Uchman (1995), which Rindsberg (2012) champions as a way to establish trace nominal groups of similar forms with related behaviors without the formal taxonomic debate. In such scheme funnel-feeding species of *Altichnus*, *Schaubcylindrichnus*, and *Tursia* should all lie within the *Altichnus* group, since the species of *Altichnus* dominantly represent this behavior, where as the other may not.

5.7 CONCLUSIONS

Three new ichnospecies of *Altichnus* are named from the Ferron Sandstone. *Altichnus* isp. A represents the simplest form of a continuum of U-shaped constructions composed of an anterior enlarged aperture (funnel or fusiform) connected to a J-shaped tube. *Altichnus foeyni* is revised to represent the end member of *Altichnus* with distinct branching of the funnel/fusiform from a parent funnel/fusiform. Conversely, *Altichnus* isp. B represents branching of the tube structure in the basal reaches of the tube. The ethology of *Altichnus* for these species is attributed to a stoping deposit feeder, such as modern lugworms, which circulates water anteriorly. This often results in cleaner sand within funnel/fusiform structures. The fourth species of *Altichnus*, *Altichnus* isp. C is inferred to be ethologically and morphologically different due to the branching of a tangential to bed, non-flaring arm. This suggests a stope-feeder, which circulated water posteriorly, like modern *Balanoglossus*. The interpretation of stope feeders for *Altichnus* species from the Ferron Sandstone is much different than what has been previously acknowledged only as a suspension feeding trace behavior. Additionally, it is suggested herein that the enlarged aperture with stoped biogenic structure takes taxonomic priority over the U-construction shape. As such, the Ichnofamily Fundibulidae is created for stoping funnel feeders to link traces containing the most distinctive taxonomic characteristic.

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CHAPTER 6: HIGH RESOLUTION STRATIGRAPHY IN DELTAIC DEPOSITS OF THE FERRON SANDSTONE USING ETHOLOGY TO PARTITION WAVE VERSUS RIVER INFLUENCED FACIES

6.1 INTRODUCTION

Ichnological work has often been used as a high-resolution tool for depositional environment interpretation, and thus ichnofacies analysis has been instrumental in helping to subdivide deltaic deposits into their respective hydrodynamic end members (fluvial-, tide-, and wave-dominated)(e.g., Bann and Fielding, 2004; MacEachern et al., 2005). Initially, this framework was established in terms of how these trace assemblages were represented on a parasequence scale, in various degrees of basinal (wave/tide) versus riverine processes (e.g., Coates and MacEachern, 2005; Hanson and MacEachern, 2005; Dafoe and Pemberton, 2005). Building on this, Gani et al. (2009) showed that trace assemblages can be used to paint a higher resolution picture of the rapid vertical changes in storm, wave, tide, and river processes within individual parasequences from the Turonian Ferron Sandstone and Wall Creek Member. This study expands on this premise by examining the lateral expression/continuity of facies associations (subenvironments), vertical changes between wave and river-dominated process, as well as comparison of subenvironments of the Ferron Sandstone to upper Cretaceous case studies that were used to create river and wave influenced subenvironmental deltaic models. Additionally, transgressive overprinting is examined in an attempt to isolate the transgressive signal from the depositional environment signal in proximal facies. The main parasequence examined is wave influenced deltaics, but the top of underlying parasequence is utilized for a river-dominated deltaic comparison of associations as well as to define the parasequence boundary. Five closely spaced cores from the Muddy Creek area of upper Ferron Sandstone were examined (Figure 6.1a,b). Closely spaced core compared to outcrop photomosaics of Anderson et al. (2003), and the sequence stratigraphic frameworks of Anderson and Ryer (2004) and Garrison and van den Bergh (2004) allow testing of both the ichnological lateral variation down dip, and use of ichnofacies in stratigraphic correlation, as well as what components are consistent across the distal and proximal delta front deposits of the disparate parasequence. Lateral consistency may also allow for decoupling of overprinting ichnotaxa related to the transgression/abandonment of each system, as well as recognition

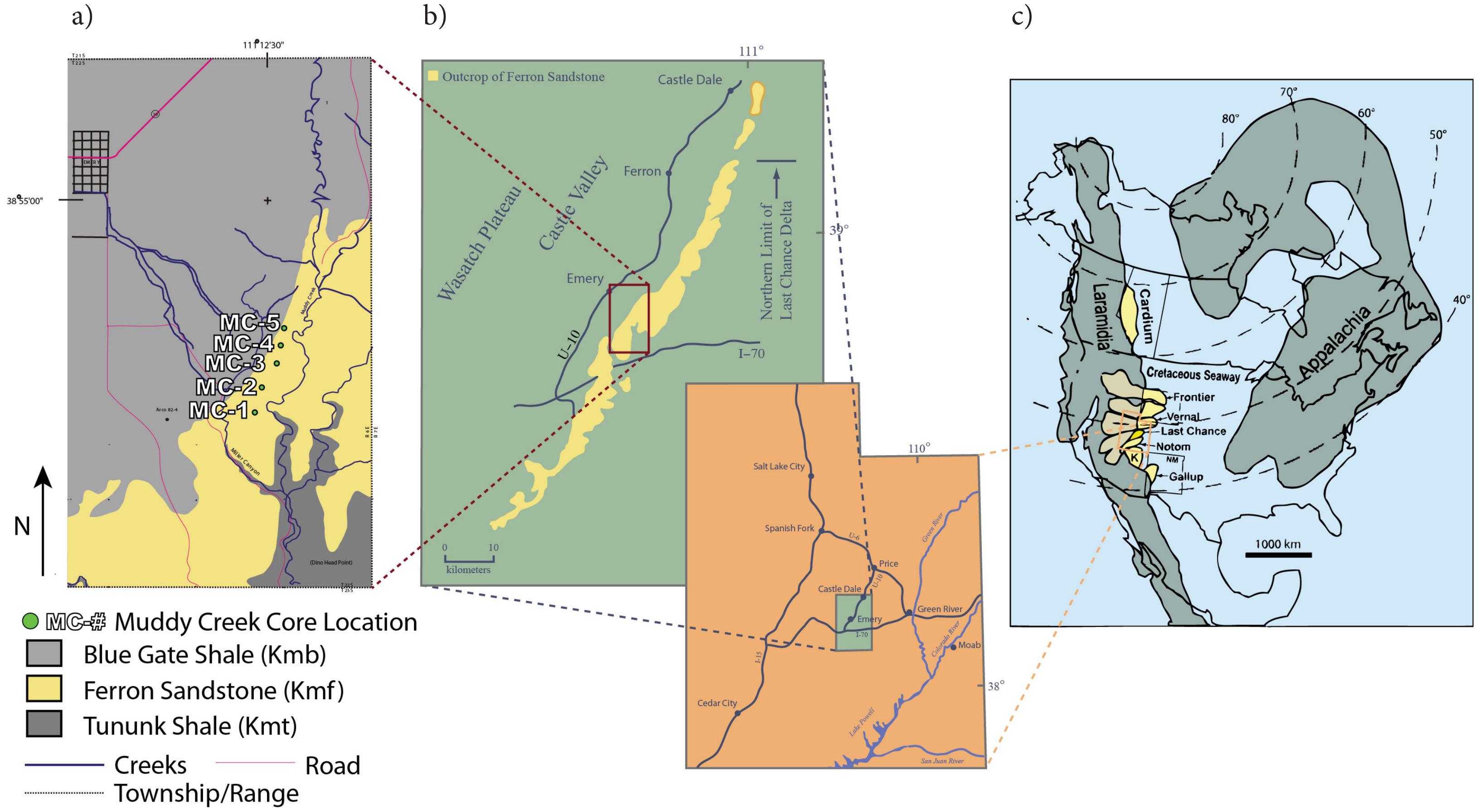


Figure 6.1: Location of study area on geological and paleogeographic maps: a) location of cores (MC1-MC5) used in study (modified from Anderson et al., 2003), b) outcrop of the Ferron Sandstone in central Utah (modified from Garrison and van den Bergh, 2004; after Cotter, 1975), and c) paleogeographic locations of major clastic depocenters, during Turonian time, along the western margin of the Interior Seaway (modified from Bhattacharya and MacEachern, 2009; which was derived from a compilation of a large body of work by other authors).

of subtle stratigraphic surfaces.

6.2 GEOLOGIC SETTING

6.2.1 Lithostratigraphic Context

Charles T. Lupton named the Ferron Sandstone in 1914, and described it as a member of the Mancos Shale in 1916 (Ryer 2004). Ryer and Lovekin (1986) and Gardner (1995b) have suggested the mapable units of Turonian strata (including the Ferron Sandstone) occupy distinct clastic depocenters along the western margin of the Western Interior Seaway created/maintained by structural/tectonic controls (Figure 6.1c). The Ferron Sandstone has two depocenters the “Notom Delta” (*sensu* Hill, 1982) and the “Last Chance Delta” (*sensu* Hale, 1972)(Garrison, 2003; Ryer, 2004). The core from this study comes from the Muddy Creek area, which is located in the upper Ferron Sandstone (*sensu* Davis 1954) of the Last Chance Delta depocenter. This upper lithostratigraphic unit is dominantly comprised of shallow-marine and fluvial sandstones with interrelated coals.

6.2.2 Sequence Stratigraphic Context

Cotter (1975, 1976) was the first to clearly recognize the cyclicity in these shallow-marine sandstones were the result of delta progradation, abandonment, and transgression. Ryer et al. (1980) and Ryer (1981, 1983) built on this using the “stratigraphic rise” concept through correlation of coals (namely the “C” coal) containing tonsteins in order to distinguish transgressive-regressive (delta-front) cycles as 4th order cycles (*sensu* Vail et al., 1977), each named Kf-#. Subsequent work (e.g., Gardner 1995a; Anderson et al. 1997; Garrison and van den Bergh 1997; Garrison and van den Bergh 2004) has identified eight cycles (Figure 6.2). Each author uses their own cycle descriptions (Ryer (Kf-#), Gardner (Stratigraphic Cycles [SC] or Genetic Sequences [GS]), and depositional sequences of Garrison and van den Bergh are fairly synonymous; however, each may contain multiple parasequence sets as detailed by Garrison and van den Bergh (Ryer, 2004; Garrison and van den Bergh, 2004). However, it is important to state which classification you are using because of the difference between T-R and R-T classification, as discussed in Chapter 2. In this study, we compare the two fully developed parasequences in Muddy Creek.

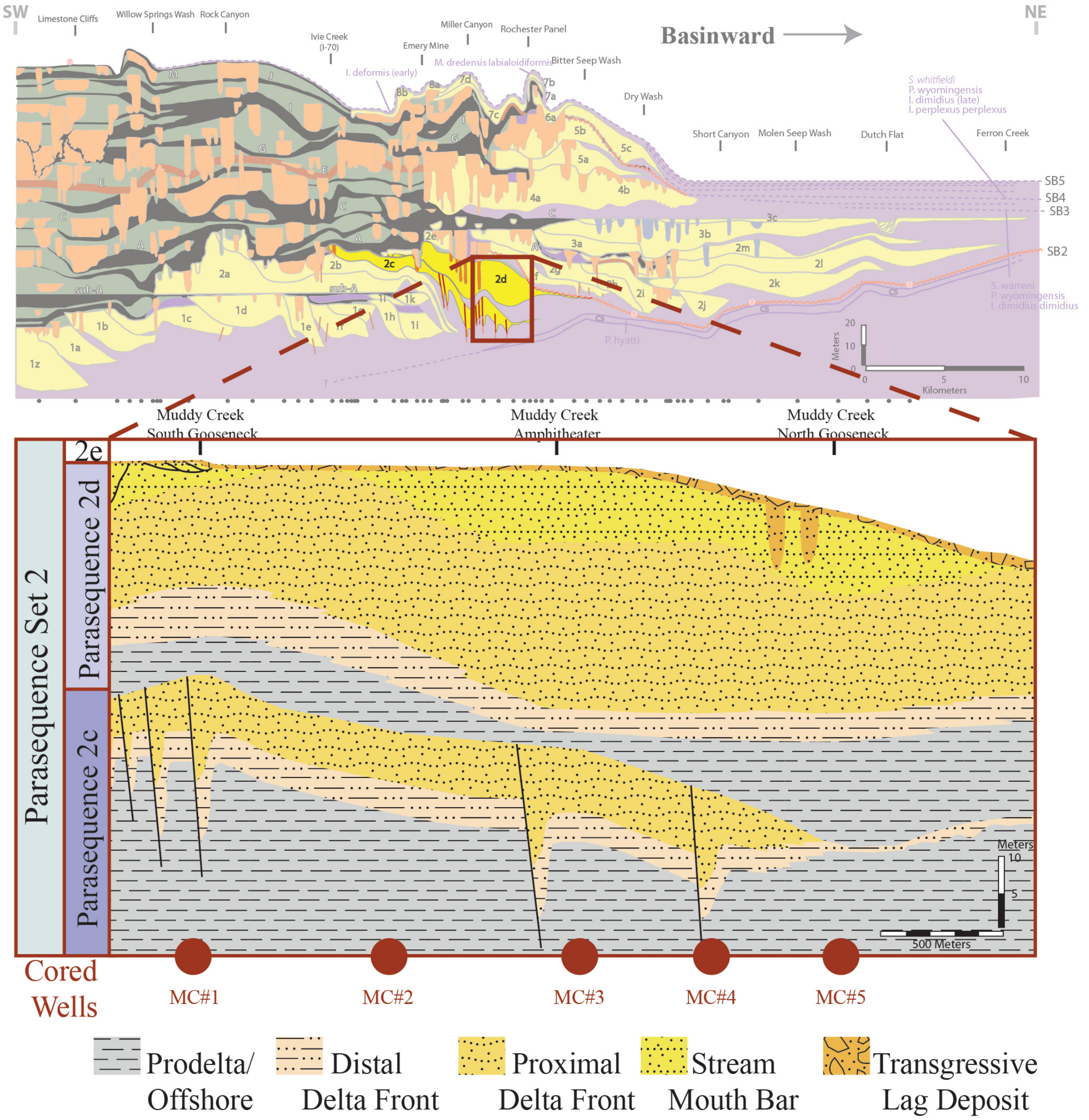


Figure 6.2: Stratigraphic and depositional framework of the Muddy Creek study area (modified from Garrison and van den Bergh, 2004) showing the dominance of distal facies in the study area, and separation of the eight parasequence sets. This study focuses on the Parasequence 2d. Parasequence 2c is used for comparison purposes, but is difficult to laterally relate due to the large growth faults within as shown in figure. Both parasequences are dominantly interpreted as delta front deposits in this area. The approximate location of the Muddy Creek wells are indicated in red at the bottom of the diagram.

According to the terminology of Anderson and Ryer (2004), these would be Kf-2-Mi-a and the overlying Kf-2-Mi-b, which are the first (a) and second (b) parasequence of the Miller Canyon (Mi) area in the second parasequence set (2) of the Cretaceous Ferron Sandstone (Kf). Conversely, these would be termed PSS2A-2c and PSS2A-2d by Garrison and van den Bergh (2004) (Figure 6.2). For simplicity's sake we will just refer to them as PS2c and PS2d respectively.

6.2.3 Depositional Environments and Stratigraphy of PS2c and PS2d

PS2c and PS2d are wave-modified river-dominated deltaics that prograde to the NW (25º and 50º respectively)(Garrison and van den Bergh, 2004)(Figure 6.3a-c). PS2c is interpreted as a river-dominated delta crevassing into a shallow bay (<25m deep) (Bhattacharya and Davies, 2004). PS2c is a smaller delta lobe and has less wave influence than PS2d and displays prominent growth faults in the Muddy Creek area (Garrison and van den Bergh, 2004)(Figure 6.3a). In this area, the strata is largely composed mouthbar sandstones that are heavily normally-faulted due to the rapid deposition on the unstable substrate. Burrows are rare, show low diversity (*Planolites*, *Skolithos*, *Arenicolites*, *Thalassinoides*, *Ophiomorpha*, *Rosselia*, and *Teredolites*) and generally of a diminutive size (<0.5cm)(Bhattacharya and Davies, 2004). PS2c is overlain by a marine flooding surface (Garrison and van den Bergh, 2004). An overprinting assemblage of large diameter (1cm) *Ophiomorpha* and *Skolithos* can be seen distending from this marine-flooding surface along the outcrop (Bhattacharya and Davies, 2004).

PS2d has a geometry indicative of high sedimentation rate and shows a moderate degree of wave reworking of the delta front deposits, and is complex showing at least four mouth bar complexes (Garrison and van den Bergh, 2004). In Muddy Creek, the mouthbar and delta front deposits show signs of frequently being reworked into shoreface deposits (van den Bergh and Garrison, 2004). The changes in the depositional style within this parasequence may be complex, but does not necessarily suggest a change in the parasequence (Anderson and Ryer, 2004). Shoreface deposits are noted in Muddy Creek with the "white cap" at the top of this parasequence often being referenced as foreshore deposits due to the close relationship (Ryer and Anderson, 2004). Garrison and van den Bergh (2004) suggest there is a transgressive ravinement surface at the top of this parasequence. Ryer and Anderson (2004) indicate that the marine-flooding surface lies just above the flat, abrupt contact at the top of the "white cap" (Figure 6.3b,c) and that

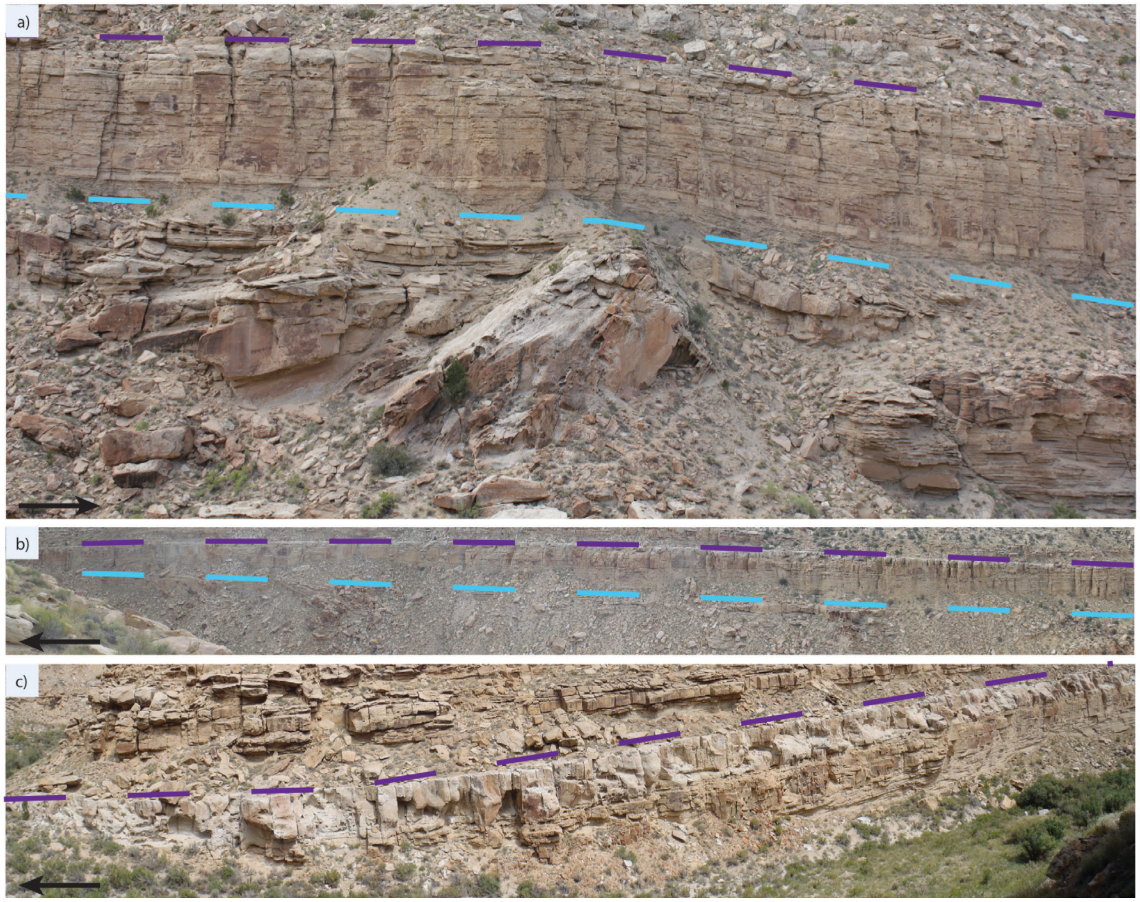


Figure 6.3: Outcrop photos of PS2c and PS2d: a) outcrop in front of where MC1 was drilled just south of the southern gooseneck in Muddy Creek, b) outcrop across the canyon from where MC3 was drilled in the Muddy Creek amphitheater, and c) outcrop across from where MC5 was drilled in the northern gooseneck of Muddy Creek. Blue dashed lines indicate the parasequence boundary between PS2c and PS2d, and the purple dashed lines indicate the boundary at the top of PS2d. The black arrows point towards the northwest which is the same general direction of the subtle clinoform dip seen in PS2d. The extensive growth faulting can be seen in PS2c of (a) and in the left part of the photo of (b). The “white cap” can be seen becoming more prominent and sharp-based from the south in photo (a) to the north where PS2d dips into the subsurface in photo (b). The vertical distance between the lines in (a) is around 18 meters and in (b) is approximately 22 meters. From the purple line down to the ground in (c) is close to 18 meters thick.

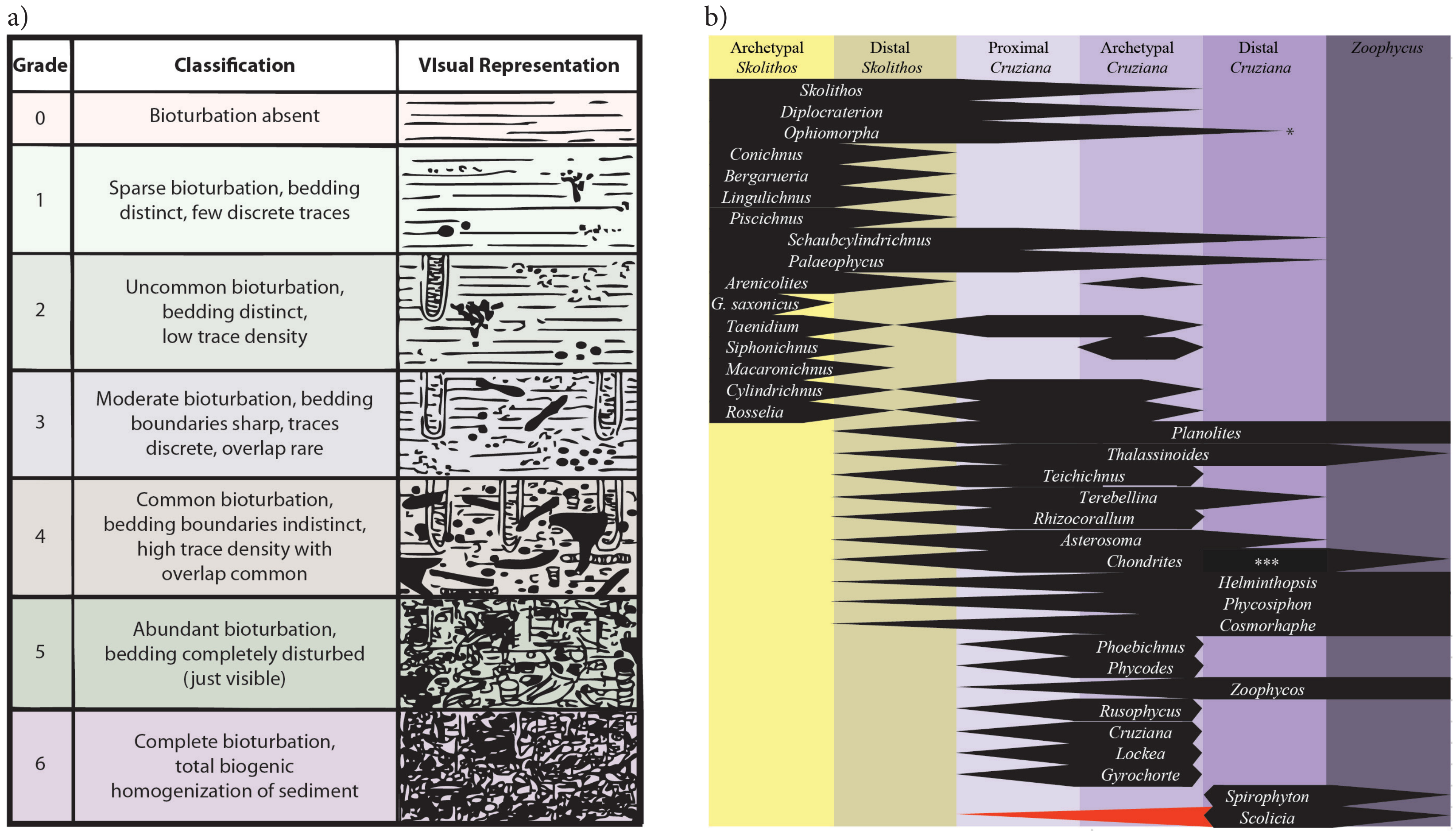
overprinting *Ophiomorpha* and *Skolithos* can be seen just below the transgressive surface of erosion. Ichnology of these wave-modified deposits (such as PS2d) is often limited in outcrop exposure and thus many facies study's models are limited to few ichnotaxa for interpretation (e.g., *Skolithos*, *Arenicolites*, *Planolites*, *Thalassinoides*, and *Ophiomorpha*). However, these models have illustrated that the abundance and size of taxa is larger in the more wave-modified facies of the Ferron Sandstone (Barton et al., 2004; Garrison and van den Bergh, 2004; Ryer and Anderson, 2004). Moiola et al. (2004) showed that there is potential to identify more diverse forms in this interval when using core, and that some more complex trace behaviors can be present in the offshore facies of the Ferron. The use of traces for ichnofacies analysis has been limited, and as van den Berg and Garrison (2004) have shown, the *Skolithos* and *Cruziana* Ichnofacies are the key assemblages in almost all wave-modified deltaic facies. Gani et al. (2009) showed that in PS2a of Muddy Creek, the *Skolithos* and *Cruziana* Ichnofacies utilized on the level of ichnofacies expression (i.e., proximal, archetypal, and distal) present a way to distinguish wave-modification of the delta front from river-dominated delta front deposits at a scale as low as two meters.

Below, the trace assemblages will be defined using ichnofacies analysis. The part of PS2c and all PS2d are divided according to sedimentary structure defined facies, which are grouped into facies associations according to facies and ichnofacies. Bioturbation is accessed in terms of ichnotaxa, diversity, abundance (via bioturbation index; Figure 6.4a), and the transgressive overprinting. Ichnofacies are defined using the synthesized descriptions of MacEachern et al., (2007) (Figure 6.4b) for comparison to the bioturbation of individual facies associations in this study. The focus will mainly be on facies association in PS2d, since the large amounts of soft sediment deformation and growth faulting in PS2c makes it unfeasible to assess lateral relationships and in some cases assess the ichnology. However, facies associations in upper portion of PS2c will be used as a gauge to determine which association in PS2d may have the same depositional environmental restrictions, as well as to assess where the boundary between the two parasequences occurs.

6.3 FACIES

6.3.1 Description of Key Facies

In the PS2d interval three subdivisions of facies exist: massive, physical sedimentary



a)

Grade	Classification	Visual Representation
0	Bioturbation absent	
1	Sparse bioturbation, bedding distinct, few discrete traces	
2	Uncommon bioturbation, bedding distinct, low trace density	
3	Moderate bioturbation, bedding boundaries sharp, traces discrete, overlap rare	
4	Common bioturbation, bedding boundaries indistinct, high trace density with overlap common	
5	Abundant bioturbation, bedding completely disturbed (just visible)	
6	Complete bioturbation, total biogenic homogenization of sediment	

Figure 6.4: Ichnological classifications: a) quantification of bioturbation using a bioturbation index (modified from Bann et al., 2004; after Reineck, 1963; Taylor and Goldring, 1993; and Bann, 1998), b) traces occurrences in the different expression of the *Skolithos* to *Zoophycos* Ichnofacies (visual representation of the text of MacEachern et al., 2007). * indicates occurrence of *Granularia,* lighter color and *** indicates abundance of smaller forms of *Chondrites*. Red shading of *Scolicia* range indicates the extended range in this study of diminutive forms.

structured, and graded. Massive facies are dominantly the result of bioturbation. Physical sedimentary structured facies contain sedimentary structures with direct connotation to the processes present (e.g., oscillation-rippled sandstone), the hydraulic energy (e.g., rippled versus laminated structures), and the accumulation rates (e.g., climbing and in-phase ripples). The graded facies are a very important building block of this system, but typically occur as distinctive facies on the order of a few centimeters thick (Figure 6.5a-c). There are two types of graded facies: normal grading and inverse grading. The normal graded facies occur on two different scales, one that is typically less than five centimeters (Figure 6.5a), and the other which is usually tens of centimeters thick (Figure 6.5b). The smaller sized facies may contain sedimentary structures, but is normally massive white sandstone with a sharp undulatory base. The grain size is normally very fine, and in the rare occurrence of fine grains, the top may be flat. The thicker normally graded sandstones can be massive or contain laminar bedding or low angle structures that may decrease in thickness and grain size upwards. Mudstone clasts may be present in the base. The inversely graded facies (Figure 6.5c) can be a few centimeters to tens of centimeters thick, and often are dirtied by abundant organic detritus. In the lower portion, the inversely graded lamina/beds thicken upwards as the grain size increases, and climbing or aggradational wave ripples may be present. Many times this lower portion overlies a small normally graded bed. As the inversely graded facies continue upwards the inverse lamina become thinner, the grain size fines, and eventually becomes massive in appearance. This upper part may be removed sharply by a normally graded sandstone bed or convoluted. Any of these facies may have oscillation ripples or bioturbation along the tops.

6.3.2 Interpretation of Key Facies

These facies represent event bed facies. The top down bioturbation is a characteristic indicator of event beds (e.g., Pemberton and MacEachern, 1997). The normal graded beds represent waning deposits, whereas the inverse graded beds indicate waxing deposits. The thin normally graded beds dominantly represent Bouma's (1962) subdivision A (massive sandstone) going rapidly into subdivisions D (parallel laminated siltstone) and E (mudstone). These beds are indicative of turbidite deposition. Zavala et al. (2012) refers to these as "I" turbidites since their generation is related to sediment failure within the basin (intrabasinally).

The larger normally graded beds could comprise coarser versions of Bouma's

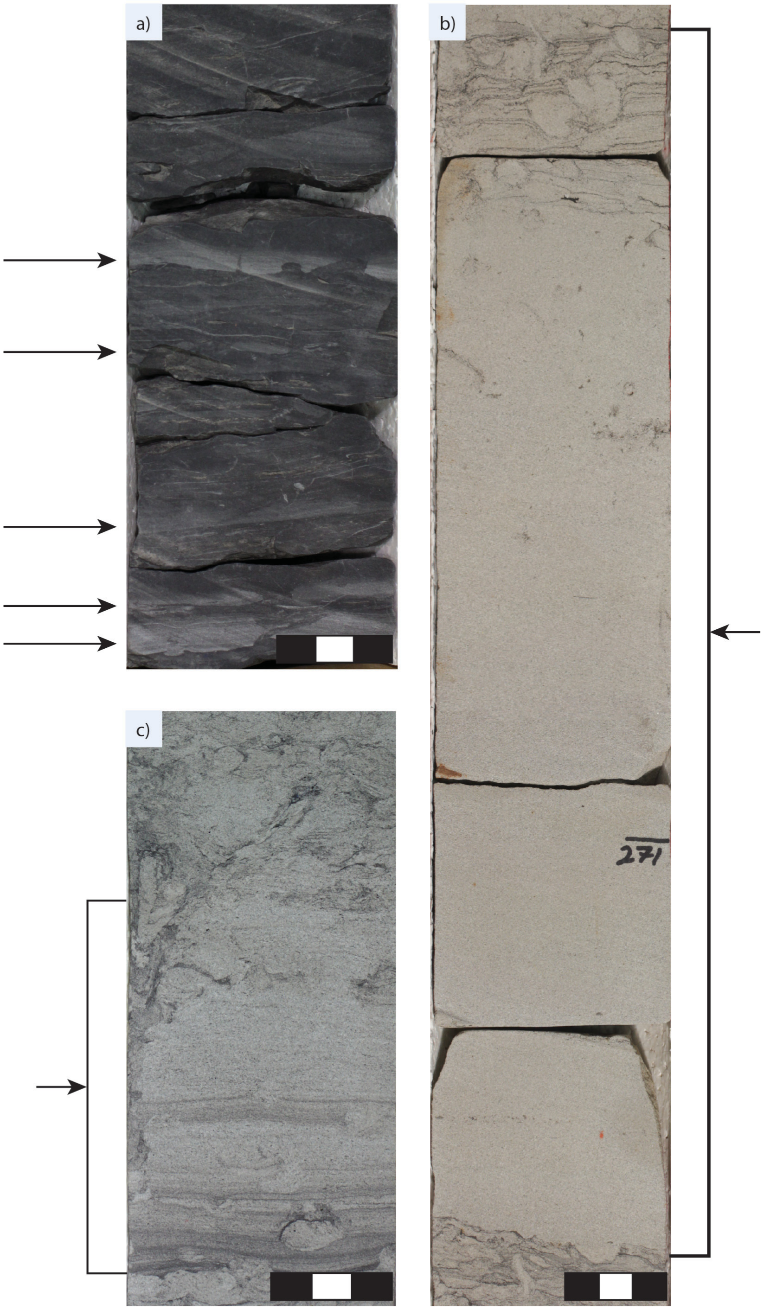


Figure 6.5: Graded facies: a) small normally graded beds/lamina with sharp bases representing Bouma Sequences (arrows) from MC2, b) larger scale bed with a sharp base and normal grading, and increase in organics upwards, from MC5, and c) inversely graded beds representing hyperpycnite deposition from well MC5. Scale represents three centimeters.

(1962) subdivision A (massive sandstone) and B (planar parallel lamination). However, it is difficult to ascertain what is truly massive versus what is due to the clean character of the sandstone, especially where bedding remains at a consistent low angle throughout. Similar characters can be seen in the event beds of the delta front (Bhattacharya, 2010), tempestites (e.g., Harms et al. 1975), and fluvial sediments (Allen 1970).

The inversely graded facies represent waxing flow conditions associated with hyperpycnal turbidity currents, in which coarsening and bed lamina thickening are formed during the increase in discharge, erosion may occur during peak discharge, and a fining or normal grading accompanies the decrease in discharge (Mulder et al., 2001). These are often referred to as "hyperpycnites" (Mulder et al., 2003). Zavala et al. (2012) refers to these hyperpycnites as "E" turbidites since the hyperpycnal flow is generated from river discharge, which is an extrabasinal derivation. In this paper, the term turbidite will be used for description of the thin normally graded facies, the larger normally graded facies will be discussed within their inherent facies association, and facies begin with inverse graded beds will be referred to as hyperpycnites.

6.4 FACIES ASSOCIATIONS

The facies associations (Table 6.1; Figure 6.6) in this study are defined foremost by lithology (i.e., percentage sandstone versus mudstone). The highest level of nomenclature is differentiated as "S" for associations with less than 10% mudstone, or as "H" for associations with consistently more than 10% mudstone. This cutoff was chosen based on the facies work by Garrison and van den Bergh (2004), which uses 10% mudstone as the cutoff between proximal and distal delta front successions. The "S" facies associations are named in a fashion similar to Miall (1985) in which "S" denotes sand-rich and the proceeding letter defines the most abundant or defining facies in each association. "Sx" is cross-bedded sandstone, "Sl" is low angle to horizontal bedded sandstone, "Sg" is graded or aggradational facies, and "Sm" is massive sandstone. Facies association "H" is subdivided based on cut-off percentage around 25%, where "Ha" represent heterolithic associations with ~10-25% mudstone, and "Hb" indicates heterolithics with greater than 25% mudstone. This percentage was picked based on the median between the cutoff Garrison and van den Bergh (2004) use for the wave reworked prodelta (>20% mudstone) from the river-dominated prodelta facies (>30% mudstone). The number designation after

	Facies Association Sx			Facies Association Sl					FA Sg	Facies Association Sm				Facies Association Ha			Facies Association Hb		
	Sx1a	**Sx1b**	**Sx2**	**Sl1a**	**Sl1b**	**Sl1c**	**Sl2a**	**Sl2b**	**Sg**	**Sm2a**	**Sm2b**	**Sm3a**	**Sm3b**	**Ha1**	**Ha2**	**Ha3**	**Hb1**	**Hb2**	**Hb3**
Skolithos		RUX	R			?OM	CL,U	R	R	CU	CU	RU	R	R	R-C, UK	R, UK			R
Diplocraterion	X					X	R, X?							?					
Ophiomorpha	X	RX	AL, AX	X		R	C-R,V	AL	X	AOG, V	AO, V	A	A	RD	R-C,D, GO	C		R-C	
Schaubcylindrichnus										R	R	R	AL		R				C
Palaeophycus tubularis		ROX	CX			RO	CL, C, D, OG	AL, O		AOG	AOG	C	A, K		R-C, GO	C, some G	RK		C
Palaeophycus heberti			CL, AX			R	CM, CL, R	AL	RM	A	A	C	CL	AL, M	R-DC	C	R	R-C	C
fugichnia							C-A	R	R			R	R	R	R	C	R		C
Arenicolites										R					R	R			R
Cylindrichnus																			
Siphonichnus															R			Bivalve Eq	AL
Rosselia																		R	
Planolites			AL, AX			R			R				A	R	R	C	R	C-A	A
Thalassinoides			AL, AX			R	R			?			A	R	R	C	R	C-A	A
Teichichnus			AX			X						A	C			C			C
Terebellina (S. freyi)			CX								C	C	AL			R	RD	R	C
Rhizocorallum												R							
Asterosoma	Rip up											R	AL			R			AL
Chondrites			AX, BS			X					R	C	A, BS	R	R	C	R	N-A	A
Helminthopsis												C	CL			CL	R		C
Phycosiphon											R	C	CL						AL
Phoebichnus										?	?								
Zoophycos												R	AL			R	RD		
Scolicia						X					R	C	C			CL	RD, RX	R	C
Additional Bioturbation			*Teredolites*			*Teredolites*			*Teredolites*			*Teredolites*	*Teredolites*			*Teredolites*			
Bioturbation Abundance	BI=0-1	BI=0-1	Typically BI=0-2; Top and Sandy MS is BI=4-6	BI=0-1		BI=0-2; typically <1; overprint >4	Typically BI=1-2, small intervals can be up to BI=4	Typically BI=1-3, top few cem can be BI>4	BI=0-1; except pause planes which can be >4	BI=4-6;bands of BI=1-2	Mainly BI=4-6; event beds BI<4	Typically BI=5-6	Typically 4-6; event beds BI=1-3	BI=3-6, thin event bed of BI=1	BI=0-3	BI=2-3; bands of 4-6	BI=0-3; dominantly BI=1-2	Alternating BI=1-3 and BI=4-6	BI=4-6; hyperpycnites BI=1-3
Dominant Comparable Ichnofacies	Overprint of Archetypal *Skolithos*	Overprint of Archetypal *Skolithos*	Mixed *Skolithos/ Cruziana*	Overprint of Archetypal *Skolithos*	N/A	Archetypal *Skolithos*	Archetypal *Skolithos*	Archetypal *Skolithos*	Archetypal *Skolithos*	Distal *Skolithos*	Mixed *Cruziana/ Skolithos*	Proximal *Cruziana*	Archetypal *Cruziana*	Distal *Skolithos*	Distal *Skolithos*	Mixed *Cruziana/ Skolithos*	Depauperate *Cruziana*	Proximal *Cruziana*	Archetypal *Cruziana*
Depositional Environment Interpretation	River-Dominated Inner Distributary Mouthbar	Tidal Channel / Distributary Channel	Tidal Channel	River-Dominated Proximal Delta Front to Distal Distributary	River-Dominated Distal Mouthbar (Terminal Distributary Related)	River-Dominated (Brackish Bay) Proximal Delta Front	Wave Reworked to Dominated Proximal Delta Front	Wave Reworked and River-Dominated Distal Terminal Distributary	River-Dominated (Flood Stage) Middle to Distal Delta Front	Middle Shoreface	Proximal Lower Shoreface	Distal Lower Shoreface	Upper Offshore/ Distal Prodelta	River-Dominated Distal Delta Front	Wave Reworked Middle-Distal Delta Front	Wave Reworked Proximal Prodelta	River-Dominated (Brackish Bay) Proximal Prodelta	River-Dominated (Marine) Proximal Prodelta	Distal Prodelta/ Offshore

Table 6.1: Facies Associations with ichnotaxa and comparable ichnofacies expressions. Abbreviations are abundant (A, darkest cell shading), common (C, medium cell shading), rare (R, light cell shading), local (L), overprinting ichnotaxa (X, and cell strike through), monospecific (M), organic-lined (O), mud-lined (K), unlined (U), lined (S), small trace (D), vertical trace (V), questionable ichnotaxa (?), and grouped traces (G).

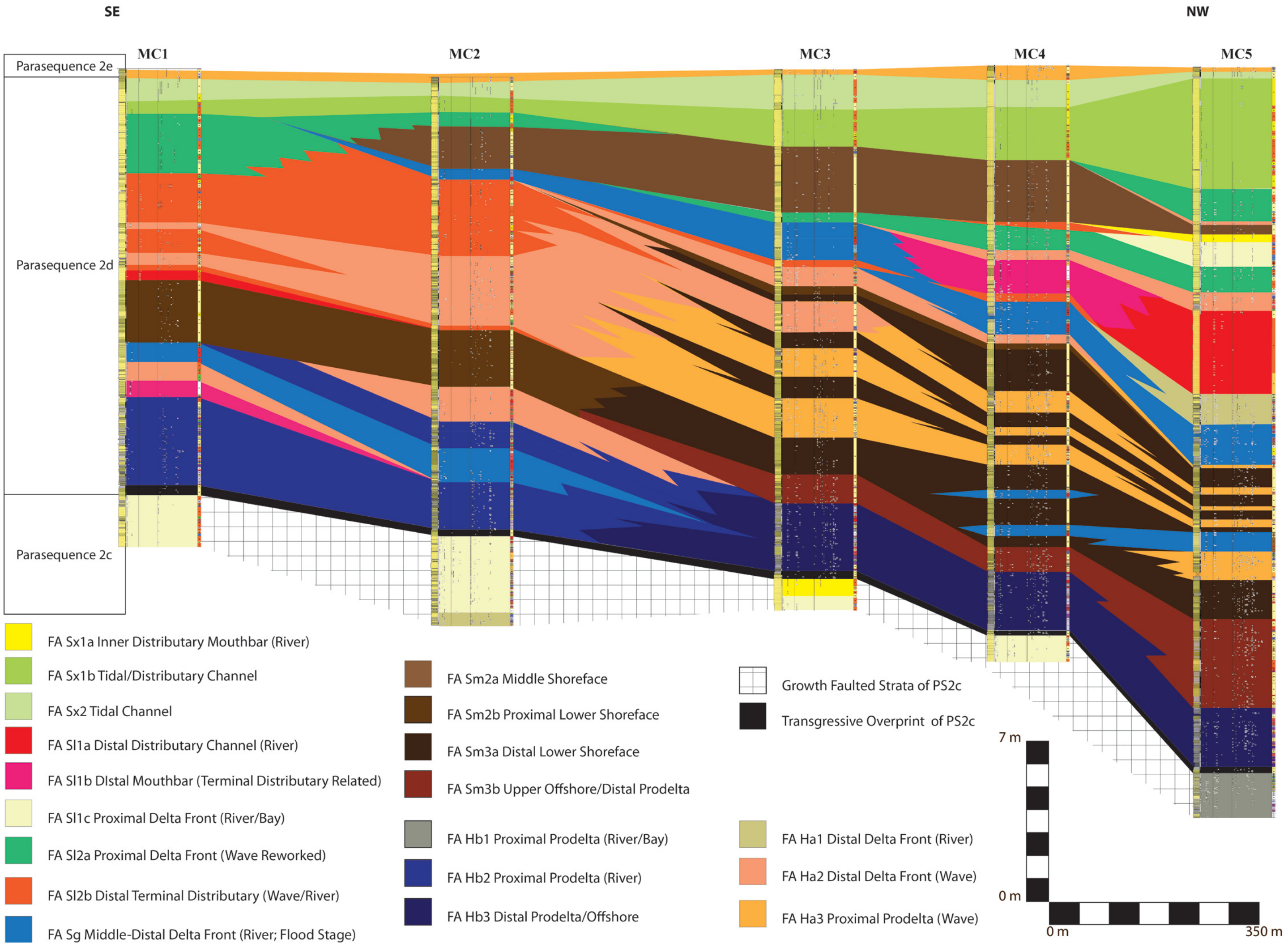


Figure 6.6: Facies Association Distribution in wells MC1-MC5. Larger versions of the lithologs are provided in the appendix.

this indicates the relative level of bioturbation throughout: rare to absent=1, moderate=2, heavy=3. Any additional subdivision will include an additional letter to the abbreviation and will be defined in the text below.

6.4.1 Facies Association Sx

6.4.1.1 Description of Facies Association Sx1a

Facies Association Sx1a (FA Sx1a) is composed of clean, high angle (>10º), cross-bedded, fine- to medium-grained sandstone (Figure 6.7a). A few, several centimeter thick intervals of massive sandstone may be present. Organic debris and mudstone clasts are rare. Basal contact is sharp, whereas the upper contact is bioturbated. BI is 1, mainly in the form of *Ophiomorpha*, but the top few centimeters may be heavily bioturbated including *Diplocraterion* or *Asterosoma* locally. This facies association is the smallest (less than a meter thick) and occurs in the top of PS2c in MC3, and the upper one-third of PS2d in MC5 (Figure 6.6). FA Sx1a is not laterally persistent like the other facies associations. It always overlies the proximal delta front (river-dominated bay) facies association (FA Sl1c), and underlies the middle shoreface facies association (FA Sm2a) or the distal prodelta/offshore facies association (FA Hb3).

6.4.1.2 Interpretation of Facies Association Sx1a

FA Sx1a is consistent with interpretations of river-dominated distributary mouthbar facies for the Ferron by Garrison and van den Bergh (2004). Bhattacharya and Davies (2004) suggest dune forms are more indicative of the inner mouthbar. No ichnofacies is assigned for this association because the present ichnotaxa (i.e., *Ophiomorpha* and *Diplocraterion*) is interpreted to be the result of overprinting by the overlying change to more favorable bioturbation conditions (i.e., middle shoreface or distal prodelta/offshore facies). The *Asterosoma* appears to be ripped up at the base of a thin cross-bedded sandstone at the top, which likely represent a thin erosive transgressive deposit (discussed later). Bhattacharya and Davies (2004) have described these facies (minus the ripped up trace fossils) from PS2c as stressed bay conditions. The massive intervals could be the result of the lack of lithologic heterogeneity, or may be the result of cryptic bioturbation. Cryptic bioturbation from the Ferron Sandstone, and cryptic bioturbation associated with high angle cross-beds, is reported by Pemberton et al. (2008).

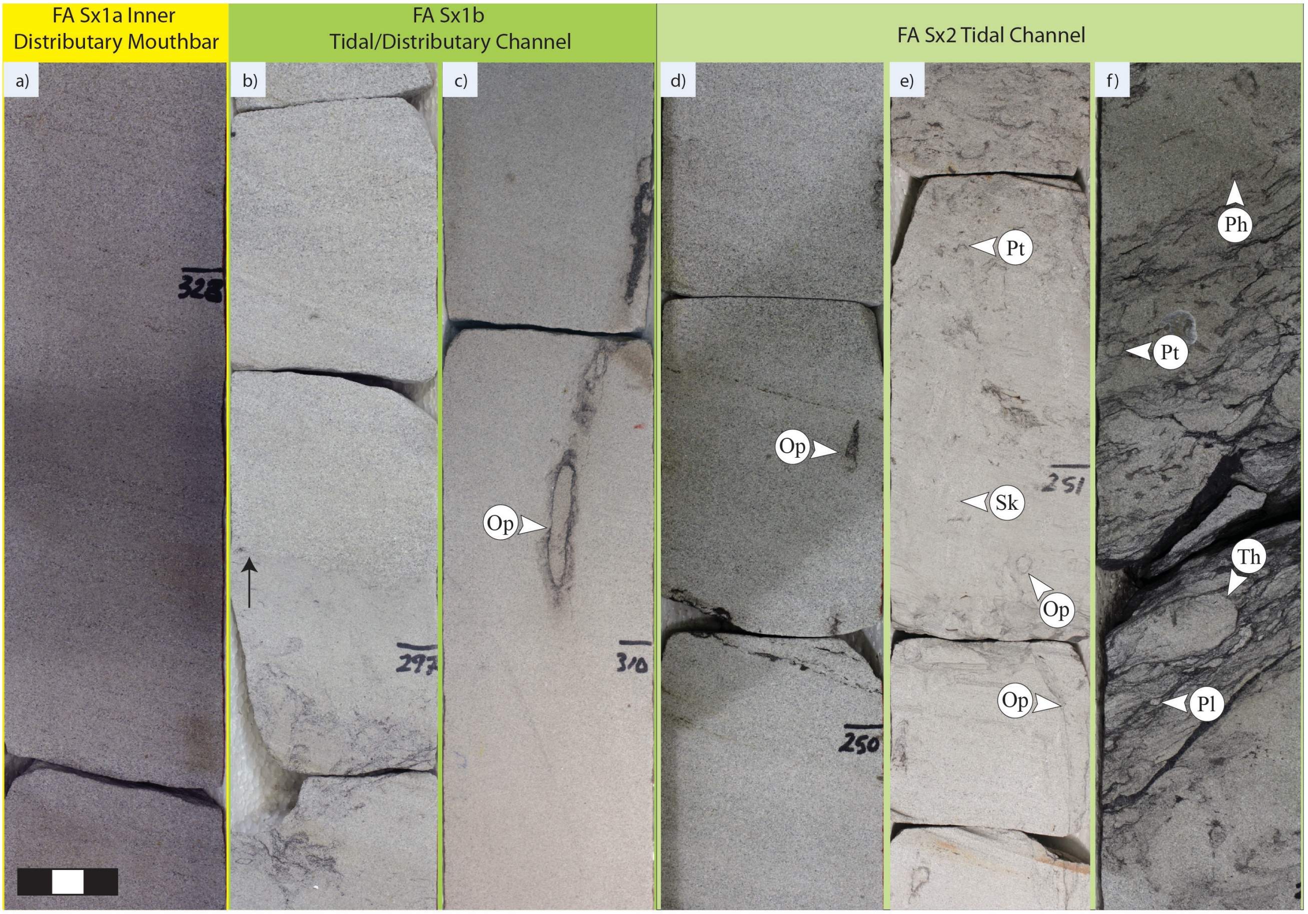


Figure 6.7: Facies Associations of Sx (FA Sx): a) an example of cross-bedded facies of FA Sx1 from well MC3, b) sharp-based contact (arrow) of FA Sx1b in MC4, c) thick-walled *Ophiomorpha* (Op) overprinting FA Sx1b in MC5, d) inclined thick-walled *Ophiomorpha* within FA Sx2 along with small organics along cross-beds in MC3, e) increase in bioturbation (due to overprinting) at the top of FA Sx2 in MC2, and f) heavily bioturbated muddy sandstone that lies between FA Sx1b and FA Sx2 in MC3 just above 253'. Trace abbreviations are *Ophiomorpha* (Op), *Palaeophycus tubularis* (Pt), *Palaeophycus heberti* (Ph), *Skolithos* (Sk), *Thalassinoides* (Th), and *Planolites* (Pl). The three centimeter scale is consistent across photos.

6.4.1.3 Description of Facies Association Sx1b

Facies Association Sx1b (FA Sx1b) is a clean, white, fine- to medium-grained sandstone with fining upward sequences of high angled and low angled cross strata, some troughs, and rare ripples. Rare localized organics are present along bedding or in mud draped tops, with normally graded lamina and graded ripples. The base and top of FA Sx1b is sharp (Figure 6.7b), with the top surface often angled and bioturbated. Bioturbation is sparse (BI of 1 or less). Bioturbation is from top down thick-walled *Ophiomorpha* (Figure 6.7c), and rare, unlined, cryptic *Skolithos* and organic-lined *Palaeophycus tubularis*. FA Sx1b is consistently present along one horizon in the upper one quarter of PS2d (Figure 6.6). FA Sx1b thickens from MC1 to MC5, with expansion of contacts both upward and downward. This facies association sharply overlies either FA Sl2a (wave reworked proximal delta front) or FA Sm2a (middle shoreface), and sharply underlies Sx2 (tidal channel).

6.4.1.4 Interpretation of Facies Association Sx1b

Facies Association Sx1b is similar to the afore described FA Sx1a in that they both have similar facies, and represent similar stressed high-energy conditions with bioturbation being attributed to overprinting, which may suggest that FA Sx1b is also representative of distributary mouthbar facies. However, the direct relationship with the overlying FA Sx2 may suggest that these facies are more representative of a tidal channel (discussed below). While a sharp bedded, clean cross-bedded sandstone could indicate a rip-current channel progression into upper shoreface (e.g., Ryer and Anderson, 2004; Pemberton et al., 2012) from the underlying middle shoreface, the fining upward and lack of inherent bioturbation makes this seem a more unlikely interpretation.

6.4.1.5 Description of Facies Association Sx2

Facies Association Sx2 (FA Sx2) are clean fine- to medium-grained sandstones dirtying upward, with low and high angled cross-beds in thicker sections (Figure 6.7d), whereas thin sections are completely bioturbated. FA Sx2 has a sharp base and a heavy bioturbated top (Figure 6.7e). Bioturbation abundance is typically BI=0-2. However, the base may contain a decimeter bed of sandy mudstone to muddy sandstone, with abundant (BI>4) *Planolites* and *Thalassinoides* burrows, some organic-lined *Palaeophycus heberti* (Figure 6.7f). Within the sandstone facies, there is some shell material, *Teredolites*, and *Ophiomorpha*. Thick-walled vertical *Ophiomorpha* typically distending from base (MC3-

5), more rarely *Planolites* and *Thalassinoides* (MC1-2), may be sporadically distributed throughout. Some small organic clasts, and elongate grey mudstone clasts occur along bedding mainly near the base. Top dirties, with bioturbation becoming heavy (BI>4) with *Ophiomorpha*, unlined *Skolithos*, organic-lined *Palaeophycus heberti*, up to large *Chondrites* and *Teichichnus,* with some *Schaubcylindrichnus freyi* , small *Chondrites*, *Ophiomorpha irregulaire*, *Planolites*, and *Thalassinoides*. FA Sx2 is present along the top of PS2d across all wells, with a similar thickness until MC5, where it thins to one quarter the size (Figure 6.6). Facies Association Sx2 sharply overlies Sx1b (distributary mouthbar/ tidal channel) and underlies prodeltaics of FA Ha3 that mark the start of the overlying parasequence (PS2e).

6.4.1.6 Interpretation of Facies Association Sx2

Facies Association Sx2 is similar to Sx1a and Sx1b in facies content representing high energy stressed conditions, with an overprinting of bioturbation over the top of the facies. Ryer and Anderson (2004) have noted the overprinting along this surface by *Ophiomorpha* and *Skolithos*. Conversely, Sx2 has bioturbation at, and along, the base that is not present within the other two previously described associations. The appearance of similar vertical *Ophiomorpha* distending from the base of FA Sx2 suggest a low abundance/ low diversity trace assemblage throughout the sandstone (not including the upper overprint) facies consistent with the Archetypal *Skolithos* Ichnofacies (e.g., MacEachern et al., 2007). The muddy sandstone to sandy mudstone facies show low diversity, but high abundance representing a depauperate expression of the *Cruziana* Ichnofacies (e.g., MacEachern et al., 2007), which is indicative of brackish water systems Pemberton and Wightman (1992). FA Sx2 is very similar to the tidal channel migration facies described in Chapter 4, in which the sandstones are representative of the tidal channel model (e.g., Barwis, 1978; Barwis and Hayes, 1979), where as the sandy mudstone-muddy sandstone would indicate intertidal flats (e.g., Gingras et al., 2011) or brackish bays. Conversely, the sand-filled traces also may be ripped up and redeposited at the base of the channel in FA Sx2 (Figure 6.7f). The differences between FA Sx2 and the Tidal Channel Association are the lack of *Siphonichnus* and sparseness of organics in FA Sx2. The cleanness of the sand might prevent the *Siphonichnus* from clear toponomic expression, or FA Sx2 might represent higher energy or more stressed conditions than described in Chapter 4. The change in organic content is probably due to the facies association in Chapter 4's eroded organic-rich strata, whereas FA Sx2 is eroded sand-rich mouthbar, middle shoreface, or proximal delta front facies. This cannibalization makes it difficult to tell whether the preceding FA Sx1b is just the lower, higher energy expression of the FA Sx2 tidal channel(s), or whether it is river-dominated mouthbars that become reworked by the tidal channel that initiate during abandonment. An additional difference in FA Sx2 from the tidal channels in Chapter 4 and the Barwis model, is the lack of subaerial facies near the top (e.g., dinosaur tracks or roots).

6.4.2 Facies Association Sl

6.4.2.1 Description of Facies Association Sl1a

Facies Association Sl1a is low angle bedded sandstone with fine- to medium-grain sizes (Figure 6.8a). Base is always sharp and rather flat. The facies, when over one meter thick, fine upward overall. Macro bioturbation is absent, except may be present, as thin *Ophiomorpha* in the top few cm of the facies association. Shell debris, possibly of thin to medium thickness *Crassostrea*, is commonly associated with organic detritus (Figure 6.8b). Organic detritus is not evenly distributed and may be sporadic in appearance. Sandstone may be calcareous or spotty calcareous. This facies association is only developed in the middle of PS2b, one small (<1m) interval in MC1, and a thick interval in MC5. Facies Association Sl1a overlies lower shoreface (FA Sm2b) and middle delta front (FA Ha1), and underlies proximal delta front (distal terminal distributary; FA Sl2b) and middle delta front (FA Ha2).

6.4.2.2 Interpretation of Facies Association Sl1a

Facies Association Sl1a is interpreted to represent the distal deposits of a terminal river distributary channel. The domination by low angle bedding suggests persistence or preservational bias of upper flow regime conditions (e.g., Harms and Fahnestock, 1965). Distributary channels elsewhere (Ivie Creek) in this parasequence set (Kf-2) are completely well-cemented sandstone, dominated by a single bedform throughout (trough cross-stratification), and contain matrix up to medium grain sizes (Mattson and Chan, 2004). While FA Sl1a is not dominated by trough cross-bedding as often interpreted in the terminal distributary channel deposits of the Ferron Sandstone (e.g., Barton 1994); the fining upward, limited areal extent, and persistence of clasts suggest a channelized affinity. This may represent the process suggested by Olariu and Bhattacharya (2006) of low angle mouthbar sand deposits backfilling the terminal distributaries. Distributary channels in the

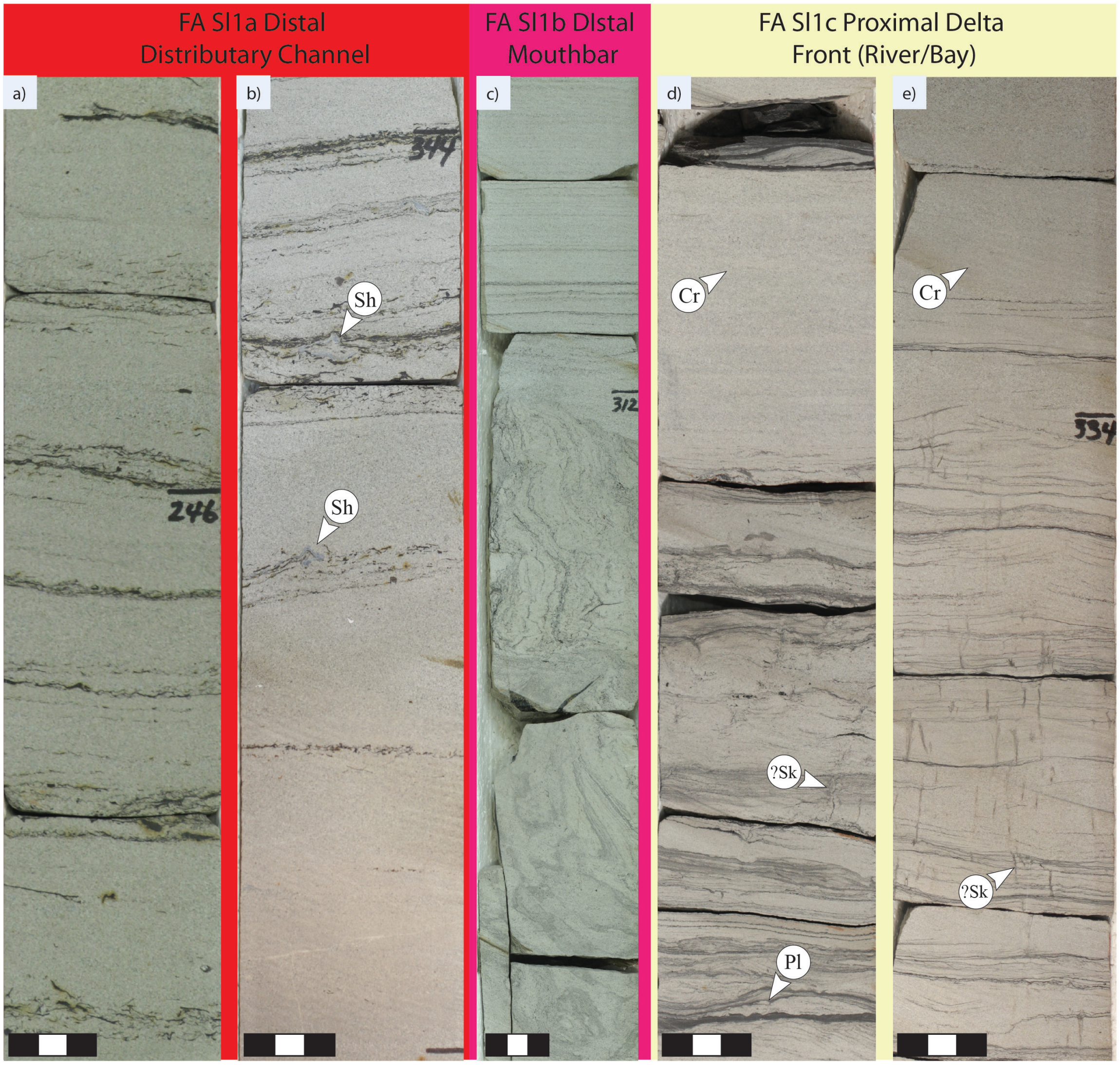


Figure 6.8: Facies Associations of Sl1 (FA Sl1): a) FA Sl1a from MC1, b) FA Sl1a from MC5 containing shell debris (Sh), c) FA Sl1b with highly convoluted beds and eroding low angle bedding, d) FA Sl1c from PS2c of well MC2 just below 320' contain *Planolites* (Pl) with *?Skolithos* (?Sk) and cryptic bioturbation (Cr), and e) similar facies in FA Sl1c from PS2d in well MC5. Scales each represent three centimeters.

modern Mississippi River similarly have sharp bases, organic debris, but typically lack the brackish fauna such as *Crassostrea* (Gould, 1970). However, the *Crassostrea* are clasts that could be reworked from adjacent brackish water deposits, or reworked, in channel, abandonment intervals. The calcareous cements are likely related to dissolution of the shell material. One large difference is that distal, or terminal distributary channels, often show some degree of interbedding with mudstone, and this facies association doesn't. Additionally, this facies association looks visually similar to some tidal channel facies association. However there are no high angle cross-beds, nor inherent bioturbation. Ryer and Anderson (2004) suggest that some distributary channels are actually tidal creeks, and this may be the case here. The rarity of bioturbation is noted in distributary channels in the modern Mississippi Delta by Coleman and Gagliano (1960). Occurrence of FA Sl1a over the brackish distal delta front deposits in MC5 supports this interpretation of a river-dominated distributary channel, but occurrence over lower shoreface shows a rapid shift in environments. The presence of wave influenced deltaics over this facies association may represent abandonment or infilling of the created topographic low.

6.4.2.3 Description of Facies Association Sl1b

Facies Association Sl1b (FA Sl1b) is composed of thick (>1m) intervals dominated by very fine- to fine-grained convoluted sandstone. FA Sl1b can be interbedded and cut by low angle bedded sandstones and likely was this facies prior to convolution (Figure 6.8c). The base is rather sharp and may contain a several centimeter thick organic rich mudstone bed. The top is also sharp. FA Sl1b contains abundant organics in the sandstone along lamina (low angle or convoluted). Bioturbation is generally absent or not discernable due to convolution. FA Sl1b is present in the lower one-third PS2d in MC1, and in the upper one-third of PS2d in MC4 (Figure 6.6). Facies Association Sl1b overlies FA Hb2 (river-dominated proximal prodelta) and FA Sl2b (proximal delta front; distal terminal distributary), and underlies FA Ha2 (middle delta front).

6.4.2.4 Interpretation of Facies Association Sl1b

Facies Association Sl1b is interpreted as river-dominated proximal delta front (terminal distributary related). These comprise floodwater deposits related to rapid channelized flow, which result in rapid loading of the prodelta or related to terminal distributary processes. Convolution is commonly related to subenvironments (e.g. subaqueous levees) that have high turbulence and current velocities during flood stages in the modern Mississippi Delta (Coleman and Gagliano, 1960). The FA Sl1b in MC4 could be part of a similar levee succession of increase in current conditions upward as drafted by these authors showing a progression from aggradational facies (FA Sg) upward into current related low angle beds and convolution. However, a thin occurrence of clast-bearing FA Sl2b lies between these two. This may suggest that FA Sl1b represents part of a convoluted terminal distributary channel as described in the Ferron Sandstone by Olariu and Bhattacharya (2006) after the work of Barton (1994). The close lateral relationship with the river-dominated distributary channel in MC5 supports the interpretation of FA Sl1b, in this case, as a terminal distributary/levee system. Conversely, where FA Sl1b occurs in the lower part of MC1 is likely due to rapid sedimentation and overpressuring of the underlying prodeltaic deposits (FA Hb2)(e.g., Bhattacharya, 2010). This facies association appears to be a convoluted representation of flood stage rapid sedimentation, which is equivalent to FA Sg as discussed later. Therefore, the overlying distal, wave influenced delta front facies may just represent typical conditions rather than event conditions. As noted by Olariu and Bhattacharya (2006) deposits related to terminal distributaries are often subject to basin conditions such as wave reworking, and are encased in delta front deposits.

6.4.2.5 Description of Facies Association Sl1c

Facies Association Sl1c is composed of clean Sla or rippled sandstones, with organic mud drapes along oscillation, combined flow, and aggradational ripples (Figure 6.8d,e). Interbedded mudstone may be present, but it typically less than 10%. Bases can be sharp or gradational, and tops are sharp or bioturbated. Bioturbation outside of cryptic bioturbation is rare. *Ophiomorpha* and organic-lined *Palaeophycus tubularis* may be present, but normally only along the tops of beds. BI is typically less than one, but *?Skolithos* can be present as monospecific occurrence up to BI of 2 (Figure 6.8d,e). The *?Skolithos* is distinctive due to the persistent, but inconsistent, organic lining. Similar organic lining is seen in burrows of modern polychaetes (*Alitta virens*) where organics from lamina often become concentrated along the mucus-coated walls of the burrows creating both *Skolithos*-like and *Palaeophycus*-like (U-shaped forms) cross-sections (Herringshaw et al., 2010). *Palaeophycus heberti* is rare. Mudstones rarely display bioturbation in the form of *Planolites* and *Thalassinoides*, and may contain some small syneresis cracks. Hummocks occur occasionally near the tops of this association. Facies Association Sl1c is a dominant component of the top of PS2c, but is only present in the upper one third of PS2d in MC5. Heavy bioturbation (BI>4) may be present in the upper ten centimeters of FA Sl1c when overlain by FA Hb2 (proximal prodelta) or FA Hb3 (distal prodelta). This contains the additional traces of *Chondrites*, *Teichichnus*, *Teredolites* and *Scolicia*. Conversely, the upper boundary is sharp when overlain by FA Sx1a (distributary mouthbar). Facies Association Sl1c overlies either FA Ha1 (middle delta front), or FA Ha2 (middle delta front).

6.4.2.6 Interpretation of Facies Association Sl1c

Facies Association Sl1c is interpreted to represent brackish river-dominated proximal delta front deposits. This is in agreement with Bhattacharya and Davies (2004) interpretation of these facies in PS2c. Similar facies occur in PS2d of MC5 suggesting persistence or reestablishment of these conditions at least locally upward. FA Sl1c is dominantly comparable to the Archetypal Skolithos Ichnofacies (e.g., MacEachern et al., 2007) with low diversity dominated by vertical dwelling burrows of interpreted passive carnivores and suspension feeders *(?Skolithos*, *Ophiomorpha*, and possibly *Palaeophycus tubularis*) with rare mobile organisms (*Palaeophycus heberti*) and horizontal burrows (*Planolites* and *Thalassinoides*). This indicates a highly stressed or persistently erosive environment. Archetypal Skolithos is often associated with wave-dominated delta front facies (MacEachern et al., 2007). While some hummocks and oscillation ripples are present indicating wave action, syneresis cracks are also present suggesting salinity fluctuations (e.g., MacEachern et al., 2005). Garrison and van den Bergh (2004) note that hummocky cross-stratification is often present as a minor component of the river-dominated deltaics of the Ferron Sandstone. Interpretation of this facies as a brackish river-dominated delta front deposits is consistent with the previous interpretations of the facies in PS2c by Bhattacharya and Davies (2004), as well as their description of transgressive overprinting at the top of the facies by higher abundance bioturbation in the top few centimeters with thick-walled *Ophiomorpha*. This overprinting occurs where FA Sl1c underlies prodeltaic facies. In PS2d, a more conformable expression is topped with river-dominated mouthbar deposits. Facies Association Sl1c overlies distal river-dominated and wave reworked distal delta front deposits, which supports the interpretation of FA Sl1c as proximal delta front facies.

6.4.2.7 Description of Facies Association Sl2a

Facies Association Sl2a (FA Sl2a) is composed of dominantly fine-grained sandstone with <5% mudstone. The base is sharp and rarely may show loading when overlying mudstone. Tops can be sharp or bioturbated. Facies are dominantly low angle bedded and oscillation rippled sandstone (Figure 6.9a). Low angle bedded sandstones typically increase in proportion upward, whereas oscillation ripples generally decrease. Oscillation ripples often have organic mud drapes, whereas as organics are sparse in the other facies. Trough cross-bedded sandstone and thin (<3cm) laminated mudstone are rare. Massive sandstone facies make up less than 50% of this facies. The massive sandstone can be clean, or disrupted by abundant burrowing. Typically, the bioturbation index for this facies is between 1-2, however small (<5cm) intervals with BI<4 do occur. Bioturbation lessens overall upwards. Heavy bioturbation is often by *Palaeophycus heberti*, with some thin-walled *Ophiomorpha*, and thin-walled, organic-lined *Palaeophycus tubularis* (Figure 6.9b,c). *P. tubularis* is or typically small, and rarely groups together. Occasionally, large groups of *P. tubularis* or *Diplocraterion* may be present at the top of this facies association (Figure 6.9c). *Ophiomorpha* are often vertical (Figure 6.9a,d) or display cross-sections with a thicker triangle-shaped lining at the top (Figure 6.9e). Small diameter cryptic (unlined) *Skolithos,* or fugichnia can locally be common. *Thalassinoides* is extremely rare, only occurring in one thin mudstone bed. Facies Association Sl2a is only developed in the upper one-third of Parasequence 2d (Figure 6.6). FA Sl2a overlies FA Ha2 (middle delta front), FA Sg (middle-distal delta front), FA Sl2b (distal distributary), and FA Sm2a (middle shoreface). Facies Association Sl2a underlies FA Sx1b (distributary mouthbar/ tidal channel), FA Sm2a (middle shoreface), FA Sl2b (distal distributary), and FA Sl1c (proximal delta front).

6.4.2.8 Interpretation of Facies Association Sl2a

Facies Association Sl2a is interpreted to represent wave reworked to wave-dominated proximal delta front deposits. The low angle bedded sandstone and oscillation rippled sandstone suggest alternations of high energy and low energy conditions. The massive sandstone cleanness likely prevents the identification of additional high-energy structures. The destruction of the sedimentary structures in these massive facies is probably also the result of cryptic bioturbation. Cryptic bioturbation is typically found in high-energy environments (e.g., Pemberton et al., 2008). Additionally, dominance by vertical and inclined *Ophiomorpha* orientation has been linked with higher energy marginal marine deposits from the Cretaceous (e.g., Anderson and Droser, 1998). FA Sl2a is comparable to FA Sl1c in diversity containing similar traces, however abundance is greater (BI=1-3, more rarely small bands of BI>4) in FA Sl2a and produces heterogeneous distribution that is similar to event bed colonization of Pemberton and MacEachern (1997). The bioturbation

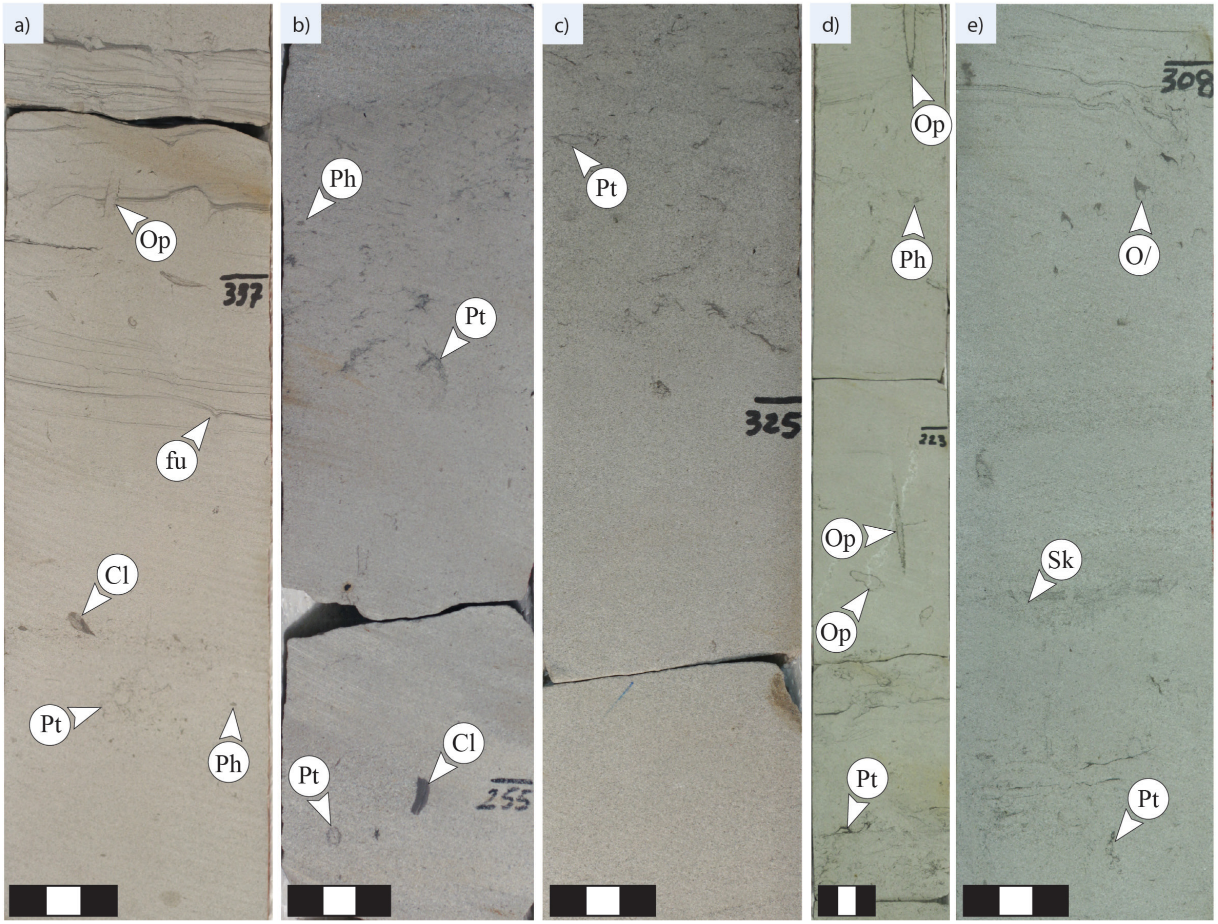


Figure 6.9: Facies Association Sl2a (FA Sl2a): a) cryptic bioturbation of low angle bedding of FA Sl2a (wave reworked proximal delta front) from MC5 with vertical *Ophiomorpha* (Op), fugichnia (fu), *Palaeophycus tubularis* (Pt), *Palaeophycus heberti* (Ph), and rare mudstone clasts (Cl), b) similar facies of FA Sl2a from MC2 with rare clasts, c) FA Sl2a from MC5 dominated by cryptic bioturbation and organic-lined *Palaeophycus tubularis*, d) FA Sl2a from MC1 with prominent vertical *Ophiomorpha*, and e) inclined *Ophiomorpha* (O/) with thickened triangular top of cross-section and unlined *Skolithos* (Sk) from FA Sl2a in MC4.

in FA Sl2a is a less stressed expression, and more distal expression of Archetypal Skolithos than described in FA Sl1c. The increased abundance of passive carnivores (*Palaeophycus*) is indicative of the Distal *Skolithos* expression, but FA Sl2a does not contain the abundance of facies-crossing deposit feeders and grazing structures that are inclusive to the Distal *Skolithos* Ichnofacies (e.g., MacEachern et al., 2007), hence why it is more comparable to Archetypal *Skolithos*. The interrelationship with middle shoreface and distal distributary facies associations, as well as presence over more distal delta front facies associations supports the interpretation of proximal delta front deposits.

6.4.2.9 Description of Facies Association Sl2b

Facies Association Sl2b (FA Sl2b) is composed of very fine- to fine-grained sandstones comprised of individual fining upwards bedsets (Figure 6.10a). Bedding may have a few organic drapes. Basal contacts are sharp with mudstone clasts often present in the basal few centimeters, and sometime present individually along bedding. Mudstone clasts are mainly <2 cm long, grey flat, elongate with angular edges. Rarely mudstone clasts are larger and subrounded (one surface) (Figure 6.10b), or fill in a gutter(?) structure (Figure 6.10c). The main facies is normally low angle bedded sandstone, with low organic content. The facies may appear massive in clean sandstone. Top can grade into organic mud draped combined flow ripples, sharply cut out, or may be heavily bioturbated (BI>4) from the top of the sets down with organic-lined *Palaeophycus tubularis* or *Ophiomorpha*. *Palaeophycus heberti* is also an important component (Figure 6.10d). Rare *Skolithos* and fugichnia are present. Facies Association Sl2b only developed in the upper one-third of PS2b (Figure 6.6). A thick package is present in MC1 and MC2, whereas only a couple of thin packages (<1m thickness) are present in MC3 and MC4 (Figure 6.6). FA Sl2b most often is sharp (incision) or grades upwards into FA Ha2, however can overly FA Sl1a (river-dominated proximal delta front), FA Sg (middle-distal river-dominated delta front), FA Sl2a (wave reworked proximal delta front), and underlie FA Sl2a (wave reworked proximal delta front), FA Sg (middle-distal river-dominated delta front), and FA Sm2a (middle shoreface).

6.4.2.10 Interpretation of Facies Association Sl2b

Facies Association Sl2b constitutes both wave reworked and river-dominated terminal distributary deposits. The thin horizons of this association in MC3 and MC4 with little to no bioturbation and more rounded clasts are directly related to river-dominated

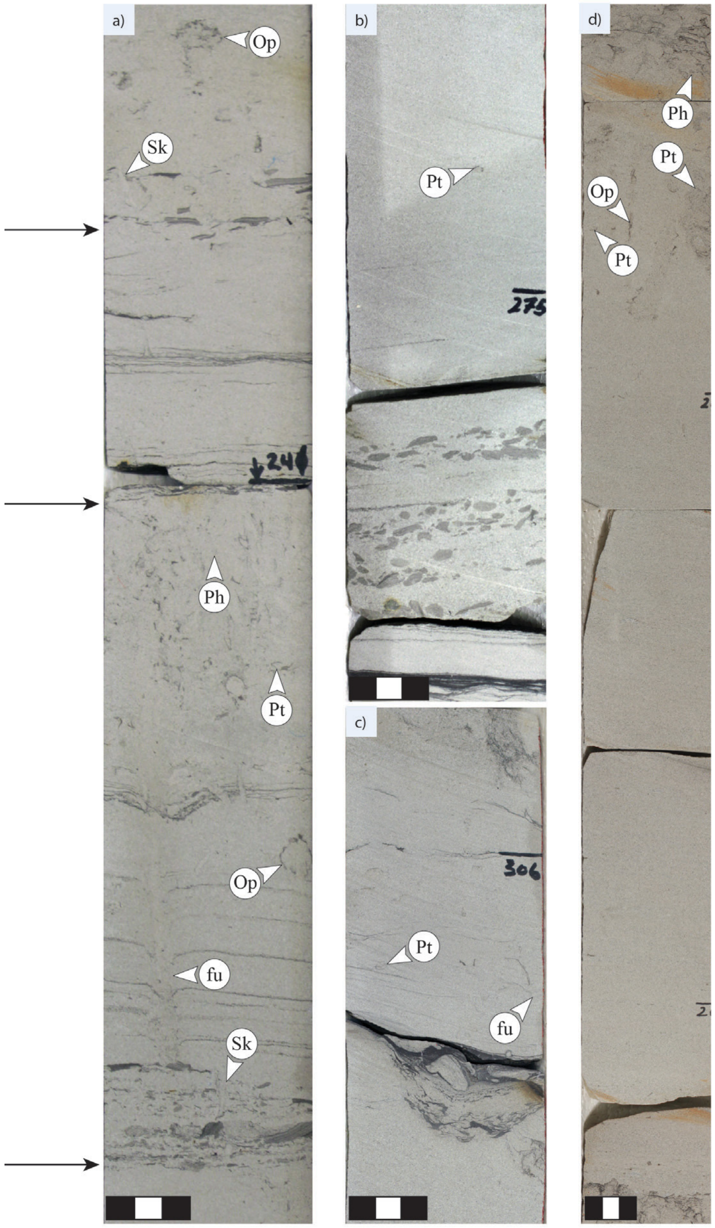


Figure 6.10: Facies Association Sl2b (FA Sl2b): a) three clast-based cycles (arrows marking base) in FA Sl2b (distal terminal distributary) of MC1 showing top down bioturbation by *Ophiomorpha* (Op), *Palaeophycus heberti* (Ph), *Palaeophycus tubularis* (Pt), and *Skolithos* (Sk), as well as, fugichnia escape traces (fu), b) an example from MC3 of more rounded clasts in this association, c) an example from MC4 of clasts filling a gutter(?) cast with overlying cryptic bioturbation, and d) clean, cryptic bioturbated cycle from MC2 with limited clasts along the sharp base.

conditions, which is further evidenced by their close relationship with the aggradational deposits of FA Sg.

The FA Sl2b in MC1, MC2, and the thin upper occurrence in MC4 are more indicative of wave reworked terminal distributary/mouthbar deposits. This is a departure from Gani et al. (2009) interpretation in MC2 of river-dominated delta front, although this paper uses a smaller scale for interpretation, which results in a slightly different subdivision. This variation of FA Sl2b is similar to mouthbar deposits of Olariu and Bhattacharya (2006) of the Campanian Panther Tongue (fine-grained parallel laminated sandstone, silting and bioturbation increasing upward), but it is difficult to access from the descriptions of terminal distributary facies from the Ferron Sandstone (after Barton, 1994) due to discrepancies between the text, table, and figures. The likely descriptions of the terminal in the Ferron Sandstone are described with dominance by high angle cross-strata, with occasional flute casts, containing mud-chip clay clasts and organic matter. While the cross-strata is not high-angled, the clay clasts and occasional sharp erosional features (grooves?) are an important component of FA Sl2b. Similar grooves (?) are seen in the Ferron Sandstone in the inclined erosional surfaces of meandering distributary channels point bars that fill laterally as well as upstream (Corbeanu et al., 2004), but are topped by trough cross-beds. This may be due to a complex interrelationship between the proximal delta front deposits of lobate deltaics (mouthbar and terminal distributary channel), as alluded to by Olariu and Bhattacharya (2006). The lobate nature of deltas, hence interfingering deposits, are the result of wave reworking/distribution (e.g., Coleman and Wright, 1975). The repeated heterogeneous pattern of bioturbation and silting at the top of the sharp based often clast-bearing cycles, suggest event bedding (e.g., Pemberton and MacEachern, 1997). It is unclear whether the clasts are representative of river deposition by a terminal distributary, rapidly followed by wave reworking deposition and bioturbation, or whether these cycle represent the irregular scour and planar bedding deposition characteristic of the initial combined flow state of hummocky cross-stratification (e.g., Duke et al., 1991). Facies Association Sl2b likely represents both wave and river processes in forming these cycles, the river input is needed for transportation the clasts and organics, and their disappearance basinward (from MC1 to MC2).

While both the wave-reworked and river-dominated variations of this facies are comparable to the Archetypal *Skolithos*, the river-dominated version is impoverished suggesting high stress or low preservational potential, whereas the wave-reworked is more akin to the distal expression of Archetypal Skolithos of FA Sl2a with similar trace assemblages. The main difference between FA Sl2a and FA Sl2b being the abundance of traces is typically greater in FA Sl2b and the *Ophiomorpha* are more rarely vertical.

6.4.3 Facies Association Sg

6.4.3.1 Description of Facies Association Sg

Facies Association Sg (FA Sg) is comprised of laminated, climbing, aggradational oscillation rippled, very fine to fine grained sandstone with typically <10% mudstone interbeds, that has >10% organic debris along lamina, cleans upwards in cycles, although sometimes larger debris may be present in top, may have erosional low angle bedded white sandstone, or white sandstone lenses (Figure 6.11a-g). Some convolution may be present. Aggradational oscillation and climbing rippled may be present in the lower portion. The base is typically gradational, and the top is usually a bioturbated contact. Bioturbation is sparse (BI=1) except along flooding surfaces (often *Ophiomorpha*; Figure 6.11b) and small beds of monospecific assemblages of *Palaeophycus heberti* (Figure 6.11d,f,g). FA Sg is present in the lower one-third of PS2d in MC1-2, MC4-5, and present in the middle one-third of PS2d from MC2-5 (Figure 6.6). Facies Association Sg is underlain by FA Ha2 (middle delta front), FA Ha3 (proximal prodelta), FA Sl2b (proximal delta front), FA Hb2 (proximal prodelta), and FA Sm3a (lower shoreface/offshore transition). FA Sg is overlain by FA Sm2b (lower shoreface), FA Hb2 (proximal prodelta), FA Hb3 (lower shoreface/offshore transition), FA Ha1 (middle delta front), FA Sl2b (proximal delta front), and FA Sl2a (proximal delta front).

6.4.3.2 Interpretation of Facies Association Sg

Facies Association Sg represents flood stage, river-dominated delta front deposits, likely of the distal portion. Aggradational bedforms are characteristic of the areas with high turbulence and currents during flood stage, such as at the edge of the terminal distributary or in subaqueous levees (Coleman and Gagliano, 1960; Coleman et al., 1964). Additionally, flood runoff is also a means by which to accumulate abundant organic detritus in the delta front (via hyperpycnites, which may be deposited as low angle bedding), and may transport fine- to medium-grained sediments for a great distance away from the input (Zavala et al., 2012). This makes it difficult to place a definitive proximal distal relationship on this facies association, however preservation potential would be greater in the distal portion of the

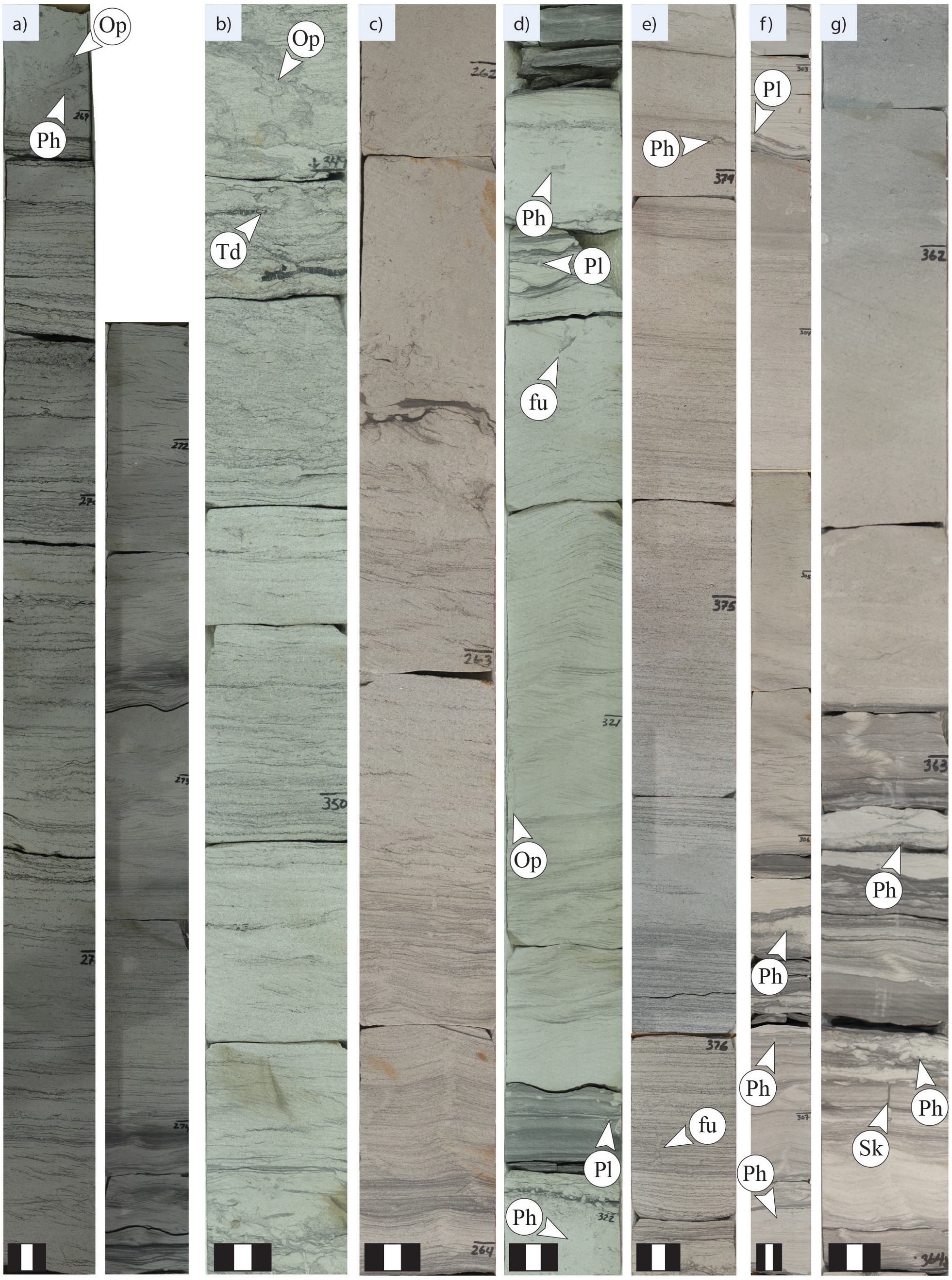


Figure 6.11: Facies Association Sg (FA Sg): a) transition from aggradational to current forms and an increase in organic size upwards (bottom right to top left in core) in MC3, b) sharp-based example of this association from MC4 containing *Teredolites* (Td), c) example of aggradational to current forms upwards from MC2, d) a cycle from MC4 showing an increase of aggradation upward until wave reworking and monospecific beds of *Palaeophycus heberti* (Ph) and cryptic bioturbation, with rare other taxa such as *Planolites* (Pl), fugichnia (fu), and overprinting vertical *Ophiomorpha* (Op), e) cleaning upward of organic-rich, low angle lamina in MC5, and f,g) hyperpycnite expressions from MC2 and MC5 punctuated by clean low angle beds and monospecific beds of *Palaeophycus heberti* and rarely *Skolithos* (Sk).

delta front where there is more accommodation and less wave reworking. Aggradational oscillation ripples suggest wave influence. Punctuations by heavily bioturbated *Palaeophycus heberti* beds with rare top down diminutive vertical *Ophiomorpha* suggest occasional periods of river-dominated quiescence (wave-reworking). *Palaeophycus* rather monospecific occurrence has been attributed to high-energy marginal marine setting (e.g., Saunders and Pemberton, 1990) and may preferentially preserve because their horizontal orientation protects them from the return flow of waves (Pemberton et al., 1992). Facies Association Sg is comparable to the Archetypal Skolithos Ichnofacies. FA Sg is similar to FA Sl2a and FA Sl2b in heavy bioturbation by Archetypal Skolithos assemblages at the top of the event bed, however FA Sg is topping hyperpycnite events, with smaller intervals of heavy bioturbation, and *Palaeophycus heberti* is dominant instead of *Palaeophycus tubularis*. The complex spatial interpretation is indicated by the great variety of Facies Associations that FA Sg overlies and underlies, from interrelationships with proximal delta front facies to those of the lower shoreface/offshore transition. It is likely that FA Sg comprise both hyperpycnites of the prodelta to more proximal deposits of the subaqueous levee.

6.4.4 Facies Association Sm

6.4.4.1 Description of Facies Association Sm2a

Facies Association Sm2a (FA Sm2a) is fine-grained sandstone interbedded with silty sandstone, cleaning upward (Figure 6.12a). Massive sandstone is the dominant facies. Oscillation ripples have organic-rich mud drapes. Low angle bedding is diffuse to see in the core, partially due to cryptic bioturbation. Mudstone clasts are rare. The bottom contact is sharply bioturbated, whereas the top contact is sharp. Bioturbation intensity varies from BI=6 in some places to interbeds of BI=1-2 (Figure 6.12a). Bioturbation is typically large groupings of organic-lined *Palaeophycus tubularis* and *Ophiomorpha* burrows, cryptic bioturbation, and *Palaeophycus heberti* burrows. Some small, vertical *Ophiomorpha* may be present, as well as unlined *Skolithos*, possible *Phoebichnus*, rare *Arenicolites* and rare *Schaubcylindrichnus*. FA Sm2a developed in one horizon in the upper one-third of PS2d. This facies association maintains the same approximate thickness from MC2-MC4, but is less than one meter thick in MC5 (Figure 6.6). Facies Association Sm2a overlies FA Sg (middle to distal delta front), FA Sl2a (proximal delta front), FA Sl2b (proximal delta front), and FA Sx1a (mouthbar). This association underlies FA Sl2a (proximal delta front),

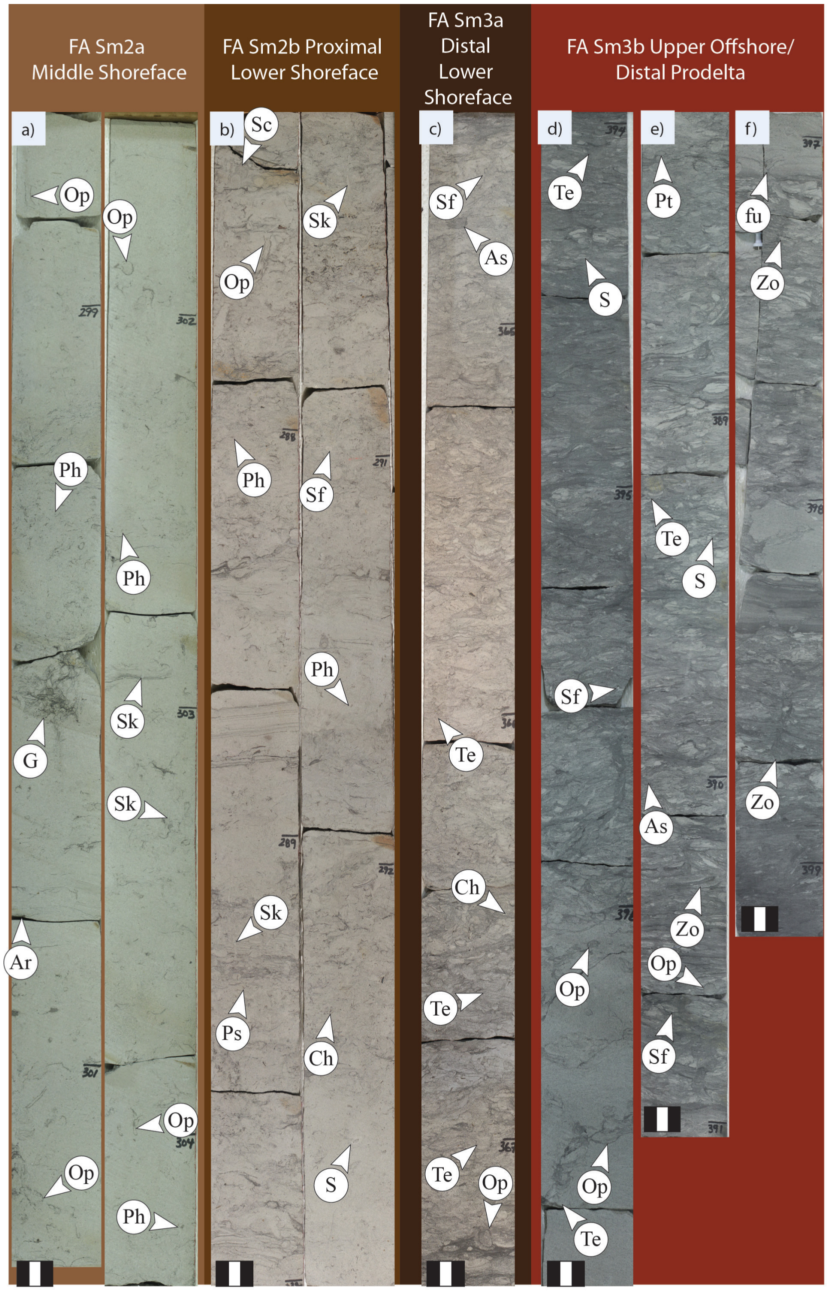


Figure 6.12: Facies Associations of Sm (FA Sm): a) FA Sm2a in MC4 (core base is bottom right) with abundant *Ophiomorpha* (Op), *Palaeophycus heberti* (Ph), cryptic bioturbation, *Skolithos* (Sk), distinctive groupings of organic-lined *Palaeophycus tubularis* and *Ophiomorpha* (G), and rare *Arenicolites* (Ar), b) heavier bioturbation of FA Sm2b in MC2 (core base is bottom right) with similar occurrence of *Ophiomorpha*, *Palaeophycus heberti*, and *Skolithos*, with some *Schaubcylindrichnus* (S), *Schaubcylindrichnus freyi* (Sf), rare *Phycosiphon* (Ps), *Chondrites* (Ch), and *Scolicia* (Sc), c) FA Sm3a in MC5 with abundant *Teichichnus* (Te), *Chondrites*, *Asterosoma* (As), some *Schuabcylindrichnus freyi*, and *Ophiomorpha*, d-f) heavily bioturbated FA Sm3b in MC5 with hyperpycnite event beds; diverse traces include *Teichichnus*, *Schaubcylindrichnus*, *Schaubcylindrichnus freyi*, *Ophiomorpha*, *Palaeophycus tubularis* (Pt), *Asterosoma*, fugichnia (fu) and *Zoophycos* (Zo).

FA Ha2 (middle delta front), and FA Sx1b (distributary mouthbar/tidal channel).

6.4.4.2 Interpretation of Facies Association Sm2a

Facies Association Sm2a is interpreted as middle shoreface. This is consistent with the interpretation by Gani et al. (2009) for these facies in MC2. The authors consider that this association comprises a Mixed *Skolithos*-*Cruziana* Ichnofacies that is often associated with distal shoreface environments (e.g., Pemberton and Frey; 1984, Pemberton et al. 1992; Pemberton and MacEachern, 1997). An alternate interpretation to Gani et al. (2009) of a low diversity Mixed *Skolithos*-*Cruziana* is that this assemblage is comparable to a high abundance Distal *Skolithos* Ichnofacies (e.g., MacEachern et al., 2007). This contrast with the previously described of associations that are comparable to Archetypal Skolithos in that FA Sm2a has more persistent heavy bioturbation, the appearance of *Schaubcylindrichnus*, and conspicuous large groupings of organic-lined burrows.

6.4.4.3 Description of Facies Association Sm2b

Facies Association Sm2b is a heavily bioturbated very fine- to fine-sandstone, coarsening up, with <5% mudstone (Figure 6.12b). The sandstone is dominated by massive facies. The thickness of clean low angle bedded sandstones increases upwards, whereas the presence of organic material along lamina and oscillation ripples decrease. The base is sharply bioturbated, and the top is sharp. Bioturbation intensity is dominantly 5-6, with clean beds. The major burrows consist of groups of organic-lined *Palaeophycus tubularis*, *Palaeophycus heberti*, *Ophiomorpha*, unlined *Skolithos* (Figure 6.12b). A few of the *Ophiomorpha* are vertical. Some thickly line *Schaubcylindrichnus freyi*, *Chondrites*, and possibly some *Phoebichnus* are present. This facies association is only present in the middle one-third of PS2d Developed thickly in MC1 and MC2, and thinly at a slightly higher horizon in MC3 and MC4 (Figure 6.6). Facies Association Sm2b is underlain by FA Sg (middle distal delta front), FA Ha2 (middle delta front), and FA Sm3a (lower shoreface/ offshore transition). FA Sm2b is overlain by FA Sl1a (proximal delta front), FA Sl2b (Proximal delta front), and FA Ha2 (middle delta front).

6.4.4.4 Interpretation of Facies Association Sm2b

Facies Association SM2b is interpreted as lower shoreface, which is consistent with the interpretation by Gani et al. (2009) for these facies in MC2. However this appears to be a proximal expression of the lower shoreface in the study area. Gani et al., (2009) interpretation of a Mixed *Skolithos*-*Cruziana* Ichnofacies appears spot on. Bioturbation is more persistent, the sandstone is siltier, there is increase in the abundance of *Schaubcylindrichnus*, and the noticeable appearance of *Chondrites*. The lower shoreface position is consistent with the distal delta front and distal lower shoreface that FA Sm2b overlies, and always fairly rapidly transitions upward into middle-distal delta front facies.

6.4.4.5 Description of Facies Association Sm3a

Facies Association Sm3a is a very fine-grained, massive, heavily bioturbated muddy to silty sandstone with minor organic debris and <5% mudstone (Figure 6.12c). Bioturbation intensity is between 5 and 6. Bottom of beds often are bioturbated contacts overlying inversely graded facies. Tops are often cut by a several centimeter sand of the overlying association, which can be heavily bioturbated. The sandstone is typically bioturbated by *Palaeophycus heberti*, organic-lined *Palaeophycus tubularis*, unlined *Skolithos*, small *Chondrites*, *Ophiomorpha*, and *Teichichnus*. There is also some *Scolicia*, *Planolites*, *Schaubcylindrichnus freyi*, big *Chondrites*, *Ophiomorpha irregulaire, Helminthopsis*, and *Phycosiphon (basinward). Rhizocorallium*, *Schaubcylindrichnus*, fugichnia, *Zoophycos*, and *Teredolites* are rare. Facies Association Sm3a is only developed more basinward in the lower two-thirds of MC3-5 (Figure 6.6). FA Sm3a interfingers with FA Ha3 (proximal prodelta/offshore) and FA Sg (distal delta front), and may overly FA Sm3b (distal prodelta/offshore transition), and underlies FA Sm2b (lower shoreface).

6.4.4.6 Interpretation of Facies Association Sm3a

Facies Sm3a is interpreted as the distal expression of the lower shoreface. This high abundance, high diversity assemblage is comparable to the Proximal *Cruziana* Ichnofacies expression (e.g., MacEachern et al., 2007) in that it shows a wide variety of behaviors and tiering overlap with an abundance of *Teichichnus*, notable appearance of *Helminthopsis* and *Phycosiphon*, while *Zoophycos* is rare. *Scolicia* is occasionally present in this facies association, which is adverse to the model, in which *Scolicia* is a more distal behavior. Proximal *Cruziana* expressions in Cretaceous muddy sandstone are often associated with the distal portion of the lower shoreface that lies below fair-weather wave base (Pemberton et al., 2012).

6.4.4.7 Description of Facies Association Sm3b

Facies Association Sm3b (FA Sm3b) is comprised of interbedded, very fine-grained, muddy and silty sandstone. Sandy mudstone is typically <10% with the greater proportions basinward (MC5). Heavily bioturbated massive facies dominate, but contain interbeds of low abundance (BI<3) Bouma Sequences and hyperpycnites (Figure 6.12d-f). Bouma Sequences are normally more numerous near the base whereas hyperpycnites often increase proportionally upwards. Rarely hyperpycnites are topped with low angle hummocks. This facies association generally sandies upwards. Common burrows are *Ophiomorpha* (often *O. irregulaire*), mudstone- or organic-lined *Palaeophycus tubularis*, small and large *Chondrites*, *Thalassinoides*, and *Planolites*. Some *Palaeophycus heberti* are present. *Skolithos* and *Teredolites* are rare. *Phycosiphon* and *Helminthopsis* are present in the lower part of the association. *Schaubcylindrichnus*, *Schaubcylindrichnus freyi*, *Zoophycos*, and *Asterosoma* are more abundant in MC5 (basinward). This facies association is only developed in the lower one quarter of PS2d in wells MC3-MC5 (Figure 6.6). Facies Association Sm3b sharply or gradationally overlies FA Hb3 (distal prodelta/offshore), and underlies FA3a (lower shoreface/offshore transition).

6.4.4.8 Interpretation of Facies Association Sm3b

Facies Associations Sm3b is interpreted to be upper offshore (distal prodelta). The occurrence of hyperpycnites suggests a relationship with deltaics, and rare hummocks suggest these deposits are within storm wave base. However the dominance by massive facies indicate favorable conditions for bioturbation. The diversity and abundance in FA Sm3b are greater than seen in FA Sm3a. The diversity of behaviors, as well as the increase in the proportion of *Zoophycos* and *Asterosoma* are comparable to the Archetypal expression of *Cruziana* (e.g., MacEachern et al., 2007). This Ichnofacies expression is common for upper offshore Cretaceous shoreface deposits (e.g., Pemberton et al., 2012), but the slightly sandier nature of FA Sm3b may be resultant of the hyperpycnite transport of coarser sediment further basinward.

6.4.5 Facies Association Ha

6.4.5.1 Description of Facies Association Ha1

Facies Association Ha1 (FA Ha1) is clean, white, laminated or massive based

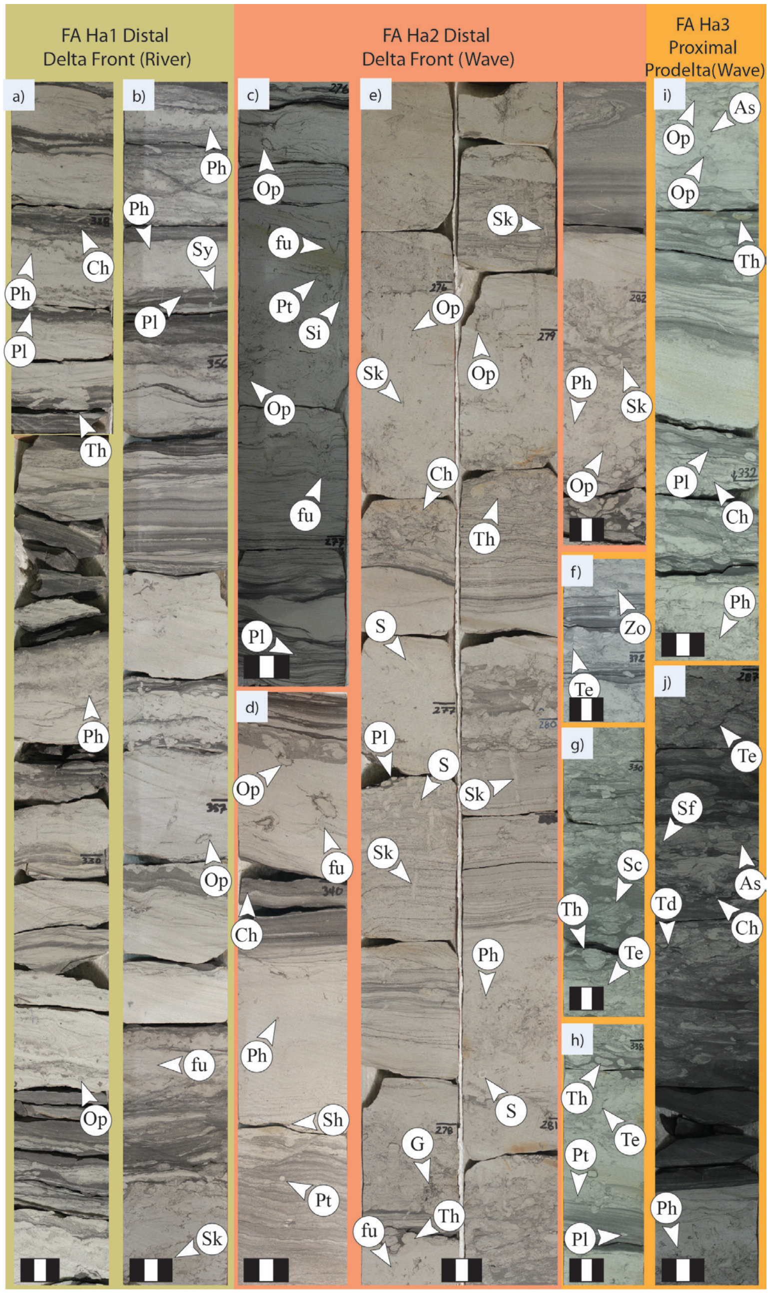


Figure 6.13: Facies Associations of Ha (FA Ha): a) heterolithic of FA Ha1 from PS2c in MC2 with dominant bioturbation by high density monospecific occurrences of *Palaeophycus heberti* (Ph) and cryptic bioturbation with rare appearances of *Planolites* (Pl), tiny *Ophiomorpha* (Op), *Chondrites* (Ch), and *Thalassinoides* (Th), b) similar trace assemblages in FA Ha1 of PS2d in MC5 with some fugichnia (fu), syneresis cracks (Sy), and *Skolithos* (Sk), c,d) the more aggradational expressions of FA Ha2 from MC3 and MC5 with larger *Ophiomorpha*, fugichnia, some *Chondrites*, *Palaeophycus tubularis* (Pt), *Siphonichnus* (Si), and shell debris (Sh), e) more heavily bioturbated expression of FA Ha2 from MC2 with similar traces and additionally more *Skolithos*, *Schaubcylindichnus* (S), and small groupings of organic-lined *Palaeophycus tubularis* (G), f-j) examples of FA Ha3 from MC3-MC5 showing greater diversity including *Teichichnus* (Te), *Scolicia* (Sc), *Asterosoma* (As), *Schaubcylindrichnus freyi* (Sf), and rare *Teredolites* (Td).

sandstones with sharp basal contact interbedded with 10-20% mudstone (Figure 6.13a,b) Sandstone beds normally have sharp tops, but some grade into tiny climbing ripple lamina. Some organic drapes can be seen along oscillation ripples, Mudstone contains normally graded sand or silt lamina, lenticular lamina, or lenticular bedding. Mudstone is sparsely bioturbated (BI=1) by *Planolites* (Possibly some are *Chondrites*), with rare tiny *Skolithos* and *Thalassinoides*. Sandstones may contain fugichnia, and rare thin walled *Ophiomorpha*, but dominant bioturbation is by high-density (BI 3-6) monospecific beds of *Palaeophycus heberti*. In rare cases, top may have *Diplocraterion*. Facies Association Ha1 is developed in the upper part of PS2c in MC2, and in the middle part of PS2d in MC5 (Figure 6.6). FA Ha1 is underlain by FA Sg (distal delta front), and is overlain by FA Sl1c (proximal delta front) and FA Sl1a (proximal delta front/ distributary).

6.4.5.2 Interpretation of Facies Association Ha1

Facies Association Ha1 is interpreted to be river-dominated distal delta front deposits. This facies association is interpreted as river-dominated delta front bay fill in PS2c by Bhattacharya and Davies (2004), and is therefore a similar interpretation for this association in PS2d. FA Ha1 is similar to the Distal *Skolithos* Ichnofacies (e.g., MacEachern et al., 2007), with this differing from the previously described Archetypal examples in the notable appearance of deposit feeders, *Chondrites*. The monospecific occurrences of *Palaeophycus heberti* in FA Ha1 reoccur more frequently than seen FA Sg, and likely also represent wave reworking. FA Ha1 may, in some cases, represent the shallower or less aggradational equivalent to FA Sg. This is supported by the occurrence over FA Sg in MC5.

6.4.5.3 Description of Facies Association Ha2

Facies Association Ha2 (FA Ha2) is composed of heterolithics with 5-30% mudstone (Figure 6.13c-e). Sandstone beds are typically sharp based, but maybe inversely graded, tops of beds may show some wave reworking. Mudstones may have graded climbing ripple lenses, lenticular bedding, and some syneresis cracks. Sandstones may have oscillation ripples, aggradational oscillation ripples, or low angle bedding. Some load structures may be present. Mud drapes are present locally. Generally organic lamina decreases upwards. Shell debris may be present. Sandstone beds contain thicker intervals of low angle bedding upwards. Contacts may be gradational or sharp. Traces are generally diminutive in size (*Palaeophycus* and *Ophiomorpha*), except for the occasional *Thalassinoides*. The *Ophiomorpha* has thin to medium thick walls. *Palaeophycus tubularis* is organic-lined but rarely groups together. Bioturbation decreases upwards in both abundance and interval thickness. Bioturbation is rare in the mudstone, with some clean *Planolites*, *Thalassinoides*, and *Arenicolites*. Sandstones can have small intervals of abundant bioturbation, much of which is cryptic bioturbation. Some *Skolithos* (lined and unlined, vertical and slightly inclined) and fugichnia are present. *Siphonichnus* and collapsed burrows are more rarely noted. The bioturbation intensity is mainly 1, with small intervals of 3 or 4. FA Ha2 is present in PS2d in the lower half of MC1-MC2, and around two-thirds of the way up in MC3-5 (Figure 6.6) Facies Association Ha2 interfingers with FA Sl2b (distal distributary), but may underlie FA Sl1c (proximal delta front), FA Sm2b (lower shoreface), or FA Sl2a (proximal delta front), or overlie FA Sm2b (lower shoreface), FA Sl1b (levee?), FA Hb2 (proximal prodelta) or Sl1a (proximal delta front/distributary).

6.4.5.4 Interpretation of Facies Association Ha2

Facies Association Ha2 is interpreted to be wave reworked distal delta front deposits. This is comparable to Gani et al. (2009) interpretation of this in MC2 as river/wave-dominated lower delta front. Wave reworking is reflected in the lenticular bedding, oscillation ripples, and low angle bedding; whereas the aggradational structures, loading, and syneresis cracks are indicative of river input. This assemblage is comparable to the Distal *Skolithos* Ichnofacies expression (e.g., MacEachern et al., 2007) in increased diversity from the Archetypal examples including facies crossing form *Siphonichnus*.

6.4.5.5 Description of Facies Association Ha3

Facies Association Ha3 (FA Ha3) is heavy bioturbated muddy sandstone interbedded with clean sandstone and approximately 10-25% mudstone (Figure 6.13f-j). The bottom contact is scoured with a clean heavily bioturbated sandstone. Top of association is bioturbated mudstone. FA Ha3 is dominantly fining upward cycles in the lower portion, with sharp based clean massive to rippled sandstones, to mud/organic mud draped aggradational or combined flow ripples, or graded lamina and mudstone. The upper portions are typically more dominated by inverse gradational mudstone and siltstone (hyperpycnites). Mud interbeds become more abundant and increase upwards in thickness (except in the bottom one to the right, MC5). Convolution and shell debris is rare. Bioturbation alternates between lower values above B=2 and complete bioturbation (BI=6). There is commonly *Planolites*, *Palaeophycus heberti*, *Palaeophycus tubularis* (sometimes in small groups), fugichnia, unlined and lined *Skolithos*, *Teredolites*, *Ophiomorpha*, *Chondrites*, *Schaubcylindrichnus* *freyi*. *Chondrites* are generally smaller basinward in this association. Occasionally there is *Teichichnus*, and the lower portions may have *Scolicia* and *Helminthopsis*. *Arenicolites* is rare. *Schaubcylindrichnus* is rare occurring in the more basinward locations. FA Ha3 is present in the lower half of MC3-5 (Figure 6.6). Facies Association FA Ha3 interfingers with FA Sm3a (lower shoreface/offshore), but can be overlain by FA Sg (distal delta front).

6.4.5.6 Interpretation of Facies Association Ha3

Facies Association Ha3 is interpreted to represent wave reworked proximal prodelta. It is essentially an interbedding of less bioturbated prodeltaic facies (FA Hb2) that is more comparable to Distal *Skolithos* and those of heavily bioturbated distal lower shoreface facies (FA Sm3a) comparable to Proximal *Cruziana*. This represents another example of a mixed *Skolithos*-*Cruziana* Ichnofacies expression.

6.4.6 Facies Association Hb

6.4.6.1 Description of Facies Association Hb1

Facies Association Hb1 is sandstone interbedded with approximately 25-50% mudstone (Figure 6.14a). There is load cast, convolution, syneresis cracks, lenticular bedding, Bouma Sequences, and some oscillation ripples. Ripples may have some organic mud drapes. Bioturbation is BI<3, but dominantly is 1 or 2. There is some *Palaeophycus tubularis*, *Helminthopsis*, *Chondrites*, *Planolites*, and *Thalassinoides*. Sandstones may also have fugichnia and some *Palaeophycus heberti*. *Schaubcylindrichnus freyi* and *Scolicia* are rare, mainly associated with few centimeters under the FA Hb3 (offshore). Almost all traces are diminutive in size. This only occurs in PS2c in MC5 (Figure 6.6).

6.4.6.2 Interpretation of Facies Association Hb1

Facies Association Hb1 is interpreted to be river-dominated proximal prodelta deposits in a brackish bay. This highly stressed environment is suggested by Bhattacharya and Davies (2004) for the lack of trace abundance and the small trace diameter.

6.4.6.3 Description of Facies Association Hb2

Facies Association Hb2 (FA Hb2) is sandstone interbedded with 20-50% mudstone. Sandstone content typically increases upwards, where as thickness of heavily bioturbated beds typically decreases. Mudstone is often silty and is dominantly composed of graded

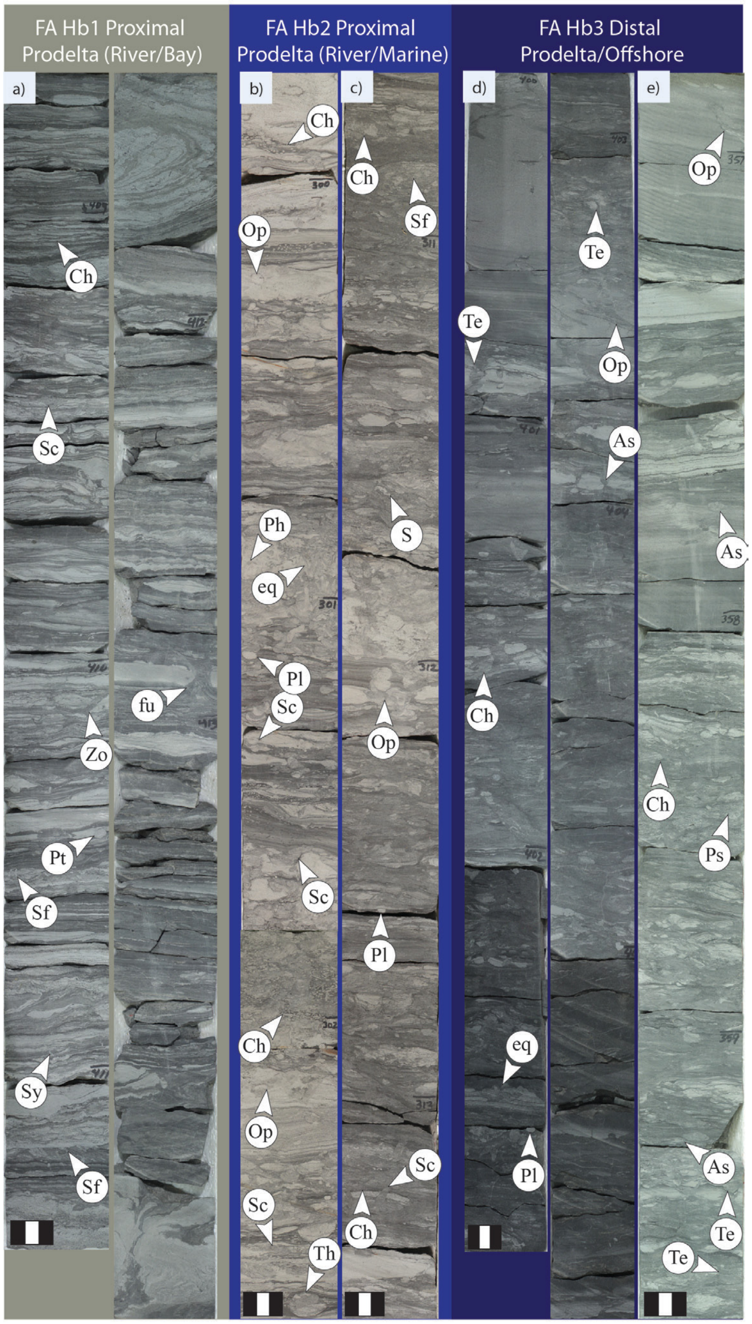


Figure 6.14: Facies Associations of Hb (FA Hb): a) heterolithics of Fa Hb1 in PS2c of MC5 (core base is bottom right) with rare and diminutive traces of *Chondrites* (Ch), *Scolicia* (Sc), *Zoophycos* (Zo), *Palaophycus tubularis* (Pt), *Schaubcylindrichnus freyi* (Sf) and fugichia (fu), as well as, syneresis cracks (Sy) and abundant soft sediment deformation, b, c) examples of FA Hb2 in PS2d from MC2 with more abundant bioturbation and more robust traces of *Ophiomorpha* (Op), *Chondrites*, *Scolicia*, *Planolites* (Pl), bivalve equilibrichnia (eq), fugichnia, *Thalassinoides* (Th), *Schaubcylindrichnus* (S), and *Schaubcylindichnus freyi*, d,e) mudstone-dominated heterolithics of FA Hb3 from MC5 and MC4 with event beds (hyperpycnites and turbidites) with intervening heavy bioturbation by *Chondrites*, *Teichichnus* (Te), *Asterosoma* (As), rare *Ophiomorpha*, *Planolites*, equilibrichnia, and *Phycosiphon* (Ps).

beds and lamina. The sand lamina have sharp bases and dominantly show normal grading. White sandstone interbeds and lamina where not thoroughly burrowed have sharp undulatory bases, and the tops often fine upwards or may be wave reworked. Bioturbation alternates between BI=1-3 and BI=4-6. Large *Chondrites* are a conspicuous feature of this facies association, as well as *Planolites* and *Thalassinoides*. Top of each sandying up cycle sharply terminate by heavy bio. *Palaeophycus heberti* and *Ophiomorpha* may dominate the sandstone beds. Additionally sandstone beds have blurred or disappearing sedimentary structures suggesting cryptobioturbation. Facies Association Hb2 lies under proximal (FA Sl1a) to distal (FA Sg, FA Ha2) delta front, and above proximal (FA Sl1c) to distal (FA Sg) delta front)(Figure 6.6).

6.4.6.4 Interpretation of Facies Association Hb2

Facies Association Hb2 is interpreted to be river-dominated prodeltaics entering into a fully marine system. This corresponds to Gani et al. (2009) interpretation of river-dominated prodelta deposits for these facies in MC2. They attributed Facies Association Hb2 to an Archetypal *Cruziana* expression, which is probably correct. This differs from the previously described Archetypal *Cruziana* facies association in this study due to the sparseness of grazers (*Phycosiphon* and *Helminthopsis*) and specialized deposit feeders (*Asterosoma* and *Zoophycos*). However, the difference in the later two could be related to taxonomonic interpretation (i.e., versus *Scolicia*). Either way these prodeltaic deposits represent a less stressed environment than the prodeltaics in FA Hb2.

6.4.6.5 Description of Facies Association Hb3

Facies Association Hb3 is interbedded bioturbated mudstone with sparsely bioturbated mudstone to sandstone. This facies association is composed of >50% mudstone which is regularly bioturbated in small intervals (<6cm thick). The highly bioturbated mudstones are interbedded with inversely graded lamina/beds of mudstone to sandstone that coarsen quickly and then fine over a larger interval. These inversely graded beds may become more massive upwards, and/or show convolution due to loading. In the lower portion to middle these facies may display aggradational oscillation ripples. Some small (<2cm), sharp, undulatory based, normally graded sandstones are present in this facies association. Both of these graded facies are sparsely burrowed, typically showing BI between 1-3. Bioturbation appears to increase upwards, but that may be due to the lithological contrast, as the unit sandies upwards. Some mud drapes and organic mud drapes are present. *Chondrites* (big and small), *Planolites*, *Thalassinoides*, are abundant, with some *Helminthopsis*, *Phycosiphon*, *Teichichnus*, *Scolicia*, *Palaeophycus* (lined), and *Schaubcylindrichnus freyi*. *Schaubcylindrichnus*, *Palaeophycus* (halo) fugichnia, *Arenicolites*, and *Skolithos* are rare. *Siphonichnus* is abundant landward in MC3, whereas *Phycosiphon* and *Asterosoma* are more abundant to the west (MC5). Some scour and fill structures occur. FA Hb3 lies over proximal (FA Sl1c) to distal (FA HA1) delta front bayfill, and under upper offshore/distal prodelta deposits (FA Sm3b)(Figure 6.6).

6.4.6.6 Interpretation of Facies Association Hb3

Facies Association HB3 is interpreted to represent distal prodelta/offshore deposits. This corresponds to offshore deposits of Pemberton et al. (2012) in mudstone dominated lithologies and trace assemblages comparable to the archetypal expressions of the *Cruziana* Ichnofacies. Conversely, the hyperpynite event beds suggest at least some deposition is reliant on deltaic input.

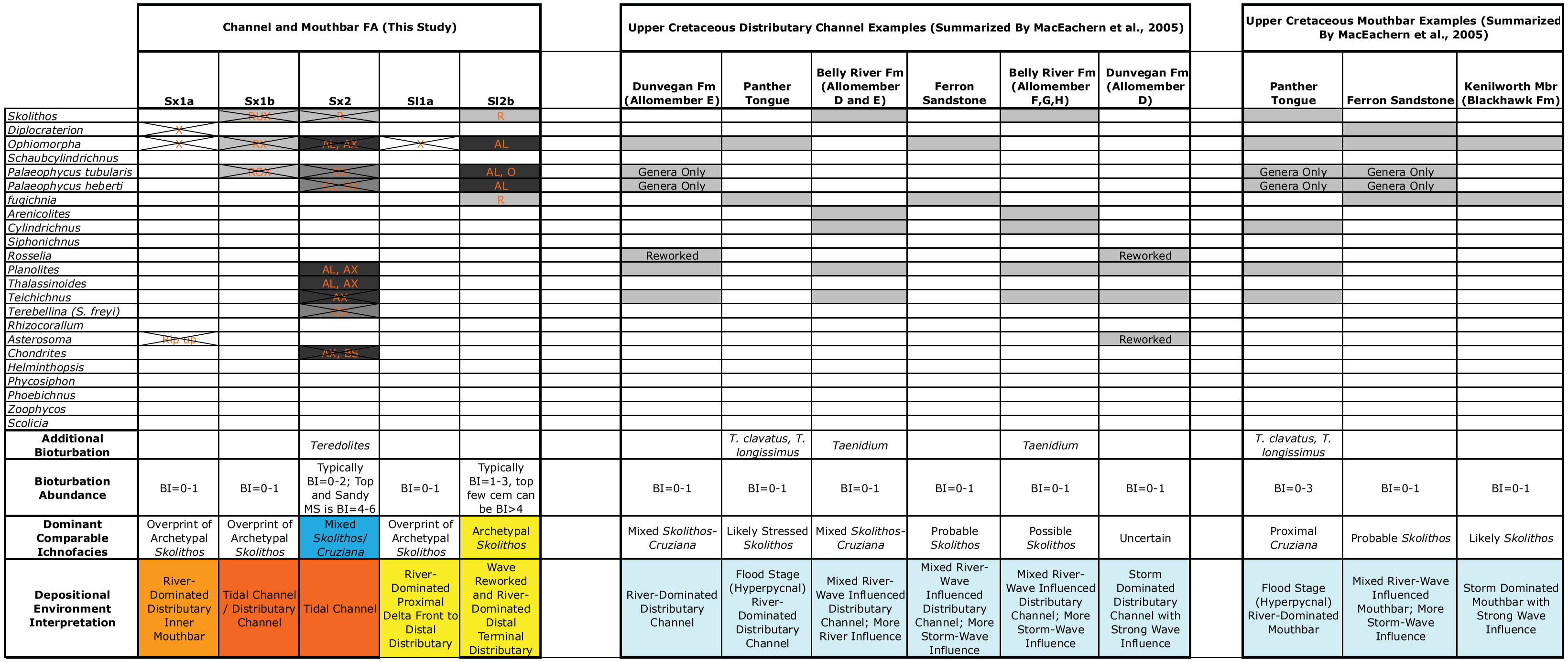
6.5 DISCUSSION

6.5.1 Ferron Assemblages versus Deltaic Ichnofacies Model

The purpose of this section is to compare the facies associations with the Upper Cretaceous deltaic examples compiled by MacEachern et al. (2005). These will be described under four generalized categories: channel/mouthbar, proximal delta front, distal delta front, and prodelta. Channel and mouthbar are lumped together due to their intergradational nature. The four wave-dominated facies associations of Sm will not be addressed, even though they likely have deltaic influence, since their nature is closer to shoreface models.

6.5.1.1 Channel/ Mouthbar

Five facies associations in this study are interpreted as channel or mouthbar deposits. Much of the bioturbation is related to the transgressive overprinting by deep-tiered burrows (e.g., *Ophiomorpha*)(Table 6.2). This is especially true in the river-dominated facies associations (FA Sx1a, FA Sl1a). The river-dominated, inner distributary mouthbar (FA Sx1a) is most comparable to the wave influenced mouthbar examples from the Ferron Sandstone and Kenilworth Member in terms of the assemblage's dominant component



	Channel and Mouthbar FA (This Study)					Upper Cretaceous Distributary Channel Examples (Summarized By MacEachern et al., 2005)						Upper Cretaceous Mouthbar Examples (Summarized By MacEachern et al., 2005)		
	Sx1a	**Sx1b**	**Sx2**	**Sl1a**	**Sl2b**	**Dunvegan Fm (Allomember E)**	**Panther Tongue**	**Belly River Fm (Allomember D and E)**	**Ferron Sandstone**	**Belly River Fm (Allomember F,G,H)**	**Dunvegan Fm (Allomember D)**	**Panther Tongue**	**Ferron Sandstone**	**Kenilworth Mbr (Blackhawk Fm)**
Skolithos		RUX	R		R			▨		▨		▨		
Diplocraterion	X												▨	
Ophiomorpha	X	RX	AL, AX	X	AL	▨	▨		▨			▨	▨	▨
Schaubcylindrichnus														
Palaeophycus tubularis		ROX	CX		AL, O	Genera Only						Genera Only	Genera Only	
Palaeophycus heberti			CL, AX		AL	Genera Only						Genera Only	Genera Only	
fugichnia					R		▨		▨				▨	▨
Arenicolites								▨		▨				
Cylindrichnus								▨		▨		▨		
Siphonichnus														
Rosselia						Reworked					Reworked			
Planolites			AL, AX			▨		▨		▨	▨	▨		
Thalassinoides			AL, AX											
Teichichnus			AX			▨		▨		▨	▨	▨		
Terebellina (S. freyi)			CX											
Rhizocorallum														
Asterosoma	Rip up										Reworked			
Chondrites			AX, BS											
Helminthopsis														
Phycosiphon														
Phoebichnus														
Zoophycos														
Scolicia														
Additional Bioturbation			*Teredolites*				*T. clavatus, T. longissimus*	*Taenidium*		*Taenidium*		*T. clavatus, T. longissimus*		
Bioturbation Abundance	BI=0-1	BI=0-1	Typically BI=0-2; Top and Sandy MS is BI=4-6	BI=0-1	Typically BI=1-3, top few cem can be BI>4	BI=0-1	BI=0-1	BI=0-1	BI=0-1	BI=0-1	BI=0-1	BI=0-3	BI=0-1	BI=0-1
Dominant Comparable Ichnofacies	Overprint of Archetypal *Skolithos*	Overprint of Archetypal *Skolithos*	Mixed *Skolithos/ Cruziana*	Overprint of Archetypal *Skolithos*	Archetypal *Skolithos*	Mixed *Skolithos-Cruziana*	Likely Stressed *Skolithos*	Mixed *Skolithos-Cruziana*	Probable *Skolithos*	Possible *Skolithos*	Uncertain	Proximal *Cruziana*	Probable *Skolithos*	Likely *Skolithos*
Depositional Environment Interpretation	River-Dominated Distributary Inner Mouthbar	Tidal Channel / Distributary Channel	Tidal Channel	River-Dominated Proximal Delta Front to Distal Distributary	Wave Reworked and River-Dominated Distal Terminal Distributary	River-Dominated Distributary Channel	Flood Stage (Hyperpycnal) River-Dominated Distributary Channel	Mixed River-Wave Influenced Distributary Channel; More River Influence	Mixed River-Wave Influenced Distributary Channel; More Storm-Wave Influence	Mixed River-Wave Influenced Distributary Channel; More Storm-Wave Influence	Storm Dominated Distributary Channel with Strong Wave Influence	Flood Stage (Hyperpycnal) River-Dominated Mouthbar	Mixed River-Wave Influenced Mouthbar; More Storm-Wave Influence	Storm Dominated Mouthbar with Strong Wave Influence

Table 6.2: Comparison of channel/mouthbar trace assemblages. The trace assemblages of channels and mouthbars from this study are on the left, whereas the examples of Upper Cretaceous distributary channel and mouthbar assemblages as compiled by MacEachern et al. (2005) are on the right. The data in this study shows that many of the traces found in these assemblages in the Ferron Sandstone are related to overprinting from the subsequent environment.

being *Ophiomorpha* (Table 6.2). However, the traces are overprinting the original deposits, and the dominance by high angle cross-beds is less suggestive of storm/wave energy. The presence of *Asterosoma* near the top of this association is an allocthonous component, likely related to a thin high-energy transgressive erosion/deposition. Reworked *Asterosoma* and *Rosselia* are seen in distributary channel deposits of both the river-dominated and storm-dominated deposits (Table 6.2). This begs the question of how many transgressive facies get lumped in with proximal deltaic facies.

The terminal distributary channel facies with wave reworking (FA Sl2b), are different from the river-dominated channel/mouthbar association and most of the case studies (from both river and wave/storm dominance) in that the bioturbation of Sl2b can be much greater. The river-dominated mouthbar example of the Panther Tongue is the closest, but shows greater diversity. As can be seen in Table 6.2, there does not appear to be an important trace in the more wave/storm dominated assemblage. Conversely, in this study both ichnotaxa of *Palaeophycus* are the dominant representatives.

The definitive tidal channel facies (FA Sx2) are similar to the river-dominated facies associations in that they are often overprinted at the top by more diverse traces, and to the wave reworked facies association in showing greater abundance than typically seen in river-dominated assemblages. The burrows along "pause planes" of MacEachern et al. (2005) are often *Planolites* in distributary assemblages, whereas the tidal channel (FA Sx2) often additionally has *Thalassinoides*. The *Ophiomorpha* initiating in/from the tidal channel are also very robust in comparison to *Ophiomorpha* that are not linked to transgressive overprinting.

6.5.1.2 Proximal Delta Front

The proximal delta front assemblages in FA Sl1c and Sl2a are similar to the channel/mouthbar assemblages with the main components being related to the Archetypal *Skolithos* Ichnofacies (*Skolithos Diplocraterion*, and both *Palaeophycus*), however abundance is slightly higher, and these ichnogenera are inherent of the depositional environment rather than overprinting related to the top of the facies association. Additionally, *Thalassinoides* becomes more representative in mudstones as the proportion of mudstone has increased. Overprinting is seen in FA Sl1c as *Teichichnus*, *Chondrites*, *Scolicia* and *Diplocraterion*. The major difference between the wave reworked and river-dominated proximal delta front associations is the slightly greater abundance and consistency of bioturbation.

In comparison to the compilation of MacEachern et al. (2005)(Table 6.3), the

	Proximal Delta Front FA (This Study)		**Upper Cretaceous Proximal Delta Front Examples (Summarized By MacEachern et al., 2005)**							
	Sl1c	**Sl2a**	**Dunvegan Fm (Allomember E)**	**Panther Tongue**	**Belly River Fm (Allomember D and E)**	**Ferron Sandstone**	**Belly River Fm (Allomember F,G,H)**	**Wilcox Fm**	**Dunvegan Fm (Allomember D)**	**Kenilworth Mbr (Blackhawk Fm)**
Skolithos	▓ ?OM	▓ CL,U				░	░	░	░	░
Diplocraterion	X	░ R, X?		░		░ *D. habichi*			░	
Ophiomorpha	░ R	░ C-R,V	░ Isolated	░		░	▓	░	░	░
Schaubcylindrichnus				░						
Palaeophycus tubularis	░ RO	▓ CL, C, D, OG				░ Genera Only				
Palaeophycus heberti	░ R	▓ CM, CL, R				░ Genera Only				
fugichnia		▓ C-A		░		░	▓	░		░
Arenicolites				░		░	░	░		░
Cylindrichnus				░			░		░	░
Siphonichnus						░ Bivalve Eq				░ Bivalve Eq
Rosselia						░	▓ Truncated		░	░
Planolites	░ R		░ Isolated		░	░	▓			
Thalassinoides	░ R	░ R				░				
Teichichnus	X		░ Isolated				▓			
Terebellina (S. freyi)										
Rhizocorallum										
Asterosoma										
Chondrites	X									
Helminthopsis										
Phycosiphon										
Phoebichnus										
Zoophycos										
Scolicia	X									
Additional Bioturbation	*Teredolites*			Teredolites *longissimus*	*Macaronichnus*, Roots	*?Conichnus*, *Teredolites*	*Macaronichnus*, Roots, uncommon *Taenidium*		*Macaronichnus*, Roots	*Macaronichnus*, Roots, *Conichnus*
Bioturbation Abundance	BI=0-2; typically <1; overprint >4	Typically BI=1-2, small intervals can be up to BI=4	BI=0-1	BI=0-2	BI=0-2; *Macaronichnus* in "toe of the beach" position reaches BI=3	BI=0-2, mainly BI=0-1	BI=0-2, mainly BI=0-1	BI=0-2	BI=0-2, rare bands of BI=5 *Macaronichnus* in "toe of the beach" assemblage	BI=0-3; mainly <2
Dominant Comparable Ichnofacies	Archetypal *Skolithos*	Archetypal *Skolithos*	Uncertain	Proximal *Cruziana*	Uncertain	Mixed *Skolithos*-*Cruziana*	Mixed *Skolithos*-*Cruziana*	*Skolithos*	Mixed *Skolithos*-*Cruziana*	Mixed *Skolithos*-*Cruziana* to Distal *Skolithos*
Depositional Environment Interpretation	River-Dominated (Brackish Bay) Proximal Delta Front	Wave Reworked to Dominated Proximal Delta Front	River-Dominated Proximal Delta Front	Flood Stage (Hyperpycnal) River-Dominated Proximal Delta Front	Mixed River-Wave Influenced Proximal Delta Front; More River Influence	Mixed River-Wave Influenced Proximal Delta Front; More Storm-Wave Influence	Mixed River-Wave Influenced Proximal Delta Front; More Storm-Wave Influence	Wave-Dominated Proximal Delta Front with Moderate to Strong Storm Influence	Storm Dominated Proximal Delta Front with Strong Wave Influence	Storm Dominated Proximal Delta Front with Strong Wave Influence

Table 6.3: Comparison of proximal delta front trace assemblages. The assemblages on the left are from this study, whereas the assemblages on the right are compiled in MacEachern et al. (2005) of Upper Cretaceous proximal delta front deposits.

assemblages of ichnotaxa are similar with little being represented in terms of deposit feeding and grazing behaviors, and in typical abundance values. Conversely, in this study there is no indication of *Arenicolites*, *Cylindrichnus*, or *Rosselia* being common components of the Ferron Sandstone proximal delta front. This could be an ethological difference or an ichnotaxonomic nomenclature bias (i.e., how much curvature/inclination between *Skolithos* and *Arenicolites*; how much lining between *Skolithos* and *Cylindrichnus*). There is no common, truly robust mudstone-lined forms (*Cylindrichnus* and *Rosselia*) seen in this study interval as compared to the typical ichnofacies models for proximal delta fronts). Additionally, much like the channel/mouthbar case studies, there is a lack of representation in the case studies, relative to the importance of the *Palaeophycus* ichnogenera seen in the trace assemblages of the facies associations. A notable difference between the river-dominated and more wave/storm dominated proximal delta front assemblages, is the occurrence of *Macaronichnus* and roots as you trend towards the basinal processes. This is important to the later discussion of the transgressive overprinting of proximal facies. *Macaronichnus* were not observed in the study interval, but *Macaronichnus* is hard to identify in more homogeneous lithologies (e.g., Pemberton et al., 1992).

The interpretation of ichnofacies in this paper is vastly different from most of the case studies (e.g., Distal *Skolithos*, mixed *Skolithos*-*Cruziana*, and Proximal *Cruziana* Ichnofacies) in that both proximal delta front facies interpretation are interpreted as being comparable to Archetypal *Skolithos*. The case studies have similar trace assemblages, and similarly lack indications of infaunal deposit feeding and grazing, which was the main reasoning for not interpreting a comparable distal or *Cruziana* expressions for the facies association. These components may however overprint the top of the facies associations during transgression.

6.5.1.3 Distal Delta Front

The distal delta front facies associations (FA Sg, FA Ha1, FA Ha2) have similar bioturbation abundance values to the more proximal facies associations with pause planes or wave reworked intervals having spikes in higher values (Table 6.4). From proximal to distal *Palaeophycus tubularis* becomes less abundant to absent, and *Chondrites* becomes noticeable. In the wave reworked delta front associations. *Schaubcylindrichnus* and *Siphonichnus* appear. These facies associations are comparable to the *Skolithos* Ichnofacies (distal where deposit feeders identified), which is different from the Upper Cretaceous case studies of which a *Cruziana* Ichnofacies affinity is more appropriate. The difference

	Distal Delta Front FA (This Study)			Upper Cretaceous Distal Delta Front Examples (Summarized By MacEachern et al., 2005)							
	Sg	**Ha1**	**Ha2**	**Dunvegan Fm (Allomember E)**	**Panther Tongue**	**Belly River Fm (Allomember D and E)**	**Ferron Sandstone**	**Belly River Fm (Allomember F,G,H)**	**Wilcox Fm**	**Dunvegan Fm (Allomember D)**	**Kenilworth Mbr (Blackhawk Fm)**
Skolithos	░ R	░ R	░ R-C, UK			░		░	░	▓	▓
Diplocraterion		?		░					░	▓	▓ D. habichi
Ophiomorpha	X	░ RD	▓ R-C,D, GO	░	▓		░	░	░		▓
Schaubcylindrichnus			░ R		▓						▓
Palaeophycus tubularis			▓ R-C, GO	░ Genera Only	░ Genera Only	░ Genera Only	░ Genera Only	▓ Genera Only	░ Genera Only	▓ Genera Only	▓ Genera Only
Palaeophycus heberti	░ RM	█ AL, M	▓ R-DC	░ Genera Only	░ Genera Only	░ Genera Only	░ Genera Only	▓ Genera Only	░ Genera Only	▓ Genera Only	▓ Genera Only
fugichnia	░ R	░ R	░ R	░	▓	░		░	░	▓	▓
Arenicolites			░ R		▓	░	░	░	░		▓
Cylindrichnus				░	▓	░	░	░	░	▓	▓
Siphonichnus			░ R		░ Bivalve Eq		░ Bivalve Eq		░		
Rosselia					▓	▓	░	▓ Truncated	░	▓	▓
Planolites	░ R	░ R	░ R	░		▓	░	▓	░	▓	▓
Thalassinoides		░ R	░ R	░	▓		░		░	▓	▓
Teichichnus				░	▓	▓		░	░	▓	
Terebellina (S. freyi)				░					░	▓	▓
Rhizocorallum				░		░					▓
Asterosoma				░			░	░	░		▓
Chondrites		░ R	░ R				░		░		▓
Helminthopsis				░		░	░		░	▓	▓
Phycosiphon				░		▓	░	▓	░	▓	▓
Phoebichnus											
Zoophycos				░					░	▓	
Scolicia									░		
Additional Bioturbation	*Teredolites*				*Lockea, Taenidium, Teredolites*	*Macaronichnus, Taenidium*	*Teredolites, Lockea*	*Macaronichnus*			*Conichnus, Macaronichnus*
Bioturbation Abundance	BI=0-1; except pause planes which can be >4	BI=3-6, thin event bed of BI=1	BI=0-3	BI=0-2	BI=0-3	BI=0-2	BI=0-3	BI=0-2; rare bands of BI=2	BI=3-5; tempestites BI=0-3	BI=0-4; mainly BI=0-3	BI=2-5; mainly 2-3; tempestites BI=0-2
Dominant Comparable Ichnofacies	Archetypal *Skolithos*	Distal *Skolithos*	Distal *Skolithos*	Archetypal *Cruziana*	Proximal *Cruziana*	Proximal *Cruziana*	Proximal *Cruziana* to Mixed *Skolithos Cruziana*	Mixed *Skolithos*-*Cruziana*	Proximal/ Archetypal *Cruziana*	Mixed *Skolithos*-*Cruziana*	Mixed *Skolithos*-*Cruziana*
Depositional Environment Interpretation	River-Dominated (Flood Stage) Middle to Distal Delta Front	River-Dominated Distal Delta Front	Wave Reworked Middle-Distal Delta Front	River-Dominated Distal Delta Front	Flood Stage (Hyperpycnal) River-Dominated Distal Delta Front	Mixed River-Wave Influenced Distal Delta Front; More River Influence	Mixed River-Wave Influenced Distal Delta Front; More Storm-Wave Influence	Mixed River-Wave Influenced Distal Delta Front; More Storm-Wave Influence	Wave-Dominated Distal Delta Front with Moderate to Strong Storm Influence	Storm Dominated Distal Delta Front with Strong Wave Influence	Storm Dominated Distal Delta Front with Strong Wave Influence

Table 6.4: Comparison of distal delta front trace assemblages. The trace assemblages on the left are from this study, whereas the distal delta front assemblages to the right are from the compilation of MacEachern et al. (2005).

between the two is likely based on how each author defines “distal delta front”, of which this study uses the definition in the Ferron Sandstone as defined by Garrison and van den Bergh (2004) for FA Ha1 and FA Ha2; and reasoning based off of hyperpycnite preservation for FA Sg. The case studies likely use a more distal expression of facies than used in this study. The standardization of what constitutes “distal delta front” versus “prodelta”, and that of distal delta front trace assemblages will probably persist as a problem in literature for the foreseeable future because lithological cutoffs are hard to establish, especially based off heterogeneity due to fluid mud input and hyperpycnal transport, which can create exceptions to the simple models of proximity to source deposition.

6.5.1.4 Prodelta

The prodeltaic facies association show much larger diversity than the distal delta front facies associations with the appearance of traces such as *Teichichnus*, *Schaubcylindrichnus freyi*, *Asterosoma*, *Helminthopsis*, *Zoophycos* and *Scolicia*. The prodeltaic facies associations in this study are divided into proximal prodeltaic versus distal prodeltaic/offshore based on a 50% mudstone cut off. The distal prodeltaic/offshore (FA Hb3) is the only one comparable to the Archetypal *Cruziana* Ichnofacies cited by a majority of the prodeltaic case studies (Table 6.5). FA Hb3 shows fluctuation in bioturbation similar to the storm/wave-dominated case studies, but the low abundance bioturbation of the storm/wave-dominated case studies is related to tempestites, whereas a majority of these event beds in FA Hb3 are hyperpycnite related. The proximal deltaics are divided into three types (wave reworked, river-dominated bay, and river-dominated marine) representing various expressions of *Cruziana*. The river-dominated bay-fill prodelta is easily distinguishable from the other two due to the low bioturbation abundance values and the diminutive size of the burrows. This depauperate expression comparable to *Cruziana* is most like the river-dominated prodeltaics of the Dunvegan Allomember E. The less stressed, marine, river-dominated prodeltaics (FA Hb2) has more robust forms and punctuated abundance that is more similar to the river-dominated end of the spectrum in terms of trace assemblage, but more similar to the wave/storm end of the spectrum in terms of bioturbation abundance values. FA Hb2 represents the proximal expression of the *Cruziana* Ichnofacies. The wave reworked proximal prodeltaics (FA Ha3) comprise a mixed *Skolithos*-*Cruziana* assemblage with higher diversity and abundance than its river-dominated counterparts. This is comparable to the prodeltaics, but perhaps more comparable to the distal delta front deposits of the wave-dominated Wilcox Formation.

	Prodelta FA (This Study)				Upper Cretaceous Prodelta Examples (Summarized By MacEachern et al., 2005)							
	Ha3	**Hb1**	**Hb2**	**Hb3**	**Dunvegan Fm (Allomember E)**	**Panther Tongue**	**Belly River Fm (Allomember D and E)**	**Ferron Sandstone**	**Belly River Fm (Allomember F,G,H)**	**Wilcox Fm**	**Dunvegan Fm (Allomember D)**	**Kenilworth Mbr (Blackhawk Fm)**
Skolithos	R, UK			R			Very Rare		░	▒	In Tempestites	
Diplocraterion										▒	In Tempestites	
Ophiomorpha	C		R-C			░	Very Rare			▒		
Schaubcylindrichnus				C								
Palaeophycus tubularis	C, some G	RK		C		Genera Only		Genera (Temp)		Genera Only		Genera Only
Palaeophycus heberti	C	R	R-C	C		Genera Only		Genera (Temp)		Genera Only		Genera Only
fugichnia	C	R		C	░		Very Rare	In Tempestites	▒	▒	▒	
Arenicolites	R			R					░			
Cylindrichnus						░		In Tempestites	▒	▒	▒	
Siphonichnus			Bivalve Eq	AL		Bivalve Eq	Very Rare	Bivalve Eq(Temp)	░	▒	▒	
Rosselia			R				░		░	▒	▒	
Planolites	C	R	C-A	A	░	░	▒	▒	▓	▒	▒	▒
Thalassinoides	C	R	C-A	A		░	░	▒	░	▒		
Teichichnus	C			C	░		▒	▒	▒	▒	▒	▒
Terebellina (S. freyi)	R	RD	R	C	░	░		▒	▒	▒	▒	▒
Rhizocorallum												
Asterosoma	R			AL		░	░	▒		▒	▒	
Chondrites	C	R	N-A	A		░	Very Rare	▒	▒	▒	▒	▒
Helminthopsis	CL	R		C	░	░	▒	▒	▓	▒	▒	▒
Phycosiphon				AL	░	░	▒	▒	▓	▒	▒	▒
Phoebichnus										▒		
Zoophycos	R	RD			░		Very Rare		░	▒	▒	
Scolicia	CL	RD, RX	R	C						▒		
Additional Bioturbation	*Teredolites*					*Monocraterion*				*Taenidium*	*Lockea*	*Lockea*
Bioturbation Abundance	BI=2-3; bands of 4-6	BI=0-3; dominantly BI=1-2	Alternating BI=1-3 and BI=4-6	BI=4-6; hyperpycnites BI=1-3	BI=0-2	BI=1-3	BI=0-2	BI=1-3	BI=0-3	BI=1-5	BI=1-3; rare bands of BI=4	BI=2-3; locally BI=4-5 bands
Dominant Comparable Ichnofacies	Mixed *Cruziana/ Skolithos*	Depauperate *Cruziana*	Proximal *Cruziana*	Archetypal *Cruziana*	*Cruziana*	Archetypal *Cruziana*	Archetypal *Cruziana*	Archetypal *Cruziana*	Archetypal *Cruziana*	Archetypal *Cruziana*	Archetypal *Cruziana*	Archetypal *Cruziana*
Depositional Environment Interpretation	Wave Reworked Proximal Prodelta	River-Dominated (Brackish Bay) Proximal Prodelta	River-Dominated (Marine) Proximal Prodelta	Distal Prodelta/ Offshore	River-Dominated Prodelta	Flood Stage (Hyperpycnal) River-Dominated Prodelta	Mixed River-Wave Influenced Prodelta; More River Influence	Mixed River-Wave Influenced Prodelta; More Storm-Wave Influence	Mixed River-Wave Influenced Prodelta; More Storm-Wave Influence	Wave-Dominated Prodelta with Moderate to Strong Storm Influence	Storm Dominated Prodelta with Strong Wave Influence	Storm Dominated Prodelta with Strong Wave Influence

Table 6.5: Comparison of prodelta trace assemblages. The examples from this study (on left) are separated into proximal and distal, with distal representing more than 50% mudstone content. The examples on the right are undifferentiated prodeltaic trace assemblages from the Upper Cretaceous as compiled by MacEachern et al. (2005).

6.5.2 The *Scolicia* Problem

In addition to the under representation of *Palaeophycus* in delta front assemblages, *Scolicia* is an important component to the distal delta facies from distal delta front basinward. Not only that, but it is found in almost every assemblage comparable to *Cruziana* in this study, not just the distal expression as suggested by MacEachern et al. (2007). Other case studies compiled in MacEachern et al. (2005) list *Scolicia* or similar backfilling structure *Taenidium* in Proximal and Archetypal expressions of *Cruziana* in deltaic facies (Table 6.4, 6.5). These occur in the river-dominated distal delta front assemblages of the Panther Tongue and Belly River Formation as *Taenidium*, and as *Scolicia* and *Taenidium* in the distal delta front and prodelta deposits of the storm-dominated Wilcox Formation. *Scolicia* has also been noted in distal delta front deposits by Olariu et al. (2010). In the modern, Frazier River Delta *Scolicia* traces are present in the downdrift side of the prodelta (Ayranci et al., 2014). The traces seen in this study are often diminutive (<2cm width), which is in agreement with the dwarfism seen in *Bichordites* of the interpreted stressed prodeltaic conditions of the Oligocene Mezardere Formation in Demírcan and Uchman (2012).

Meniscate backfilled traces with drain structures such as *Scolicia* and *Bichordites* are attributed to infaunal burrowing by irregular echinoids (Spantangoids; Smith and Crimes, 1983; Uchman, 1995). However, the drain structures may also not be present in spantangoid burrows due to collapse (Kanazawa, 1995; de Gibert and Goldring, 2008). This would result in the ichnotaxa being attributed to a simpler meniscate form. Echinoderm-produced meniscate structures (*Scolicia*) are known back to the late Jurassic (Tchoumatchenco and Uchman, 2001). Irregular echinoids (e.g., *Moira atropos* and *Echinocardium*) are known from shallow (mean low tide level) to abysmal depths (hundreds of meters deep) in modern settings (Chesher, 1963; Dörjes, 1972, Kashenko, 2006). The irregular echinoids are quick and highly efficient burrowers (Gingras et al., 2008) and the most widespread bioturbaters in modern marine environments (de Gibert and Goldring, 2008). The reason for association with these traces in the rock record with more distal ichnofacies is likely related to the taphonomic controls (e.g., Bromley and Asgaard, 1975).

According to the literature synthesis of de Gibert and Goldring (2008), the preservation of the spantangoid meniscate traces (Figure 6.15) relies on a backfilling burrowing mechanism, heterogeneous sediment, and since they are shallow-tiered burrowers (max 10-30cm) must not be overprinted by intense deep-tiered burrowing nor

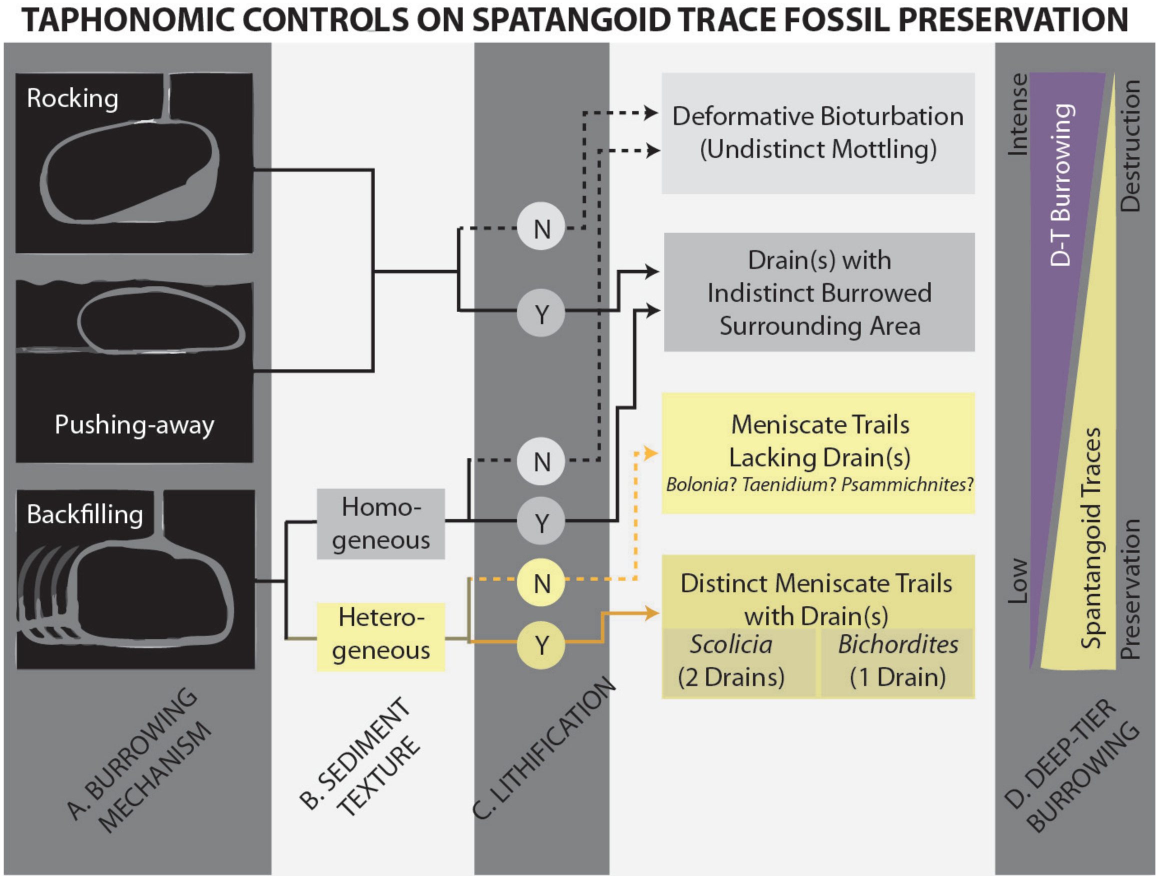


Figure 6.15: Taphonomic controls of spatangoid trace fossil preservation (modified from de Gibert and Goldring, 2008). Meniscate backfilled burrows are created in heterogeneous sediments with little or no reworking (biological or physical processes).

the sediment actively reworked by waves. The reason for the meniscate backfilled burrows association with the proximal and archetypal expressions of *Cruziana* in distal deltaic setting could be related to stresses limiting bioturbation abundance, limited colonization periods (rapid burrowing by diminutive echinoderms), and aggradation enhances preservation. Also, heterogeneity is typically greater in the delta front/proximal prodelta than it is in the lower shoreface (river-dominated distal delta front deposits can have twice the percentage mudstone, up to 30%, compared to lower shoreface deposits in the Ferron Sandstone; Garrison and van den Bergh, 2004). Furthermore, there could be less wave reworking of shallow-tiered traces, or there may be an ethological reason such as deltaic transport of food resources (the link between modern irregular echinoderm (*Echinocardium*) and high TOC, where food quantity controls the abundance of the animals, food quality controls the growth of the organisms, and decreases in abundance are linked to increased wave activity, which limits the setting of organics onto the sediment surface; Wieking and Krönke, 2003). Additionally, the food resource paradigms between shorefaces and deltas are different (Figure 6.16), and hyperpycnites would provide a means by which to trap and carry lighter nutrients, whether organic detritus or calcareous marine life.

6.5.3 Stratigraphic Boundaries and Lateral Relationships

The stratigraphic boundaries can be defined in two ways: those that relate to the parasequence boundaries of PS2d (flooding surfaces, and associated transgressive ravinement surfaces), and those related to the transition between wave-dominated and river-dominated facies (Figure 6.17). The bulk of the sediment is believed to prograde towards the northwest, but the thicker accumulation of sediment basinward (NW), thinning of facies associations landward (SE), and the disappearance of sharp boundaries basinward suggest that there is a secondary opposing or oblique source of the sediment intermittently (Figure 6.17).

6.5.3.1 Parasequence Boundaries and Associated Transgressive Erosion

The parasequence boundaries above and below PS2d are similar to what is described by Ryer and Anderson (2004) and Bhattacharya and Davies (2004) in terms of deep-tiered overprinting of *Ophiomorpha* at the flooding surface (Figure 6.18a,b). There is also a rapid increase in the abundance of bioturbation at the top of these proximal sandstone facies associations, as well as seen (*sans Ophiomorpha*) at the upper boundary of the prodelta

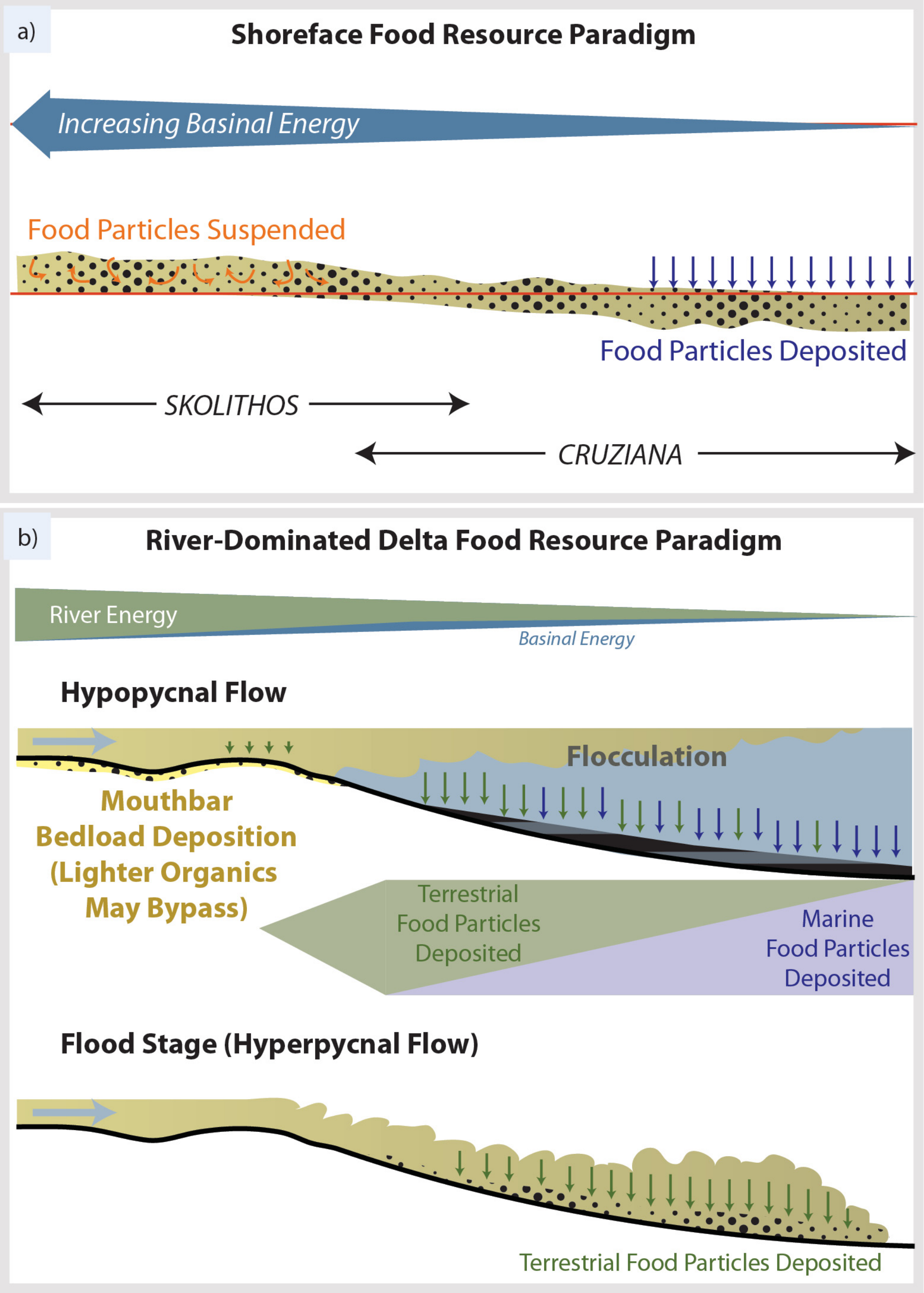


Figure 6.16: Food resource paradigms: a) the shoreface food resource paradigm focuses on how basinal processes act to suspend food closer to the shoreline (modified from Pemberton et al., 2001), and b) is hypothetical food resource distribution in river dominated deltas, with mouthbar and hypopycnal distribution typically and potential hyperpycnal distribution of resources during flood stages (modified from Fisher et al., 1969, after Bates, 1953). The shoreface paradigm applies more to marine organics, where as the deltaic paradigms involve terrestrial organics.

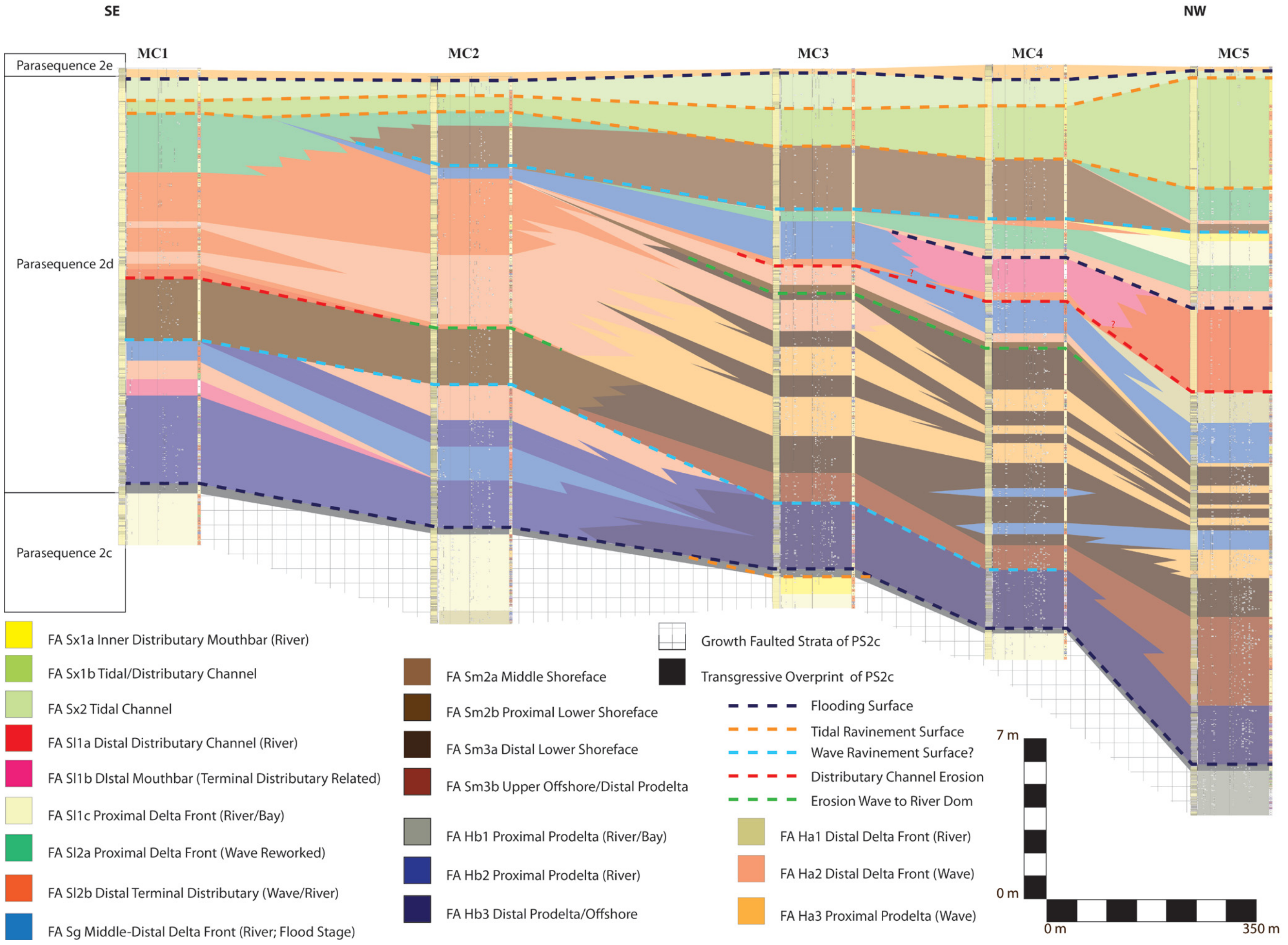


Figure 6.17: Stratigraphic surfaces in wells MC1-MC5.

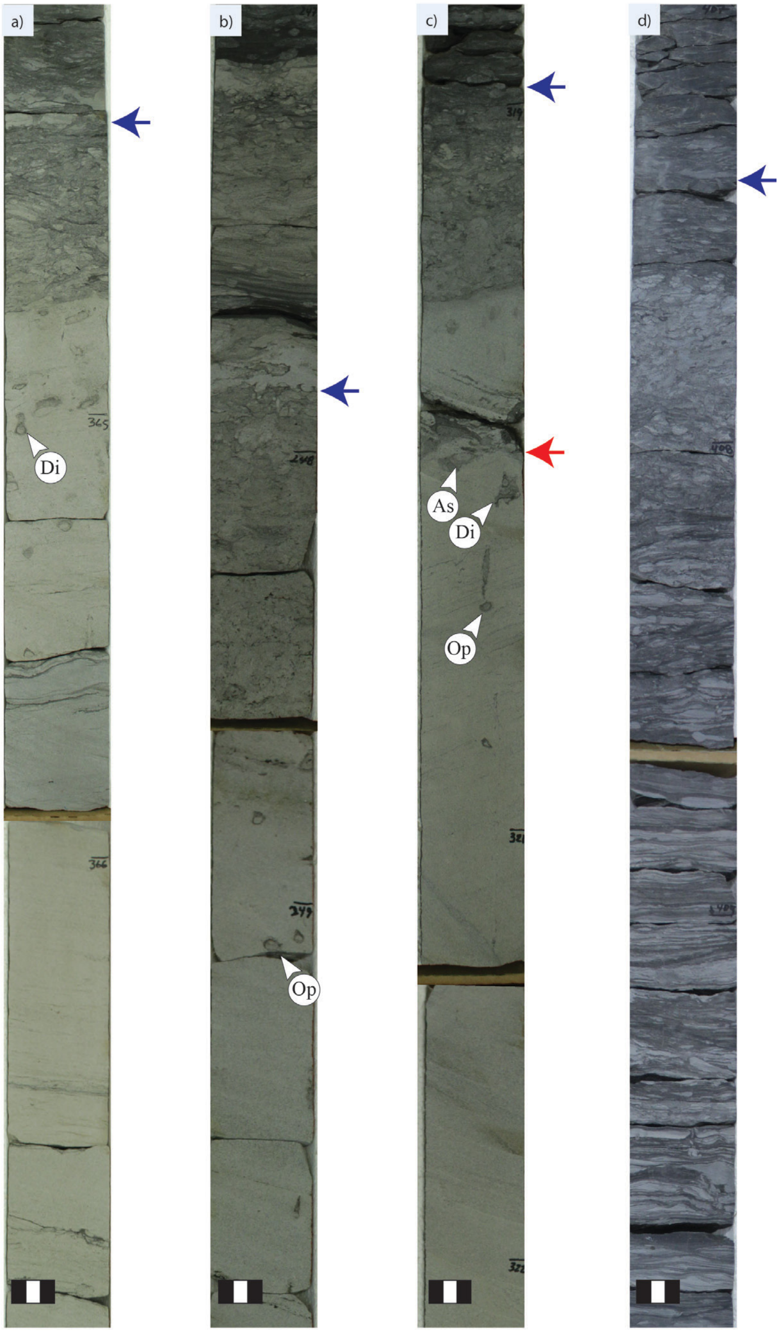


Figure 6.18: Parasequence flooding surfaces and associated erosion: a) flooding surface (purple arrow) of PS2c with distending *Diplocraterion* (*Di*), b) flooding surface of PS2d with distending robust *Ophiomorpha* (*Op*), c) flooding surface of PS2c (purple arrow) with associated transgressive sandstone (above red arrow) that has ripped up *Asterosoma* (*As*) in the base as well as distending *Diplocraterion* and *Ophiomorpha*, and d) transgressive overprinting of prodeltaic bayfill deposits resulting in high abundance below the flooding surface (purple arrow).

association in PS2c (Figure 6.18c). *Diplocraterion* are much more prevalent under the basal flooding surface of PS2d (Figure 6.18a), as well as contains more distal facies associations above, which may suggest a link between the *Diplocraterion* presence and larger landward shifts.

The deposits related to transgressive erosion are limited to a thin cross-bedded unit with ripped up *Asterosoma* along the base (Figure 6.18d). This is only seen in MC3 notably above inner mouthbar deposits, which may suggest reworking of the outer mouthbar landward into the channels low topography, or initiation of a small inlet upon abandonment. Conversely, the sandstone deposited as tidal channel transgressive facies (definitely FA Sx2, possibly FA Sx1b; Figure 6.7b-f) represent a much thicker unit that transverses the entire study (Figure 6.17). The recognition of herringbone stratification in the study area by Ryer and Anderson (2004), Garrison and van den Bergh (2004), and van den Bergh and Garrison (2004), may suggest that FA Sx1b may be included in this, but the exact location of these sedimentary structures is not specified.

What can be taken away from this is the importance of recognizing inherent bioturbation in an ichnofacies versus deep-tiered overprinting of proximal distributary facies (e.g., delta front, mouthbar, distributary channel) during transgressive overprinting. Especially in cases like river deltas where the tops may be cannibalized by tidal channels and inlets during abandonment (e.g., Penland et al., 1988) making discerning distributaries at the same stratigraphic level difficult. Additionally, this is much different than what is seen in the proximal deltaic trace assemblages of wave/storm dominated Upper Cretaceous units, which dominantly display *Macaronichnus* and roots (Table 6.3).

6.5.3.2 Transition Between Wave-Dominated to River-Dominated Units

The surfaces at the base of wave-dominated, shoreface-related, facies associations is marked by a rapid transition to heavily bioturbated sandstone, whether it be the middle shoreface (Figure 6.19a), lower shoreface (Figure 6.19b), or upper offshore (Figure 6.19c,d). This contact disappears into more gradational strata further basinward in the upper offshore. This could be due to the fall below fair-weather wave base, or could be related to buffering of an active adjacent lobe that is slightly basinward. These are not presumed to represent changes in global sea level because there is not a major shift in facies landward above these boundaries. While it does represent a shift to wave-dominated conditions, it does not necessarily mean that wave conditions increased, but may just mean that the river conditions diminished or temporarily abandoned from this direction.

Figure 6.19: Wave ravinement surfaces?: a) surface (blue arrow) marking the base of middle shoreface strata in MC2, b) surface (blue arrow) marking the base of lower shoreface strata in MC1, c) surface (blue arrow) further basinward in MC3, and d) sharp bioturbated surface (blue arrow) in MC4.

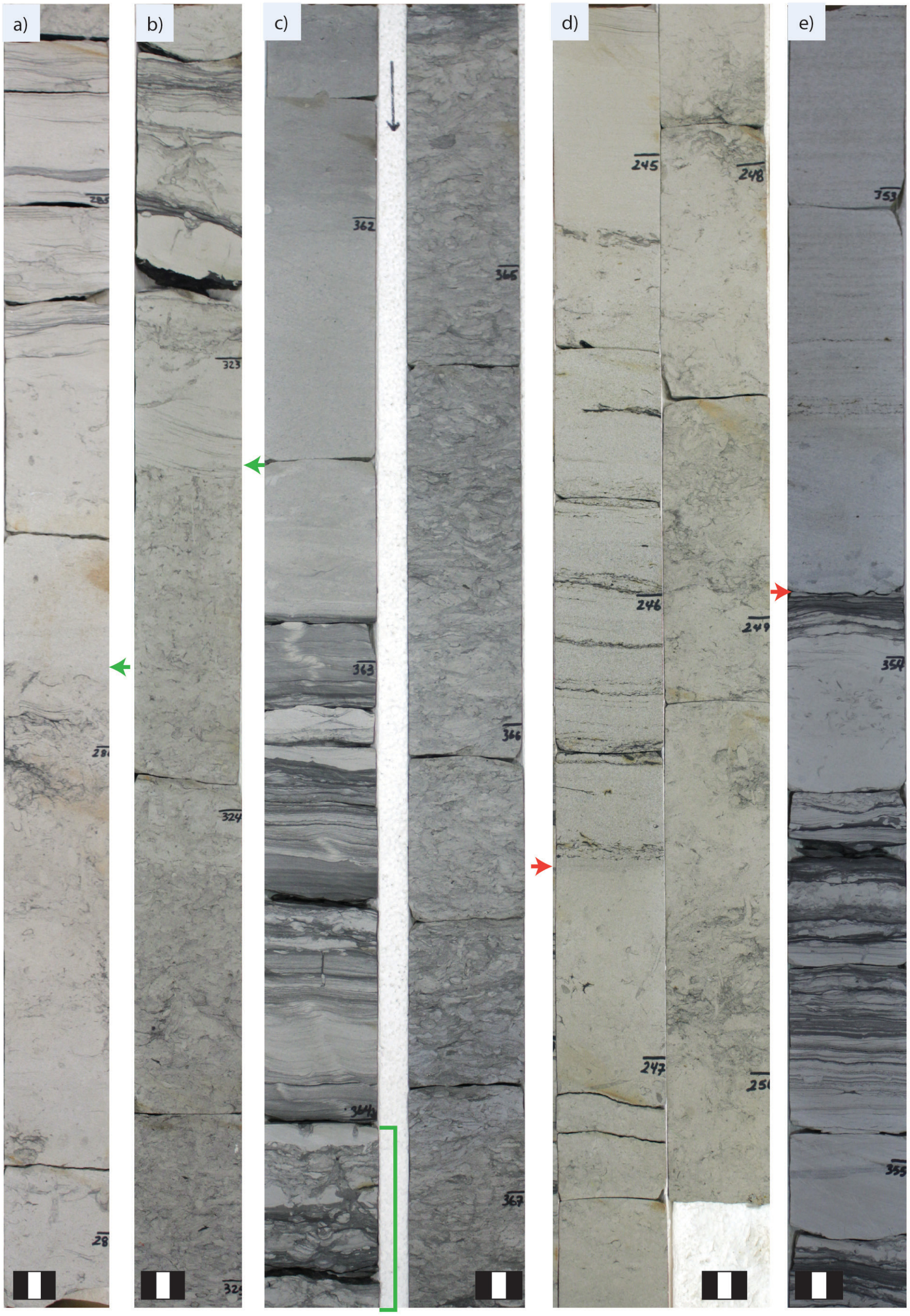


Figure 6.20: Contacts from wave to river-dominated facies and to distributary channel facies: a) sharp base (green arrow) marking the transition from lower shoreface to distal delta front in MC2, b) sharp surface marking the same transition at a stratigraphically higher location in MC4, c) more basinward, in MC4, the transition seen in (b) is more gradational (green bracket), d) base of distributary channel sharply overlaying lower shoreface in MC1, and e) sharp contact of base of channel in MC5, with similar appearance suggesting a possible genetic connection between the channel and the underlying distal delta front.

The transition from the top of the wave-dominated lower shoreface units into delta front units often have a sharp contact with long, small diameter *Skolithos* distending from the erosive contact (Figure 6.20 a,b), but basinward in MC5 this contact appears more gradational in nature (Figure 6.20c). This could be a wave erosion surface, or potentially the input of sediment from the delta preserves the last wave-related event beds from subsequent bioturbation by rapid burial. The other erosive surface seen is the sharp contact where the lower shoreface goes into the distributary channel (Figure 6.20d). The distributary channel in MC5 (Figure 6.20e) appears more similar to the underlying facies suggesting the two may be genetically connected. The thicker sand bodies in MC5 (Figure 6.21), rather than a muddying basinward suggests that there is oblique or obverse sediment sources that may onlap the southern deltaics when they are being wave reworked (abandoned?).

6.6 CONCLUSIONS

The trace assemblages of deltaic deposits in the Ferron Sandstone differs from other previously described trace assemblages in Upper Cretaceous deltaic deposits in the significance of *Palaeophycus* and meniscate backfilled traces (e.g., *Scolicia*) to these assemblages. *Palaeophycus heberti* and organic-lined *Palaeophycus tubularis* often occur in high density, sometimes monospecific assemblages in the proximal deltaic facies (river to wave-dominated). Diminutive *Scolicia* is a common component of the prodeltaic settings, which display expressions of proximal to archetypal *Cruziana*, which are more landward expressions than *Scolicia* is typically associated with. The presence of *Scolicia* in more proximal setting may suggest a deltaic taphonomic bias towards preservation (compared to shoreface ichnofacies expressions) due to increase heterogeneity, aggradation, or stress-related factors. Alternatively, it could be related to the food resource paradigm in deltaic systems. The expression of *Skolithos* Ichnofacies with *Ophiomorpha* and/or *Diplocraterion* in proximal delta facies (distributary channel, mouthbar, bayfill proximal delta front) appear dominantly to be related to the transgressive overprinting of deeper tiered burrows on the palimpsest deltaic facies, rather than colonizers of those freshwater laden environments. In regards to facies distribution, the wave-dominated shoreface facies associations are deposited at a much shallower angle than the river-dominated deposits.

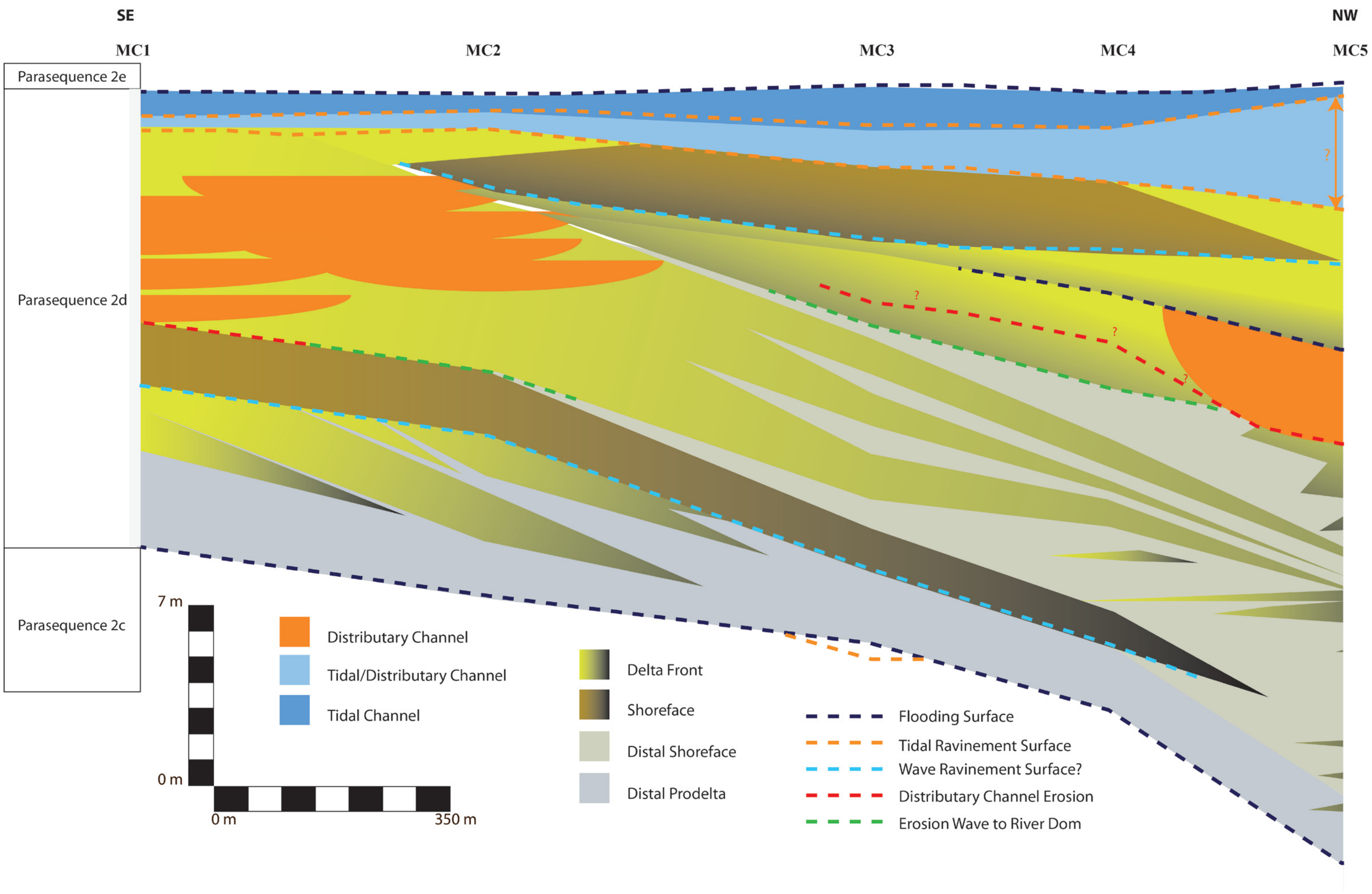


Figure 6.21: Simplified schematic of wave- versus river-dominated deposits.

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CHAPTER 7: SUMMARY AND CONCLUSIONS

The studies in this dissertation provide new information on the Ferron Sandstone, ichnology, and clastic sedimentology in three main areas: ichnotaxonomy, trace assemblages and their preservation, and trace assemblage overlap at stratigraphic surfaces.

7.1 ICHNOTAXONOMIC CONTRIBUTION

The ichnotaxa of invertebrates (*Beaconites*, *Helminthoidichnites*, and *Altichnus*), vertebrates (*Amblydactylus*, *Iguanodontipus burreyi*, *Characichnos*, and *Chelonipus*), and unnamed traces of mollusk plowing behaviors, theropod tracks, and possible wading bird tracks are first reported herein from the Ferron Sandstone. Three new ichnospecies of *Altichnus* are differentiated. One of these traces is interpreted to represent a different ethological behavior than previously noted (i.e., head-to-tail circulation). Ethological differences are also noted in the *Chelonipus* described, in which posterior pushups appear to represent a walking behavior, whereas, the less posteriorly defined and inconsistent tracks represent the swimming behavior that has been typically associated with the taxonomic descriptions of *Chelonipus*.

7.2 TRACE ASSEMBLAGE RECOGNITION

Three distinct trace assemblages are noted from deposits of channels (*Chelonipus*), interdistributary floodplains (*Beaconites*-Ornithopod tracks), and tidal flats-shallow bays (*Thalassinoides*-Ornithopod tracks). *Chelonipus* only occurs in channel deposits of the Ferron Sandstone, which is consistent with previous occurrences in the Cretaceous. The trace assemblage for the channel may contain *Mermia*-like surface traces, *Characichnos*, *Chelonipus*, and *Rhizocorallium*. The latter two have never been reported in association before now, and on their own, in fluvial context, have only been reported in a handful of locations globally. These trace assemblages are probably more abundant than previously thought, but their identification is hindered by the small scale of the traces and the preservation often resembling physically-derived sedimentary structures.

The assemblage of *Beaconites, Iguanodontipus burreyi, Amblydactylus*, and roots from the Ferron Sandstone is comparable to fluvial-lacustrine trace assemblages from the Lower Cretaceous of England. *Beaconites* can be dominant locally in these interdistributary floodplain assemblages, often destroying the physical sedimentary structures, as well as the vertebrate tracks. This leads to a bias toward the preservation of the larger tracks (ornithopod; *Iguanodontipus burreyi*) in the trace assemblage.

The distal tidal flat-shallow bay trace assemblages are similar to the abundances seen in the *Beaconites* assemblages, frequently with high abundance of invertebrate traces. Conversely, the high abundance traces are *Thalassinoides* and *Planolites* with minor *Ophiomorpha*. *Siphonichnus* or *Psilonichnus* may be present locally. Vertebrate tracks are typically *Amblydactylus*, but may include *Iguanodontipus*, small-medium theropod tracks, and possibly tracks of wading shorebirds. Much like the *Beaconites* assemblage, the vertebrate trace preservation is reliant on a lower subsequent infaunal burrow abundance or rapid burial. Although, the burrows in the *Thalassinoides* assemblage often provide the lithological heterogeneity (i.e. high abundance sand-filled burrow in mudstone) needed to initially preserve the vertebrate tracks.

The deltaic trace assemblages in this study are comparable to previous works on ichnology of Cretaceous deltaic deposits. However, there are two notable differences in the Ferron Sandstone of the inherent ichnotaxa to these assemblages. First, *Palaeophycus* is a key component in proximal deltaic assemblages (i.e., delta front), frequently with high abundance of organic-lined *P. tubularis* or *P. heberti*. *Palaeophycus heberti*, might often be overlooked because of the traces frequent cryptic appearance. The second notable difference is the occurrence of meniscate backfilled burrows (i.e., *Scolicia*) in proximal parts of the prodelta with assemblages comparable to the expressions of the proximal and archetypal *Cruziana* Ichnofacies. It is not uncommon for meniscate backfilled traces to be noted from the distal delta front or prodelta deposits from the Cretaceous, but often these diminutive traces are not given much credence in their importance to the ichnofacies models for these settings. Additionally, there may be a difference in the expression of ichnotaxa in deltaic settings, as compared to the more distal ichnofacies associations of the shoreface. The association of the diminutive *Scolicia* with the more proximal expressions of the *Cruziana* Ichnofacies is likely linked to factors such as toponomy (e.g., increased heterogeneity in distal delta front versus lower shoreface), taphonomy (e.g., rapid burial near delta), or ethology (difference in the food resource paradigm with fluvial input).

7.3 ROLE OF ASSEMBLAGE OVERLAP AT STRATIGRAPHIC SURFACES

While trace assemblages are greatly similar between the Ferron Sandstone and other Cretaceous deltaic deposits, there are not often attempts to separate the overprint assemblage from that of the inherent trace assemblage of these depositional environments. In the Ferron Sandstone, assemblage mixing manifests itself along stratigraphic surfaces in two notable ways: allochthonous clasts and flooding surfaces (transgressive overprinting).

Allochthonous clasts are seen in regressive deposits in the form of *Teredolites* from an underlying brackish floodplain incorporated into the base of a fluvial channel with a freshwater trace assemblage. In transgressive deposits, these are present in the form of ripped up *Asterosoma* along the base of a thin transgressive sandstone. This thin transgressive sandstone may erroneously be included with the similarly cross-bedded distributary mouthbar deposits that lie directly underneath.

Smaller scale flooding surfaces or bay flooding surfaces are instrumental in the preservation of vertebrate tracks most notably as molds in the Ferron Sandstone. The small scale flooding surfaces may have increased abundance of invertebrate traces just below them. However, the content of the ichnotaxa often varies according to environmental conditions. In the proximal expressions of marine flooding surfaces and the associated transgressive erosional surfaces in the Ferron Sandstone, the overprinting transgressive assemblage is always accompanied by robust, vertical to inclined *Ophiomorpha*. This overprints nearshore complex (e.g., washover fan) and proximal deltaic (e.g., distributary complex and proximal delta front) deposits in the Ferron Sandstone. This overprinting has previously resulted in misinterpretation and hiding the presence of the nearshore complex in the landward portion of a parasequence sand body, as well as the location of the true parasequence boundary. In the proximal deltaic deposits, the transgressive overprinting might be regarded as part of the trace assemblage because terminal portions of the distributary will likely always be transgressed, and hence have the overprinting assemblage present. Conversely, understanding the initiation of these traces, whether overprinting or inherent, appears, to be a vital component in deciphering distributary complex facies from those of the transgressive tidal channels, at least from what is observed in the Ferron Sandstone.

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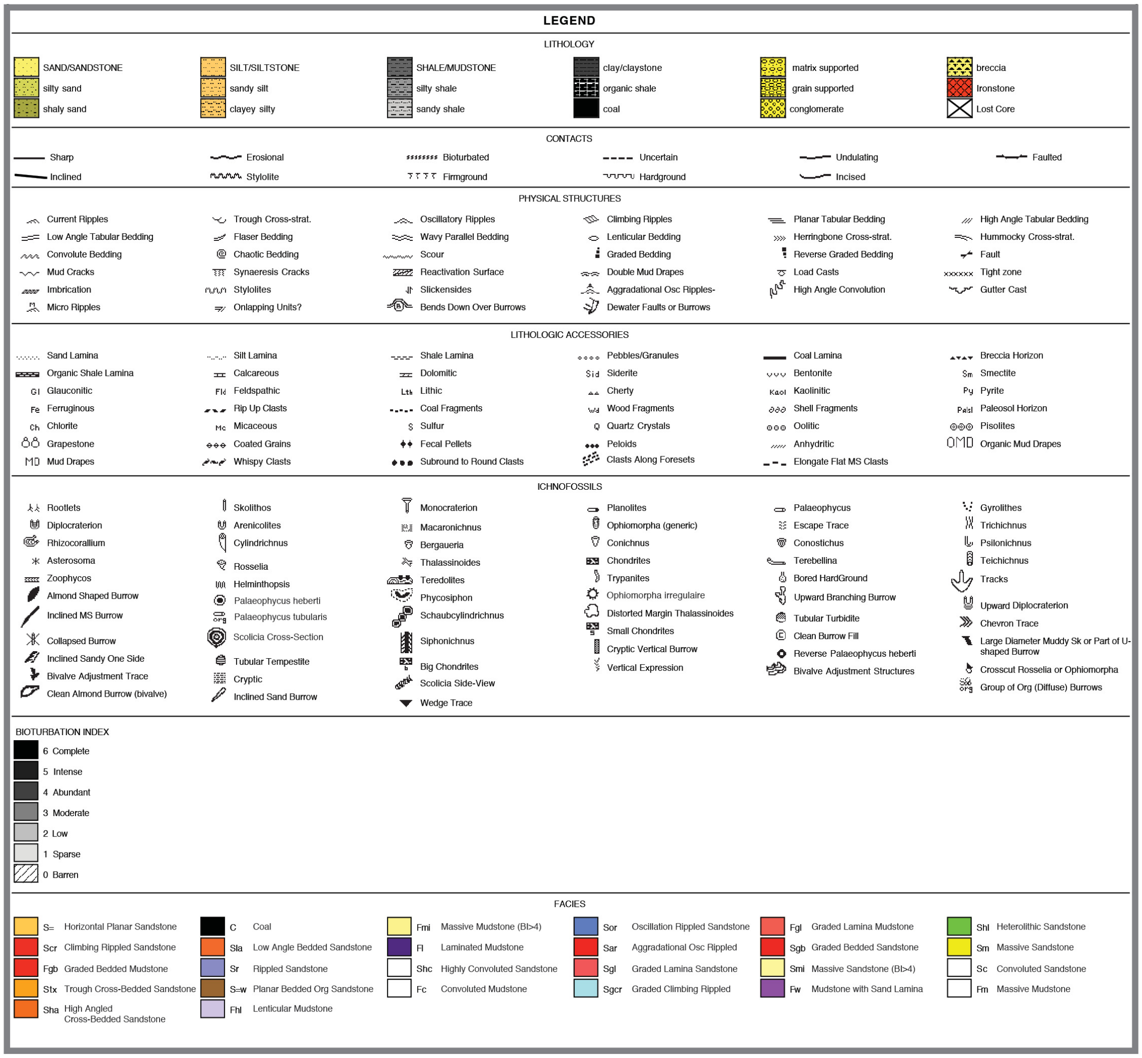
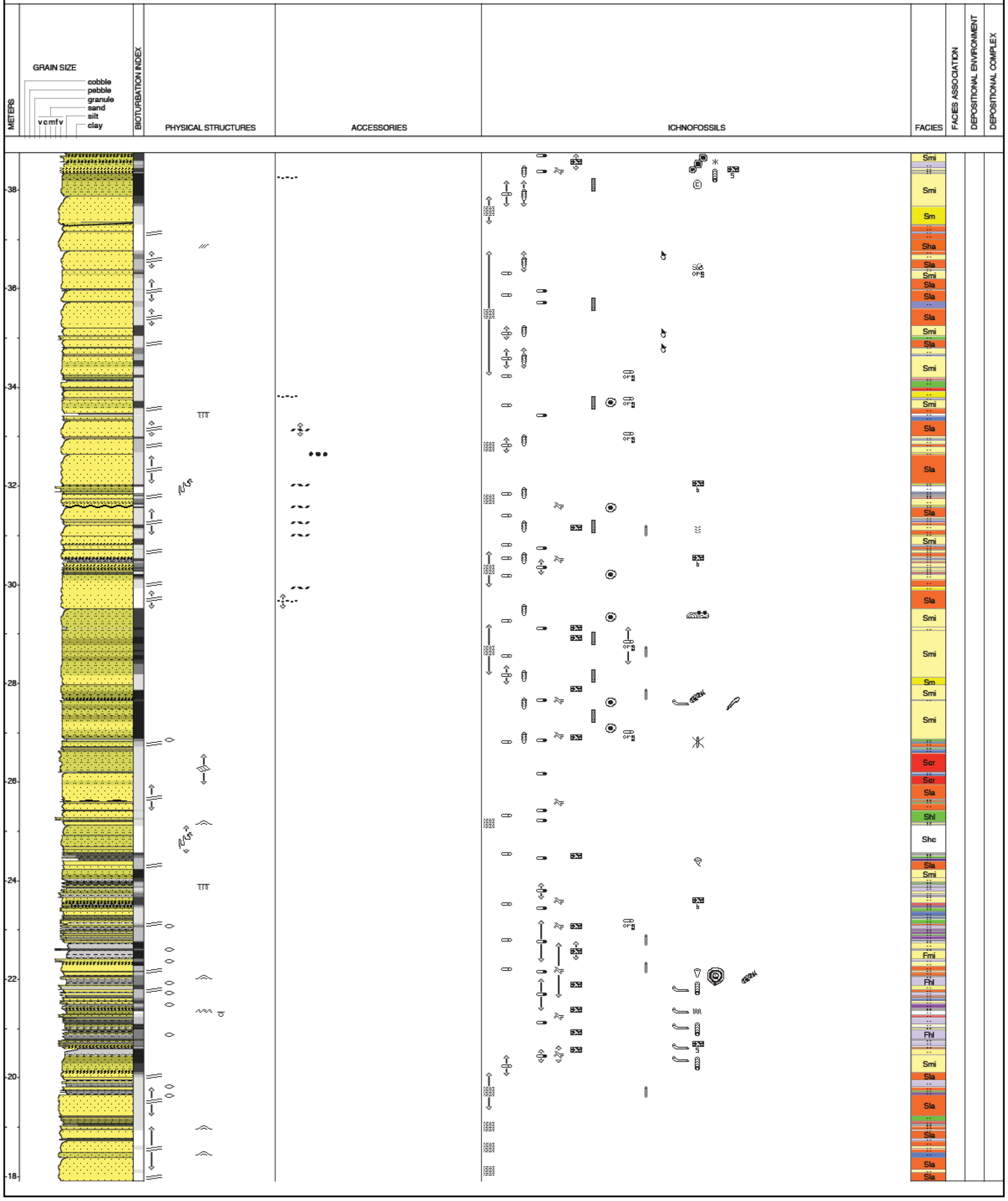
Appendix


LEGEND
LITHOLOGY
SAND/SANDSTONE
SILT/SILTSTONE
SHALE/MUDSTONE
clay/claystone
matrix supported
breccia
silty sand
sandy silt
silty shale
organic shale
grain supported
Ironstone
shaly sand
clayey silty
sandy shale
coal
conglomerate
Lost Core
CONTACTS
Sharp
Erosional
Bioturbated
Uncertain
Undulating
Faulted
Inclined
Stylolite
Firmground
Hardground
Incised
PHYSICAL STRUCTURES
Current Ripples
Trough Cross-strat.
Oscillatory Ripples
Climbing Ripples
Planar Tabular Bedding
High Angle Tabular Bedding
Low Angle Tabular Bedding
Flaser Bedding
Wavy Parallel Bedding
Lenticular Bedding
Herringbone Cross-strat.
Hummocky Cross-strat.
Convolute Bedding
Chaotic Bedding
Scour
Graded Bedding
Reverse Graded Bedding
Fault
Mud Cracks
Synaeresis Cracks
Reactivation Surface
Double Mud Drapes
Load Casts
Tight zone
Imbrication
Stylolites
Slickensides
Aggradational Osc Ripples-
High Angle Convolution
Gutter Cast
Micro Ripples
Onlapping Units?
Bends Down Over Burrows
Dewater Faults or Burrows
LITHOLOGIC ACCESSORIES
Sand Lamina
Silt Lamina
Shale Lamina
Pebbles/Granules
Coal Lamina
Breccia Horizon
Organic Shale Lamina
Calcareous
Dolomitic
Sid
Siderite
Bentonite
Sm
Smectite
Gl
Glauconitic
Fld
Feldspathic
Lth
Lithic
Cherty
Kaol
Kaolinitic
Py
Pyrite
Fe
Ferruginous
Rip Up Clasts
Coal Fragments
Wd
Wood Fragments
Shell Fragments
Palsl
Paleosol Horizon
Ch
Chlorite
Mc
Micaceous
S
Sulfur
Q
Quartz Crystals
Oolitic
Pisolites
Grapestone
Coated Grains
Fecal Pellets
Peloids
Anhydritic
OMD
Organic Mud Drapes
MD
Mud Drapes
Whispy Clasts
Subround to Round Clasts
Clasts Along Foresets
Elongate Flat MS Clasts
ICHNOFOSSILS
Rootlets
Skolithos
Monocraterion
Planolites
Palaeophycus
Gyrolithes
Diplocraterion
Arenicolites
Macaronichnus
Ophiomorpha (generic)
Escape Trace
Trichichnus
Rhizocorallium
Cylindrichnus
Bergaueria
Conichnus
Conostichus
Psilonichnus
Asterosoma
Rosselia
Thalassinoides
Chondrites
Terebellina
Teichichnus
Zoophycos
Helminthopsis
Teredolites
Trypanites
Bored HardGround
Tracks
Almond Shaped Burrow
Palaeophycus heberti
Phycosiphon
Ophiomorpha irregulaire
Upward Branching Burrow
Upward Diplocraterion
Inclined MS Burrow
Org
Palaeophycus tubularis
Schaubcylindrichnus
Distorted Margin Thalassinoides
Tubular Turbidite
Chevron Trace
Collapsed Burrow
Scolicia Cross-Section
Siphonichnus
Small Chondrites
Clean Burrow Fill
Large Diameter Muddy Sk or Part of U-shaped Burrow
Inclined Sandy One Side
Tubular Tempestite
Big Chondrites
Cryptic Vertical Burrow
Reverse Palaeophycus heberti
Crosscut Rosselia or Ophiomorpha
Bivalve Adjustment Trace
Cryptic
Scolicia Side-View
Vertical Expression
Bivalve Adjustment Structures
Org
Group of Org (Diffuse) Burrows
Clean Almond Burrow (bivalve)
Inclined Sand Burrow
Wedge Trace
BIOTURBATION INDEX
6 Complete
5 Intense
4 Abundant
3 Moderate
2 Low
1 Sparse
0 Barren
FACIES
S= Horizontal Planar Sandstone
C Coal
Fmi Massive Mudstone (Bl>4)
Sor Oscillation Rippled Sandstone
Fgl Graded Lamina Mudstone
Shl Heterolithic Sandstone
Scr Climbing Rippled Sandstone
Sla Low Angle Bedded Sandstone
Fl Laminated Mudstone
Sar Aggradational Osc Rippled
Sgb Graded Bedded Sandstone
Sm Massive Sandstone
Fgb Graded Bedded Mudstone
Sr Rippled Sandstone
Shc Highly Convoluted Sandstone
Sgl Graded Lamina Sandstone
Smi Massive Sandstone (Bl>4)
Sc Convoluted Sandstone
Stx Trough Cross-Bedded Sandstone
S=w Planar Bedded Org Sandstone
Fc Convoluted Mudstone
Sgcr Graded Climbing Rippled
Fw Mudstone with Sand Lamina
Fm Massive Mudstone
Sha High Angled Cross-Bedded Sandstone
Fhl Lenticular Mudstone

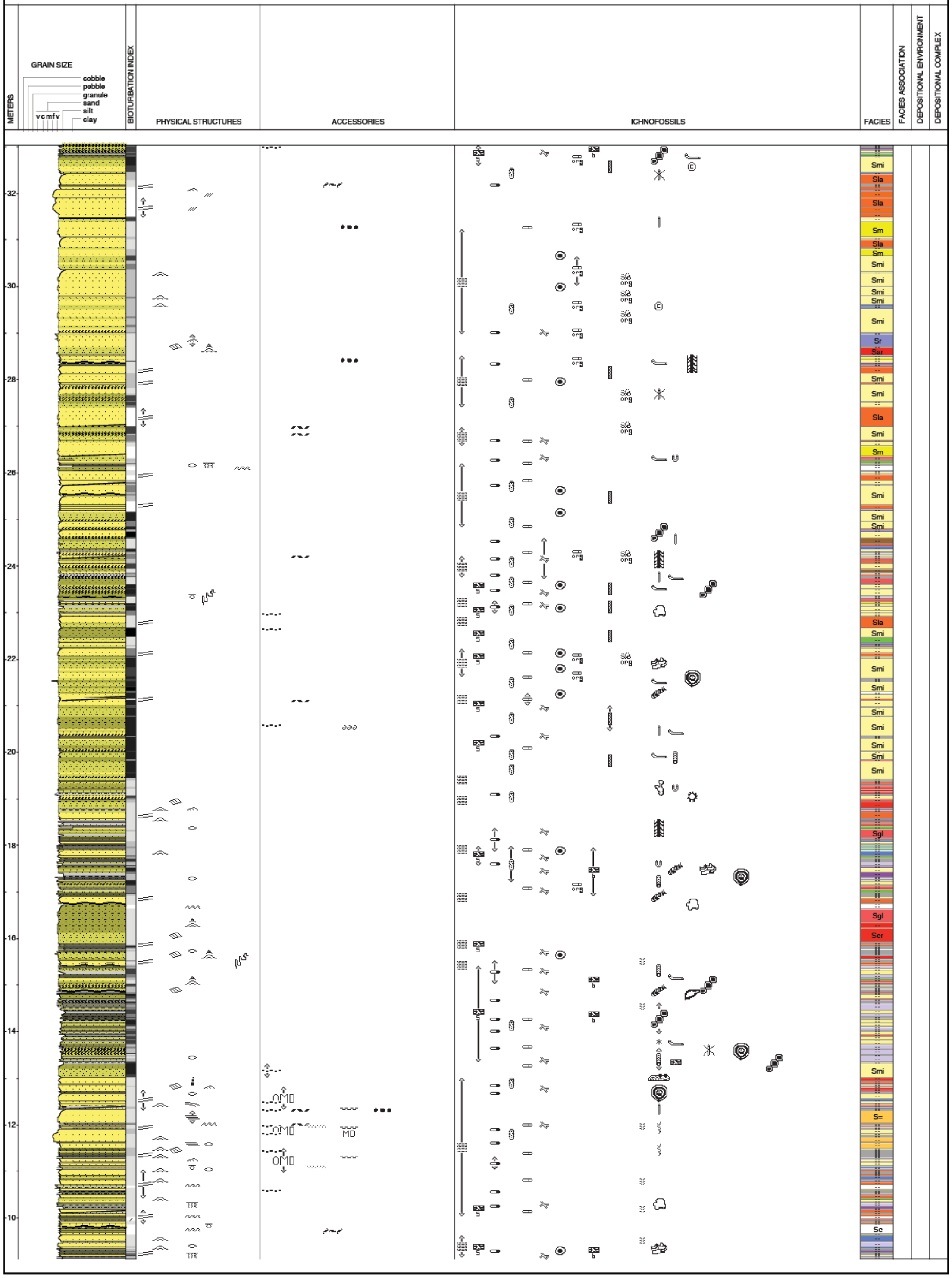
MC1

Date Logged:
Logged by: Ryan King
Ground: 0.00 m KB: 0.00 m
Remarks:



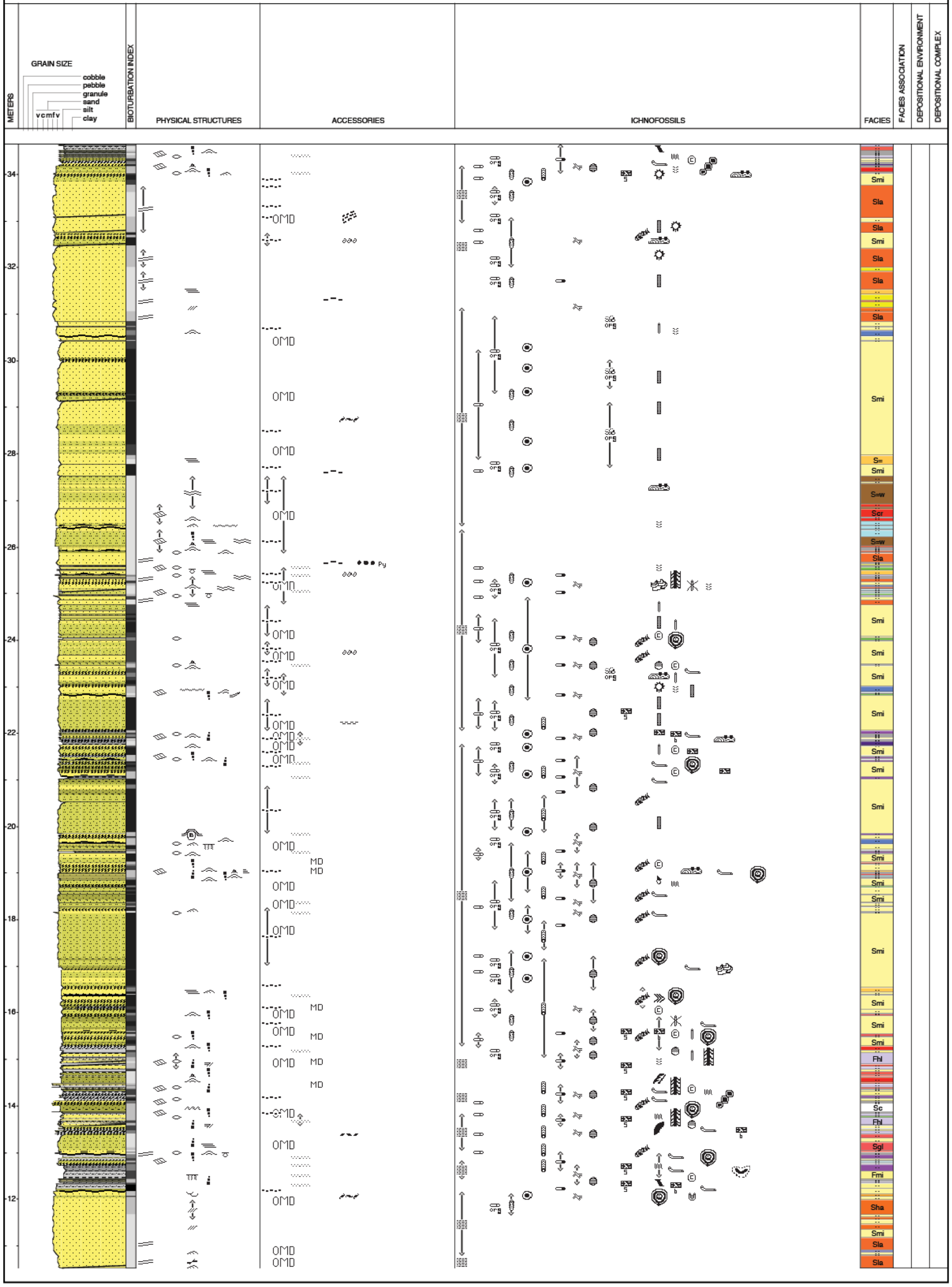
MC2

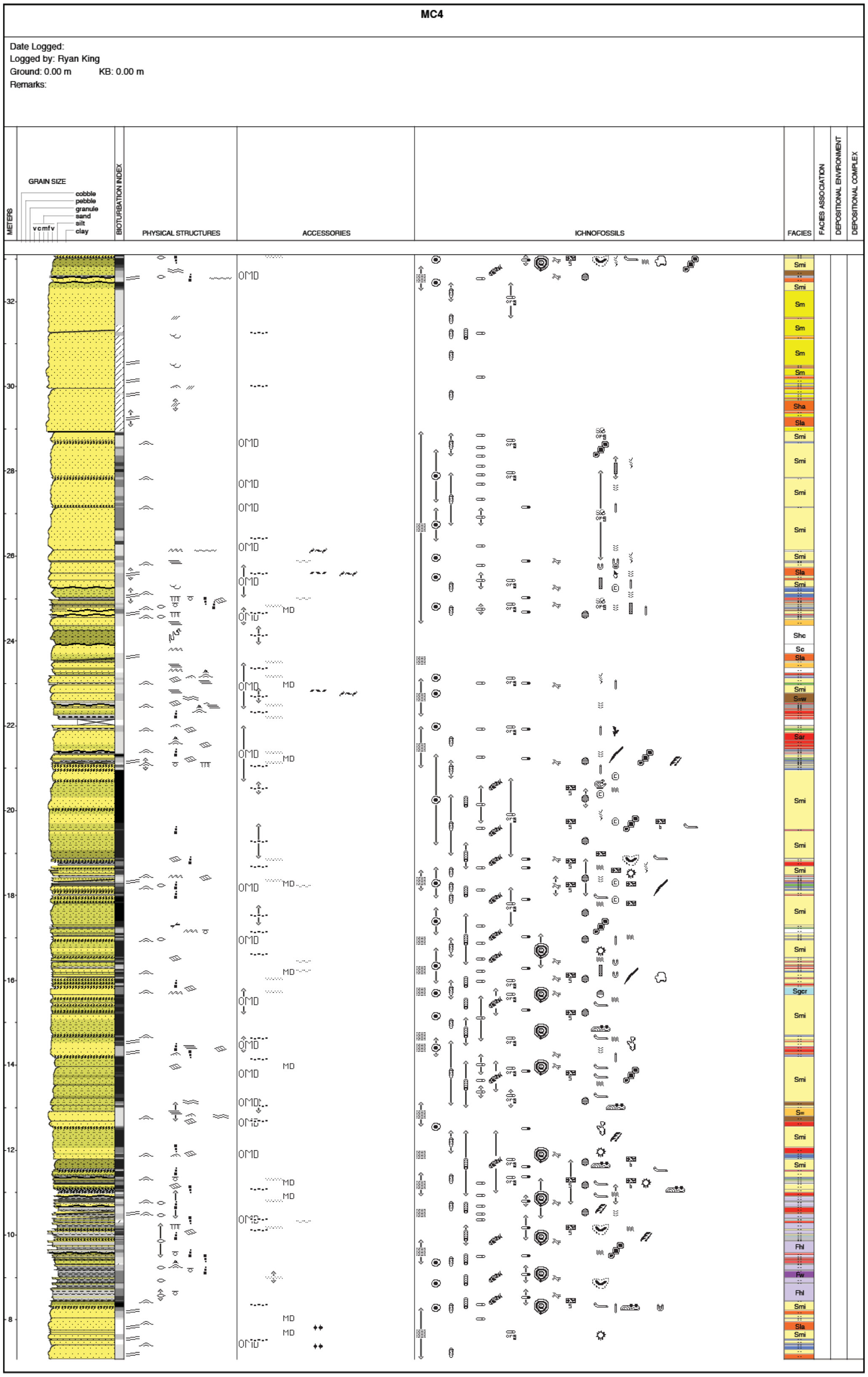
Date Logged:
Logged by: Ryan King
Ground: 0.00 m KB: 0.00 m
Remarks:



MC3

Date Logged:
Logged by: Ryan King
Ground: 0.00 m KB: 0.00 m
Remarks:




MC4
Date Logged:
Logged by: Ryan King
Ground: 0.00 m KB: 0.00 m
Remarks:
METERS
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
v c m f v
BIOTURBATION INDEX
PHYSICAL STRUCTURES
ACCESSORIES
ICHNOFOSSILS
FACIES
FACIES ASSOCIATION
DEPOSITIONAL ENVIRONMENT
DEPOSITIONAL COMPLEX
-32
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
OMD
MD
Smi
Smi
Sm
Sm
Sm
Sm
Sha
Sla
Smi
Smi
Smi
Smi
Smi
Sla
Smi
Shc
Sc
Sla
Smi
Swr
Sar
Smi
Smi
Smi
Smi
Smi
Sgcr
Smi
Smi
Ss
Smi
Smi
Fhl
Fw
Fhl
Smi
Sla
Smi

MC5

Date Logged:
Logged by: Ryan King
Ground: 0.00 m KB: 0.00 m
Remarks: