

**THREE-DIMENSIONAL OUTCROP MODELLING OF FLUVIAL AND
ESTUARINE OUTCROPS IN THE LOWER CRETACEOUS MCMURRAY
FORMATION, NORTHEAST ALBERTA, CANADA**

by

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MASTER OF SCIENCE

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ABSTRACT

While it is widely accepted that both cross-bedded sand and Inclined Heterolithic Stratification (IHS) are the two main geobodies that compose Aptian-aged middle McMurray Formation strata, the stratigraphic relationship between the two units and their physiographic depositional positions in a fluvial-estuary system remain somewhat poorly constrained. It is well-known that there is a relatively widespread distribution of fluvial or estuarine lateral accretion point-bar deposits throughout the McMurray Formation, and this has led to a bias regarding the large-scale depositional architecture of the formation as a whole. In this paradigm, the cross-bedded sand overlain by IHS are interpreted to be contemporaneous channel and point-bar deposits, respectively. Because much of the recent research on the McMurray Formation has focused on subsurface datasets, deciphering the large-scale stratigraphic relationship and facies architecture between the two geobodies remains a challenge. This results in a propensity for interpreting these two geobodies as a single continuous point-bar interval.

The best way to characterize large-scale architectural elements within the McMurray Formation is to study outcropping strata. Although this approach has been used by a handful of workers for over 40 years, much of the work has focused solely on the sedimentology (and where applicable, the ichnology) of a small subset of outcropping McMurray strata. In the time since many of the previous outcrop studies were completed, the use of unmanned aerial vehicles (UAV's, or drones) has permitted the development of high resolution georeferenced outcrop models using Structure-from-Motion photogrammetry. This thesis uses these photogrammetry techniques to acquire bed-by-bed orientation data from both cross-bedded sand and IHS geobodies to assess the large-scale depositional architecture of the outcropping strata.

This body of work shows that when architectural data are combined with sedimen-

tological and ichnological observations at the Christina River, Steepbank #3, Amphitheatre, and Crooked Rapids outcrops, several facies architectures are recognized with at least three acting as reservoir-quality units in the McMurray Formation. Notably, in the former three outcrops, it is common to see forward- or oblique forward-accreting cross-bedded sand sharply overlain by laterally accreting IHS strata. When combined with sedimentological and ichnological data, it becomes clear that the contact between cross-bedded sand and IHS is often disconformable owing to significant changes in grain size, bioturbation index, and/or architectural variability across the contact separating the individual geobodies. In contrast, at the Crooked Rapids outcrop, an inter-fingering relationship between the cross-bedded sand and overlying IHS combined with consistent accretionary growth directions between the two units suggest both were deposited contemporaneously on the same point-bar. As such, a number of facies architectures including estuarine compound dunes, simple fluvial dunes, estuarine point-bar, fluvial point-bar, and fluvial counter point-bar deposits are interpreted among the studied outcrops. The physiographic location of these deposits in a fluvial-estuary environment are defined based on sedimentological and ichnological characteristics of the aforementioned facies architectures. In short, reservoir-quality units are not only constrained to fluvial or estuarine channel thalweg to lower point-bar sand: they occur in both fluvial and estuarine channels, in addition to a middle estuary compound dune environment near the estuary mouth.

PREFACE

This thesis represents the original work of I, Derek Andrew Hayes.

Chapter 2 of this thesis is published as: Hayes, D.A., Timmer, E.R., Deutsch, J.L., Ranger, M.J. and Gingras, M.K. 2017. Analyzing dune foreset cyclicity in outcrop with photogrammetry. *Journal of Sedimentary Research*, v. 87, p. 66-74. I constructed the 3D model, performed data collection, and wrote the vast majority of the text; Timmer, E.R. completed the continuous wavelet transforms and wrote that section of the manuscript; Deutsch, J.L. provided the photograph dataset and stitched photomosaic; Ranger, M.J. and Gingras, M.K. provided edits and expert input.

Chapter 3 of this thesis has been accepted for publication in the *Bulletin of Canadian Petroleum Geology* as: Hayes, D.A., Timmer, E.R., Ranger, M.J., Kavanaugh, J.L. and Gingras, M.K. in press. Using Structure-from-Motion photogrammetry to recognize lateral *versus* forward accretion bedforms in the lower Cretaceous McMurray Formation, NE Alberta, Canada. *Bulletin of Canadian Petroleum Geology*. I performed data collection, generated the 3D outcrop models, data analysis, and wrote the majority of the manuscript; Timmer, E.R. provided code for the generation of tadpole plots and collected palaeocurrent data in the field; Ranger, M.J. provided edits, expert input, and some outcrop photos; Kavanaugh, J.L. provided clarity on the eigenvector methodology for fitting a plane to points in 3D; Gingras, M.K. provided edits, expert input, and some outcrop photos.

Chapter 4 of this thesis will be submitted for publication as: Hayes, D.A., Botterill, S.E, Timmer, E.R., Ranger, M.J., Kavanaugh, J.L. and Gingras, M.K. Sedimentological, ichnological, and architectural characterization of a fluvially-dominated outcrop using UAV-based outcrop modelling, lower Cretaceous McMurray Formation, NE Alberta, Canada. I performed data collection, generated the 3D outcrop model, data analysis, and wrote the manuscript; Botterill, S.E. provided edits and expert input (particularly on fluvial sedimentology and ichnology); Timmer, E.R. assisted with fieldwork and provided expert input; Ranger, M.J. assisted with drone data collection, provided edits and expert input; Kavanaugh, J.L. wrote the MATLAB script to fit a plane to data points; Gingras, M.K. assisted with drone data collection, provided edits and expert input.

Chapters 1 (Introduction) and 5 (Conclusions) are my own work.

DEDICATION

I dedicate this thesis to my mother, Brenda and my father, Michael for their lifelong encouragement, love, generosity, and support. I am forever indebted for everything they have provided me during my time as an academic, particularly easing the financial burden of spending seven years working toward my undergraduate and graduate degrees at the University of Alberta by providing me a place to live rent free. Your selflessness has allowed me to enjoy my time as an academic stress-free outside of my studies, and for that I am grateful.

ACKNOWLEDGMENTS

Throughout my time as a graduate student, I have had the pleasure of working with a number of people that allowed me to grow as a geologist and more importantly as a person. For that, I would like to thank the following people:

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Dr. Mike Ranger for sharing his vast knowledge of the McMurray Formation with me and coming out to do fieldwork with Murray, Eric, and I – those short field excursions were one of the highlights of my time as a grad student; Dr. George Pemberton for teaching with such a passion that allowed me to fall in love with sedimentary geology (and, introducing me to the world of ichnology – little did I know that what you taught me about Viking incised valleys as a naive undergrad would help lead me to my first full-time job in the petroleum industry); Dr. J.P. Zonneveld for discussing anything geological during my unannounced office visits and for stepping in last minute to sit on my defense committee; and Dr. Jeff Kavanaugh for assisting me with data collection by writing a script in MATLAB – if not for you, I may still be struggling trying to import outcrop models into ArcScene.

Members of the Ichnology Research Group throughout my time at the U of A for friendship, afternoon cribbage, thoughtful discussions, and general shenanigans: Eric Timmer, David Herbers, Donald Prenoslo, Carolyn Furlong, Reed Myers, Scott Botterill, Matt Sommers, Aimee Gegolick, Brette Harris, Maya LaGrange, Eric Ditzler, Daniel Baker, Calla Knudson, Olga Kovalchuk, Qi Chen, Skye Lybbert, Cole Ross, and Scott Melnyk. I'll remember those "bro" crib nights with Eric, Donald, and Ditzler forever – from Ditzler and I mopping the floor with you two to you both refusing to drink your obligatory post-game AGD (good choice, Don...) for losing. Easy peggin', fellas!

Laurence Pryer, Martin Schwangler, Joe Young, Sophie Norris, Brendan Bishop, and Donald Prenoslo – the original Wednesday beers crew. What a mid-week train wreck that so often turned into, but I wouldn't trade it for anything. It's probably for the best that the Faculty Club no longer offers \$12 pitchers and free popcorn.

Finally, my siblings. My sister, Danielle, for taking care of countless Mother's Day, Father's Day, and birthday gifts when I was too preoccupied with my thesis to go shopping, and graciously splitting the costs with me in the end. Last but certainly not least, my brother Chad, for always providing positive encouragement in regard to full-time jobs (or, more accurately the lack thereof throughout my graduate studies) and for doing what he could to connect me with other geologists in Calgary. I'm not sure I would have stuck with it for so long without you.

Cenovus Energy, Nexen Energy, Husky Energy, BP Canada, Woodside Energy, and a National Sciences and Engineering Research Council grant to MKG generously provided the necessary funding for me to complete this thesis. I would also personally like to thank Jonah Resnick, Dr. Mark Caplan, and Matt Caddel for their thoughtful discussions regarding the outcrop work I have completed.

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























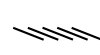









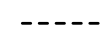




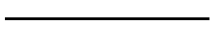

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LIST OF OUTCROP LOG SYMBOLS

| ICHTNOFOSSILS | | | BIOTURBATION INDEX | | | | | | | | | | | | | | |
|---|---|--|-----------------------------------|---|---------------------------|---|----------|-----------|--|---|-----------|---|-----------|--|----------|---|-----------|
|  | Cylindrichnus |  | Gyrolithes |  | Planolites |  | 1 Sparse | | | | | | | | | | |
|  | Skolithos |  | Siphonichnus |  | Rootlets |  | 2 Low | | | | | | | | | | |
|  | Ophiomorpha |  | Conichnus | | | | | | | | | | | | | | |
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|  | Hummocky Cross-Stratification |  | High Angle Planar-Tabular Bedding | <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2" style="text-align: center;">LITHOLOGY</th> </tr> </thead> <tbody> <tr> <td style="text-align: center;"></td> <td>Sandstone</td> </tr> <tr> <td style="text-align: center;"></td> <td>Siltstone</td> </tr> <tr> <td style="text-align: center;"></td> <td>Mudstone</td> </tr> <tr> <td style="text-align: center;"></td> <td>Limestone</td> </tr> </tbody> </table> | | | | LITHOLOGY | |  | Sandstone |  | Siltstone |  | Mudstone |  | Limestone |
| LITHOLOGY | | | | | | | | | | | | | | | | | |
|  | Sandstone | | | | | | | | | | | | | | | | |
|  | Siltstone | | | | | | | | | | | | | | | | |
|  | Mudstone | | | | | | | | | | | | | | | | |
|  | Limestone | | | | | | | | | | | | | | | | |
|  | Trough Cross-Stratification |  | Low Angle Planar-Tabular Bedding | | | | | | | | | | | | | | |
|  | Planar Bedding |  | Wavy Bedding | | | | | | | | | | | | | | |
|  | Current Ripples |  | Climbing Ripples | | | | | | | | | | | | | | |
|  | Oscillation Ripples |  | Coalified Log | | | | | | | | | | | | | | |
|  | Glauconite |  | Siderite | | | | | | | | | | | | | | |
|  | Mud Clasts |  | Shale Lamina | | | | | | | | | | | | | | |
|  | Pebble Lag |  | Organic Detritus |  | Soft Sediment Deformation | | | | | | | | | | | | |
| CONTACTS | | | | | | | | | | | | | | | | | |
|  | Erosional |  | Sharp | | | | | | | | | | | | | | |
|  | Erosional (between PB1 & PB2 - Chapter 4) | | | | | | | | | | | | | | | | |

CHAPTER ONE: INTRODUCTION

Three main oil sands deposits in the Western Canada Foreland Basin (Athabasca, Peace River, and Cold Lake) combine to host approximately 70% of the world's in-place bitumen (Hein, 2006). The largest and most extensive bitumen reserves in the province are located in the Athabasca region of northeast Alberta, with the lower Cretaceous (Aptian) McMurray Formation (Fig. 1.1) acting as the primary host of an estimated 959 billion barrels of oil (Rahnama *et al.* 2013). Considering the extreme viscosity of the oil (typically around 17.105 cP at 11°C; Musial *et al.* 2012), heat-assisted *in situ* recovery methods have become common as production has expanded beyond surface-minable regions (where overburden is less than 75 metres thick; Hein and Cotterill, 2006). However, for *in situ* recovery methods such as Steam Assisted Gravity Drainage (SAGD) or Cyclic Steam Stimulation (CSS) to be effective and cost-efficient, it is crucial to understand internal reservoir heterogeneity. In particular, the ability to predict the lateral continuity of silty mud beds within a reservoir itself is critical to maximizing production. Determining whether muddy deposits are thin and discontinuous (acting as baffles) or thick and laterally extensive (acting as barriers to steam operations) is the primary challenge to companies operating in the subsurface of the McMurray Formation. For maximum *in situ* production, the development of accurate subsurface models is crucial, and the first step to the development of these models is to understand the large-scale depositional architecture of geobodies within the McMurray Formation.

The history of research on the middle McMurray Formation is complex - Carrigy (1971) first interpreted the widespread presence of Inclined Heterolithic Stratification (IHS) (cf. Thomas *et al.* 1987) or epsilon cross-strata (cf. Allen, 1963) in the middle McMurray Formation as the foresets of a Gilbert-type Delta, with a later study by Nelson and Glaister (1978) supporting a deltaic origin. The first workers to suggest that the McMurray Formation was deposited under estuarine conditions were Stewart and MacCallum (1978), based

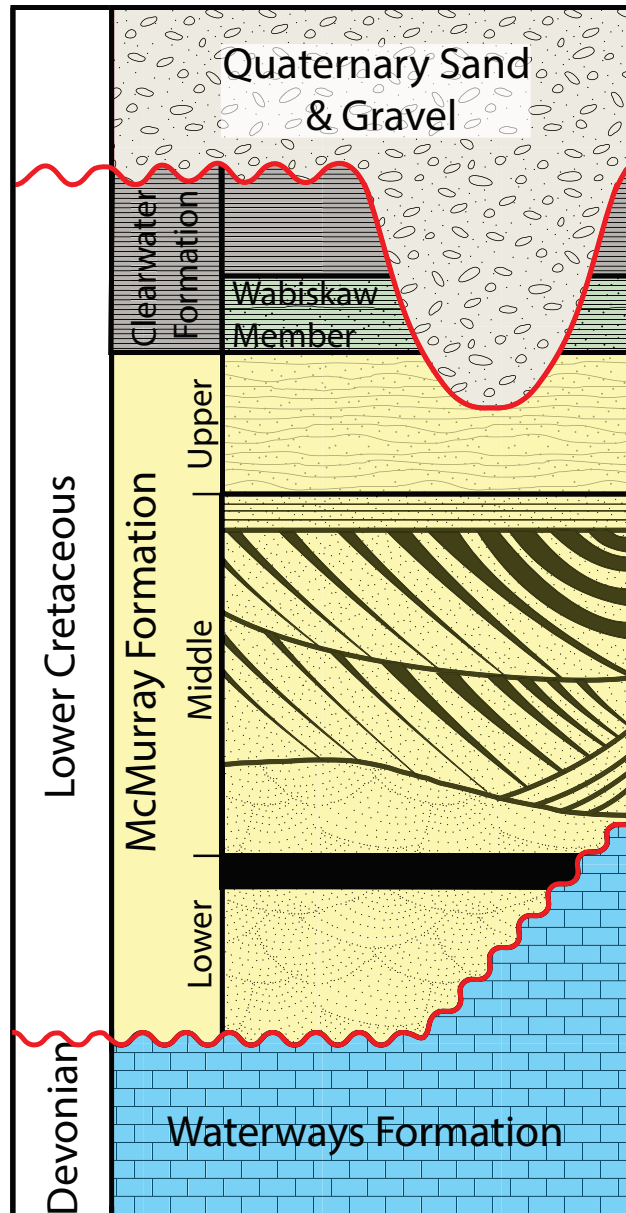


Figure 1.1: Schematic stratigraphic chart of the studied McMurray Formation strata in this thesis. The lower Cretaceous McMurray Formation unconformably overlies the upper Devonian Waterways Formation, and is overlain by the Wabiskaw Member of the Clearwater Formation. Stratigraphic chart modified from Smith, (1994) and Hubbard *et al.* (2011).

mainly on grain-size distributions and the presence of heterolithic units. It wasn't until the early 1980's that a number of studies determined that IHS in the McMurray formed as a result of the deposition of laterally-accreting point-bars, albeit the physiographic location of the point-bars (*i.e.* estuary vs. fluvial) was debated (*e.g.* Pemberton *et al.* 1982; Mossop and Flach, 1983; Flach and Mossop, 1985). By the late 1980's to early 1990's, mounting evidence including the recognition of a significant tidal influence (Smith, 1987; Smith, 1988) and continued ichnological studies (*e.g.* Ranger and Pemberton, 1992; Lettley *et al.* 2005a; Lettley *et al.* 2005b) led to the acceptance of an estuary depositional model for the McMurray Formation. However, recent advances in seismic resolution has uncovered widespread meander belts with point-bars on the scale of what is seen in large modern fluvial systems such as the Mississippi River (Smith *et al.* 2009; Hubbard *et al.* 2011; Labrecque *et al.* 2011a; Blum, 2017). As a result, the fluvial vs. estuary debate for point-bars in the McMurray Formation was renewed, with detrital zircon work (*e.g.* Blum and Pecha, 2014; Benyon *et al.* 2016) and geomorphology cited as the main arguments for a fluvially-dominated (albeit tidally influenced) depositional model. High-resolution seismic data show highly migratory point-bars with high width to thickness ratios that suggest deposition in the upper backwater reaches of a river based on modern analogues (Blum and Jennings, 2016). As such, recent geomorphological comparisons of McMurray point-bars to modern point-bars along the Mississippi River by the aforementioned authors has resulted in the "McMurray Conundrum" (Gingras and Leckie, 2017; Blum, 2017).

With the exception of 3-dimensional geomodels constructed from repeated facies analysis of open-pit mine faces (*e.g.* Barton, 2016), outcrop data remains the best way to visualize and interpret large-scale architectural elements within the McMurray Formation. The inherent sedimentological complexity in the fluvial-to-marine transition zone, as evidenced by modern studies, combined with incremental fluctuations in relative sea level throughout the Aptian (*e.g.* Ranger and Gingras, 2010) has resulted in the preservation of a number of

large-scale architectural elements in the McMurray Formation. Differentiating between these architectural elements is often difficult – for example, cross-bedded sand in the McMurray Formation is almost ubiquitously interpreted as the base of a fluvial or estuary channel deposit, perhaps due to the common occurrence of IHS overlying the cross-bedded sand. In many cases, particularly in outcrop, the sand and IHS represent two separate, genetically unrelated units that are almost always observed to occur together as a macro-couplet (Ranger and Gingras, 2010). As such, the cross-bedded sand may be ascribed to the deposition of simple fluvial dunes or forward accreting estuarine compound dunes in addition to a lower estuarine point-bar type of environment. Therefore, in order to properly interpret genetically separate geobodies, sedimentological and ichnological data must be combined with accurate architectural data such as the orientation of master bedding planes and palaeocurrent direction.

The studies presented in this thesis use a relatively new technology in geoscience – unmanned aerial vehicles (UAV's, or drones) - to produce high-resolution georeferenced outcrop models to acquire bed-by-bed orientation data. Importantly, this methodology has a number of advantages in comparison to data collection in the field: 1) beds can be analyzed along their entire visual extent, rather than at a single point while abseiling the outcrop; 2) IHS beds in the McMurray Formation typically dip anywhere from 5-12 degrees (Muwais and Smith, 1990; Strobl *et al.* 1997), so the characterization of the gently dipping beds using a 3D model is vastly superior to measurements taken with a compass where a small change in dip will not be represented accurately; 3) the accurate location of each measured bedding orientation is known, so obscured contacts (*i.e.* channel contacts while viewing an outcrop in strike-view) can be recognized with relative ease; and 4) the centimetre-scale resolution of the 3D outcrop models and orthomosaics allow for precise contacts to be picked based on subtle sedimentological and ichnological variations that were previously only possible to see while logging a vertical section of an outcrop. Overall, UAV-based 3D outcrop models are combined with sedimentological and ichnological data collected in the field to produce

robust depositional models with both small-scale and large-scale details for a number of McMurray Formation outcrops.

Chapter 2 proposes a new methodology for analyzing dune foreset cyclicity in outcrop by using 3D models to collect data rather than stitched photomosaics. In the past, photomosaic datasets have been used to collect foreset thickness measurements to interpret a tidal origin of sedimentary deposits so long as the variations in dune foreset thickness conform to a periodic sedimentation rate consistent with tidal periodicities (Kvale *et al.* 1999). These studies typically use visual or quantitative analysis techniques such as time series analysis to determine the periodicity of sedimentation rates (*e.g.* Martinius and Gowland, 2010; Kvale, 2012; Martinius *et al.* 2015; Timmer *et al.* 2016a). This study specifically compares two methods of collecting foreset thickness data from a McMurray Formation outcrop along the Christina River (Fig. 1.2): 1) directly from a stitched photomosaic; and 2) directly from a 3D outcrop model. The results show that a significant amount of noise is introduced into the data using the stitched photomosaic method, whereas the 3D model method provides a clear, distinctive periodicity that is consistent with semi-diurnal, synodic tidal cycles.

Chapter 3 is a comprehensive study of the Steepbank #3 and Amphitheatre outcrops (Fig. 1.2) completed by combining the known sedimentological and ichnological features with bed-by-bed orientation data collected from the 3D outcrop models. Notably, the strata exposed at the Steepbank #3 and Amphitheatre outcrops show the same facies association relationship (*i.e.* trough cross-bedded sand overlain by IHS) as what is commonly observed in McMurray outcrop and subsurface data. Despite this observation, a sharp, abrupt, and locally incising contact is observed between the cross-bedded sand and IHS geobodies at both outcrop locations. This contact is significant at both outcrops because: 1) there is a noticeable decrease in grain size from medium-grained cross-bedded sand below to lower fine- to very-fine grained sand in the overlying IHS; 2) the IHS units at both outcrops are pervasively

bioturbated, and overlie unbioturbated fluvial sand (Steepbank #3) or sparsely bioturbated estuarine sand (Amphitheatre); and 3) the IHS at both outcrops display a strong laterally-accreting relationship, while the sand below either has no preferred orientation (Steepbank #3) or an oblique forward-accreting architecture (Amphitheatre). As such, the Steepbank #3 outcrops are interpreted to preserve a laterally accreting point-bar complex (with the potential for four stacked, smaller-scale point-bars within the IHS overlying a genetically unrelated simple fluvial dune deposit), while the Amphitheatre outcrop is interpreted as a compound dune complex in the middle estuary that has been incised into by an inner estuary IHS-filled channel. The presence of disconformable contacts that separate the two architecturally independent geobodies at these outcrops suggests that several types of reservoir-quality geobodies exist in the McMurray Formation, and that these are not only confined to meandering channel deposits in a fluvial or inner estuary environment.

Chapter 4 focuses on characterizing the Crooked Rapids outcrop, which is a kilometre-long exposure along the Athabasca River (Fig. 1.2). Again, the outcrop is composed of metre-scale trough cross-bedded sand that is overlain by IHS deposits, similar to many other McMurray Formation outcrops. Despite this, the laterally-accreting strata at Crooked Rapids are unique among the rest of the McMurray outcrops for several reasons: 1) the cross- and planar-bedded sand at the base of the outcrop is observed to interdigitate with IHS up the point-bar surface, providing unequivocal proof that together, the two facies are genetically related to the deposition of a single point-bar; 2) there is no evidence of tidal modulation; 3) overbank fluvial levee deposits are preserved above the point-bar strata; and perhaps most importantly, 4) the point-bar deposit is devoid of bioturbation and contains abundant terrestrial detritus and coal fragments. As a result of this study, a sedimentological and ichnological fluvial baseline is established for McMurray Formation strata, and therefore subsurface deposits with similar characteristics should be interpreted as fluvial, while pervasively bioturbated IHS in the subsurface should be recognized as estuarine point-bars.

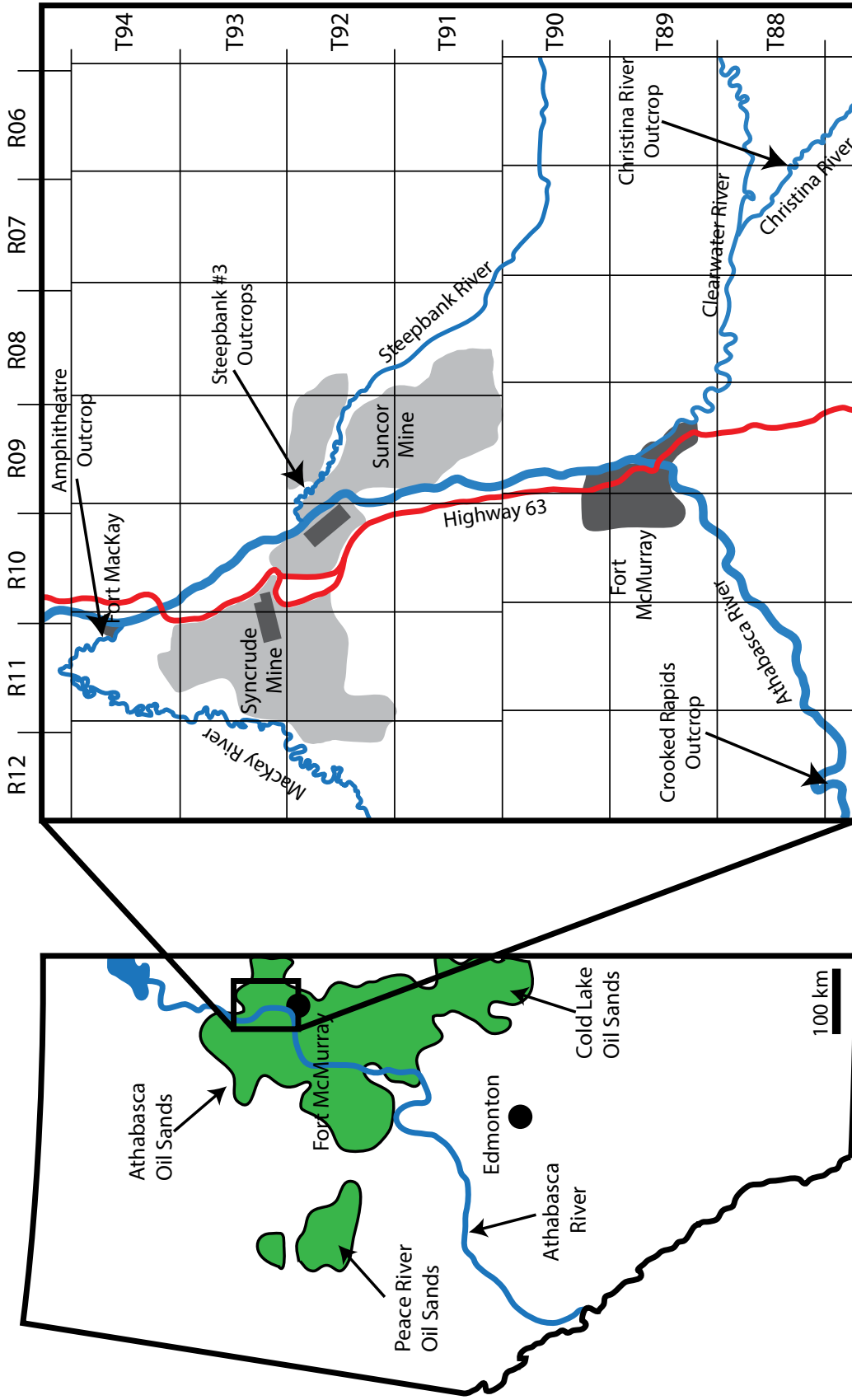


Figure 1.2: Location map of the studied outcrops in the Fort McMurray region.

As a collective effort, these three studies combine to explore the dynamic interplay of fresh-water fluvial and brackish-water estuary deposits within a highly-debated ancient drainage basin. The combined sedimentological, ichnological, and architectural observations from outcrop are used to identify and interpret a wide range of reservoir-quality sand bodies that occur at varying positions within a large fluvial-estuarine depositional system. By using 3D outcrop models, the studied outcrops are characterized on a large scale, permitting the identification and distribution of facies in fluvial and estuarine environments, which can be applied to subsurface datasets granted the same sedimentological facies are observed in core.

CHAPTER TWO: ANALYZING DUNE FORESET CYCLICITY IN OUTCROP WITH PHOTOGRAMMETRY

2.1 INTRODUCTION

Numerous studies have demonstrated that collecting and analyzing measurements of dune foreset thickness from outcrop can support interpretations related to periodicity of sedimentation rates (*e.g.* Visser, 1980; Tape *et al.* 2003; Hovikoski *et al.* 2005; Longhitano *et al.* 2012; Longhitano *et al.* 2014). This approach is useful for interpretations of datasets that lack tidal sedimentary features such as abundant double mud drapes (Dalrymple, 2010) and ichnological evidence such as tubular tidalites (*e.g.* Gingras *et al.* 2012; Wetzel *et al.* 2014; Gingras and Zonneveld, 2015). Data on dune foreset thickness are typically analyzed visually or quantitatively with techniques of time series analysis to determine the periodicity of thickness variations (*e.g.* Martinius and Gowland, 2011; Kvale, 2012; Timmer *et al.* 2016a). If the periodicities of measured foreset thickness data are similar to distinct tidal periodicities, then it is reasonable to ascribe tidal depositional processes to the measured data (Kvale *et al.* 1999).

Measuring foreset thicknesses from photographs is preferable to measuring thicknesses directly from the outcrop, given that there is minimal vegetation cover and slumping of the outcrop. This data collection technique is commonly used for studies of dune foreset cyclicity because: 1) measurements are easier to reproduce (*i.e.* the exact path of measurements is documented); 2) the quality of measurements is easily checked and critiqued; and 3) it is more time efficient. However, using photographs rather than physical outcrop measurements is not without complications. These include: 1) perspective distortion if photographs are not taken perpendicular to the outcrop face or if the outcrop face has significant relief; 2) edge effects due to camera lens distortion; and 3) the quality of photographs may be insufficient to

measure millimeter-scale thicknesses. Furthermore, the width of the interval of interest may require a photomosaic to be assembled, which can amplify perspective distortion depending on how each photograph is manipulated by photo-stitching software to project the resulting photomosaic on a plane.

This study compares two methods of collection of foreset-thickness data using only a photograph dataset. The first method measures foreset thicknesses directly from photomosaic datasets. The second method involves the use of photogrammetry techniques to build a textured 3D model of an outcrop, from which foreset thicknesses can be measured. The textured 3D models allow the researcher the advantages of measuring foreset thicknesses from photos (*sensu* 3D model creation from the photo dataset) while limiting errors due to spatial distortion. Perhaps the most significant drawback of only using photographs to record data is the inability to calculate Euclidean distance in three dimensions – meaning if the outcrop face is not perfectly flat, potentially significant errors will be associated with all foreset measurements collected, skewing the entire dataset. Using the 3D photogrammetry technique, optical and perspective distortion can be minimized by rotating the view to remain orthogonal to the outcrop while taking measurements, yielding greater precision in measurements of foreset thickness. The added precision achieved from obtaining true, three-dimensional measurements of outcrop foreset thicknesses is meaningful for interpreting the origin of the preserved dunes (*i.e.* arguing for or against a fluvial *vs.* tidal origin). To demonstrate the proposed method, we use an outcrop dataset from Christina River, NE Alberta, Canada.

2.2 METHODS

The proposed measurement method is summarized in Figure 2.1 and includes data collection, building a photogrammetry-based 3D model, and collecting thickness measurements from the 3D model. For building a 3D model, we use PhotoScan Professional (© Agi-

soft), a commercial software platform, due to its ease of use; however, multiple open-source alternatives that implement the same algorithms exist (*e.g.* Bemis *et al.* 2014, their Table 1). We use OpenPlot (Tavani *et al.* 2011, Tavani *et al.* 2014), an open-source structural geology software, to collect thickness measurements from the 3D model.

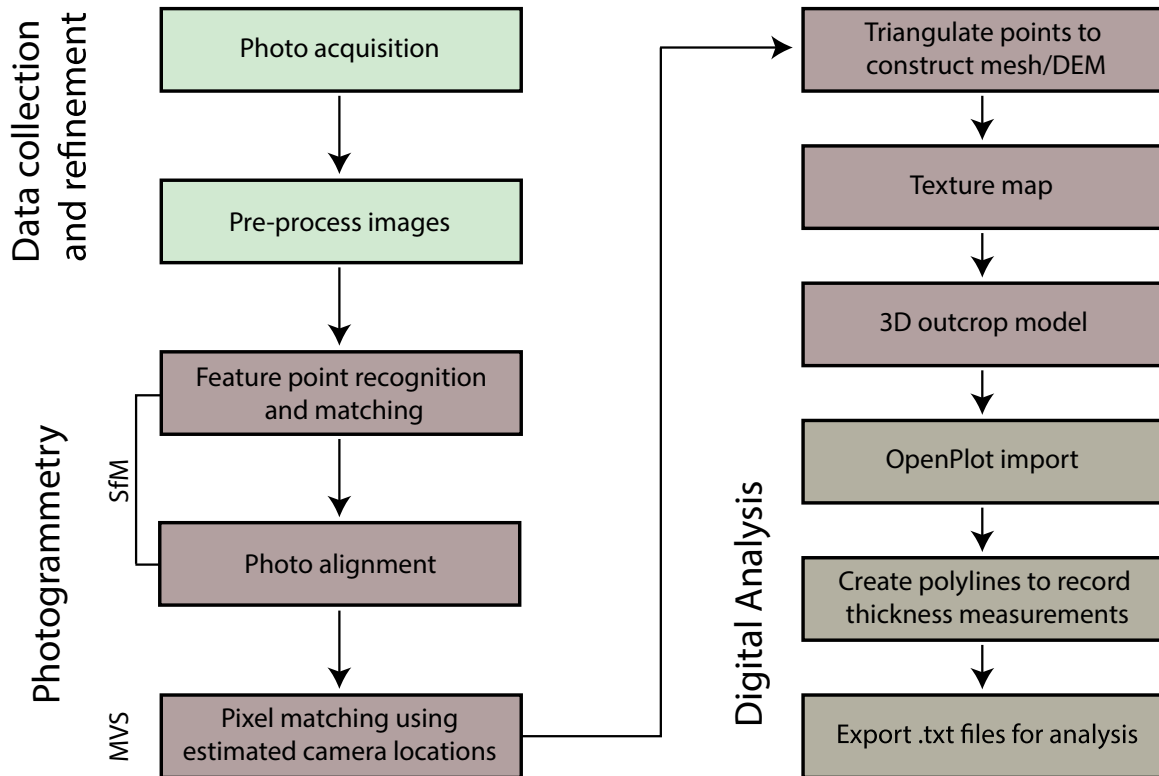


Figure 2.1: Schematic workflow of the 3D photogrammetry reconstruction process illustrating data collection, building photogrammetric models, and data analysis. Algorithms used to recreate the models, SfM and MVS, are indicated next to the appropriate boxes on the flow chart.

PHOTOGRAMMETRY

Three-dimensional photogrammetry is a data analysis method that captures information via overlapping photographs and assigns 3D locations to features portrayed in the images. At least two images of the same scene are required for 3D reconstruction: this is because any point in space can be located if the position, orientation, and focal length of the images is known or can be computed (*e.g.* Tavani *et al.* 2014). The best results are obtained when images are captured perpendicular to the object of interest, with a 60% overlap between each photograph, both vertically and horizontally (James and Robson, 2012).

Photoscan uses Structure from Motion (SfM; Ullman, 1979) algorithms in its initial step, photo alignment, which constructs a three-dimensional scene geometry from captured images (Szeliski, 2010; Fisher *et al.* 2013). Distinct feature points in an image are recognized, and the location of these points is monitored throughout other images until a 3D position can be estimated by the software (Verhoeven, 2011). Most SfM programs use the Scale Invariant Feature Transform (SIFT; Lowe, 2004) to detect feature points, but PhotoScan uses proprietary algorithms similar to SIFT for feature point detection (Semyonov, 2011; Javernick *et al.* 2014). Following this stage, the intrinsic and extrinsic orientation parameters are computed to estimate the approximate camera location (Javernick *et al.* 2014). Structure from Motion is strongly dependent on accurate camera positions in relation to each other (Szeliski, 2010), and as such is one of the critical outputs of the photo alignment step in PhotoScan. The final output is a sparse point cloud consisting of a few tens of thousands of points in 3D space, providing a preliminary glimpse of the outcrop structure.

The second step links the SfM output (sparse point cloud) with a second algorithm, Multi-View Stereo (MVS; Scharstein and Szeliski, 2002; Seitz *et al.* 2006), to dramatically increase the fidelity of the model. Instead of recognizing feature points like in the SfM algorithm, MVS matches individual pixel values of the images aligned in the first step, increasing the resolution of the model (and thus the number of data points) by two to three orders of magnitude (Scharstein and Szeliski, 2002; Seitz *et al.* 2006). Since all pixels are used in this step, the resulting output is capable of showing fine details of the outcrop such as dune foresets or sedimentary laminae. Each point in the dense cloud is used to generate a triangular mesh (essentially a digital elevation model), showing the 3D relief along the outcrop face.

The final step in generating an outcrop model in PhotoScan is to texture the mesh. Each vertex of the triangular mesh is assigned two coordinates, U and V. The original images

are stitched together, creating a texture map where the locations of U and V can be determined for each vertex (Tavani *et al.* 2014). After the coordinates are located, each triangle in the mesh will be cropped according to its location on the texture map and the resulting textured triangle is pasted onto the surface of the mesh (Tavani *et al.* 2014). This process is repeated for each triangle in the mesh, resulting in a completely textured 3D mesh of the outcrop.

MEASURING THICKNESS DATA FROM THE 3D MODEL

The outcrop model created in PhotoScan is exported as a wavefront OBJ file and subsequently imported into OpenPlot. This software contains a 3D viewing window. Every point on the outcrop model is referenced by an xyz coordinate. The thickness of each foreset in 3D space can be recorded by creating a polyline, and placing a node at the base of a foreset and at the top of the foreset.

Point data can be exported as a spreadsheet containing x, y and z coordinate values. To calculate the distance between two successive points (*i.e.* the foreset thickness) we use the Euclidean distance formula:

$$T_i = \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2 + (z_i - z_{i+1})^2}, 0 < i < n - 1$$

where T_i corresponds to thickness measurement i of n total measurements. Note that T_i is the apparent thickness of a foreset.

Notably, model processing time can be dramatically reduced if georeferenced photographs are used as the model basis. As such, cameras equipped with built-in GPS microprocessors provide optimal results. Furthermore, ground control points placed a known distance apart should ideally be included in the 3D models, in order to verify the accuracy of georef-

erencing.

2.3 CHRISTINA RIVER DATASET

In order to highlight the difference between thickness measurements collected from a photomosaic and thickness measurements collected with the 3D photogrammetry method, we use an example outcrop dataset from the lower Cretaceous McMurray Formation, of NE Alberta, Canada. The outcrop is located along the Christina River south of Fort McMurray, Alberta, Canada at $56^{\circ} 37.27' N$, $110^{\circ} 57.54' W$ (Fig. 2.2). Two hundred and forty nine high-resolution photographs spanning an area of approximately 8.5 m width by 1.3 m height were taken from the Christina River Outcrop in June 2007 with a Canon EOS 5D and a 50 mm lens. The dominant depositional process (*i.e.* tidal or fluvial) of these dunes remains the subject of debate

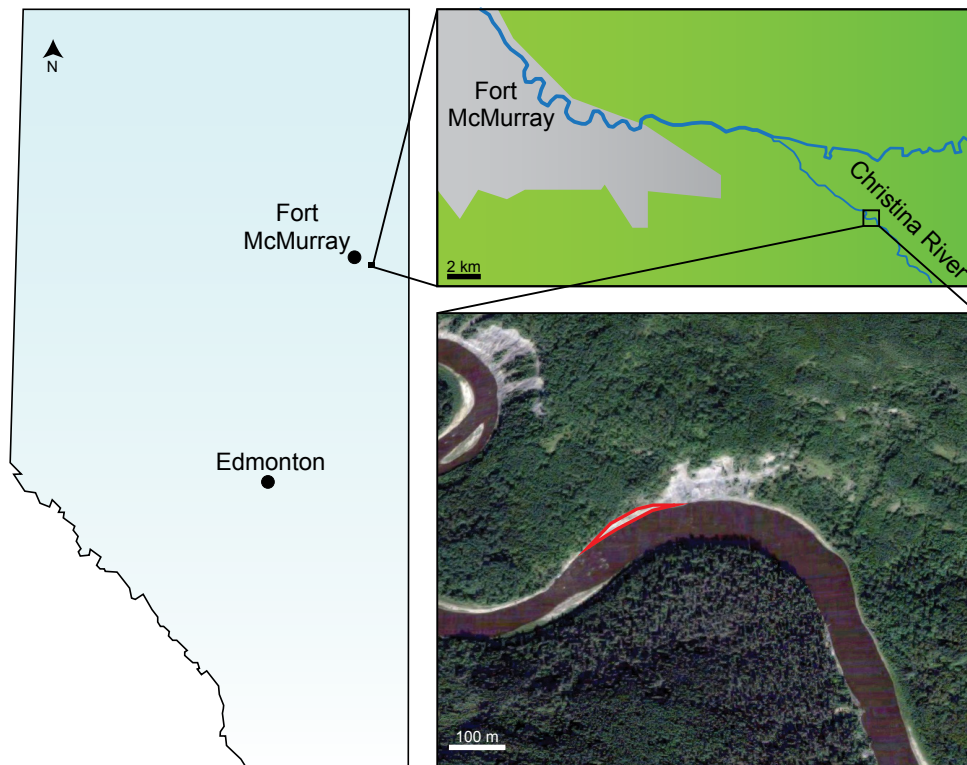


Figure 2.2: Location map of the study area outcrop in relation to Fort McMurray, Alberta, Canada. The outcrop is located at $56^{\circ} 37.27' N$, $110^{\circ} 57.54' W$. The outcrop interval that was photographed is highlighted by the red polygon.

(Martinius *et al.* 2015).

The McMurray Formation is informally subdivided into lower, middle, and upper members that are generally but not unequivocally interpreted to represent fluvial, fluvio-estuarine, and estuarine-marine deposits respectively (*e.g.* Carrigy, 1959; Ranger and Pemberton, 1997). Pre- and syn-depositional salt-solution collapse of Devonian carbonates underlying the McMurray Formation may have represented a principle control on early McMurray deposition, and played a role in constraining deposition to longitudinal, north-south-oriented valleys (Broughton, 2013). These valleys influenced much of the lower and middle McMurray deposition, until the transgression of the Boreal sea throughout Aptian to Albian time deposited regionally correlatable parasequences across the region (Caplan and Ranger, 2001).

The Christina River outcrop reported herein comprises middle McMurray cross-bedded, upper fine- to medium-grained sand dunes. At river level, the dune complex can be followed 200 m to the ENE, where approximately 25 m up the outcrop, moderately to heavily burrowed IHS rest on an abrupt and bioturbated contact to the underlying dunes.

The dunes themselves vary greatly in scale, generally ranging from 15 cm to 70 cm in thickness, but some larger dunes exceeding 1.8 m are present. The dunes are separated by master bedding planes, which represent the scoured base of the overriding (*i.e.* subsequent) dune. The master bedding surface is undulatory and variably contains countercurrent ripples, which are constrained to the scoured contact and may interfinger with dune toesets, or phytodetritus admixed with clayey silt or silty sand. Foresets commonly show grain striping (upper fine- to medium-grained sandstone), and potentially rhythmic waxing and waning of the foreset thickness. Cross-bedding orientations are generally between 200 and 250 degrees, with a subordinate set of orientations falling between 140 and 165 degrees. Master bedding surfaces dip 4 to 10 degrees WSW.

The cross-bedded sandstones are locally bioturbated. Bioturbation is constrained to rare bed tops, likely representing colonization of the distal toesets as the migrating dunes advanced. In a few instances, bioturbation is observed on the foresets of decimeter- to meter-scale dunes. The bioturbation is composed of long and robust *Cylindrichmus* and lined *Skolithos*. Monospecific assemblages of *Cylindrichmus* in particular are emblematic of brackish-water bioturbation (Gingras *et al.* 2016).

The similarity between sediment transport vectors, inferred from foreset orientations, and master bedding dip suggests that these strata can be taken to represent a compound dune that was deposited in a larger channel: channel depth may be inferable from the largest dunes; we suggest here an approximate minimum depth of 6 m and maximum depth of 19 m. Notably, master bedding orientations and bedform orientations are not consistent with point-bar deposits. Moreover, the presence of bioturbation in the form of large and “healthy” *Cylindrichmus* implies the presence of tides and a tidal-current transport vector. The presence of tides is further evidenced by rare bedding orientations that are 100 to 120 degrees out of phase with the model sediment transport direction. The most parsimonious interpretation of the compound dune is that it represents a tidally influenced bar in an estuary. As discussed below, Martinius *et al.* (2015) rejected this conclusion on the basis of frequency analysis of dune foresets; we show why that conclusion can be revised.

Variations in tidal energy typically produce variations in laminae or bedding thickness that coincide with diurnal or semidiurnal tides. Diurnal tidal regimes can produce between 0 (if no laminae are preserved or deposited) and 4 (1 flood tide laminae, 2 slackwater laminae, and 1 ebb tide laminae) laminae per day. Semidiurnal tidal regimes can produce anywhere between 0 and 8 laminae per day. Daily tidal periods combine with longer cycles for a broad range of periodicities. Fortnightly cycles produce, for example, 14 laminae per cycle if one

lamina is deposited daily or 28 laminae per cycle if two laminae are deposited daily, that is, ideal fortnightly cycles are integer products of 14. Monthly (or synodic) cycles produce, for example, 28 laminae per cycle if one lamina is deposited daily, or 56 laminae per cycle if two laminae are deposited daily, that is, ideal monthly cycles are integer products of 28. Longer depositional cycles such as seasonal and annual periodicities are more variable.

METHODS

A photomosaic was generated using AutoStitch (© 2006, Matthew Brown) and Adobe Photoshop CC (© 2016, Adobe Systems Inc.; Fig. 2.3A). Measurements of foreset thickness were obtained using the measuring tool in Photoshop and calibrated to a scale bar that was included in the photomosaic. The measurement path is shown in Figure 2.3B. All measurements were taken orthogonally between each successive foreset (Fig. 2.4).

Using the same photographs used to generate the photomosaic, a 3D photogrammetry model was built with Photoscan (Fig. 2.5A). The resulting 3D textured model was imported into OpenPlot. We closely followed the measurement path that was taken with the photomosaic to collect foreset measurements from the 3D model (Figs. 2.5B and 2.5C). These data were exported as a tabulated text file. A Python script was used to calculate foreset thicknesses from these data and to generate plots for time-series analysis (Timmer *et al.* 2016). The data collection technique and quantitative analysis workflow is summarized in Figure 2.6.

Bar plots were used to visually summarize and analyze measurements of foreset thickness. The continuous wavelet transform (CWT) technique was employed to supplement visual interpretations of cyclicity. This technique transforms the thickness-data time series from the time domain into the frequency domain, while maintaining time referencing (*e.g.* Torrence and Compo, 1998). This method works by shifting a wavelet (a periodic mathematical function) multiple times (the wavelet is squeezed or stretched to correspond to approx-



Figure 2.3: **A)** Photomosaic of the analyzed dune. **B)** Photomosaic indicating the exact foreset-thickness measurement path, spanning from right to left along the dune. Note that each scale card is 9 cm in length. Thickness measurements were completed in Adobe Photoshop. Calibration of scale was completed using the scale card outlined by the red box.

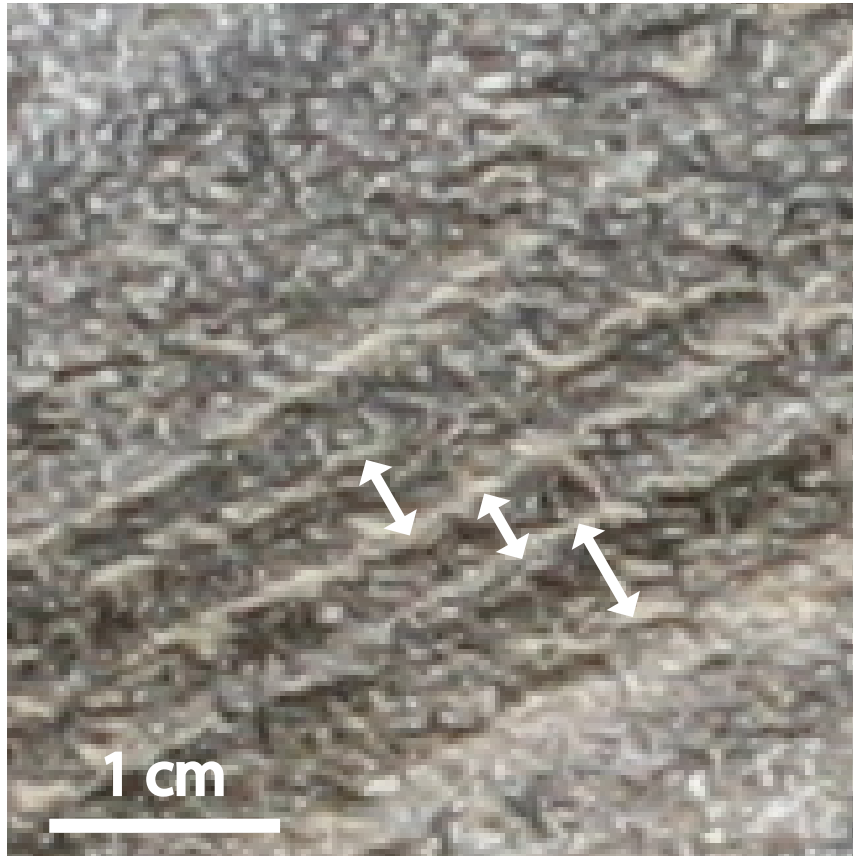


Figure 2.4: Close-up view of dune foresets in outcrop. Measurements of laminae thickness were taken perpendicular to each foreset.

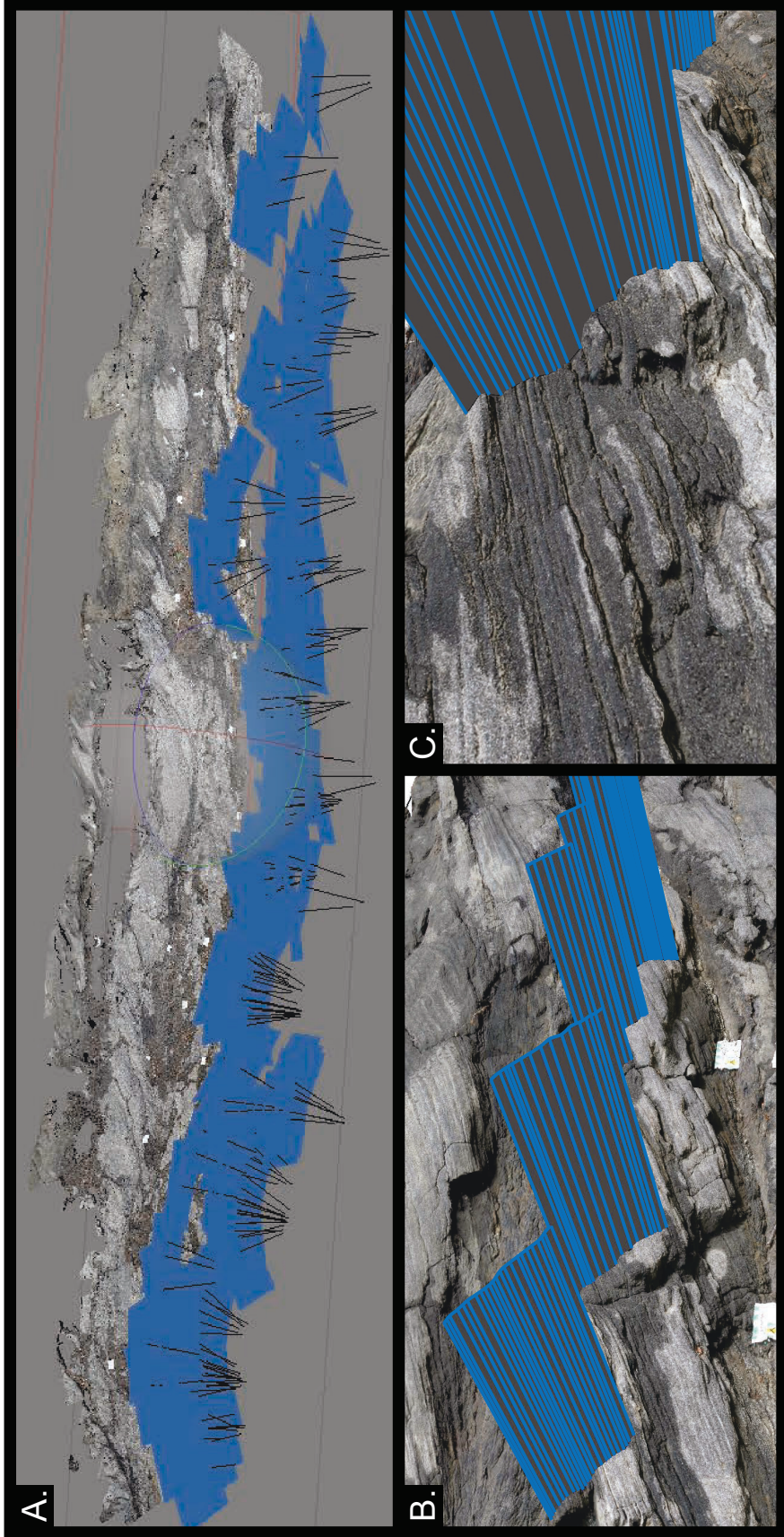


Figure 2.5: A) Overhead view of the generated 3D photogrammetric model in PhotoScan. Blue rectangles mark the approximate photographer location for each photo used to create the model. B) Measurement path along the studied dune as shown in OpenPlot. Nodes dropped along laminae are indicated by the blue lines, with the thickness between laminae shown as a grey plane between nodes. C) Close-up view of a studied section. The end of the blue lines marks the location where nodes are dropped.

imate frequencies) along the steps of a time series (*e.g.* measurements of successive foreset thicknesses; Fig. 2.6). A Morlet wavelet, which is composed of sinusoids, is typically used for extracting periodic signals from time series. We employ a Morlet wavelet in this study because cyclical components in time series are generally represented by sinusoidal functions. At each time-series step, the correlation between the wavelet and the thickness data is calculated. Stronger correlation coefficients correspond to the presence of stronger cyclical components. For each convolution, the wavelet is squeezed or stretched to correspond to approximately different Fourier frequencies. The results of a CWT are typically interpreted via a contoured matrix of correlation coefficients plot referred to as a scalogram. Cyclical intervals are marked by continuous, high correlation coefficients (which are typically contoured in warmer colors) and less cyclical components are marked by lower correlation coefficients (which are typically contoured in cooler colors). Note that high-frequency noise can significantly affect the interpretation of periodicity from scalograms.

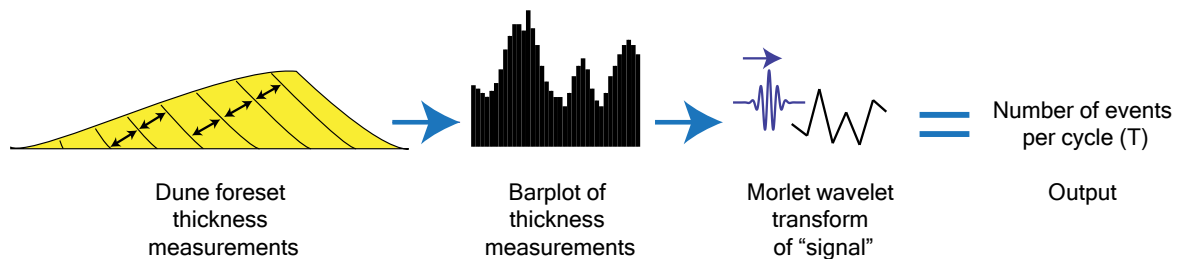
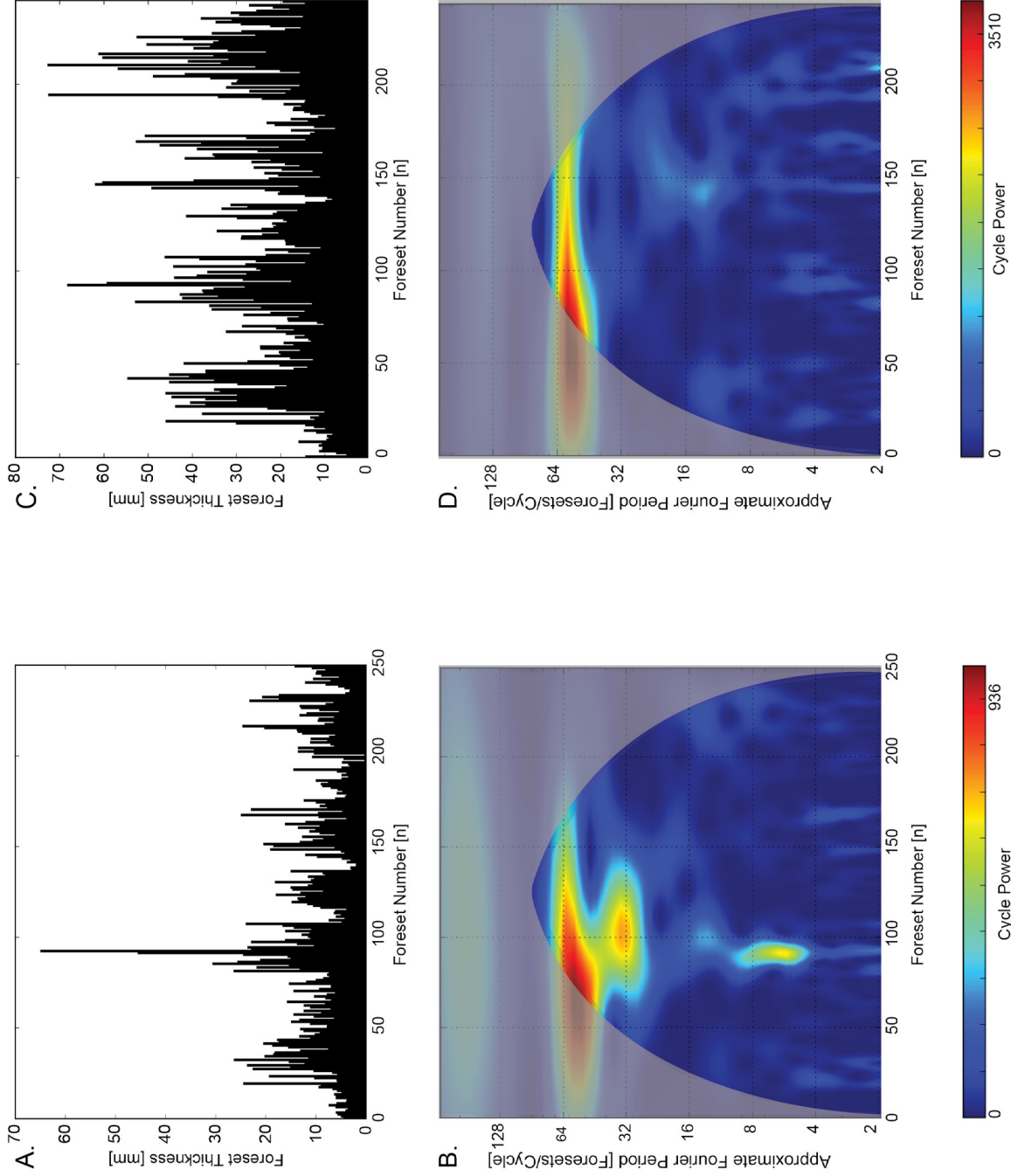


Figure 2.6: Schematic diagram depicting the quantitative methods workflow used in this study. Data on dune foreset thickness are collected via 3D photogrammetry model or 2D photomosaic and converted into a time signal, where foreset measurements represent time steps and thickness data represent the signal at each time step. The signal is then analyzed using a Morlet wavelet transform, where the periodicities are determined based on the strength of the correlation coefficient at a given cyclicity in the dataset. Modified from Timmer *et al.* (2016).

RESULTS

Measurements from the photomosaic and from the 3D photogrammetry model are summarized with the bar plots and scalograms that are shown in Figure 2.7. The thickness measurements from the photomosaic are shown in Figure 2.7A and 2.7B, and the thickness measurements from the 3D photogrammetry model are shown in Figure 2.7C and 2.7D.

Figure 2.7: **A)** Bar plot of thickness measurements from the photomosaic. 250 consecutive foreset measurements are included in the plot. **B)** Scalogram of thickness measurements from the photomosaic. The strongest periodic cycles occur at periods of approximately 56 and 33 foresets per cycle. These periods coincide with the warmer (*i.e.*, red and yellow) color spectra. **C)** Bar plot of thickness measurements obtained from the 3D photogrammetry model. 245 consecutive foreset measurements are included in the plot. **D)** Scalogram of thickness measurements from the 3D photogrammetry model. A single, strong periodic cycle occurs at a period of approximately 56 foresets per cycle.



Both datasets contain five distinct regions of relatively thick foreset thicknesses that are bounded by regions of relatively thin foreset thicknesses (Figs. 2.7A, 2.7C). The thickness of both the thinner and the thicker foresets measured from the 3D photogrammetry model are noticeably larger when compared to the photomosaic. In addition, the foreset-thickness measurements of the 3D model follow a stronger sinusoidal pattern (Fig. 2.7C) than the photomosaic (Fig. 2.7A), where thickness measurements are more variable.

The relatively chaotic nature of the foreset thicknesses measured from the photomosaic is reflected in the scalogram (Fig. 2.7B), whereby the strongest periodicity is split into two zones coinciding with periods of approximately 33 and 56 foresets per cycle. In contrast, the scalogram derived from the 3D photogrammetry model displays a uniform periodic signal coinciding with approximately 56 foresets per cycle (Fig. 2.7D).

2.4 DISCUSSION

CHRISTINA RIVER DATASET

The projected 2D thicknesses of thin laminae show distributions similar to those of the 3D model (Fig. 2.7A, 2.7C). However, thick foresets are apparently much more abundant in the 3D dataset (Fig. 2.7C). This may be because thick laminae are more likely to be influenced by slight changes of outcrop orientation (*i.e.* failing to record measurements orthogonal to the dune) and are thereby more difficult to measure accurately from 2D datasets. These differences in measurement, particularly in the thicker foresets, are due to perspective distortion, which occurs when a three-dimensional object is projected onto a plane. Without a 3D photogrammetry model, the thickness data appear to indicate that either: 1) the dune migration direction is variably oblique to the outcrop face; or 2) there is an interval of relatively thicker foresets preserved in the dune. Although both of these factors likely have some effect on the variability of foreset thickness, the magnitude of these biases are mitigated in the 3D

photogrammetry model, largely because spatial distortion due to optics and perspective is eliminated from the dataset.

The perspective distortion from the photomosaic obscures the periodic signal of the foreset measurements, which ultimately increases the difficulty of supporting cyclic depositional interpretations. Martinius *et al.* (2015) recently studied and analyzed measurements of dune foreset thickness from the Christina River outcrop. Using wavelet transforms, they determined that the variations in dune foreset thickness occur at two split periods of approximately 30 and approximately 40 foresets per cycle. The two-period split shown in Figure 12.19 of Martinius *et al.* (2015) is similar to the split we observed in our photomosaic scalogram (Fig. 2.7B) and is likely a perspective artifact (Martinius *et al.* (2015) do not report their measurement technique): because of this periodicity split, the authors were unable to conclusively interpret their scalogram results. Although the authors acknowledged the presence of sedimentary structures indicative of a tidal origin (*i.e.* backflow cross lamination and reactivation surfaces) and a brackish-water trace-fossil assemblage, Martinius *et al.* (2015) interpreted a fluvially dominated, tidally influenced setting largely due to the lack of a recognizable tidal periodicity in the two-period split of their obscured scalogram results.

We observe, from the 3D model, a periodicity occurring at 56 foresets per cycle. The time it takes the moon to rotate around the earth is a synodic month (*i.e.* the period of time from new moon to new moon), which lasts 29.53 days (Kvale, 2006). Within each synodic month, there are two spring cycles and two neap cycles. The absence of fine-grained sediment in the Christina River sand dunes indicates the lack of slackwater deposition, meaning only two laminae are deposited daily (flood and ebb tide deposits). As such, the scalogram derived from the 3D model is best interpreted as resulting from semidiurnal synodic deposition, whereby two laminae are deposited per day over approximately 28 days.

PHOTOGRAMMETRY MEASUREMENT ERRORS

Measurement errors associated with photogrammetry are classified according to two main categories: 1) systematic error due to camera and lens factors; and 2) systematic error due to poor planning of the camera network geometry (Dai *et al.* 2014). The former deals with aspects such as camera-lens distortion, principal-point distance, and overall photo resolution whereas the latter includes shooting distance, the amount of overlap between photos, the percentage of photo overlaps, intersection angles, and angles of incidence (Dai *et al.* 2014). Each of these factors can contribute to overall measurement error within a photogrammetric dataset.

Given that all cameras exhibit some degree of lens distortion, these errors are unavoidable; however, photogrammetry applications often feature techniques to minimize the effect of these errors (Dai *et al.* 2014). Examples include PhotoModeler (Eos System Inc, 2012), Camera-Calibrator (Photometrix, 2012), and Camera Calibration (Agisoft LLC, 2016). In contrast, errors associated with poor planning of the camera network geometry cannot be altered or adjusted without collecting more photos for photogrammetry software suites to use during processing stages. To avoid these types of errors, researchers should ensure that camera settings, lighting, image overlap, and image orientation with respect to the outcrop are consistent.

In PhotoScan, images are sorted into calibration groups automatically upon import according to resolution and EXIF metadata such as camera model and focal length (Agisoft LLC, 2016). If consistency between camera type and settings exists within the dataset, all photos are grouped into a single calibration group. During the “Align Photos” processing stage, both the intrinsic and extrinsic orientation parameters are estimated, thereby automatically adjusting the initial calibration data. Following the completion of this stage, the adjusted calibration data are available to view in order to verify the accuracy of the aligned

photos in terms of focal length, principal point coordinates, radial distortion coefficients, and tangential distortion coefficients (Agisoft LLC, 2016). The generation of these data ensures that errors associated with camera factors are minimized for a given dataset, thereby creating a more precise model. Readers are directed to Dai and Lu (2010) and Dai *et al.* (2014) for a more detailed discussion of systematic error corrections.

3D Photogrammetric techniques are widely used by a number of disciplines, including but not limited to archaeology, civil engineering, geology, and GIS (Doneus *et al.* 2011; Verhoeven *et al.* 2012; James and Robson 2012; Javernick *et al.* 2014; Dai and Lu 2010). Dai and Lu (2010) provide the most in-depth discussion of 3D photogrammetric measurement accuracy, statistically proving an almost linear relationship between tape-measured and model-measured features on a construction site. These researchers concluded that the achievable accuracy level is sufficient for use in construction engineering as errors in measurement of several meter-scale objects were in the millimeter range. James and Robson (2012) applied SfM-MVS techniques to create geological models ranging in spatial scales from centimeters to kilometers while recording precisions of 1:1000 (*i.e.* centimeter-level precision over distances of tens of meters) using an open-source SfM-MVS software. These authors speculate that expected precisions should be better in commercial software such as PhotoScan as it contains more flexible camera models.

With regard to the Christina River case study, the measurement errors associated with the 3D photogrammetry model and the photomosaic are summarized in Table 2.1. Both the 3D model and the photomosaic are scaled to 9 cm scale cards, and measurements of these cards are recorded using Openplot for the 3D model (to record xyz coordinates of the length of each scale card in order to calculate Euclidean distance) and Photoshop CC (© 2016, Adobe Systems Inc.) for the photomosaic. In the 3D model, the results are encouraging with only two outlier points outside the standard deviation of 0.13 cm. The photomosaic, however, has

a much larger standard deviation of 1.75 cm, and five of the recorded scale card lengths are outside this standard deviation. Given these results, particularly the large range in scale card lengths measured from the photomosaic, we recommend constructing 3D photogrammetry models in order to record data on dune foreset thickness from outcrop.

| Scale Card Number | 3D Model Length (cm) | 2D Photomosaic Length (cm) |
|-------------------|----------------------|----------------------------|
| 1 | 9.08 | 4.90 |
| 2 | 9.02 | 4.96 |
| 3 | 9.42 | 5.21 |
| 4 | 8.97 | 6.54 |
| 5 | 9.09 | 6.65 |
| 6 | 8.91 | 7.27 |
| 7 | 9.00 | 9.00 |
| 8 | 9.04 | 9.23 |
| 9 | 9.19 | 9.11 |
| 10 | 9.08 | 9.39 |
| | | |
| Range | 8.91-9.42 | 4.90-9.39 |
| Standard Dev. | 0.13 | 1.75 |

Table 2.1: A quantitative comparison of both the 3D photogrammetry and 2D photomosaic data collection methods. The 9 cm scale cards visible in Figures 3A and 3B were used for this analysis. The 3D model results are much more accurate, shown by the measurements close to 9 cm as well as the small standard deviation of 0.13 cm. The images on the left side of the photomosaic in Figure 3 appear to be distorted the most, shown by the increasing length of scale-card measurements in the table. One scale card was omitted from the results because it was not completely visible on both the 3D model and the photomosaic.

2.5 SUMMARY

Photogrammetry-generated 3D models provide an efficient and relatively simple method for increasing the accuracy of measurements of dune foreset thickness from outcrop photographs. These models allow the user to minimize the effects of perspective distortion along an outcrop face by: 1) removing the process of photomosaic stitching, which can distort and/or rotate images to successfully pair them; and 2) allowing the user to remain or-

thogonal to the outcrop face while recording measurements by rotating the 3D model. 3D photogrammetry models not only eliminate obscurities resulting from perspective distortion, but also allow Euclidean distance to be calculated in three dimensions, for more precise foreset-thickness measurements that mimic foreset thicknesses measured from the outcrop directly.

The frequency analysis of the Christina River outcrop using 3D photogrammetry models to collect data indicates a tidal origin for the preserved dunes. This is in contrast to data collection with 2D photomosaics, which have shown a split periodicity that is difficult to conclusively interpret not only in this study but in previous studies on the Christina River outcrop as well. Given the periodicity of 56 obtained from Morlet wavelet transform analysis, the interpretation of semidiurnal synodic deposition at this locale further strengthens the argument for a dominant tidal origin over a fluvial origin. This interpretation is supported by the presence of tidal sedimentary structures and a brackish-water ichnological assemblage in the outcrop. The use of 3D photogrammetry models for analysis of depositional cyclicity is further strengthened by the small standard deviation of measurement error using 3D photogrammetry models in comparison to the large standard deviation captured by using the photomosaic.

As demonstrated in the Christina River case study, legacy photograph datasets can be used to generate these models. However, for a more efficient workflow, GPS calibrated photographs should ideally be used. The thickness measurements from the Christina River photomosaic differ significantly from the 3D photogrammetry model due to the perspective distortion introduced by collecting measurements of three-dimensional geological features in only two dimensions. The 3D model limits distortion bias, which is conducive to a less noisy dataset. This was demonstrated by highlighting the differences between bar plots and scalograms obtained from the 3D photogrammetry dataset compared to the photomosaic dataset.

Notably, the bar plot of the photomosaic indicates that both the thinner and thicker foresets are reduced in thickness when measured in two dimensions instead of three. In addition, the range and standard deviation of measured scale-card lengths from both methods were calculated, with the 3D photogrammetry model having much smaller values than the photomosaic. The added precision in data collection by using 3D photogrammetry over photomosaics for analysis of depositional cyclicity produces more conclusive results with less noise in the scalogram, effectively making them less ambiguous to interpret.

CHAPTER THREE: USING STRUCTURE-FROM-MOTION PHOTOGRAMMETRY TO RECOGNIZE LATERAL *VERSUS* FORWARD ACCRETION BEDFORMS IN THE LOWER CRETACEOUS McMURRAY FORMATION, NE ALBERTA, CANADA

3.1 INTRODUCTION

The lower Cretaceous McMurray Formation is the primary reservoir for the Athabasca Oil Sands, and as such has been the focus of research for over 100 years. Sedimentological research has accelerated in recent years due to the development of economic *in situ* recovery techniques. The McMurray Formation is informally subdivided into the lower, middle, and upper members (Carrigy, 1959). These subdivisions roughly coincide with increasing marine influence from the lower through to the upper McMurray. The start of the modern era of research can be assigned to the work of Flach and Mossop in the 1970s and 80s (Flach, 1977, Flach, 1984; Mossop, 1980; Mossop and Flach, 1983; Flach and Mossop, 1985). Their research established that Inclined Heterolithic Stratification (IHS), a common depositional element in the middle McMurray Formation, forms as laterally-accreted point-bar deposits of meandering channels (Mossop and Flach, 1983). At that time, the physiographic association of these point-bars was strongly debated (*e.g.* Stewart and MacCallum, 1978; Pemberton *et al.* 1982; Mossop and Flach, 1983; Flach and Mossop, 1985; Thomas *et al.* 1987). Mossop and Flach (1983) and Flach and Mossop (1985) suggested that the processes of channel formation were dominantly fluvial, as opposed to Stewart and MacCallum (1978) who adopted the concept of estuarine deposition. Pemberton *et al.* (1982) suggested that much of the McMurray Formation was deposited under brackish-water conditions, leading to the general acceptance of an estuary depositional model for the McMurray Formation (Ranger and Pemberton, 1992; Wightman and Pemberton, 1997; Crerar and Arnott, 2007, and numerous references therein). Recently, the case for a fluvial origin (albeit tidally influenced) for IHS

units of the middle McMurray has been increasingly put forth (*e.g.* Peacock, 2010; Hubbard *et al.* 2011; Musial *et al.* 2012; Blum and Jennings, 2016)

It is a common observation from numerous outcrops and subsurface studies that these middle McMurray deposits generally have a fining-upward stacking pattern wherein the IHS overlies cross-bedded, megarippled dune sands. The dune sands are of prime economic importance because they constitute the best bitumen reservoirs and are the exclusive reservoir target for *in situ* recovery schemes using current technology. In the fluvial point bar model, the dune sands are generally considered to be a component facies of the migrating channel fill, whereby the sands are the traction load in the deepest part of the channel, and merge upward gradationally into the IHS point bar facies as a single genetic unit (Mossop and Flach, 1983; Flach and Mossop, 1985). This model places the dune sands either in a fresh-water fluvial bar environment (Mossop, 1980; Mossop and Flach, 1983; Flach and Mossop, 1985), or tidally influenced fluvial bar environment (Crerar and Arnott, 2007; Hubbard *et al.* 2011; Musial *et al.* 2012; Martinius *et al.* 2015, Jablonski and Dalrymple, 2016). In opposition to the single genetic unit model, an erosional discontinuity has been recognised in all outcrops that contain the bi-partite cross-bedded dune sands overlain by IHS (Ranger and Gingras, 2008; Ranger and Gingras, 2010). Ranger and Gingras thus proposed that in many cases the cross-bedded dune sands and the IHS represent two separate units, which are not genetically related. In this case the cross-bedded dune sands are estuarine bars, and not directly related to the inner or middle reach of a fluvial system (Wightman and Pemberton, 1997; Ranger and Gingras, 2008; Ranger and Gingras, 2010).

Some of the more recent research conducted on the McMurray Formation has focused on subsurface point-bar architecture in a local region within the extensive Athabasca oil sands deposit (*e.g.* Smith *et al.* 2009; Labrecque *et al.* 2011a, Labrecque *et al.* 2011b; Hubbard *et al.* 2011; Blum, 2017). Notably, all of these studies suggest the vertical transition

from cross-bedded sand into IHS represents the growth of large-scale, laterally accreting point-bars through time. Work by the aforementioned authors and others have led to the conclusion that most geobodies in McMurray Formation are point-bars, particularly in subsurface studies (*e.g.* Crerar and Arnott, 2007; Fustic *et al.* 2012; Shchepetkina *et al.* 2016a). Although a substantial proportion of the McMurray Formation is dominated by lateral accretion point-bar deposits, they are not ubiquitous. We demonstrate below that thick, reservoir quality sands also occur as tidally influenced, forward-accreting compound dune complexes. In general, very little work has focused on discriminating point bar *versus* composite dune facies associations in outcrop and subsurface studies in the McMurray Formation.

The objectives of this study are to recognize both lateral- and forward-accretion bedforms (*i.e.* point-bars and compound dunes) in outcrops along the Steepbank and MacKay Rivers and discuss the stratigraphic significance of these two architectural elements coexisting within the middle McMurray Formation. To do this, an unmanned aerial vehicle (UAV), or drone, is used to capture images of the outcrops for the purpose of constructing three-dimensional outcrop models using Structure-from-Motion photogrammetry. The conventional view of the Steepbank #3 outcrops is that a basal cross-bedded sand facies overlain by an IHS facies together represent the deposition of a single, 30 to 40 metre thick, laterally accreting point-bar (*e.g.* Mossop and Flach, 1983; Flach and Mossop, 1985; Wightman and Pemberton, 1997; Musial *et al.* 2012; Jablonski and Dalrymple, 2016). At the Amphitheatre outcrop, a 16 metre thick cross-bedded sand unit is disconformably overlain by two thin, mud-dominated IHS channel-fill deposits. Notably, the lowermost sand unit contains bioturbation, bimodal sediment transport directions, and shows evidence of forward accretion. The overlying IHS is 4 to 8 metres thick, thinly bedded, and in part vertically accreted. These observations differ from those at the Steepbank #3 outcrops, where the basal sand unit is unburrowed, shows little evidence of tidal transport, and is sharply overlain by thick, medium bedded, pervasively bioturbated laterally-accreted strata. As such, the dominant architectural element at the Am-

phitheatre outcrop is different than the record of lateral accretion that dominates the exposure at Steepbank, making these outcrops excellent candidates for a comparative study.

3.2 BACKGROUND

Outcrops along the Steepbank River are probably the most studied exposures of McMurray Formation strata, due in part to the fact that almost the entire middle and upper McMurray succession is exposed. Together, the middle and upper members comprise the most substantial bitumen reservoirs. It is widely accepted that these outcrops mainly comprise fluvial or estuary point-bar lateral accretion deposits of the middle McMurray Formation (*e.g.* Pemberton *et al.* 1982; Mossop and Flach, 1983; Flach and Mossop, 1985; Strobl *et al.* 1997; Musial *et al.* 2012; Musial *et al.* 2013; Jablonski and Dalrymple, 2016). Early work along the Steepbank River by Flach (1977), Mossop (1980) and Mossop and Flach (1983) concluded that fluvial channels ranging from 30 to 45 metres thick were preserved in outcrop exposures. These authors noted the presence of lateral accretion deposits – later identified as IHS – conformably overlying trough cross-bedded sand. Together, these two units comprise middle McMurray strata at the Steepbank River outcrops and were interpreted as a single fluvial channel. At the same time, the brackish water ichnological model developed by Pemberton *et al.* (1982) argued that a fluvial interpretation contradicts the trace fossil assemblage at the Steepbank outcrops. A lithofacies classification developed by Smith (1987) for meandering river-estuarine point-bar deposits based on the research of contemporaneous point-bars along the Willapa, Daule, and Babahovo Rivers support the channelized, brackish-water interpretation for the McMurray Formation point-bars. Furthermore, Smith (1988) reported the presence of tidal bundles within McMurray Formation IHS near Steepbank, supporting the estuary interpretation. In general, the large, single-channel interpretation has been the accepted depositional model for the Steepbank #3 outcrops (outcrop number after Flach, 1977) for over 35 years, while the physiographic depositional position (*i.e.* estuarine *versus* fluvial)

of the channel has been debated in the most recent research on these outcrops (*e.g.* Musial *et al.* 2012; Jablonski and Dalrymple, 2016).

The Amphitheatre outcrop near Fort MacKay displays a different depositional architecture than the Steepbank #3 outcrop exposures. The most thorough study of the Amphitheatre outcrop to date was conducted by Wightman and Pemberton (1997), but overall this locale is not often discussed in published literature. Importantly, Wightman and Pemberton (1997) concluded that at Amphitheatre, the basal, locally bioturbated, cross-bedded sand facies represent an open estuarine, subtidal sandwave (*i.e.* compound dune) dominated environment closer to the estuary mouth, as opposed to lower point-bar or channel thalweg facies in sinuous tidal-fluvial channels. Their interpretation is crucial and worth testing: the recognition and differentiation of different geobodies in the McMurray Formation is important for the development of local and regional stratigraphic models for subsurface exploration and production.

3.3 STUDY AREA

The studied McMurray Formation sections are exposed along the Steepbank and MacKay Rivers in northeast Alberta, Canada (Fig. 3.1). The Steepbank #3 outcrops, herein referred to as Steepbank 3A, 3B, and 3C are located approximately 30 kilometres north of Fort McMurray in Township 92, Range 9 W4 (57° 01' 0.75" N, 111° 26' 2.19" W). The Amphitheatre outcrop is approximately 60 kilometres north of Fort McMurray and one kilometre west of Fort MacKay in Township 94, Range 11 W4 (57° 11' 34.30" N, 111° 39' 50.09" W).

The schematic stratigraphy for the study area is shown in Figure 3.2. In the study areas, the McMurray Formation unconformably overlies the Devonian-aged Waterways Formation. Pre- and syn-depositional salt dissolution of middle Devonian halite caused exten-

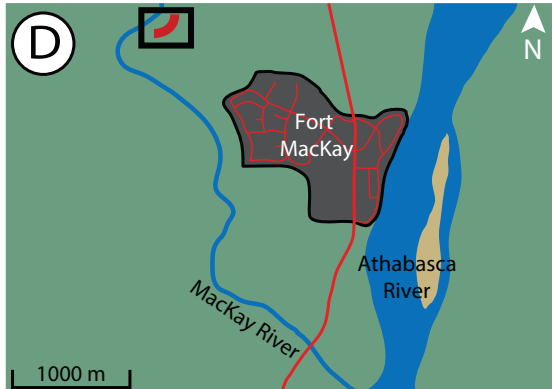
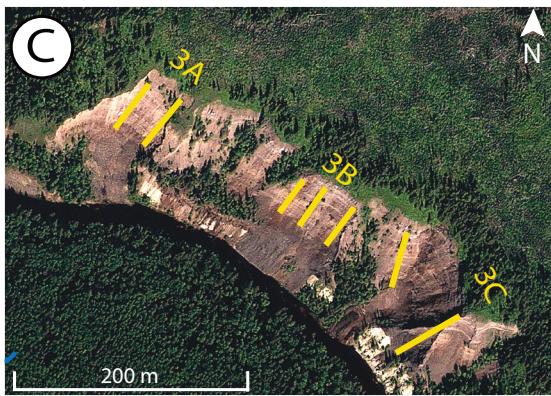
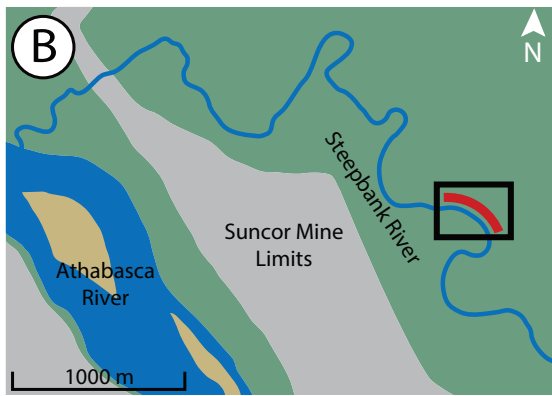
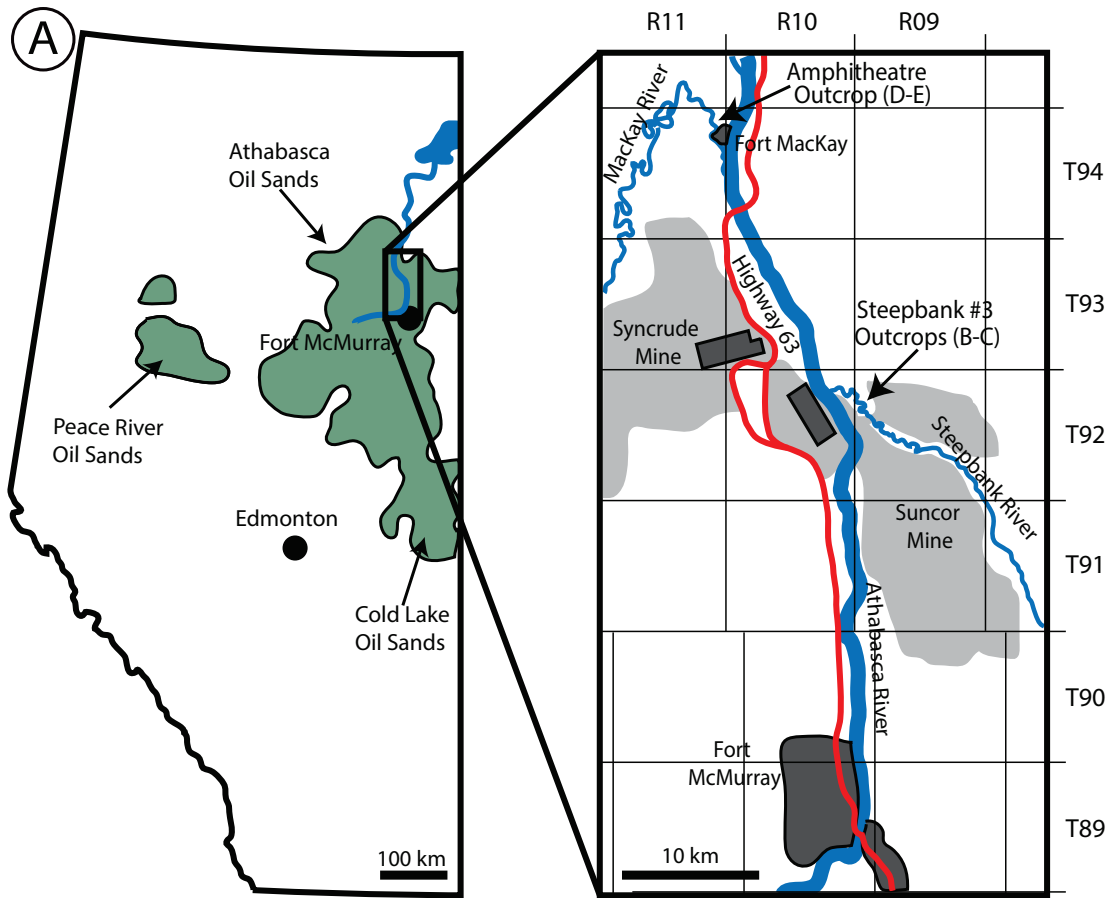


Figure 3.1 (previous page): **A)** Location map of the studied outcrops in relation to Fort McMurray, Alberta, Canada. **B)** Map showing the exact meander bend along the Steepbank River where the Steepbank #3 outcrops are located, denoted by the black box. **C)** Satellite image of the Steepbank #3 outcrops, located at 57° 01' 0.75" N, 111° 26' 2.19" W. **D)** Map showing the exact meander bend along the MacKay River where the Amphitheatre outcrop is located, denoted by the black box. **E)** Satellite image of the Amphitheatre outcrop, located at 57° 11' 34.30" N, 111° 39' 50.09" W. Yellow lines on the satellite images indicate the location where tadpole plots are produced for each outcrop in this study. Satellite images are courtesy of Google Earth © 2017.

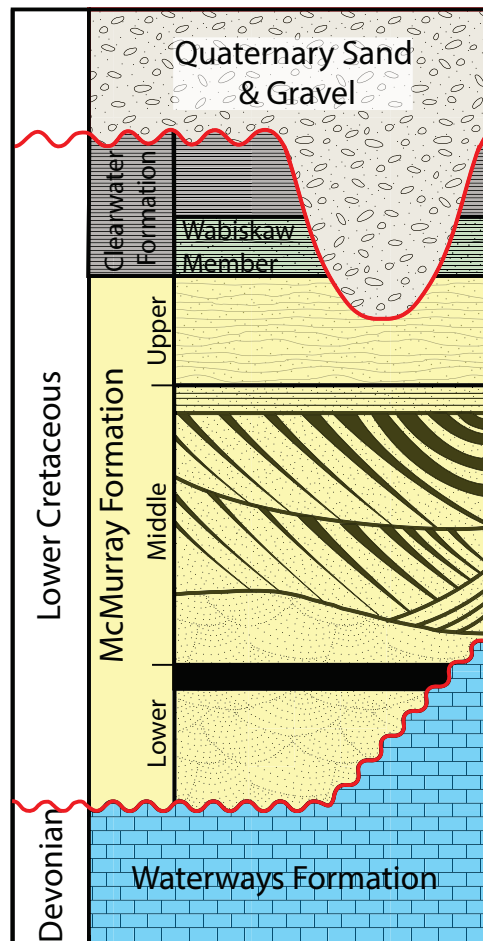


Figure 3.2: Schematic stratigraphic chart of the studied McMurray Formation strata. The lower Cretaceous McMurray Formation unconformably overlies the upper Devonian Waterways Formation. At the Steepbank #3 outcrops, the Wabiskaw Member of the Clearwater Formation is exposed above the McMurray Formation strata. At the Amphitheatre outcrop, upper McMurray deposits are eroded by Quaternary sediment. Stratigraphic chart modified from Smith, (1994) and Hubbard *et al.* (2011).

sive karstification of this underlying carbonate unit (Broughton, 2013; Broughton, 2014). This influenced early McMurray deposition, with the lower and middle members largely confined to regional palaeovalleys. The Clearwater Formation overlying the McMurray Formation in the study areas has been erosionally removed, with the exception of thin Wabiskaw member silt- and mud units locally present in the upper 5 metres of the Steepbank outcrops.

3.4 METHODS

The characterization of the McMurray Formation outcrops in this study is achieved by using Structure-from-Motion (SfM) photogrammetry to produce high-resolution 3D outcrop models and 2D photomosaics to be used in conjunction with traditional field logging and palaeocurrent data collection. By using SfM photogrammetry, a view orthogonal to the outcrop face is available at any elevation, in contrast to previous studies where images are captured at the base of the outcrop looking up (*e.g.* Jablonski and Dalrymple, 2016, their Figs. 9A and 9E). The ability to remain orthogonal to the outcrop face removes bias from perspective distortion, allowing for an increased understanding of important outcrop features. For a more detailed discussion of the application of SfM photogrammetry to outcrop, readers are directed to Hayes *et al.* (2017).

In this study, we use a commercial SfM photogrammetry software, PhotoScan Professional (© Agisoft) to construct georeferenced 3D outcrop models. The only inputs required for the software are georeferenced photographs of the outcrops that are captured orthogonal to the outcrop face approximately five to ten metres away. The photograph dataset used to create the 3D outcrop models in this study was captured using a DJI Inspire 1 unmanned aerial vehicle (UAV) equipped with a 12 megapixel Zenmuse X3 camera. A sweeping method was employed to capture the images - meaning the UAV operator would fly the drone at a constant elevation, approximately five to ten metres away from the outcrop face, and photo-

graphs would be taken laterally with approximately 40% overlap between successive images. Following a sweep of the outcrop face at a constant elevation, the UAV operator repositions the drone at a different elevation (while maintaining sufficient image overlap vertically), for another sweep to be completed. This process is repeated until the entire outcrop face has been photographed. Following the collection of the photograph dataset, the images are processed using Adobe’s Photoshop and Lightroom (© Adobe) to minimize contrast and colour irregularities resulting from changes in sunlight during data collection.

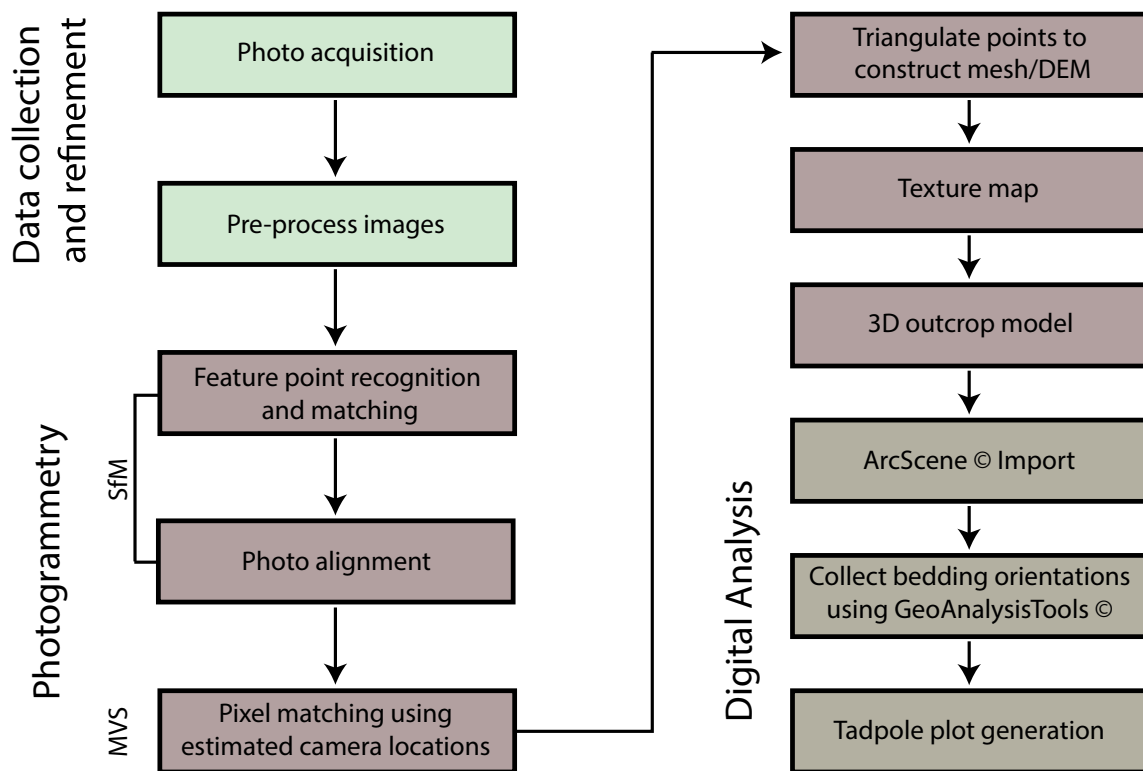


Figure 3.3: Schematic workflow of the 3D photogrammetry method used to characterize McMurray Formation strata in outcrop in this study. Modified from Hayes *et al.* (2017).

These outcrop models are an expedient, inexpensive technique to characterize medium to large-scale bedding (*e.g.* IHS bedding). In particular, bedding orientations of IHS deposits are key to differentiating stacked IHS sets - herein referred to as lateral accretion sets (*LAS sensu* Nardin *et al.* 2013 – not to be confused with digital wireline log files, denoted as .las files). The 3D outcrop methodology is summarized in Figure 3.3. Palaeocurrent data was collected in the field via abseiling the Amphitheatre outcrop exposure in September

2013. The palaeocurrent data used in this study from the Steepbank #3 outcrops is from the appendix sections of Jablonski (2012).

THREE-DIMENSIONAL PHOTOGRAMMETRY

Three-dimensional photogrammetry is a data collection technique that uses Structure-from-Motion (SfM; Ullman, 1979) algorithms to align two-dimensional photographs for the purpose of 3D model construction. In order for successful scene construction using 3D photogrammetry, at least two images depicting the same object (or in the case of this study, the same part of an outcrop) are required: this is because any point in space can be located if the position, orientation, and focal length are known or can be estimated (Tavani *et al.* 2014).

During the processing stages, PhotoScan implements a series of algorithms that output sparse point clouds based on feature points, and later on dense point clouds using the pixels of each image throughout the photograph dataset. The output of the first algorithm, SfM, is two-fold: it consists of 1) a sparse 3D point cloud built based on the recognition of prominent feature points among the photograph dataset (Fisher *et al.* 2013; Szeliski, 2010) and 2) the location of each camera position (*i.e.* the location where each photograph was captured) in relation to the others in the dataset is computed. The quality of 3D photogrammetry models is strongly dependent on accurate camera locations, making this a critical output of the SfM algorithm.

The subsequent, second algorithm, Multi-View Stereo (MVS; Scharstein and Szeliski, 2002; Seitz *et al.* 2006) matches individual pixel values of the images aligned by the SfM algorithm to increase the resolution of the model. The resulting output is a dense point cloud, with the number of points increased from the sparse point cloud by two to three orders of magnitude (Scharstein and Szeliski, 2002; Seitz *et al.* 2006). At this stage, the dense point cloud is of sufficient quality for resolving the finer features of the outcrop (*i.e.* alternating

sand-mud couplets in IHS bedding). In addition, the highly detailed dense point cloud has a sufficient number of points to produce a triangular mesh, to show the 3D relief along the outcrop face.

The final step in the processing stages of PhotoScan is to texture (*i.e.* place georeferenced images on) the triangular mesh. The vertex points of the mesh are assigned two coordinate values, U and V, for the purpose of cropping the original images at the vertex points of each triangle (Tavani *et al.* 2014). During this step PhotoScan creates a texture map, which is essentially all of the images stitched together with the coordinate locations of the triangular vertex points recorded. After the coordinate points for a triangle in the mesh are located on the texture map, that region of the texture map is cropped and the resulting textured triangle is pasted directly onto the triangular mesh (Tavani *et al.* 2014). This process is then repeated for the entire mesh, until the model is completely textured.

BED ORIENTATION DATA COLLECTION

Following the completion of the textured 3D outcrop models, they are exported as Virtual Reality Modeling Language (.wrl) files and imported into ArcScene 10.2 (© ESRI), a 3D visualization GIS program. In order to extract structural bedding orientation data of middle and upper McMurray deposits from the 3D models, a toolbar extension for ArcScene called GeoAnalysisTools (© Geological & Historical Virtual Models, LLC) is required. GeoAnalysisTools provides a number of sedimentary analysis and structural geology tools to analyze outcrops digitally (GHVM, 2013). With regard to this study, the tool to measure strike and dip of bedding planes is used to generate tadpole plots for the purpose of differentiating lateral accretion sets. Using 3D outcrop models to achieve this allows for bed-by-bed data collection of gently-dipping strata (typically less than 20°) where bedding planes are exposed. Furthermore, bed orientation measurements can be collected along bedding planes that are traced for metres to tens-of-metres rather than at a point source while abseiling the

outcrop exposure.

To measure strike and dip, points are placed along a bedding plane in locations where there is three-dimensional relief along the length of the bed. The software finds a best-fit plane for all the points along the studied bed by solving a 3-point problem (if only three points are placed) or by using an eigenvector method to fit a plane to four or more data points (GHVM, 2013). Given that the model is georeferenced, the strike and dip tool is capable of assessing the orientation of a bed while estimating degree errors for the computed bed azimuth and dip. Overall, this allows for accurate measurements to be recorded by eliminating large-error measurements resulting from the lack of significant relief along the outcrop face from the dataset. For the purposes of this study, an error cutoff of 2.5° is used to ensure accuracy of the measured beds. This cutoff is used because it is a small enough value that the conclusions drawn from bed orientation data in this study would not be compromised within this error range.

This methodology allows for dense bed-orientation data collection from the outcrops (*via* the 3D outcrop models) to generate a dataset analogous to dip-meter logs, a key tool for recognizing changing depositional architecture styles (*e.g.* Muwais and Smith, 1990; Strobl *et al.* 1997). Pseudo dipmeter logs (*i.e.* tadpole plots) were produced to supplement visual and sedimentological observations at the Steepbank #3 and Amphitheatre outcrops. Generating the tadpole plots requires a number of bedding orientations to be recorded in a vertical succession along the outcrop. These bedding orientations were exported as tabulated text files, and then processed by a Python script that converts strike and dip to dip and dip azimuth, completing the process by plotting a tadpole dipmeter log.

ROTATION OF UPPER McMURRAY FORMATION BED ORIENTATION DATA TO SHOW DEPOSITIONAL DIP

The upper McMurray parasequence deposits at Steepbank are assumed to possess a negligible depositional dip. However, analysis of bed orientation data from the Steepbank #3 outcrops indicate that these outcrops form an open anticline, dipping 4.4° N at outcrop 3A in the northwest to 6.8° SE at outcrop 3C in the southeast. This deformation is not discussed further, but it is not unexpected in the McMurray Formation as pre-, syn-, and post-McMurray salt tectonics occurred throughout the region (Broughton, 2013).

In order to display the true orientations of IHS lateral accretion beds, the orientation measurements collected at the Steepbank #3 outcrops were re-oriented in order to remove post-deposition structural deformation effects. This was achieved using an open-source structural geology software called Stereonet (© R.W. Allmendinger; Allmendinger *et al.* 2013; Cardozo and Allmendinger, 2013). This software permits the rotation of bedding orientations around a specific dip/dip direction data point. The average upper McMurray bed orientation was computed from the dataset for each outcrop individually (*e.g.* Steepbank 3A, 3B, 3C). The bedding orientations were then rotated around the average upper McMurray bed orientation corresponding to the same outcrop, providing tadpole plots that better show the original depositional dip of the underlying lateral accretion deposits. These plots only show master bedding orientations – no palaeocurrent data is depicted on the tadpole plots in this study.

3.5 STEEPBANK #3 OUTCROPS

RESULTS

The measured sections of the Steepbank outcrops are shown in Figure 3.4. The Steepbank outcrops are characterized by a thick medium-grained sand unit devoid of bioturbation at the base of the succession. The sand facies is thickly bedded, with beds that range

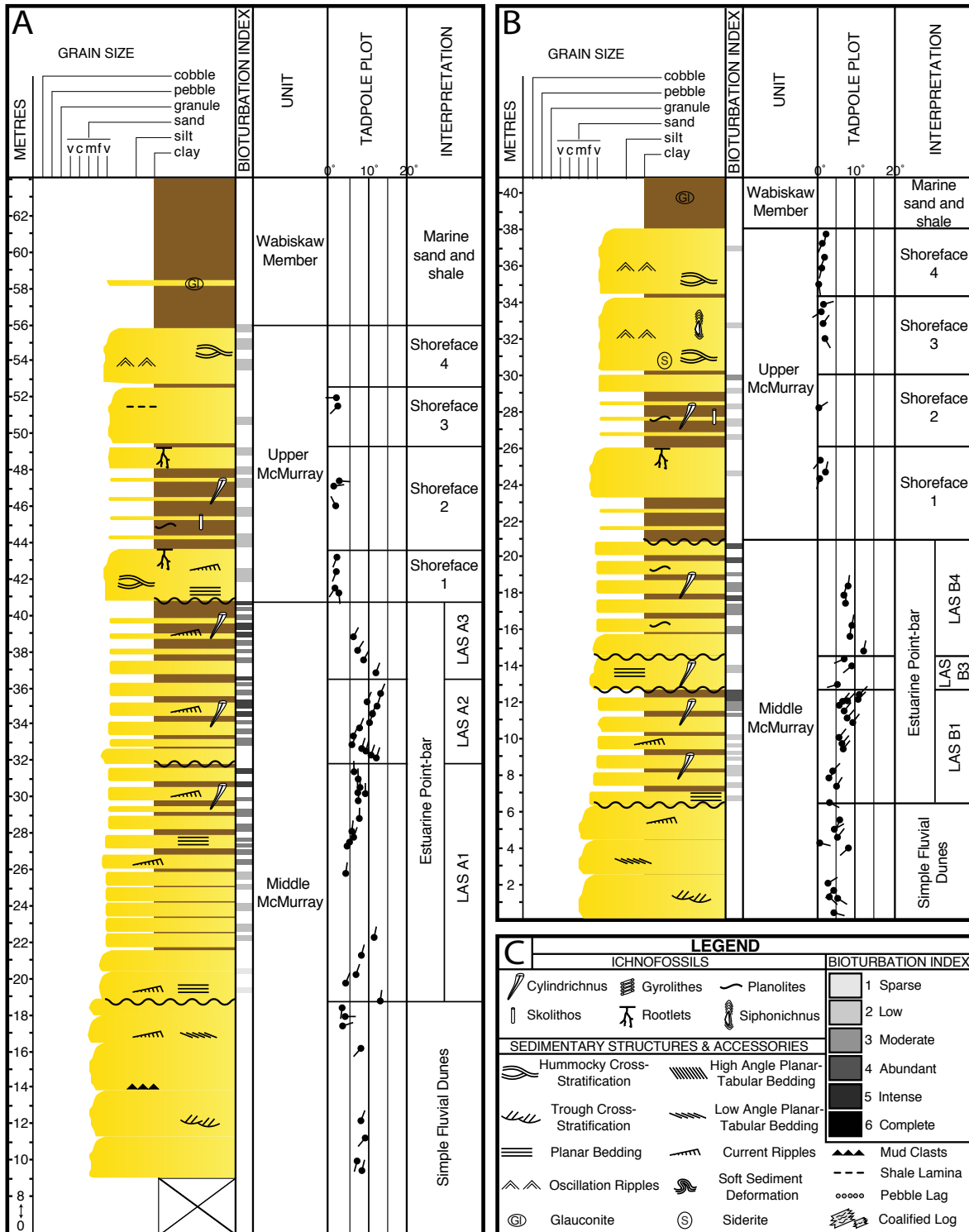


Figure 3.4: Measured sections of the Steepbank #3 outcrops. The tadpole plots near the line of sections show master bedding of the sand and IHS geobodies, to illustrate the differences in bedding character between the separate depositional units. **A)** Log of the Steepbank 3A outcrop. **B)** Log of the Steepbank 3B outcrop. **C)** Legend for the outcrop logs in this study.

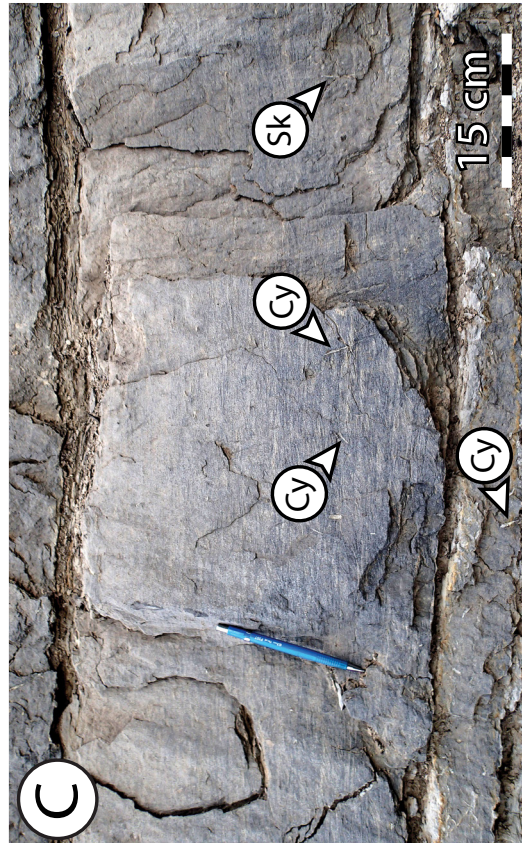
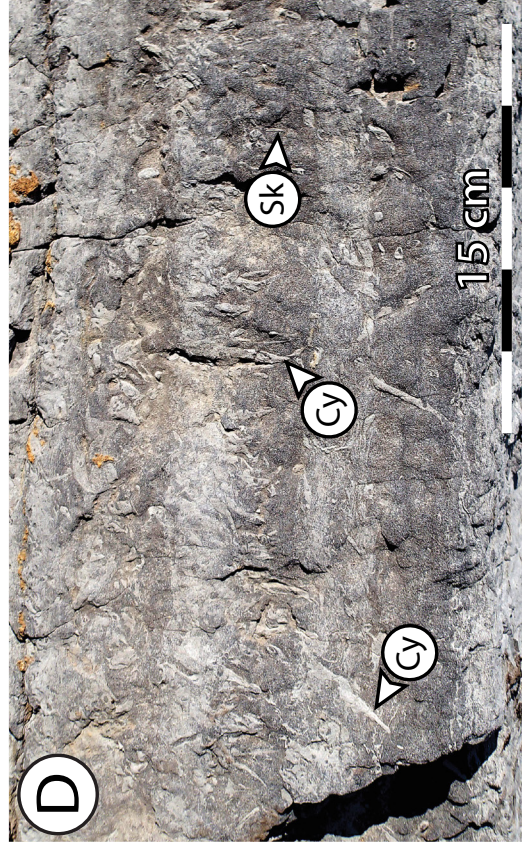


Figure 3.5 (previous page): Outcrop photos of the basal cross-bedded sand and overlying IHS facies at the Steepbank #3 outcrops. **A)** Metre-scale high angle tabular, medium-grained cross-bedded sand. **B)** Decimetre-scale cross-beds with mud lining the toesets of the dunes. The sand is medium-grained. **C)** Sand-dominated IHS, located near the base of an IHS set. The sand is upper very fine- to lower fine-grained, and contains sharp based current ripples, *Cylindrichnus*, and *Skolithos* trace fossils. **D)** Mud-dominated IHS located near the top of an IHS set. The sand is very fine-grained, and pervasively bioturbated. The sand and mud beds contain *Cylindrichnus* and *Skolithos*.

from 30 centimetres to two metres thick. Sedimentary structures are limited to decimetre- to metre-scale trough cross stratification, decimetre- to metre-scale high-angle planar tabular cross stratification and planar bedding (Fig. 3.5A). Thin interbeds of rippled sand to decimetre-scale dunes with mud clasts in the toesets are observed (Fig. 3.5B). Bedding contacts are sharp or scoured in the cross-bedded sand unit.

This unit is abruptly overlain by an inclined, interbedded sand and mud facies with abundant *Cylindrichnus* burrows throughout. The sharp contact between the thickly bedded, unburrowed sand and the overlying heterolithic succession is discernable at all of the Steepbank #3 outcrops (Fig. 3.6). The interbedded sand-mud facies (IHS facies) is typically between 20 and 28 metres thick, and is characterized by several prominent erosional contacts internally within the succession. Sharp-based current ripples and planar-tabular bedding are common in the sand beds of the IHS facies. Sand beds are fine- to very fine-grained and rarely burrowed near the base of the IHS sets, but they commonly contain *Cylindrichnus* and *Skolithos* upwards (Figs. 3.5C and 3.5D). *Cylindrichnus* and *Planolites* burrows are common in the mud beds throughout the IHS sets. Bioturbation index of the IHS varies from 1 to 4. Although this facies is heterolithic, it is composed of approximately 80% sand. Above the IHS deposits, in what we consider to be the upper McMurray, several parasequences consisting of horizontally bedded sand and mud cap the Steepbank #3 outcrop succession. These deposits are laterally continuous between the three studied outcrops, and contain organic detritus as well as the trace fossils *Cylindrichnus*, *Planolites*, *Skolithos*, and *Siphonichnus*. These parasequences are composed of dominantly very fine- to lower fine-grained sand, with common sedimentary structures including oscillation ripples, planar bedding, and hummocky

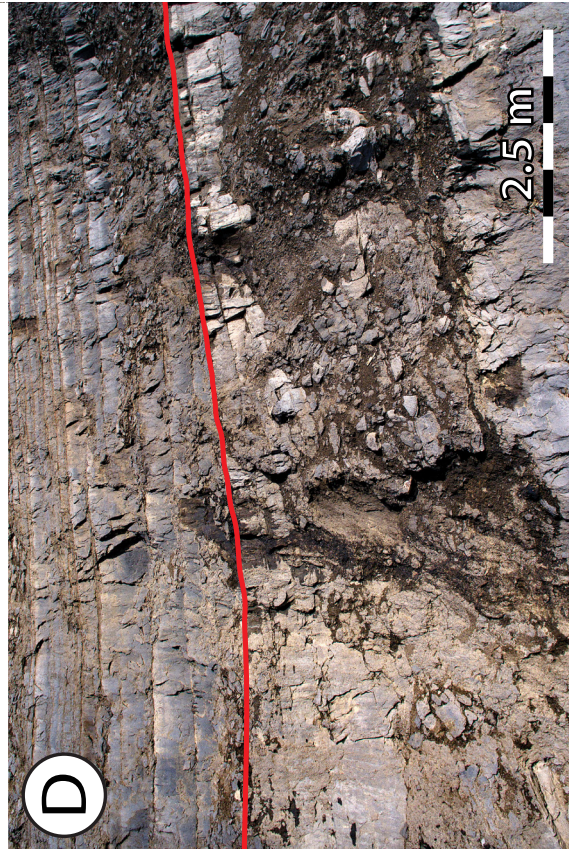
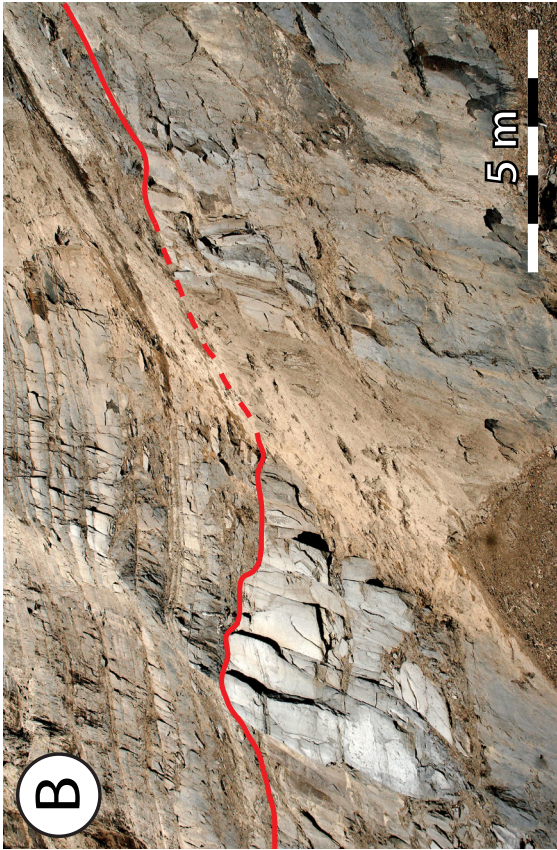


Figure 3.6 (previous page): Outcrop photos of the sharp contact between the basal, medium-grained, unbioturbated cross-bedded sand facies and the overlying fine- to very fine-grained pervasively bioturbated IHS facies at the Steepbank #3 outcrops. **A)** Uninterpreted image at the Steepbank 3A outcrop. **B)** Interpreted contact at the Steepbank 3A outcrop. Note the scouring of the IHS into the cross-bedded sand. **C)** Uninterpreted contact at the Steepbank 3C outcrop. **D)** Interpreted contact at the Steepbank 3C outcrop. The contact here is undulatory and sharp.

cross-stratification. The top of the lower two parasequences are marked by a rooted and illuviated horizon.

Bed orientation data collected at Steepbank show that the IHS successions at each outcrop display natural breaks in bedding orientation and/or degree of dip. Above these breaks, at the base of the succeeding IHS set, thicker sand beds are present. The sand beds become progressively thinner — ranging from greater than 50 centimetres thick at the base of an IHS set to 3 centimetres near the top — whereas the mud beds become thicker and more abundant upward until the next discontinuity in bedding orientation is observed. Each of these contacts is expressed as a marked bed orientation change between successive beds (up to a 10° difference in bed dip and normally a 20° difference or less in dip azimuth). Upper McMurray deposition is represented on tadpole plots by very shallowly dipping beds (often less than 2°) throughout the Steepbank region following the correction of bed orientations for structural effects. Such low dips are probably within the range of error, and therefore the dip azimuth of the upper McMurray beds is erratic and ambiguous.

Bed orientation data collected from the 3D outcrop models in this study is also used in conjunction with sediment transport directions in order to define accretion direction of the studied bar forms. Although master bedding and IHS bedding orientations can be collected with SfM techniques, ripple and cross-bed orientations are not normally discernible on the 3D photogrammetry models — this is due to resolution issues for ripples and the general lack of 3D relief for cross-bedding on the models. The palaeocurrent data reported herein at the Steepbank #3 outcrops are from the appendix sections of Jablonski (2012).

The relationship between master bedding accretion direction and flow direction is shown for the cross-bedded sand and IHS geobodies in Figure 3.7. Of note, in the cross-bedded sand, master bedding surfaces show no dominant orientation and are variably-dipping (typically above 8°), while flow direction is oriented west to northwest (Figs. 3.7A and 3.7B). The overlying IHS facies, in contrast, dominantly accretes toward the northeast, with flow direction oriented consistently orthogonal to the accretion direction of the IHS beds (Fig. 3.7C). Poles to bedding in the IHS facies shows a more consistent trend of bedding, but more variability in the degree of bed dip (Fig. 3.7D).

INTERPRETATION

The interpreted Steepbank outcrop mosaics are shown in Figures 3.8A-C. The sand is ascribed to sedimentation under dominantly unidirectional flow since sediment transport direction is nearly unimodal (Fig. 3.7A). The cross-stratification, a result of migrating dunes, indicates current transport in a channel that is several metres deep. Furthermore, the lack of a consistent dip on master bedding planes suggests that the dominant sedimentary record of the lower sand is that of migrating simple dunes (within a channel confine; Fig. 3.7B). Variations in current energy are evidenced by the presence of ripples, a range of dune scales and transitions to planar bedding. Although this unit is well exposed, there is a complete absence of bioturbation everywhere. Other cross-bedded units in McMurray Formation outcrops including Christina River (Martinius *et al.* 2015; Hayes *et al.* 2017) and Amphitheatre (Wightman and Pemberton, 1997; this paper) contain bioturbation. Accordingly, we interpret this unit as being deposited under variable energy conditions in the presence of fresh water. Taken together, the observations from the Steepbank basal sand are best interpreted as simple dunes associated with a fluvial channel.

In the IHS beds overlying the dune sands, abrupt changes in bedding orientation, as

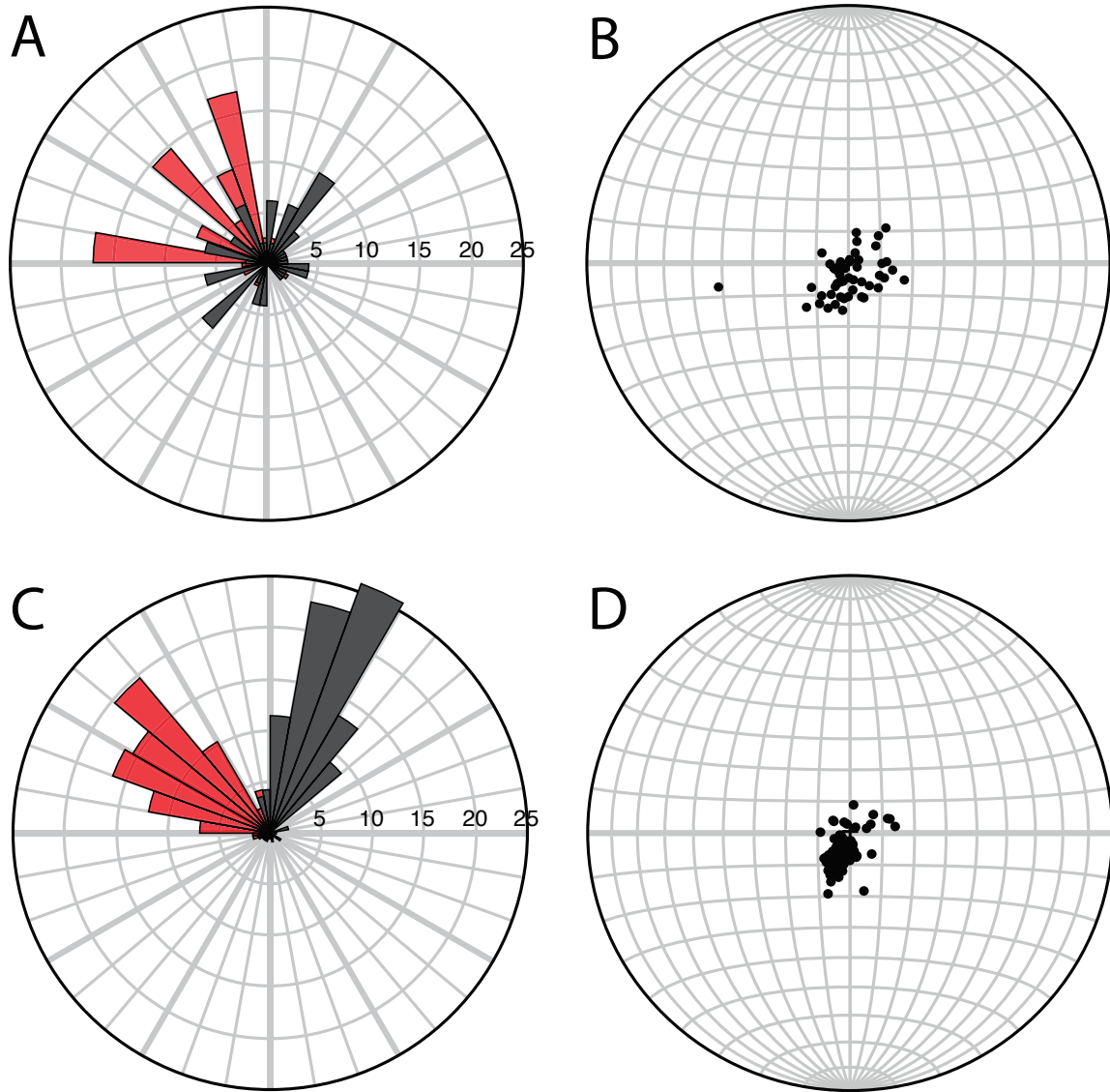
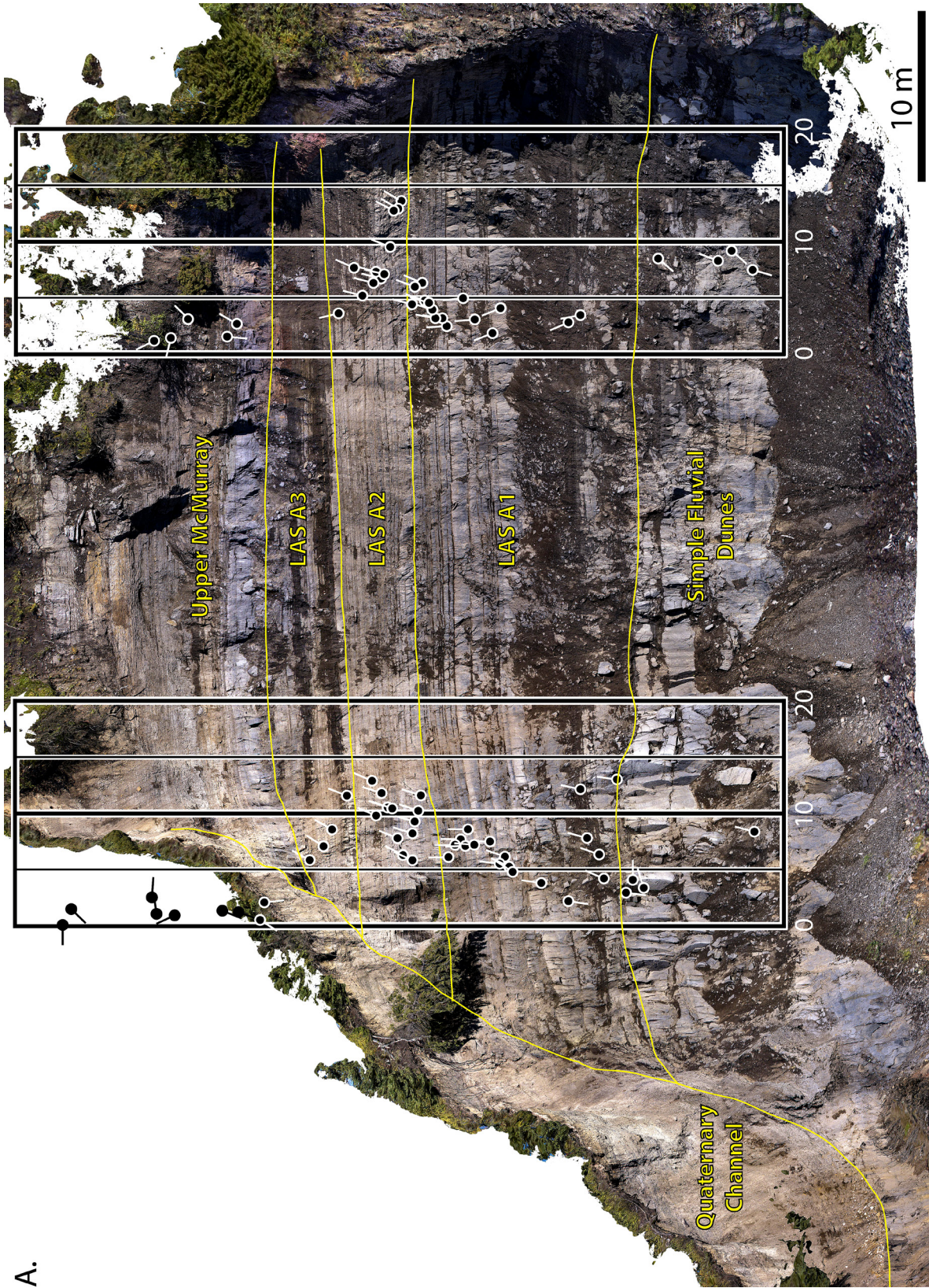
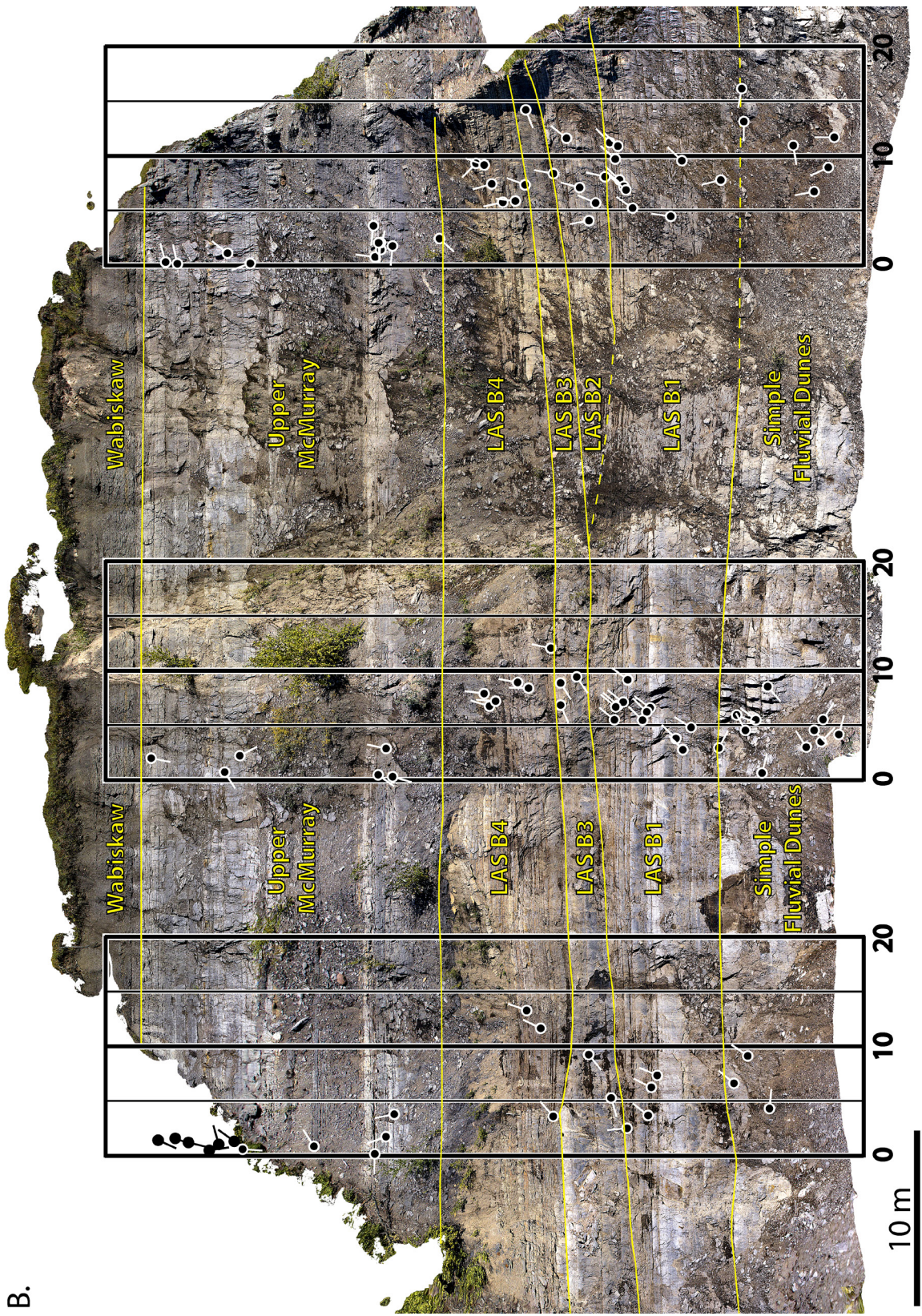


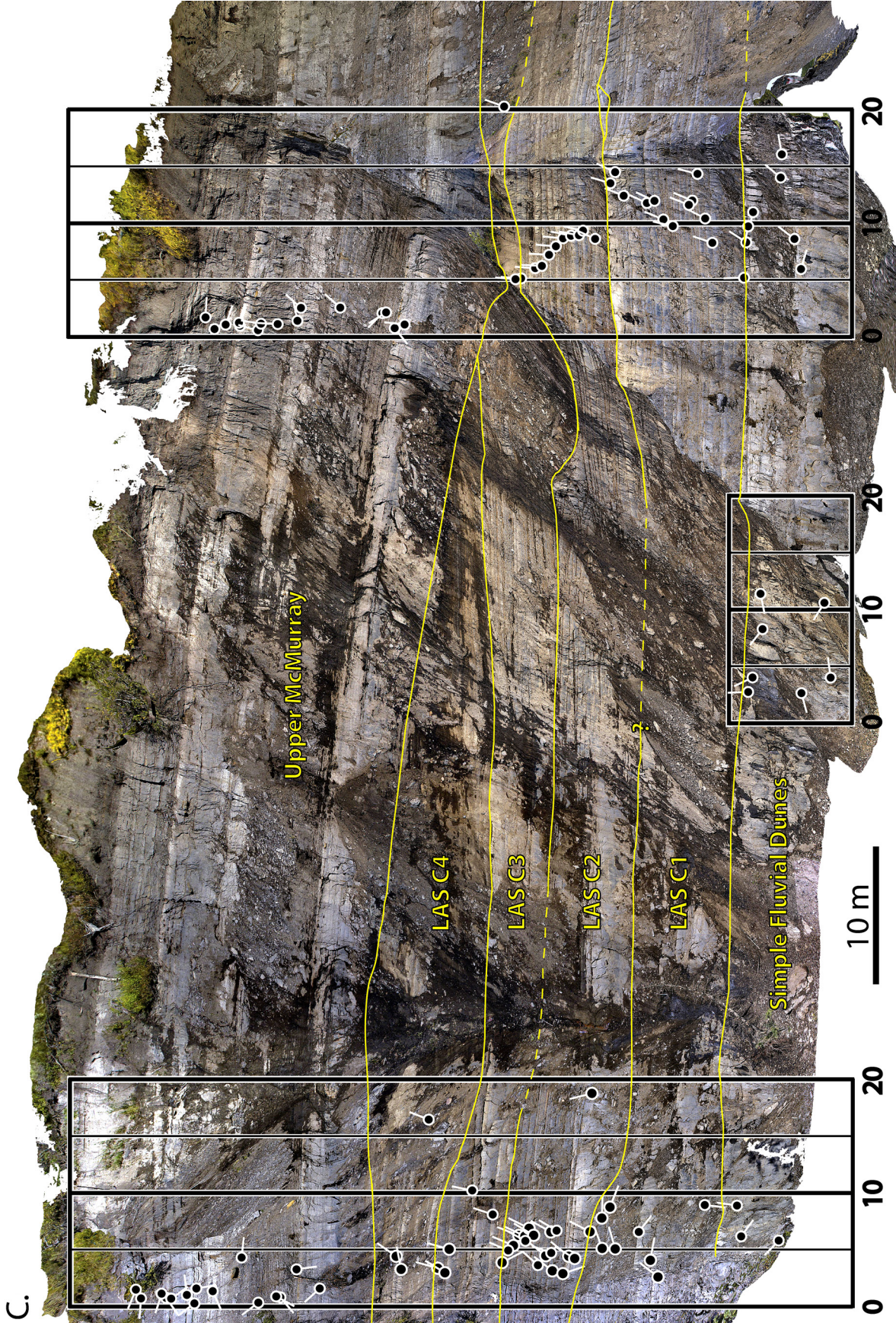
Figure 3.7: Rose and poles to bedding diagrams of the cross-bedded sand and IHS geobodies at the Steepbank #3 outcrops. Black petals on the rose diagram represents the master bedding orientations, while red petals represent palaeocurrent data for these geobodies. **A)** Rose diagram for the cross-bedded sand unit. Master bedding orientations ($n=49$) are variable showing only a minimal northeast-southwest mode, while sediment transport directions ($n=41$) are nearly unimodal toward the northwest. No average orientation is calculated due to the variability within the data. **B)** Poles to bedding diagram for the cross-bedded sand. Note the significant scatter of the poles, owing to the variability in bed orientation and degree of dip of the bedding. **C)** Rose diagram for the IHS geobody. There is a dominant northeast mode (average dip direction of 22° , $n=167$) for master bedding orientation, while palaeocurrent is oriented toward the west-northwest (average of dip direction of 305° , $n=117$). **D)** Poles to bedding diagram for the IHS geobody. When compared to the cross-bedded sand, the IHS follows a more consistent trend owing to variably dipping beds and a consistent dip direction of the IHS beds. Palaeocurrent data from the Steepbank #3 outcrops are courtesy of Jablonski, (2012).

A.



B.





C

Figure 3.8 (previous pages): Interpreted photomosaics of the Steepbank #3 outcrops generated using Agisoft PhotoScan Professional ©. Contacts between interpreted lateral accretion sets were traced on 3D outcrop models and transferred to the photomosaics afterwards. Dashed lines on the interpreted outcrop mosaics indicate inferred contacts where overburden masks bedding contacts. The tadpole plots overlain on the outcrops show the orientation of master bedding surfaces. **A)** Interpreted Steepbank 3A outcrop mosaic. Three stacked LAS are interpreted to overlie simple fluvial dunes at the base of the outcrop. A Quaternary channel incision truncates the LAS on the left (northwest) side of the outcrop. **B)** Interpreted Steepbank 3B outcrop mosaic. Four stacked LAS are interpreted to overlie simple fluvial dunes at the base of the outcrop. LAS B1, B3, and B4 are laterally continuous across the entire outcrop exposure. LAS B2 is only present on the right (southeast) side of the outcrop, and pinches out toward the middle of the exposure. **C)** Interpreted Steepbank 3C outcrop mosaic. Four stacked LAS are interpreted to overlie simple fluvial dunes at the base of the outcrop. All four LAS are visible on the left (northwest) side of the outcrop. Only three LAS are present on the right (southeast) region of the outcrop.

depicted with tadpole plots, are interpreted to represent erosional contacts between separate lateral accretion sets (LAS) at Steepbank (*sensu* Muwais and Smith, 1990; Nardin *et al.* 2013). A typical LAS identified in this study is 4 to 11 metres thick, and displays a muddy-ing-upward trend with thick sand beds present at the base that become progressively thinner upward. The sharp-based current ripples and planar-tabular bedding within sand beds suggest shifting substrate under mainly unidirectional flow conditions. Bioturbation within a single LAS increases upwards, which is consistent with estuarine point bar lithofacies models developed by Smith (1987), Allen (1991), and Gingras and MacEachern (2012) as well as with many examples of McMurray Formation strata, typically over a 5 to 8 metre scale (Gingras *et al.* 2016). The low-diversity trace fossil assemblage consisting of simple vertical and horizontal trace fossil morphologies in these lateral accretion sets is consistent with deposition in a brackish-water environment (Pemberton *et al.* 1982; Beynon *et al.* 1988; Gingras and MacEachern, 2012). Notably, the *Cylindrichnus* tracemaker is considered to be a marine polychaete, which provides direct evidence of tidal processes influencing these deposits as the organism's larvae must be advected by currents from the marine realm (Gingras *et al.* 2016; Gingras and Leckie, 2017). Overall, the tadpole plots allow for the differentiation of at least three lateral accretion sets at Steepbank 3A (Fig. 3.8A), while four lateral accretion sets are recognized at Steepbank 3B and 3C (Figs. 3.8B and 3.8C). We are unable to correlate lateral accretion sets confidently between the 3A, 3B, and 3C outcrops due to the complexity

of the exposed strata.

Erosional contacts are observed throughout the vertical succession of IHS at each outcrop of Steepbank #3. In some cases, an incision or a scour into an underlying unit can be observed visually - in other cases, tadpole plots in conjunction with visual analysis of bedding trends reveal an erosional surface. An example of the former is apparent at Steepbank 3B, where the IHS comprising LAS B4 incises into the planar-bedded sand beds of LAS B3 (Figs. 3.9A and 3.9B). These units are interpreted to be distinct lateral accretion sets on the basis of a visual erosion surface in addition to the sudden bed re-orientation, where LAS B3 dips toward the west-southwest and the overlying LAS B4 dips toward the north-northeast. Notably, LAS B4 has no developed lower point-bar or thalweg deposit at the base. Furthermore, the underlying LAS B1 pinches out against the planar-bedded sand of LAS B3.

Examples of cryptic erosional surfaces are common in outcrop 3A, where the exposure is oriented in strike-view. At this locale, three lateral accretion sets are stacked with few visual cues to reveal the presence of LAS-associated erosional contacts (Figs. 3.9C and 3.9D). These contacts are interpreted dominantly from bed orientation data, but also sand-bed thickness as the sand beds are characteristically thickest at the base of a lateral accretion set. Furthermore, the sand near the base of each lateral accretion set contains planar-tabular bedding, whereas the overlying sand beds tend to be current-rippled.

Within the interpreted lateral accretion sets, the dominant sediment transport direction inferred from palaeocurrent directions is west-northwest (average dip direction of 305°), whereas master bedding is oriented north-northeast (average dip direction of 22°) (Fig. 3.7C). The accretion of master bedding at a high angle to palaeocurrent direction (on average, 77° at the Steepbank #3 outcrops) strongly supports earlier interpretations that the IHS bedding formed as a result of lateral accretion (*e.g.* Mossop and Flach, 1983; Jablonski and Dalry-

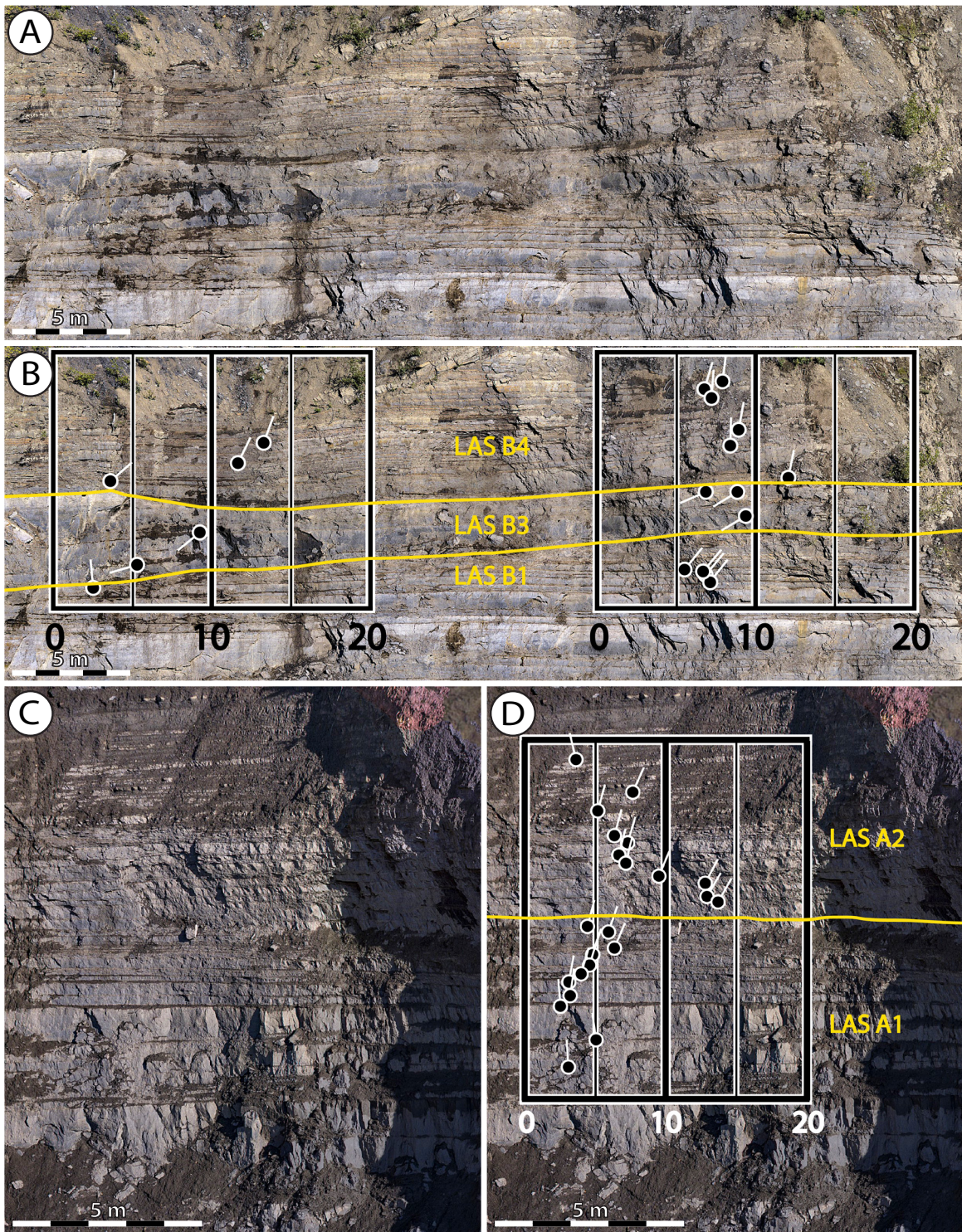


Figure 3.9: Outcrop photos of uninterpreted and interpreted contacts between stacked lateral accretion sets at the Steepbank #3 outcrops. **A)** Uninterpreted stacking of LAS at the Steepbank 3B outcrop. Since this outcrop is oriented oblique to strike, scouring and bed truncation is visible. **B)** Interpreted contacts between stacked LAS at outcrop 3B. Note the incision of LAS B4 into the underlying LAS B3, and the differences in bedding orientation between LAS B1, LAS B3, and LAS B4. **C)** Uninterpreted stacking of LAS at the Steepbank 3A outcrop. No visible incision is observed

Figure 3.9 cont.: as this outcrop is strike-oriented. **D)** Stacked LAS at the Steepbank 3A outcrop. In the absence of a visible scour, bed orientation discontinuities, ichnology trends, and subtle changes in sand bed thickness are used to interpret the stacking of LAS.

mple, 2016) since flow over the bar is more or less parallel to the strike of the accretionary units (Miall, 2010). As such, we suggest that the LAS identified in this study can be interpreted in two ways: 1) as abrupt shifts in the bar position or orientation related to large-scale flooding events of a single, thick, point bar complex, or 2) that the accreting bar forms represent stacked IHS geobodies that share similar (but different) orientations with respect to one another. The latter interpretation is similar to what Crerar and Arnott (2007) interpreted as multiple-stacked middle McMurray channel deposits in the subsurface two townships to the east. Importantly, as stated above, each LAS displays: 1) a discontinuity to underlying strata; 2) bedsets that thin and muddy upwards; and 3) bioturbation increasing upwards. These characteristics are difficult to explain in a single fluvial point-bar but are entirely consistent with the vertical successions produced by laterally accreting bars in tidally influenced brackish-water settings (Gingras *et al.* 1999; MacEachern *et al.* 2010).

3.6 AMPHITHEATRE OUTCROP

RESULTS

The measured sections along the Amphitheatre outcrop are shown in Figure 3.10. At this locale, the basal portion of the outcrop is characterized by approximately 15 metres of locally bioturbated, thinly- to thickly-bedded (0.1-2 metres) medium-grained sand. In general, these sand beds thin upwards. Bioturbation in the sand unit mainly comprises *Cylindrichnus* and rare *Siphonichnus*. Bioturbation is sporadic and unevenly distributed, with bioturbation index ranging from 1-3. The sand is low-angle planar tabular, high-angle planar tabular and trough cross-stratified, containing current ripples and shale laminae. Locally, current reversals are observed in the toesets of this unit (Fig. 3.11). The sand unit is truncated by an IHS-filled channel that scours into the cross-bedded sand on the northeast end of the outcrop (Fig.

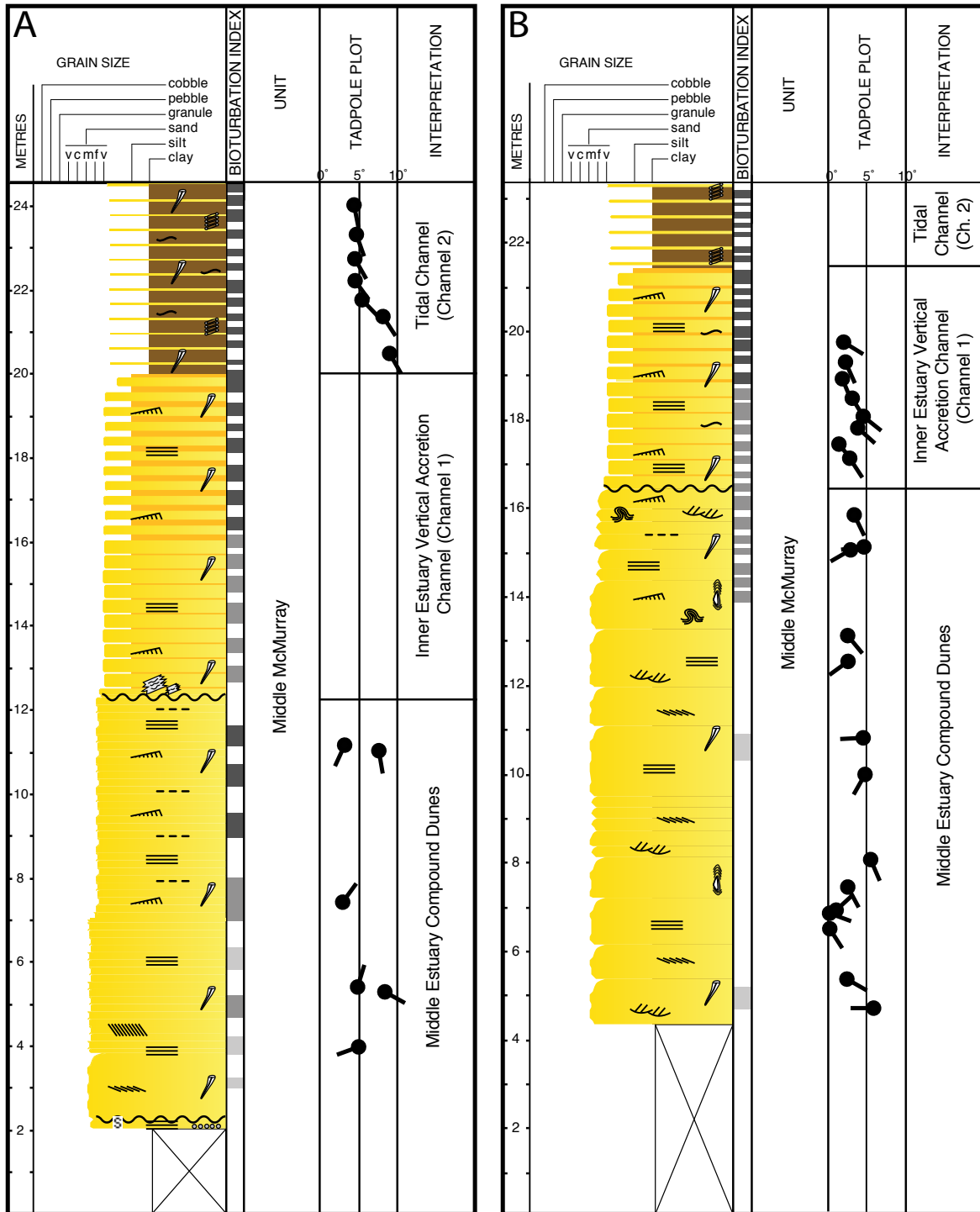


Figure 3.10: Measured sections of the Amphitheatre outcrop. The legend is shown in Figure 4C. The tadpoles represent the orientation of master bedding surfaces in the basal sand and overlying IHS geobodies. **A)** Log of the left (northeast) side of the outcrop. **B)** Log of the central (southwest) region of the outcrop. Refer to Figure 3.1E for the exact location of these logged sections.

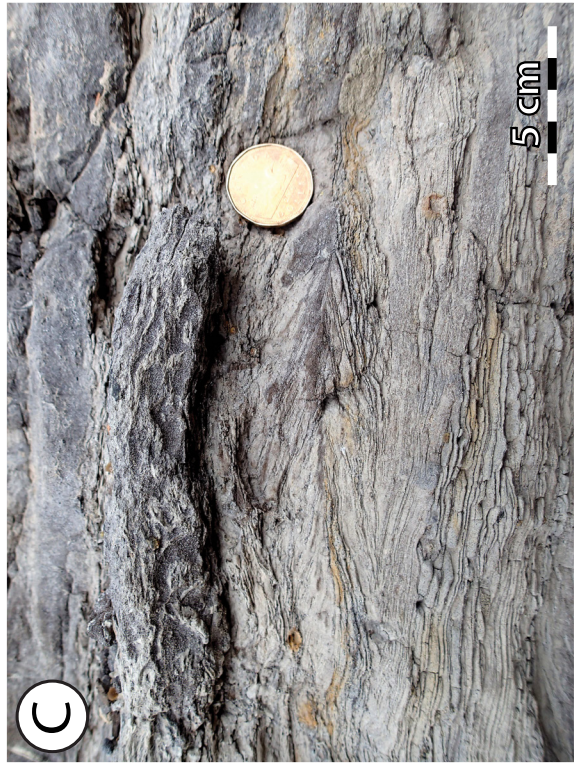
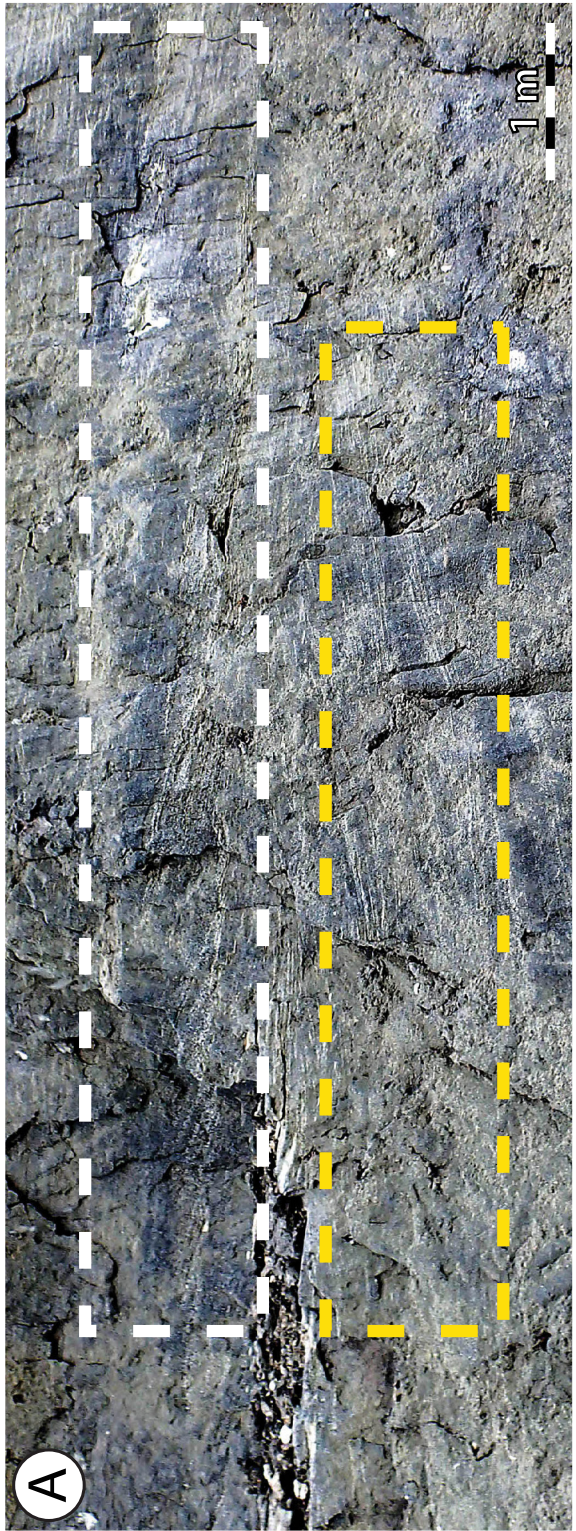


Figure 3.11 (previous page): Outcrop photos from the Amphitheatre outcrop showing flow reversals. **A)** Metre-scale cross bedding showing a reversal in sediment transport direction. The white dashed box shows crossbedding oriented toward the southwest (right in the image), whereas the yellow dashed box shows northeast-oriented crossbedding (left in the image). **B)** Current reversal in decimetre-scale cross-bedded strata. **C)** Current reversal in current ripples within the heterolithic IHS channel fill.

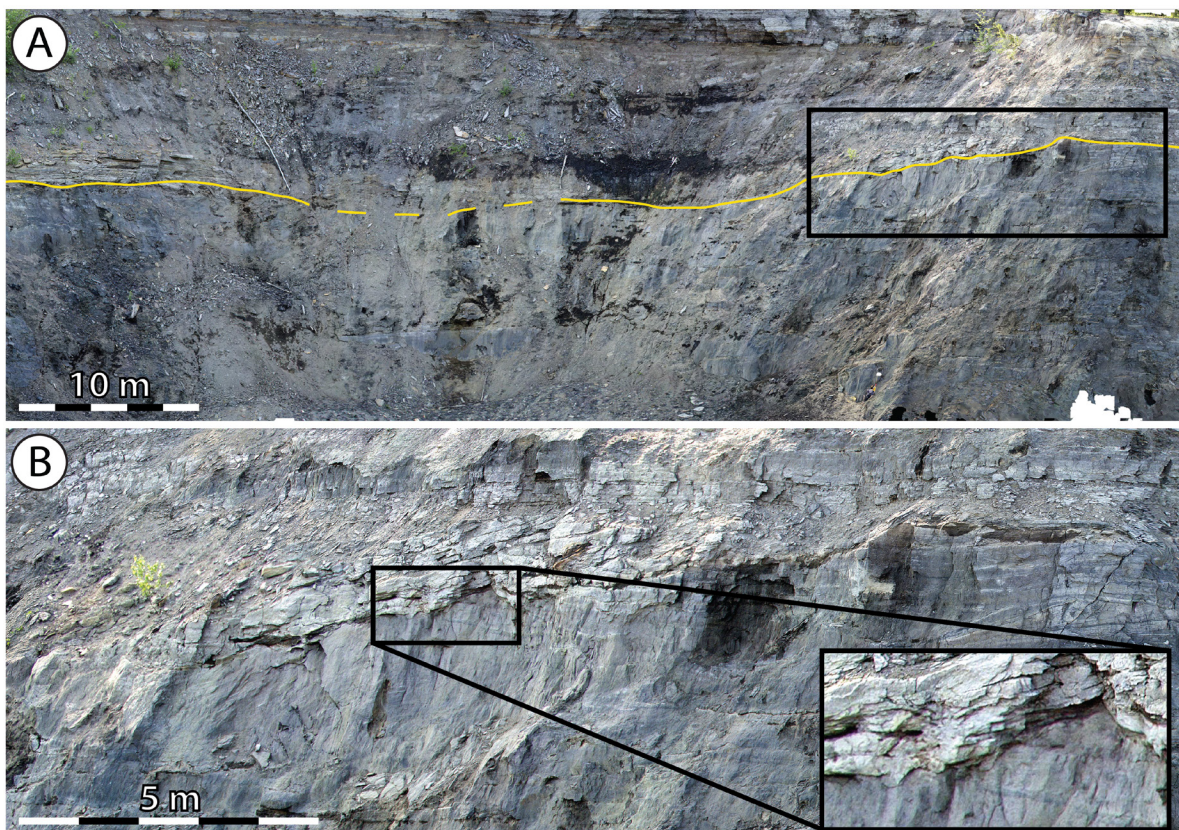


Figure 3.12: **A)** Incision of an IHS-filled channel into the underlying cross-bedded sand unit at the Amphitheatre outcrop. The incision is located on the left (northeast) side of the outcrop. **B)** Close-up views of the incised contact. The location of this image is indicated by a black box in Figure 3.12A. Note the truncation of cross-bedded strata by heterolithic deposits.

3.12). The channel fill conforms to the concave-upward shape of the scour, and a coalified log is observed near the lowest point of the channel scour. The channel-associated IHS is composed of dipping (3° - 9°), interbedded fine- to very-fine grained sand and silt beds. The bioturbation index is typically 1-4 in this unit, and observed trace fossils are *Cylindrichnus* and *Planolites*. In the northeast part of the outcrop, this unit is approximately 7.5 metres thick, and it thins to the southwest to approximately 4-5 metres thick. Overlying the sand-silt IHS succession is a mud-dominated heterolithic unit that is 2-4 metres thick and is truncated by Quaternary erosion. This unit exhibits a bioturbation index of 4, and contains *Gyrolithes*, *Planolites*, and *Cylindrichnus* trace fossils.

Bed orientation data collected from the Amphitheatre 3D outcrop model show a number of vertical and lateral trends along the exposure. The thick cross-bedded sand unit at the base of the outcrop is characterized by gently-dipping master bedding surfaces (typically less than 5°) and variable dip directions. Above the basal sands in the southwest region of the outcrop, the IHS bedding dip measurements shallow upward (from 10° near the base of the unit to 4° near the top). The mud-dominated heterolithic unit at the top of the exposure is sub-horizontally-bedded (1° - 2° bedding dip). To the northeast, the IHS unit overlying the sand is partially covered by loose sediment on the outcrop, so bed orientation measurements could not be collected immediately above the channel base. Above the partially covered section, a second shallowing-upward IHS dip trend is observed (from 10° at the base to 4° at the top of the unit).

The master bedding data collected from the exposed cross-bedded sand unit on the 3D photogrammetry model is combined with palaeocurrent directions measured from cross-bedding in the field (Fig. 3.13A). The rose diagram for the Amphitheatre sand unit indicates that the accretion direction of master bedding planes is oriented in three directions – northeast, southeast, and southwest, with southwest being the dominant mode. The palaeocurrent di-

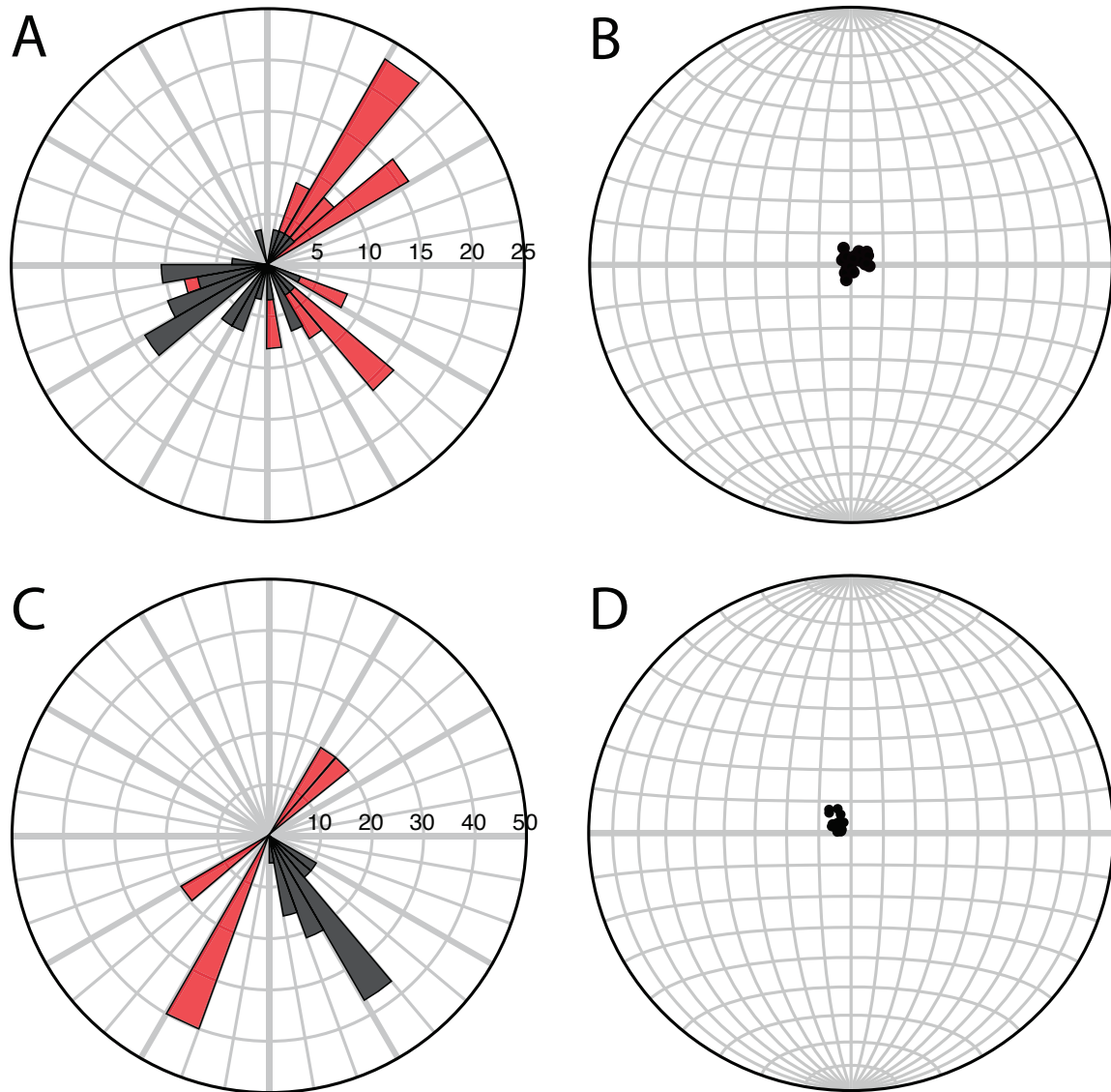


Figure 3.13: Rose and poles to bedding diagrams of the cross-bedded sand and IHS geobodies at the Amphitheatre. Black petals on the rose diagrams represents the master bedding orientations, while red petals represent palaeocurrent data for these units. **A)** Rose diagram showing the relationship between master bedding and palaeocurrent in the cross-bedded sand unit. Master bedding ($n=29$) is oriented in a northeast-southwest trend, with a subordinate dataset oriented toward the southeast. Palaeocurrent ($n=13$) follows the same directional trends as master bedding in this unit. **B)** Poles to bedding in the cross-bedded sand unit. Variable orientations and consistently gently-dipping master bedding is represented by a cluster of poles near the centre of the stereonet. **C)** Rose diagram comparing master bedding accretion direction and flow direction in the IHS unit. Master bedding ($n=19$) is unimodal toward the southeast, while palaeocurrent ($n=5$) displays a northeast-southwest trend. The bimodal trend in flow direction is the result of the reversal of current ripples in the IHS beds. **D)** Poles to bedding of the IHS unit. A more consistent, linear trend is shown here, owing to the consistent orientation of master bedding in the IHS and the changing dips of the beds.

rections from Amphitheatre are dominated by northeast sediment-transport directions with a subordinate southeast subset. The poles to bedding are clustered near the centre of the stereonet, suggesting that the master bedding is variable in orientation and gently-dipping (Fig. 3.13B). As a whole, the bedding-current datasets indicate that sediment transport was typically oriented parallel to master bedding dip directions and that sediment transport was generally up the master-bedding surfaces. The overlying IHS unit that scours into the cross-bedded sand shows master bedding dip consistently toward the southeast, with palaeocurrent oriented orthogonal to bedding, in a northeast-southwest trend (Fig. 3.13C). Poles to bedding in the IHS unit show a more uniform distribution, owing to the consistent master bedding dip direction in this unit (Fig. 3.13D).

INTERPRETATION

The tadpole plots generated from the Amphitheatre outcrop are different than those from Steepbank #3 (*e.g.* Figs. 3.8 and 3.14). Notably, the cross-bedded sand unit at the base of the outcrop is thicker and characterized by more irregular bedding orientations, whereas the IHS of the upper regions of the outcrop is characterized by almost unimodal dip azimuth, and decreasing-upward bedding dips. The low-diversity ichnological assemblage comprised of *Cylindrichnus* and *Siphonichnus* is consistent with brackish-water deposition of the cross-bedded sands. *Siphonichnus* is associated with a number of environments including deltaic units, intertidal flats, shorefaces, and estuarine channels (Zonneveld and Gingras, 2013). The occurrence of these burrows, along with evidence of flow reversals in the toesets of cross-bedded strata, suggests that the Amphitheatre locale is tidally-influenced.

Bed orientations in the cross-bedded sand unit are most similar to bed orientations expected of sandwave (*i.e.* compound dune) successions (*e.g.* Strobl *et al.* 1997; their Figure 3): the dip of master bedding surfaces are low and bed orientations show more variability than do lateral accretion sets. Importantly, a tendency for sediment transport to be parallel to master

bedding is an important feature that discriminates laterally accreted bars from compound dunes (Dalrymple, 2010; Olariu *et al.* 2012a). In this case, because the dunes are generally migrating up master bedding surfaces (refer to the rose plot in Table 3.1), we must interpret the sand beds at Amphitheatre as the forward edge of a large compound dune, with the tailing edge situated to the northeast in the subsurface. Of note, there is a subordinate dataset of dune accretion toward the southeast at the Amphitheatre outcrop – this is ascribed to the flow of water in the troughs of the larger-scale dunes during the tidal cycle.

The interpreted Amphitheatre outcrop mosaic is shown in Figure 3.14. An erosional contact along the entire extent of the exposure separates the compound dune complex below from the heterolithic channel deposit above (Ch. 1), which is interpreted to be a thinly-bedded, brackish-water, sand- and silt-dominated channel-fill IHS succession. The concave-upward channel base with heterolithic deposits conforming to the shape of the scour (Figs. 3.12 and 3.14) suggests there is a component of vertical accretion in channel 1 in the northeast (*e.g.* Muwais and Smith, 1990; Wightman and Pemberton, 1997). A second channel (Ch. 2) on the northeast side of the outcrop is interpreted on the basis of a decreasing-upward bedding dip trend and the presence of a typical mud-dominated IHS ichnological assemblage. In particular, *Gyrolithes*, *Planolites*, and *Cylindrichnus* are common brackish-water burrows in mud-dominated IHS deposits in the McMurray Formation (Shchepetkina *et al.* 2016a; Gingras *et al.* 2016). On the southwest side of the exposure, bed dips of only 1°-2° toward the southwest is shown by bed orientation data in the upper 2-4 metres of the outcrop. This very gently-dipping unit is interpreted to be a tidal flat overlying the channel-fill IHS unit (Ch. 1). This tidal flat is truncated by a Quaternary channel in the central region of the outcrop.

We emphasize here that the cross-bedded sand at Amphitheatre is interpreted to represent a subaqueous compound dune, as opposed to lower point-bar or channel thalweg facies that cross-bedded sand is often assigned to in the McMurray Formation (Mossop and

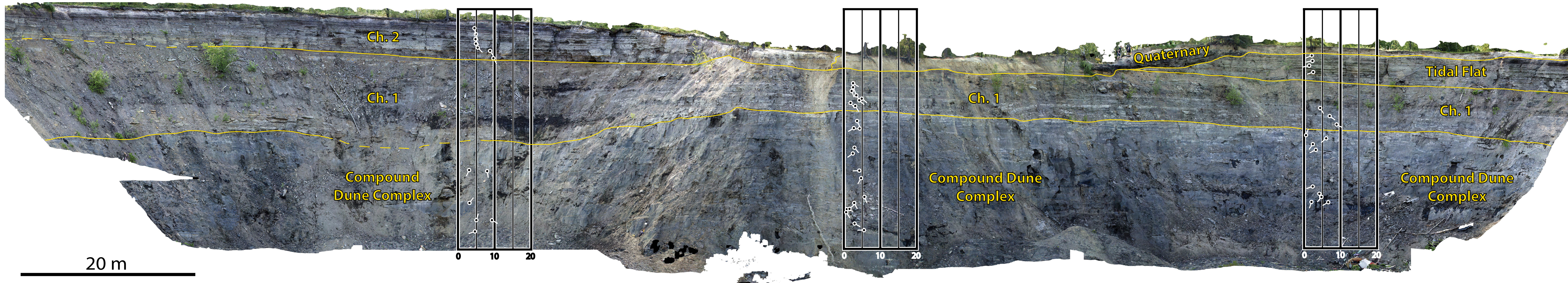


Figure 3.14 (previous page): Interpreted photomosaic of the Amphitheatre outcrop generated using Agisoft PhotoScan Professional ©. Contacts between the interpreted depositional units were traced on 3D outcrop models and transferred to the photomosaics afterwards. The exposed outcrop in this figure is approximately 150 metres wide. Two channels overlie the compound dune complex on the left (northeast) side of the exposure. Only channel 1 overlies the compound dune complex in the southwest region (toward the right), which is overlain by quaternary channel deposits in the central region of the outcrop and a small tidal flat on the far right (southwest region) of the exposure. The tadpole plots depicted show only master bedding accretion data.

Flach, 1983; Crerar and Arnott, 2007; Hubbard *et al.* 2011; Musial *et al.* 2013; Martinus *et al.* 2015; Jablonski and Dalrymple, 2016). Our interpretation is constrained by four observations discussed above: 1) the modal, but admittedly noisy correspondence of sediment transport direction and bed orientations; 2) the low dip of master-bedding surfaces; 3) the sharp discontinuity between the IHS and the underlying sand; and 4) the stratigraphically thin (approximately 6 metres) and very fine-grained nature of the IHS make it very unlikely that it is related to the underlying thick (approximately 15 metres) cross-bedded sand unit. The IHS is thinly-bedded and in part vertically accreted, and therefore is interpreted to be deposited under much quieter, lower energy conditions when compared to the underlying metre-scale cross-bedded sand. Moreover, the compound dune displays tidal reworking and bioturbation consistent with brackish water and is best interpreted as an estuary-associated compound dune.

3.7 DISCUSSION

A summary of the main differences between the cross-bedded sand and IHS deposits at both outcrop locations is provided in Table 3.1. We ascribe the notable contrast of vertical profile and bed orientations between Amphitheatre and Steepbank to the fact that each outcrop represents a different type of facies association. At the Amphitheatre outcrop, the dominant northeast-southwest oriented trend of master bedding surfaces and sediment transport direction and subordinate southeast oriented trend strongly supports that the outcrop is characterized by a compound dune complex that is truncated by a sharp-based IHS channel fill. The dominant trend shows master bedding surfaces are gently dipping and flood-tide

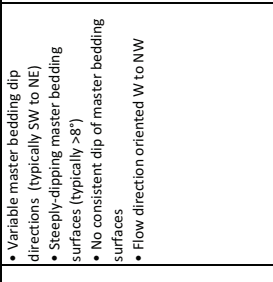
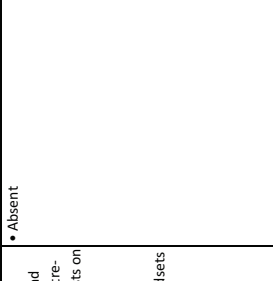
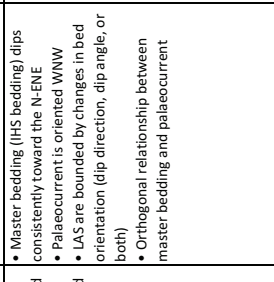
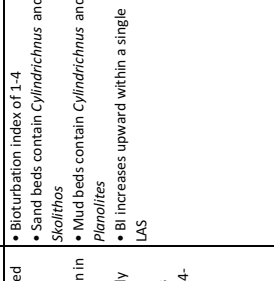
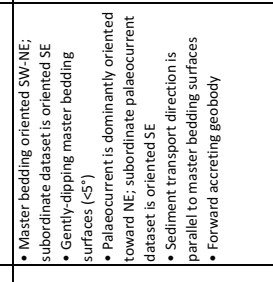
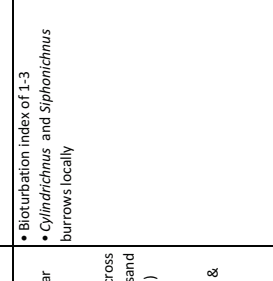
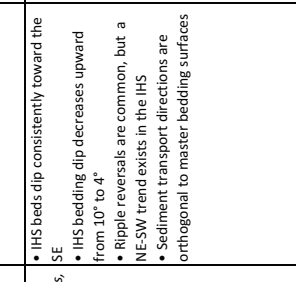
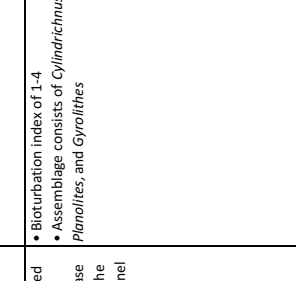
| Sedimentology | Ichnology | Photogrammetry & Orientation Data | Master Bedding & Palaeocurrent Rose Diagram | Poles to Bedding | Interpretation |
|---|--|--|---|---|---|
| <ul style="list-style-type: none"> • Medium-grained • Metre-scale high angle tabular and trough cross-bedded sand; decimetre-scale dune interbeds with mud clasts on dune foresets occur locally • Planar bedded • Sharp bedding contacts • Thickly bedded (0.3-2m) with bedsets generally decreasing in thickness upward | <ul style="list-style-type: none"> • Absent | <ul style="list-style-type: none"> • Variable master bedding dip directions (typically SW to NE) • Steeply-dipping master bedding surfaces (typically >8°) • No consistent dip of master bedding surfaces • Flow direction oriented W to NW |  |  | <ul style="list-style-type: none"> • Deposited under varying energy conditions in the presence of fresh water • Unimodal sediment transport direction and the lack of a consistent dip on master bedding surfaces suggests channelized deposition, and oblique-forward accretion • Simple fluvial dunes |
| <ul style="list-style-type: none"> • Very fine-grained sand interbedded with mud • Sharp-based current ripples and planar-tabular bedding are common in sand beds • Thinly bedded (sand beds typically range from 2cm-20cm thick) • Bedsets thin and muddy upwards within a single LAS (on the scale of 4-8m) | <ul style="list-style-type: none"> • Bioturbation index of 1-4 • Sand beds contain <i>Cylindrichnus</i> and <i>Skolithos</i> • Mud beds contain <i>Cylindrichnus</i> and <i>Planolites</i> • BI increases upward within a single LAS | <ul style="list-style-type: none"> • Master bedding (IHS bedding) dips consistently toward the N-ENE • Palaeocurrent is oriented WNW • LAS are bounded by changes in bed orientation (dip direction, dip angle, or both) • Orthogonal relationship between master bedding and palaeocurrent |  |  | <ul style="list-style-type: none"> • Bioturbation is typical of brackish-water conditions • Orthogonal relationship between master bedding and palaeocurrent suggests a lateral accretion geobody • Inner estuary, sand-dominated laterally accreted point-bars |
| <ul style="list-style-type: none"> • Medium-grained • Low- and high-angle planar tabular bedding • Trough cross stratification • Current reversals in metre-scale cross beds and centimetre-scale rippled sand • Thinly- to thickly-bedded (0.1-2m) • Wavy shale laminae • Soft-sediment deformation • Reactivation surfaces (Wightman & Pemberton, 1997) | <ul style="list-style-type: none"> • Bioturbation index of 1-3 • <i>Cylindrichnus</i> and <i>Siphonichnus</i> burrows locally | <ul style="list-style-type: none"> • Master bedding oriented SW-NE; subordinate dataset is oriented SE • Gently-dipping master bedding surfaces (<5°) • Palaeocurrent is dominantly oriented toward NE; subordinate palaeocurrent dataset is oriented SE • Sediment transport direction is parallel to master bedding surfaces • Forward accreting geobody |  |  | <ul style="list-style-type: none"> • Low-diversity ichnological assemblage is consistent with brackish-water deposition • Low dip of master bedding surfaces and the tendency for sediment transport to be parallel to master bedding accretion is characteristic of compound dunes • Middle estuary compound dune complex |
| <ul style="list-style-type: none"> • Very fine-grained sand interbedded with silt and mud • Coalified log is observed at the base • Channel fill deposits conform to the concave-upward shape of the channel scour | <ul style="list-style-type: none"> • Bioturbation index of 1-4 • Assemblage consists of <i>Cylindrichnus</i>, <i>Planolites</i>, and <i>Gyrolithes</i> | <ul style="list-style-type: none"> • IHS beds dip consistently toward the SE • IHS bedding dip decreases upward from 10° to 4° • Ripple reversals are common, but a NE-SW trend exists in the IHS • Sediment transport directions are orthogonal to master bedding surfaces |  |  | <ul style="list-style-type: none"> • Low-diversity ichnological assemblage typical of deposition in a brackish-water setting • Orthogonal relationship between palaeocurrent and master bedding suggests lateral accretion • Inner Estuary Silt-dominated laterally (and in part, vertically) accreted point-bar |

Table 3.1 (previous page): Defining characteristics of the cross-bedded sand and IHS facies at the Steepbank and Amphitheatre outcrops. The rose plots show master bedding (black petals) and palaeocurrent (red petals) orientations. The pole to bedding plots show the degree of dip of the master bedding surfaces collected in this study. Note the similarities in the rose and poles to bedding diagrams of the IHS geobodies at the Steepbank and Amphitheatre outcrops. In general, the poles to bedding indicates a unimodal master bedding accretion direction and more variability in the bedding dips in the IHS units than in the cross-bedded sand units.

oriented, with ebb-tide oriented palaeocurrent structures preserved on the upcurrent edge of a large, estuary-associated compound dune. In contrast, data collected at the Steepbank #3 outcrops suggest that fluviially dominated simple dunes are sharply overlain by thick IHS sets that represent stacked laterally accreting estuarine point-bars. This contact marks an abrupt change in grain size and bioturbation index, where the medium-grained cross-bedded sand is characterized by the complete absence of bioturbation below the contact and the fine- to very-fine grained IHS above is pervasively bioturbated. Like Amphitheatre, the cross-bedded sand at the base of the Steepbank #3 outcrops is interpreted to be unassociated with the overlying IHS, however the LAS show more thickly bedded sand at their base, which can be interpreted as thalweg-associated sand. Importantly, in spite of the presence of similar facies at Christina River outcrop (Martinius *et al.* 2015; Hayes *et al.* 2017), High Hill outcrop (Wightman and Pemberton, 1997) and potentially in the Muskeg River and Jackpot mines (Barton, 2016), very little effort has been made to identify and interpret Amphitheatre-style compound dunes in the subsurface.

COMPOUND DUNES AND LATERALLY ACCRETED BARS

Dunes may be observed as simple dunes, compound dunes or as bedforms on laterally accreted bars (Olariu *et al.* 2012a; Olariu *et al.* 2012b). Although simple dunes are readily discerned, the thicknesses of sandy point bars and compound dunes can occur on similar scales, complicating the task of distinguishing these bedforms in the rock record. Simple dunes do have some discernible characteristics. They tend to migrate along low-dip surfaces (though steeper than surfaces in a compound dune (Allen, 1980)) and show no strong relationship between sediment transport direction and master-bedding orientation. Compound dunes (pre-

viously referred to as sandwaves by Allen, (1980) and Dalrymple, (1984a)) are composite bedforms that have a migration vector oriented approximately parallel to the depositional currents and thereby parallel to the dip of master bedding. In association with compound dunes, composite simple dunes migrate up, then down the depositional dip of accretion surfaces (*i.e.* master bedding), ultimately building the geomorphological entity through forward accretion (Olariu *et al.* 2012a). As such, the palaeocurrent direction typically occurs within the same quadrant as the dip direction of master bedding surfaces, or opposite to master bedding dip direction, on the upcurrent edge of the compound dune (Miall, 2010; Dalrymple, 2010).

From a sedimentological perspective, the compound dunes at the Amphitheatre outcrop are similar in scale to those reported from Cobequid Bay, Bay of Fundy (Fig. 3.15; Knight, 1977; Dalrymple *et al.* 1978; Dalrymple, 1984a; Dalrymple, 1984b; Dalrymple *et al.* 1990). Here, the compound dune succession can be up to several kilometres long and a kilometre wide. The Cobequid Bay compound dunes display a dominant northeast-southwest flood- and ebb-tide master bedding accretion direction with subordinate bedforms oriented northwest-southeast (Fig. 3.15B). These subordinate bedforms form as a result of flowing water between larger-scale dunes during the tidal cycle, and may manifest as microdeltas with an internal structure that consists of linguoid-shaped cross-beds oriented approximately orthogonal to compound dune accretion (Dalrymple, 1984b). Coincidentally, the Amphitheatre dataset follows a similar trend: a dominant northeast-southwest oriented flood- and ebb-tide master bedding accretion direction with subordinate dunes migrating toward the southeast (Fig. 3.13A; Table 3.1). In both modern and ancient compound dune successions, subordinate dunes that accrete orthogonal to the dominant flood- and ebb-tide master bedding accretion direction are commonly observed (Dalrymple, 1984b; Hirst, 2016) and this relationship is expressed in the compound dune deposit at the Amphitheatre outcrop.

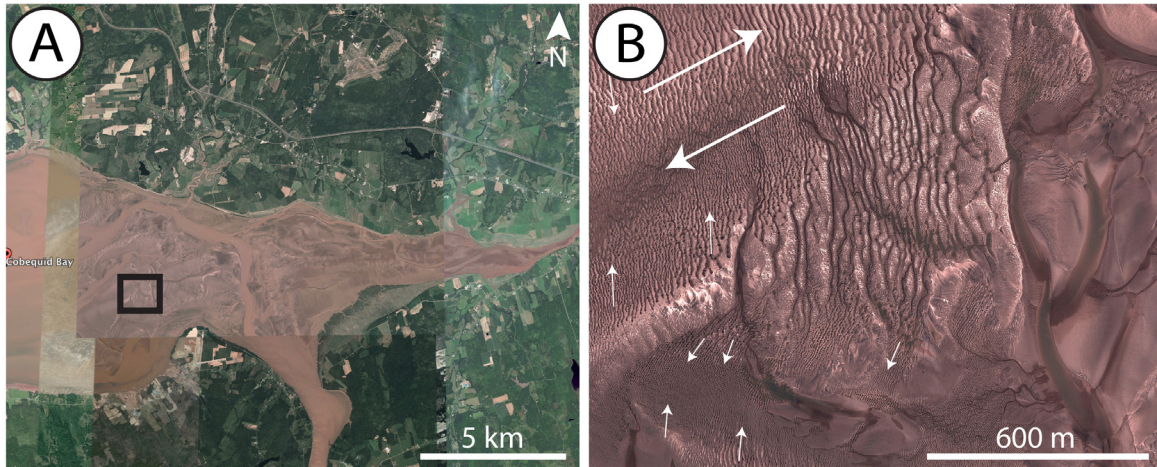


Figure 3.15: **A)** Map of Cobequid Bay in the Bay of Fundy, where compound dunes similar in scale to the Amphitheatre compound dunes are observed on large sand bars in the middle estuary. **B)** Close-up view of the compound dunes in Cobequid Bay. The location of the image is indicated by a black box in Figure 3.14A. The dominant flood- and ebb-tide master bedding accretion directions of the compound dune complex are indicated by large white arrows (oriented in a northeast-southwest trend). Subordinate dune accretion, shown by smaller white arrows, occurs in the troughs of the large-scale dunes, oriented approximately perpendicular to the trend of flood- and ebb-tide dune accretion. A similar trend oriented perpendicular to the dominant flood- and ebb-tide direction is apparent at the Amphitheatre outcrop. Satellite images are courtesy of Google Earth © 2017.

A notable difference between the Cobequid Bay and Amphitheatre compound dunes is that because Cobequid Bay is a macrotidal setting, the compound dunes there typically coarsen upward at the dune crest, since current speed is higher at the dune crest than in the dune troughs (Dalrymple *et al.* 2012). In contrast, the Amphitheatre compound dunes show a subtle fining-upwards grain size trend with sand beds thinning upwards. This bedding character is similar to compound dunes in mesotidal settings, where the shallower intertidal zone above the compound dune attenuates current energy upwards (Clifton and Phillips, 1980; Gingras *et al.* 2007).

Laterally accreting bars, in contrast, have growth vectors oriented approximately perpendicular to the depositional currents and are more prevalent in the inner part of estuaries and in low-gradient fluvial settings (Miall, 2010; Olariu *et al.* 2012a). Laterally accreting bar architectures vary based on the physiographic location of the bar in an estuary or fluvial setting, but typically sand grain-size will fine-upward since current energy is highest in the

channel thalweg. Although mud bed abundance commonly increases upwards in these deposits, the mud content is strongly dependent on river character, seasonality, and the presence or absence of tides or brackish water (Lettley *et al.* 2005a; Gingras and MacEachern, 2012). In the McMurray Formation, tidal bar deposits are commonly expressed as tidal point-bars in sinuous estuarine channels. These point-bars are comprised of IHS, whereby sand-mud couplets fine upward and typically become progressively muddy upward as depositional energy decreases towards the top of the bar.

DEPOSITIONAL ARCHITECTURE OF THE STEEPBANK #3 OUTCROPS

The recognition and significance of lateral accretion sets is a matter of debate. Most workers (*e.g.* Mossop and Flach, 1983; Wightman and Pemberton, 1997; Musial *et al.* 2013) did not specifically report the presence of multiple discrete sets of IHS (referred to as LAS) at the Steepbank #3 outcrops. Jablonski and Dalrymple (2016) did recognize similar sediment packages on a smaller scale (0.5-3.5 metre thick cycles), referring to these cycles as metre-scale cycles (MSC's). The MSC's reveal an order of depositional cyclicity not reported in earlier work. These authors suggest the MSC's represent decadal river flooding events on a single, continental-scale fluvial point-bar that may be related to El Niño climate cycles, but unlike lateral accretion sets from this study, they are not bound by changes in bedding orientation. Due to the difficulties of measuring shallowly dipping orientations in outcrop, these authors were unable to identify bounding discontinuities on a larger scale and therefore interpreted the succession as a single point-bar that was subjected to varying salinity and sedimentation patterns. The LAS characteristics could be partially explained in a single point bar if rhythmic climate cycles, such as today's El Niño cycles, modulated hydraulic discharge as suggested by Jablonski and Dalrymple (2016). Dai *et al.* (2009) (their Figure 5) show some correlation between continental-scale drainage systems and decadal climate cycles, but overall, most rivers with very large catchments do not show statistically-significant trends. Owing to this, along with evidence of a significant brackish-water influence on the LAS, we

do not ascribe the LAS to rhythmic climatic cycles on a continental-scale fluvial point-bar in this study.

Because Steepbank 3A, 3B, and parts of 3C are oriented in strike or oblique-strike view, the recognition of the bounding discontinuities that separate the LAS is challenging without a dense bedding orientation dataset. This may be a reason why the single-channel interpretation for the Steepbank #3 outcrops has been largely unchallenged - the acquisition of a dense bed orientation dataset from these exposures was not feasible in the past. We consider the presence of bedding discontinuities between stacked LAS, bedsets that thin and muddy upwards, and bioturbation intensity increasing upwards within a single LAS to at the very least indicate that the interpretation of the Steepbank #3 outcrops as a single point-bar to be equivocal. Since each LAS conforms to estuarine point-bar lithofacies classifications (Smith, 1987; Gingras and MacEachern, 2012), and that tadpole plots show bedding discontinuities between successive LAS, the interpretation that each LAS represents an individual laterally accreting point-bar is justified.

3.8 STRATIGRAPHIC IMPLICATIONS

NATURE OF THE CROSS-BEDDED SAND/IHS CONTACT

A sharp contact between cross-bedded sand and overlying IHS is observed at both outcrop locations. At the Amphitheatre outcrop, the disconformable contact between the cross-bedded compound dune deposits and overlying IHS channel-fill may be a critical surface for the stratigraphy of the McMurray Formation (Figs. 3.12 and 3.14). The best explanation for the juxtaposition of these units at the Amphitheatre outcrop is that a progradational relationship exists between the compound dune complex and the IHS channel-fill. Based on evidence for tides, brackish-water conditions, and the parallel relationship between the master bedding migration direction and depositional currents, the compound dune complex is

best interpreted as a middle estuary unit, while the overlying IHS channel-fill is interpreted as inner-estuary tidal-fluvial channels (Table 3.1). The lithosome distributions represent a single transgression-regression cycle.

A potentially analogous surface is present at the Steepbank #3 outcrops, separating the IHS units from the underlying cross-bedded sand (Fig. 3.6). As is the case at the Amphitheatre outcrop, the lowermost cross-bedded sand unit at the Steepbank #3 outcrops is sedimentologically and ichnologically distinct from the overlying IHS. This unit is interpreted as the lower point-bar by Jablonski and Dalrymple (2016) on the basis of IHS interfingering with the cross-bedded sand (Fig. 3.16A). We instead recognize a sharp, abrupt contact between the two geobodies (Fig. 3.16B). Jablonski and Dalrymple (2016) only highlight two instances of interfingering of these units, both at the Steepbank 3C outcrop. Upon close investigation with our 3D outcrop models, it is deemed that the outcrop is either covered by slumped sediment, or that the thin interbeds of rippled sand and decimetre-scale dunes with mud clasts in the toesets are simply prominent at these locations (Figs. 3.5B and 3.16C). Furthermore, the master bedding orientation data points from the cross-bedded sand unit at the Steepbank outcrops are best ascribed to simple dunes in a fluvial channel and should not be associated to the overlying pervasively bioturbated, brackish-water associated IHS.

EVIDENCE FOR MULTIPLE STACKED POINT-BARS AT STEEPBANK IS EQUIVOCAL

Although this study has recognized three to four separate lateral accretion sets at the Steepbank #3 outcrops, the relationship between lateral accretion set and point-bar is unclear. The term “lateral accretion set” merely implies sedimentological and ichnological discontinuities in lateral accretion deposits. Nardin *et al.* (2013) developed a stratigraphic hierarchy for McMurray Formation lateral accretion deposits, breaking down a point-bar at the nearby Syncrude Mildred Lake Mine into one or more lateral accretion sets. Lateral accretion sets are then subdivided into stories, and stories subdivided into bedsets. Essentially, the defini-

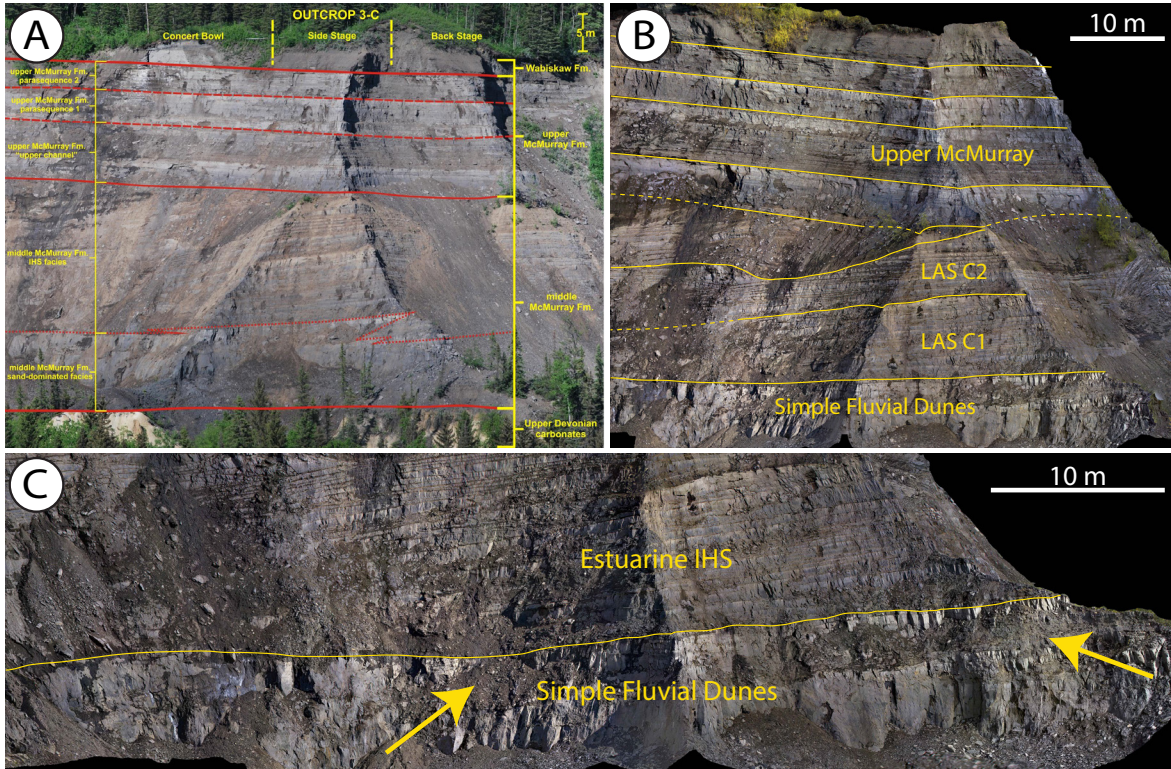


Figure 3.16: Comparison of the overall depositional architecture of the Steepbank 3C outcrop suggested by Jablonski and Dalrymple (2016) to the depositional architecture interpreted in this study. **A)** Interpretation of the Steepbank 3C outcrop by Jablonski (2012) and Jablonski and Dalrymple (2016). Image is from Jablonski (2012), their Figure 4.2. Note the interfingering cross-bedded sand/IHS contact shown in the middle McMurray strata by a dotted red line. This interpretation suggests the succession is a single point-bar, where the cross-bedded sand is the lower point-bar and the overlying IHS is a middle point-bar deposit. **B)** Interpretation of the Steepbank 3C outcrop in this study. We recognize an abrupt contact between the unburrowed cross-bedded sand and the overlying, pervasively bioturbated IHS, and interpret the two units to be separate geobodies that are not genetically related. The sand is interpreted to be simple fluvial dunes in a channelized environment, while the IHS (LAS) is interpreted to represent the deposition of estuarine point-bars. **C)** A rotated close-up view of the abrupt cross-bedded sand/IHS contact. Note the loose sediment and the presence of decimetre-scale rippled crossbeds as shown by the arrows. The arrows are located at the approximate locations where Jablonski (2012) and Jablonski and Dalrymple (2016) interpret interfingering of IHS with the cross-bedded sand.

tion of these hierarchical elements is the same – just the scale varies (*i.e.* a story is one or more genetically related, stacked bedsets bounded by erosional or discordant surfaces; a lateral accretion set is one or more genetically related, stacked stories bounded by erosional or discordant surfaces, and so on). According to these definitions, a point-bar may consist of one or more genetically related lateral accretion sets. In the McMurray Formation, particularly in outcrops where finer-grained sediments are more prone to erosion, intertidal and supratidal bar tops are not preserved – meaning there is no definitive way to determine whether the succession is one large point-bar consisting of several lateral accretion sets or a number of smaller, stacked point-bars consisting of one to two lateral accretion sets. However, the sedimentological, ichnological, and bedding orientation discontinuities recognized at this locale suggest that the IHS at Steepbank is equivocal, with the potential for more than one point-bar to be present in the region contrary to the results of past studies.

**NOT ALL CROSS-BEDDED SAND-IHS PACKAGES ARE
CONTINUOUS VERTICAL POINT-BAR SUCCESSIONS**

The results from the Steepbank and Amphitheatre outcrops in this study are important when discussed in terms of subsurface stratigraphy. The majority of the literature from the McMurray Formation, specifically recent publications, promote the notion that any cross-bedded sand unit overlain by IHS can together be taken to represent continuous vertical successions of a single point-bar deposit (*e.g.* Mossop and Flach, 1983; Hubbard *et al.* 2011; Musial *et al.* 2012; Musial *et al.* 2013; Martinius *et al.* 2015; Jablonski and Dalrymple, 2016). As a result, a bias has developed regarding how facies distributions are used to interpret the sequence stratigraphic architecture of the McMurray Formation IHS deposits. This influences the community's view on the overall stratigraphy of the McMurray Formation, and how development plans are prepared, especially for steam assisted gravity drainage (SAGD), a bitumen extraction method whereby subsurface bitumen is mobilized and collected via injected steam.

In this study, bed orientation data from outcrop suggest that there exist more than one type of geobody in the middle McMurray Formation - at the very least, there are: 1) transition from cross-bedded sand bodies to IHS laterally accreted bars; 2) sharp-based IHS packages with no well-developed thalweg deposit; and 3) compound dunes. Two of these geobodies may act as *in situ* reservoir units using current technology, and as such must be considered for subsurface stratigraphic models throughout the extent of the McMurray Formation in the subsurface.

3.9 CONCLUSION

This study documents two distinct depositional architectures in the middle McMurray Formation. The well-studied Steepbank #3 outcrops are characterized by estuarine point-bar deposits sharply overlying fluviially-associated simple dunes. Overall, up to four stacked point-bars are recognized in the IHS succession, and therefore a laterally-accreting point-bar complex is preserved at the Steepbank #3 outcrops. This is further evidenced by the accretion of master bedding surfaces at a high angle to sediment transport direction. At the Amphitheatre outcrop, master bedding surfaces are mainly parallel to sediment transport direction in a metre-scale cross-bedded sand geobody. This suggests that the dominant middle McMurray strata at this locale, the cross-bedded sand unit, formed as a result of forward accretion. Given this relationship, along with evidence of tidal reworking in metre-scale dunes and bioturbation consistent in brackish-water settings, the origin of the cross-bedded sand geobody at the Amphitheatre outcrop is ascribed to the growth of a compound dune complex in the middle estuary.

Discrete lateral accretion sets (LAS) at the Steepbank #3 outcrops are identified based on bed orientation discontinuities, bedset character and ichnological trends. Each LAS dis-

plays a bedding discontinuity with respect to the underlying strata, with bedsets that typically thin and increase in mud content associated with increased bioturbation upwards. The recognition of separate and discrete LAS that conform to estuarine point-bar lithofacies models suggest that the most appropriate interpretation for the middle McMurray strata at the Steepbank #3 outcrops is that each LAS comprises an individual laterally accreting bar. However, the evidence for multiple stacked point-bars at the Steepbank #3 outcrops is equivocal: whether or not these LAS belong to a single accreting point bar or represent stacked channel deposits simply cannot be demonstrated with absolute certainty from the outcrop data. The stacked point-bar interpretation contrasts with previous interpretations of this outcrop, whereby it was a foregone conclusion that the IHS packages are considered to stem from deposition of a single point-bar in a 30-40 metre thick channel.

Considering that not all cross-bedded sand units in the McMurray Formation can be ascribed to lower point-bar or channel thalweg deposition, a number of implications for subsurface stratigraphy are presented. First, compound dunes are recognized in outcrop throughout the McMurray Formation, but this architectural element is rarely acknowledged in the subsurface. In addition, the juxtaposition of inner estuary IHS channel-fill deposits disconformably overlying a middle estuary compound dune complex at the Amphitheatre outcrop reveals an important stratigraphic surface in the McMurray Formation that should be applied to stratigraphic models. The fact that the contact between cross-bedded sand and IHS at the Steepbank #3 and Amphitheatre outcrops are disconformable suggests that several types of reservoir-quality geobodies exist within the McMurray Formation.

CHAPTER FOUR: SEDIMENTOLOGICAL, ICHNOLOGICAL, AND ARCHITECTURAL CHARACTERIZATION OF A FLUVIALLY-DOMINATED OUTCROP USING UAV-BASED OUTCROP MODELLING, LOWER CRETACEOUS McMURRAY FORMATION, NE ALBERTA, CANADA

4.1 INTRODUCTION

The lower Cretaceous McMurray Formation acts as the main reservoir unit for the Athabasca Oil Sands, and therefore has been the subject of numerous sedimentological, ichnological, palynological, and geophysical studies over the past 50 years. As such, a variety of sedimentary environments were assigned to the McMurray in the 1970's and 1980's including deltaic (*e.g.* Carrigy, 1971; Nelson and Glaister, 1978), fluvial (*e.g.* Mossop, 1980; Mossop and Flach, 1983; Flach and Mossop, 1985), and estuary (*e.g.* Stewart and McCallum, 1978; Pemberton *et al.* 1982; Smith, 1987, Smith, 1988). Currently, there are two contrasting interpretations pertaining to the depositional affinity of the McMurray Formation: 1) a fluvially dominated environment, an interpretation derived mainly from 3D seismic datasets and detrital zircon studies located south of the outcropping McMurray strata (*e.g.* Smith *et al.* 2009; Hubbard *et al.* 2011; Labrecque *et al.* 2011a; Blum and Pecha, 2014; Martinius *et al.* 2015; Benyon *et al.* 2016; Blum and Jennings, 2016; Durkin *et al.* 2017); and 2) an estuarine environment, largely interpreted from the presence of trace fossils characteristic of marine-derived faunal colonization in brackish-water settings and sedimentological evidence of tidal modulation (*e.g.* Stewart and McCallum, 1978; Pemberton *et al.* 1982; Smith, 1987; Smith, 1988; Wightman and Pemberton, 1997; Ranger *et al.* 2008; Ranger and Gingras, 2010; Gingras *et al.* 2016; Shchepetkina *et al.* 2016a, Shchepetkina *et al.* 2017; Timmer *et al.* 2016a; Timmer *et al.* 2016b; Hayes *et al.* 2017, Hayes *et al.* in press).

It is generally accepted that the dominant architectural element of the McMurray

Formation is laterally-accreting point-bar deposits, and therefore much of the recent research on the McMurray Formation has focused on the characterization of point-bar architecture (Smith *et al.* 2009; Hubbard *et al.* 2011; Labrecque *et al.* 2011a; Blum, 2017) or the analysis of meander belt evolution (Durkin *et al.* 2017) using high-quality 3D seismic. The datasets used in these studies suggest that the point-bars are fluvial in origin based on the geomorphology seen in seismic images, but despite this a number of core studies conducted in the same study areas show sedimentary facies that are suggestive of deposition in estuarine channel settings (Gingras *et al.* 2016; Ditzler *et al.* in review; Gingras and Leckie, 2017). These studies have sparked a debate among researchers – are point-bars in the McMurray Formation dominantly fluvial or estuarine?

While many outcrop exposures of McMurray strata including High Hill (Wightman and Pemberton, 1997), Christina River (Hayes *et al.* 2017), Steepbank River #3 (Wightman and Pemberton, 1997; Langenberg *et al.* 2002; Hayes *et al.* in press), the Type Section (Smith, 1988), and Amphitheatre (Wightman and Pemberton, 1997; Hayes *et al.* in press) preserve tidal sedimentary structures, bioturbation characteristic of infaunal colonization in a brackish-water setting, and in some cases, forward-accreting geobodies interpreted to be middle estuary compound dune deposits, one outcropping locale displays vastly different characteristics. The strata exposed at the Crooked Rapids outcrop along the Athabasca River is unique among exposed McMurray strata for several reasons: 1) although it is similar lithologically to other McMurray Formation outcrops (*i.e.* a basal cross-bedded sand geobody overlain by Inclined Heterolithic Strata (IHS geobody)), the Crooked Rapids outcrop is the only exposure where IHS is observed to interdigitate with the cross-bedded sand; 2) there is an absence of bioturbation and abundant terrestrial organic detritus and coalified debris in both the cross-bedded sand and IHS geobodies; 3) there is no sedimentological evidence of tidal modulation; and 4) there is little evidence to suggest forward-accreting middle estuary compound dune deposits are present. These observations contrast with all other outcrops

previously studied in the McMurray Formation, and therefore are taken together to represent a significant landward shift of facies toward a fluvially dominated depositional environment in the study area.

The objectives of this study are to use an unmanned aerial vehicle (UAV) and Structure-from-Motion photogrammetry to characterize the large-scale depositional architecture of a fluvially dominated McMurray Formation outcrop. The Crooked Rapids outcrop is unique among the McMurray Formation outcrops because the exposure is over a kilometre long, providing extensive and continuous views of the preserved point-bar geobodies. Importantly, this outcrop provides a sedimentological and ichnological fluvial baseline for deposits in the McMurray Formation. Therefore, deposits with similar sedimentological and ichnological characteristics in the subsurface should be classified as fluvially dominated, while the point-bars studied in recent years that have been previously ascribed to fluvially dominated deposition (*e.g.* Hubbard *et al.* 2011; Labrecque *et al.* 2011a; Blum, 2017) should be recognized as estuarine point-bar deposits.

4.2 STUDY AREA AND BACKGROUND

The Crooked Rapids outcrop is located approximately 30 kilometres west of the city of Fort McMurray along the Athabasca River, in Townships 87 and 88, Range 12 west of the fourth meridian (56° 35' 38.98" N, 111° 52' 6.57" W) (Fig. 4.1). McMurray Formation strata unconformably overlie the upper Devonian Waterways Formation, and are overlain by the Wabiskaw Member of the Clearwater Formation. A schematic stratigraphic chart for the study area is presented in Figure 4.2.

Despite the Crooked Rapids outcrop offering the most complete continuous exposure of McMurray Formation strata outside of the surface mines, no detailed work exists in

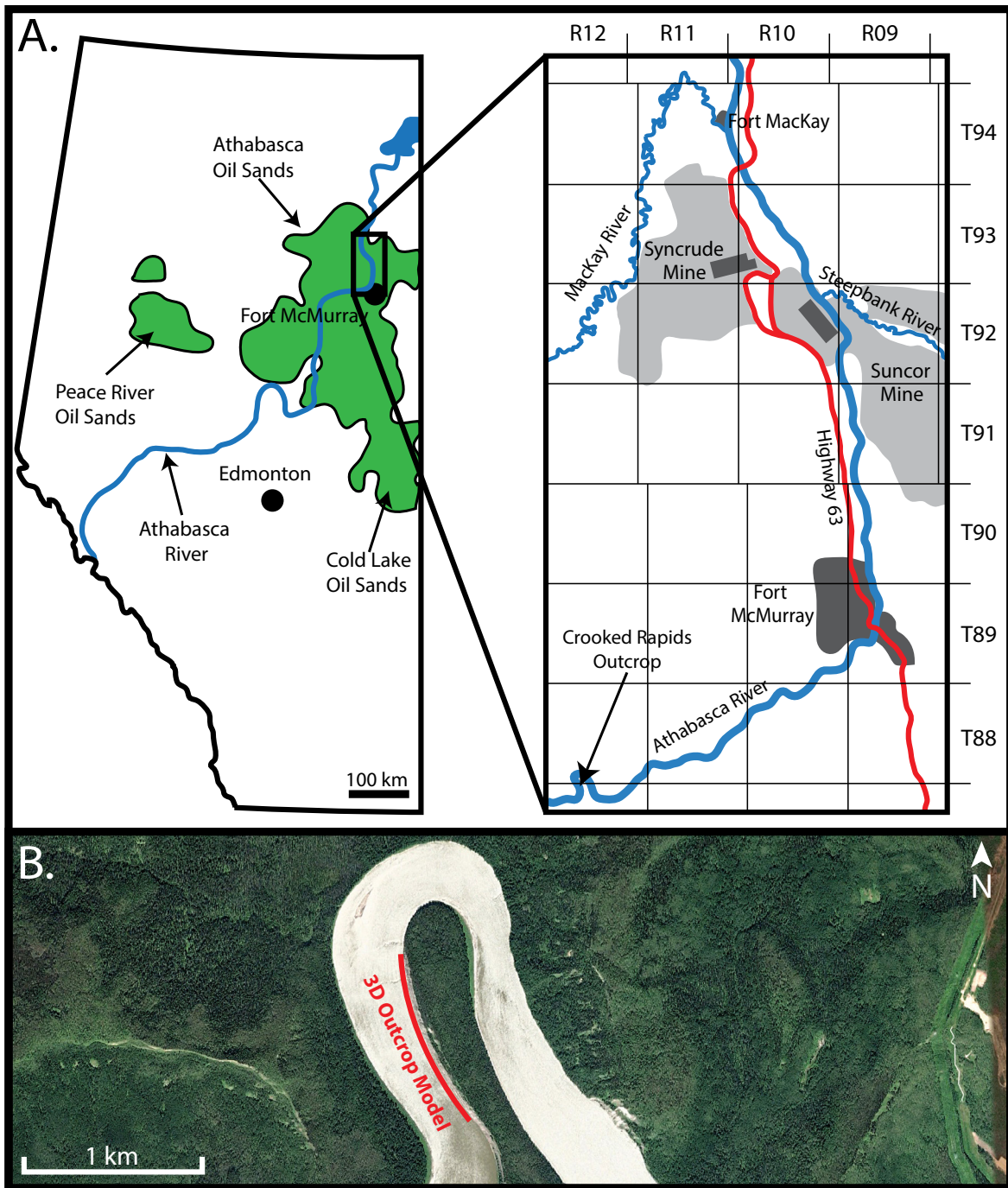


Figure 4.1: A) Location map of the studied outcrop in relation to Fort McMurray, Alberta, Canada. B) Satellite image of the Crooked Rapids outcrop along the Athabasca River. The approximate extent of the 3D outcrop model used in this study is shown by the red line. Image courtesy of Google Earth © 2017.

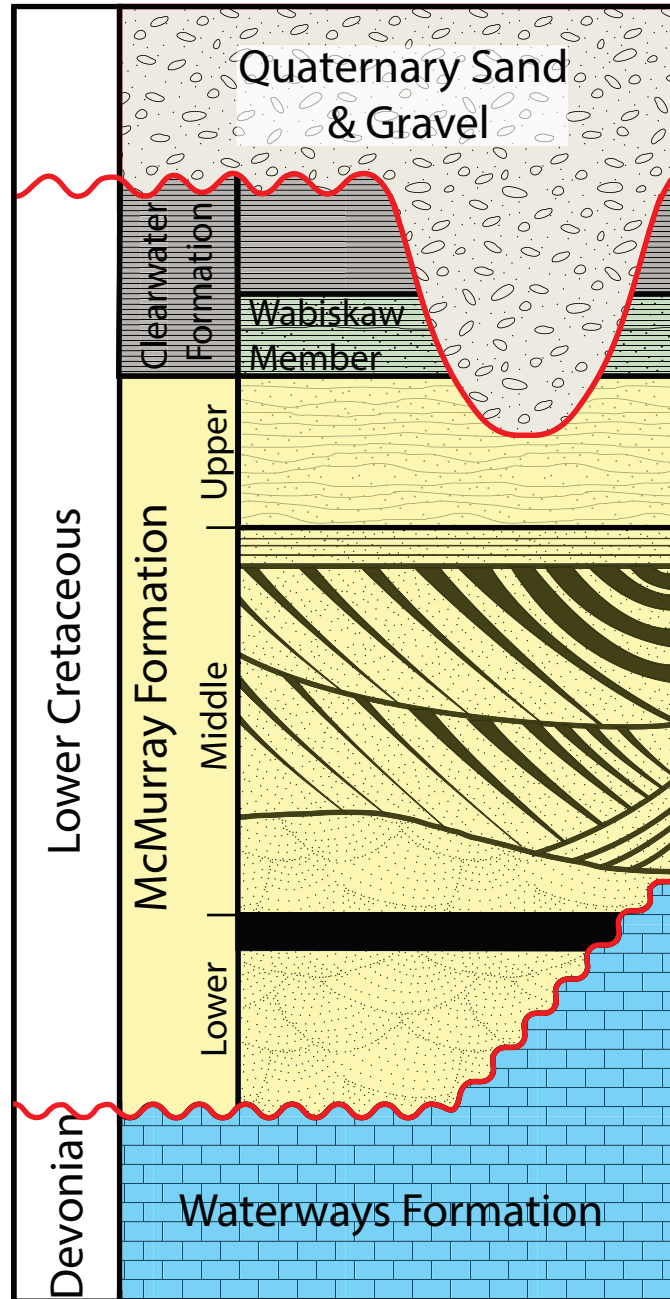


Figure 4.2: Schematic stratigraphic chart of the studied McMurray Formation strata courtesy of Hayes *et al.* (in press). At the Crooked Rapids outcrop, the lower Cretaceous McMurray Formation unconformably overlies the upper Devonian Waterways Formation, and is capped by the Wabiskaw Member of the Clearwater Formation. Stratigraphic chart modified from Smith (1994) and Hubbard *et al.* (2011).

published literature regarding the depositional architecture of the outcrop. Mossop and Flach (1983) and Strobl *et al.* (1997) briefly discuss the facies relationship of the cross-bedded sand and overlying inclined heterolithic stratification (IHS) at Crooked Rapids in relation to the McMurray as a whole, and note that as the cross-bedded sand facies thins the overlying IHS facies thickens until the heterolithic beds downlap the underlying Devonian-aged limestone. These authors suggest that the transition from sand-dominated in the north to IHS-dominated in the south across the extent of the entire exposure likely represents the gradual abandonment of a channel, where the length of the outcrop records the waning of flow during deposition. The results of this study indicate that in general this interpretation still holds true, however the outcrop itself can be subdivided into a number of depositional units that represent the amalgamation of two fluvially dominated point-bar geobodies, both with apparent dips toward the south, creating the illusion of a single point-bar deposit.

4.3 METHODS

In this study, Structure-from-Motion (SfM; Ullman, 1979) photogrammetry and an unmanned aerial vehicle (UAV) equipped with a 12 megapixel Zenmuse X3 camera are used to construct three-dimensional outcrop models for the large-scale characterization of the exposed McMurray Formation strata at the Crooked Rapids outcrop. In particular, the advantages of using SfM photogrammetry include: 1) important contacts between geobodies can be traced laterally for hundreds of metres on the outcrop; 2) orientation data can be collected from any bed or cross-bed with sufficient three-dimensional relief at any location on the 3D model, rather than from specific locations where sections are logged; and 3) orientation data collected from the 3D model itself is precisely located, allowing for the accurate subdivision of geobodies on a macroscopic scale. Combined with logging the outcrop in the field, this methodology allows for a comprehensive study of the kilometre-long outcrop to be completed. Once the large-scale geobodies are differentiated, sedimentological and ichnological data

is easily acquired via abseiling the outcrop.

The 3D outcrop methodology is summarized in Figure 4.3. To construct the 3D outcrop model, a commercial Structure-from-Motion software, PhotoScan Professional (© Agisoft) is used. PhotoScan requires georeferenced images as its only input – the images of the outcrop to be used for the construction of the 3D model should be captured orthogonal to the outcrop face, approximately five metres away. Using the UAV, images are collected using a sweeping method, where the drone hovers at a constant elevation and photographs are captured laterally along the extent of the outcrop with approximately 40% overlap between images. After a sweep is complete, the UAV operator repositions the drone at a higher elevation, and the same sweeping method is employed until images of the entire outcrop have been captured. Following the data collection phase, the captured photos are processed in Adobe Lightroom (© Adobe) to eliminate colour irregularities and reduce the effect of uneven sun-

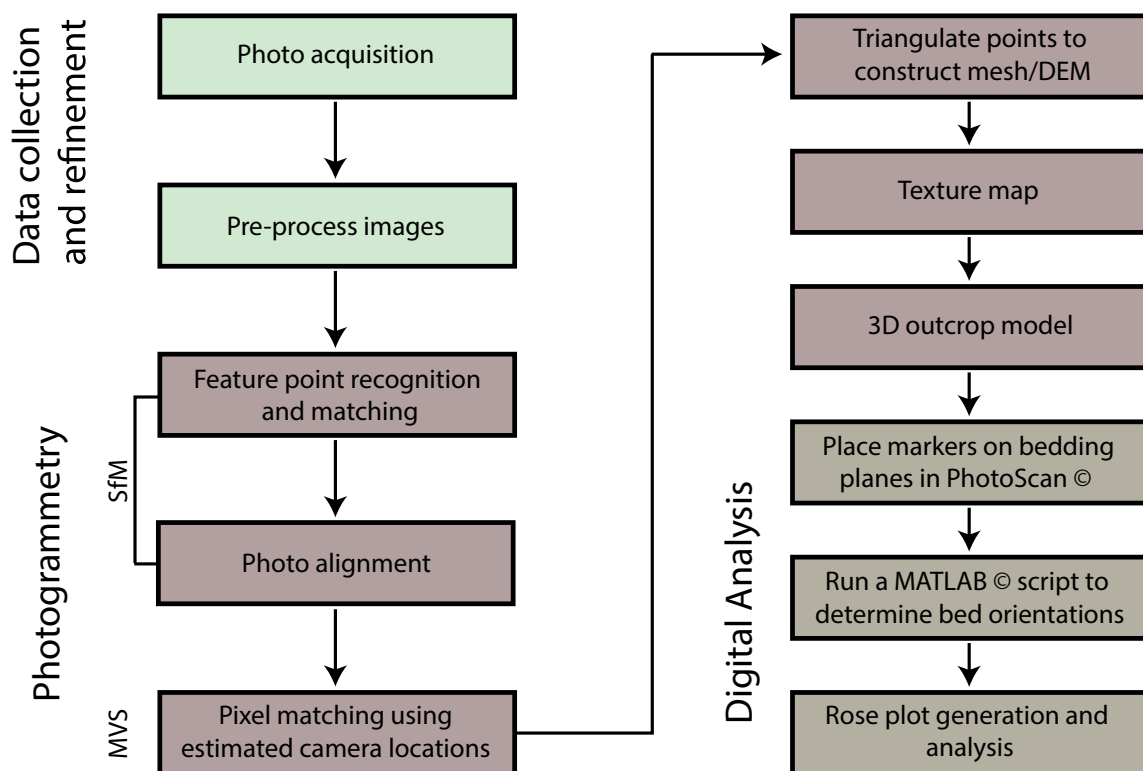


Figure 4.3: Schematic workflow of the 3D photogrammetry method used to characterize McMurray Formation strata in outcrop. Modified from Hayes *et al.* (2017).

light and shadows on the images. For a comprehensive review of Structure-from-Motion photogrammetry and the methodology of 3D model construction in PhotoScan, readers are directed to Hayes *et al.* (2017).

Following construction of the 3D outcrop model, analysis of bedding plane orientation and palaeocurrent orientation is achieved by placing markers along the extent of a bed (or cross-bed) in PhotoScan. Because the outcrop is georeferenced, each marker has a unique point in three-dimensional space and is therefore referenced by latitude, longitude, and elevation. The marker points for a bed are exported as text files, and a MATLAB (© MathWorks) script is used to fit a plane to the points along the bedding plane, representing the orientation of a specific bed. Readers are directed to Fernandez (2005) for further information regarding how a best fit plane is achieved through georeferenced data in three dimensions, specifically using the estimated moment of inertia method to identify the pole to the best fit plane, and therefore the orientation of the best-fit plane in three-dimensional space. For quality control of measured bed orientations, Fernandez (2005) uses two constants, M and K as proposed by Woodcock (1977). M represents the degree of fit of the plane with regard to the placed markers, while K represents the reliability of the best fit plane based on the collinearity of the markers. Fernandez (2005) stated that for the fit of a best-fit plane to be sufficient, M should be greater than four while reliable plane orientation measurements should yield a K value below 0.8. Therefore, these are the cutoffs applied to the collected bed orientation data in this study.

4.4 ARCHITECTURAL ELEMENTS AT THE CROOKED RAPIDS OUTCROP

At the Crooked Rapids outcrop, six genetically separate depositional units (DU1-DU6) are recognized based on distinct bed orientation, palaeocurrent orientation, sedimen-

tological, and ichnological features. In general, DU1-DU4 comprise fluvially dominated deposits, while DU5 and DU6 represent horizontally-bedded, brackish- and marine-associated deposition within the upper McMurray parasequences and the Wabiskaw Member of the Clearwater Formation. This study focuses on DU1-DU4. Each fluvial depositional unit (DU1-DU4) represents a large-scale fluvial architectural element (*sensu* Miall 1996) and therefore are discussed and interpreted separately (Table 4.1). The depositional units recognized in this study are discussed in order from oldest (DU1) to youngest (DU6). The locations of measured sections along the outcrop are shown in Figure 4.4.

DEPOSITIONAL UNIT 1: FLUVIAL CHANNEL & POINT-BAR

Description

Depositional Unit 1 (DU1) is confined to the northern section of the exposure, unconformably overlying the Waterways Formation (Table 4.1). DU1 consists of two sand facies: a lowermost medium-grained, metre-scale trough and planar tabular cross-stratified sand that is overlain by a planar-bedded and current rippled fine-grained sand facies (Figs. 4.5A-D). The lower trough cross-bedded sand is 10 metres thick, extends laterally for approximately 200 metres, and is devoid of bioturbation. The thickness of the cross-beds varies from 1.5-2 metres in the north to 0.5-1.25 metres in the southern sections of the outcrop where DU1 is exposed. Additionally, the trough cross-bedded sand appears to grade laterally into the planar tabular cross-strata comprising Depositional Unit 2. Master bedding dips and palaeocurrent orientation in this facies are oriented north to northeast (average bedding dip direction of 43°), and northwest, respectively. Of note, the master bedding and palaeocurrent data show more variability in DU1 than in other identified depositional units (Table 4.1).

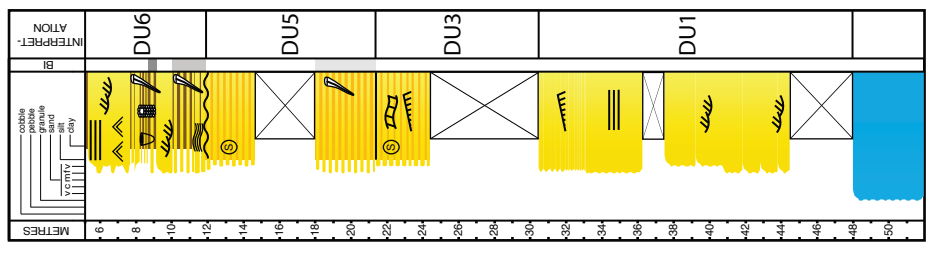
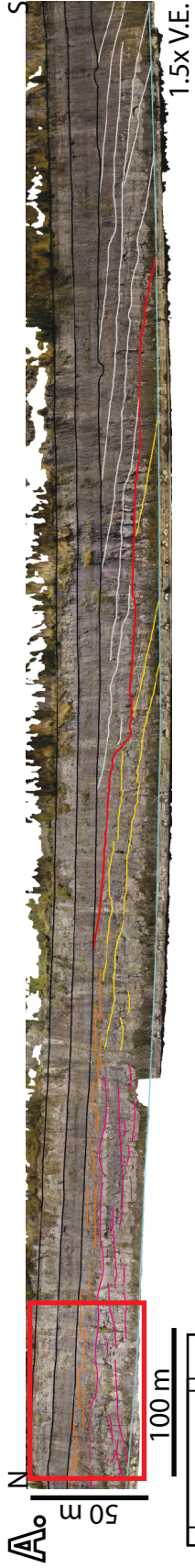
The overlying planar bedded sand erosionally overlies the trough cross-bedded sand (Fig. 4.5D). It grades upward into current-rippled sand, with bedding thickness decreasing upward from metre- to decimetre-scale bedding in the planar-bedded sand to decimetre- to

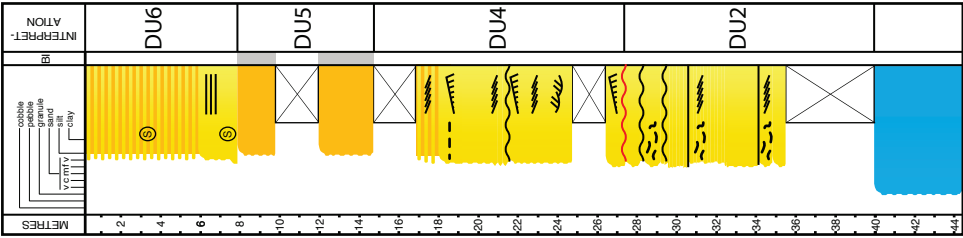
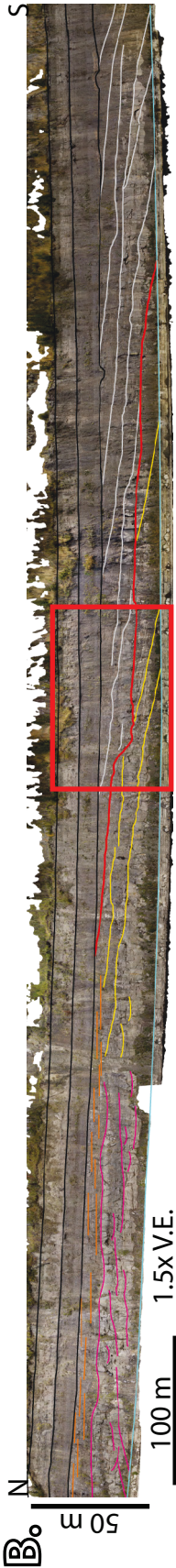


| | Sedimentology | Ichology | Photogrammetry & Orientation Data | Master Bedding & Palaeocurrent Rose Diagram | Poles to Bedding | Interpretation |
|-------------|---|--|---|---|------------------|---|
| DU 1 | <ul style="list-style-type: none"> Medium-grained trough and planar tabular cross-bedded sand overlain by fine-grained planar-bedded to current-rippled sand Cross-beds range from 0.5-2m thick Lacks a tidal influence (no reactivation surfaces, double mud drapes, or flow reversals) | <ul style="list-style-type: none"> Absent | <ul style="list-style-type: none"> Some variability in master bedding accretion surfaces and palaeocurrent direction Master bedding accretes dominantly toward the N to NE Palaeocurrent is oriented N to NW | <p>N = 33 N = 49</p> | <p>N = 33</p> | <ul style="list-style-type: none"> Elements of both lateral accretion and forward accretion, as evidenced by noisy orientation data Consistent with migrating sinuous dunes in a channelized setting Fluvial channel or lowermost fluvial point-bar deposit |
| DU 2 | <ul style="list-style-type: none"> Fine-grained, low- and high-angle planar tabular cross-bedded sand Cross-beds range from 0.5-1m thick Organic detritus is abundant in dune bottomsets and foresets Coalified debris scattered throughout Internal erosion surfaces are prevalent Lacks a discernable tidal influence | <ul style="list-style-type: none"> Absent | <ul style="list-style-type: none"> Master bedding is consistently oriented ENE to SE Palaeocurrent is oriented N to NE Significant lateral variation in average bedding orientation (from 43° in the north to 109° in the south) | <p>N = 45 N = 25</p> | <p>N = 45</p> | <ul style="list-style-type: none"> Orthogonal relationship between master bedding and palaeocurrent suggests lateral accretion Lack of tidal indicators and bioturbation, combined with the abundance of organics and coal suggests a continental origin Fluvial point-bar with lateral variations in dip direction from north to south representing a scroll-bar morphology |
| DU 3 | <ul style="list-style-type: none"> Rhythmically interbedded fine to very fine sand and silt Abundant siderite horizons, extending for 10's of metres Sand beds are 15-50cm thick, sharp-based, and contain current and climbing ripples | <ul style="list-style-type: none"> Absent | <ul style="list-style-type: none"> Bedding is very gentle (less than 5°), dipping E or W Due to the shallow nature of the bedding, the dip direction can not be determined accurately | <p>N = 40</p> | <p>N = 40</p> | <ul style="list-style-type: none"> The rhythmically-bedded, sharp-based decimetre-scale sand beds and centimetre-scale silt beds are consistent with sheetflood deposits Fluvial overbank deposition: levee |
| DU 4 | <ul style="list-style-type: none"> Characterized by low-angle cross-beds, planar-bedded sand, and current rippled sand Sand beds climb up inclined surfaces and grade laterally into IHS IHS contains sand beds up to 50cm thick; organic-rich silt beds are 1-5cm thick Sideritized beds and organic detritus are very common | <ul style="list-style-type: none"> Absent | <ul style="list-style-type: none"> Both sand and IHS units accrete W to SW Sand and IHS clearly interdigitate Bedding dips typically range from 4° to 16° DU4 truncates the underlying DU2 | <p>N = 38</p> | <p>N = 38</p> | <ul style="list-style-type: none"> IHS is unique compared to other McMurray Formation outcrops - completely devoid of bioturbation, and visibly interfingers with cross-bedded sand Accretionary growth direction is opposite of the underlying DU2 Sand:mud is low Fluvial counter point-bar |

| | Sedimentology | Ichonology | Photogrammetry & Orientation Data | Master Bedding & Palaeocurrent Rose Diagram | Poles to Bedding | Interpretation |
|------------|---|---|--|--|--|---|
| DU5 | <ul style="list-style-type: none"> Fine-grained sandy siltstone that coarsens upward into a fine-grained silty sandstone Sand beds are 5-10cm thick Silt beds are 1-3cm thick Centimetre-scale cross-bedding Small siderite nodules scattered throughout the upper 3m | <ul style="list-style-type: none"> BI of 1-3 Most common trace fossil is <i>Cylindrichnus</i> | <ul style="list-style-type: none"> Not analyzed in this study | <ul style="list-style-type: none"> Not analyzed in this study | <ul style="list-style-type: none"> Not analyzed in this study | <ul style="list-style-type: none"> Monospecific ichnological assemblage suggests these strata were likely deposited under stressed conditions in the presence of brackish water DU 5 represents a flooding surface that deposits marginal marine strata above fluvial deposits (overlies DU 2, DU 3, and DU 4) Mixed wave/fluvial influenced bayhead delta (Caplan and Ranger, 2001) |
| DU6 | <ul style="list-style-type: none"> Fine- to very fine-grained sand interbedded with mud Overall increase in sand content upward Sand beds are 5-15cm thick with 1-3cm thick wavy mud interbeds Low-angle cross-bedding, oscillation ripples, and planar bedding are common in sand beds | <ul style="list-style-type: none"> BI of 1-4 <i>Conichnus</i>, <i>Cylindrichnus</i>, and <i>Ophiomorpha</i> | <ul style="list-style-type: none"> Not analyzed in this study | <ul style="list-style-type: none"> Not analyzed in this study | <ul style="list-style-type: none"> Not analyzed in this study | <ul style="list-style-type: none"> More diverse ichnological assemblage than underlying DU 5 suggests deposition in a more stable environment (albeit still brackish- to stressed marine waters) Oscillation ripples suggest wave modulation Marine-associated shoreface |

Table 4.1 (including previous page): Defining characteristics of the fluvial (DU1-DU4) and marginal marine (DU5-DU6) depositional units at the Crooked Rapids outcrop. A colour-coded schematic of the outcrop is shown above the table to illustrate the locations of each depositional unit. DU5 and DU6 are above the interpreted fluvial deposits, both shaded in green (DU5 is overlain by DU6). Red lines on the outcrop show erosional contacts between depositional units. Solid black lines show conformable, but sharp contacts, and the black dashed line shows a gradational contact. Rose plots show master bedding (black petals) and palaeocurrent (red petals) in the depositional units. Pole to bedding plots illustrate the degree of dip of master bedding surfaces in this study. Rose diagrams are generated using Stereonet (© R.W. Allmendinger; Allmendinger *et al.* 2013; Cardozo and Allmendinger, 2013).





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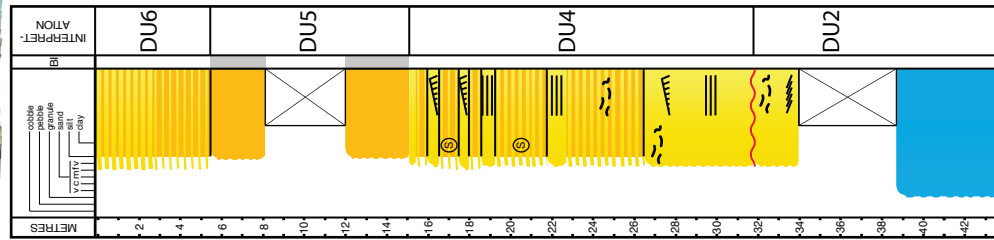
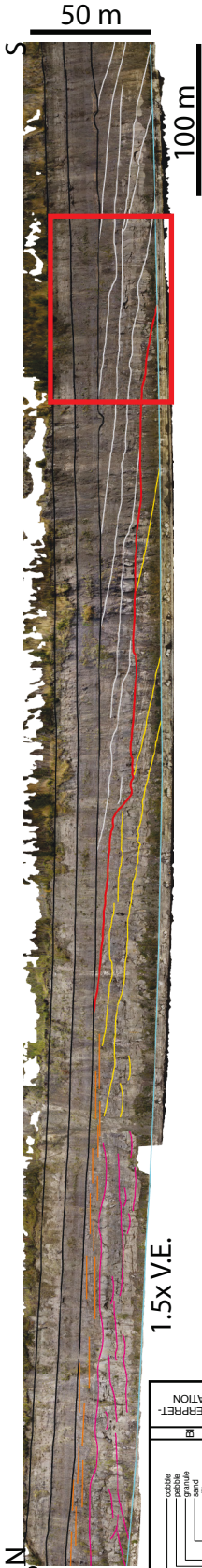


Figure 4.4 (previous pages): Measured sections of the Crooked Rapids outcrop in the north (A), central (B) and south (C) regions of the exposure. The exact location of each outcrop log is indicated by a white line on the uninterpreted outcrop images. The approximate location of each outcrop image is marked by a red box on the 1.5x V.E. outcrop orthomosaic.

centimetre-scale bedding in the current-rippled sand. Bedding is poorly exposed, so minimal orientation data was collected from the planar-bedded sand.

Interpretation

The upward transition from trough cross-bedded sand into planar bedded and current-rippled sand is consistent with an upwards decrease in depositional energy (Allen, 1970; Walker and Cant, 1982). Combined with the fining-upward grain size trend, this unit is interpreted to be a preserved fluvial channel and lower point-bar deposit. The presence of trough cross-bedding suggests that the sand originated as sinuous-crested, three-dimensional dunes migrating laterally and obliquely to flow direction in the lower part of a channel, as evidenced by the master bedding and palaeocurrent data in Table 4.1. An irregular contact between the lower trough cross-bedded sand and overlying planar bedded sand may be explained by a high-energy flooding event which caused intrapoint-bar erosion (*e.g.* Fig. 4.4A) (*cf.* Durkin *et al.* 2015). As the river returned to normal flow conditions, planar bedded sand was deposited on the point-bar above the scoured surface as a result of decreasing energy levels associated with shallower water depths in the channel (Allen, 1970; Walker and Cant, 1982). The transition from planar bedded sand to current rippled sand is interpreted as deposition closer to the bar top (Allen, 1970; Wang and Bhattacharya, 2018). The lack of bioturbation is explained by the physiographic location of the river in the fresh-water fluvial zone: when placed in a fresh-water setting, burrows are commonly absent due to the constantly shifting sediments, the impoverished fresh-water biomass, and because much of the bioturbation in fluvial environments occurs in overbank settings (Gingras *et al.* 2016).

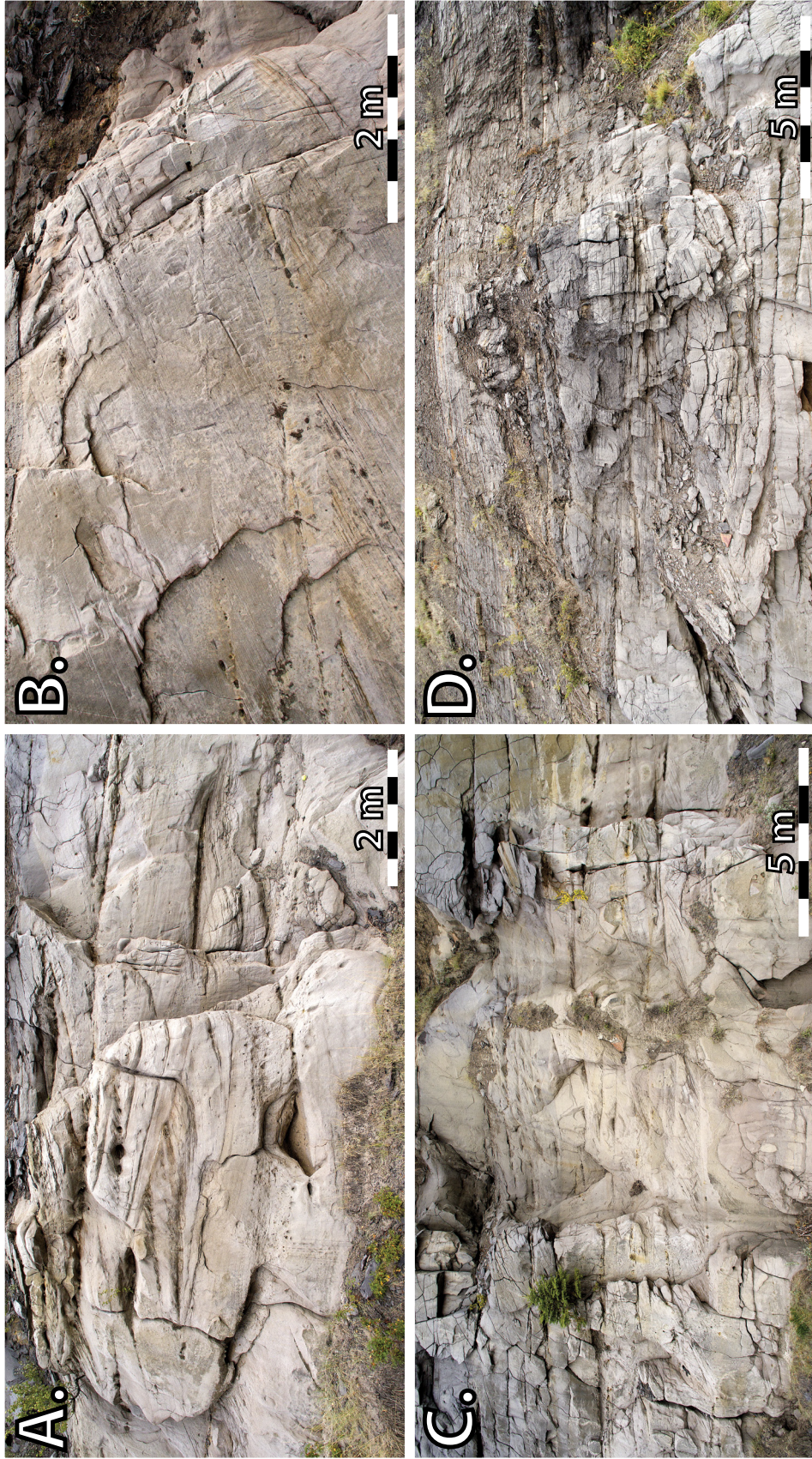


Figure 4.5: Facies plate showing the sedimentology of DU1. **A)** Metre-scale trough cross-bedding. **B-C)** Metre-scale planar-tabular cross-bedding. **D)** Metre-scale trough cross-beds sharply overlain by decimetre- to centimetre-scale planar bedded and current rippled sand.

DEPOSITIONAL UNIT 2: FLUVIAL POINT-BAR

Description

Depositional unit 2 (DU2) is a laterally extensive geobody. It is not present in the northern end of the exposure, but is a significant architectural unit in the central and southern regions of the outcrop where it unconformably overlies the Waterways Formation (Table 4.1). The thickness of the exposed unit ranges from 29 metres at its northernmost position to 6 metres in the south until it pinches out against the underlying Waterways Formation. Notably, the thickness of DU2 is controlled by the overlying DU4 (and to a lesser extent, DU3): as DU2 thins southward, DU4 becomes progressively thicker. Overall, this depositional unit is bounded by sharp, abrupt contacts.

DU2 is represented at the Crooked Rapids outcrop by a single sand-dominated facies association. Sedimentologically, it consists of low- and high-angle, fine-grained planar tabular cross stratified sand (Fig. 4.6A). Organic detritus commonly drapes the dune foresets, and abundant coal fragments are observed in massively appearing sands (Fig. 4.6B-D). The cross-beds are on a decimetre- to metre-scale. Internal erosional contacts are common in this unit, especially toward the north. Additionally, features such as deformed cross-beds are present toward the north, where the unit is truncated by younger DU4 strata (*e.g.* Fig. 4.10B, in PB1). Within DU2, master bedding planes consistently dip toward the east along the entire extent of the exposed strata (approximately 400 metres), while palaeocurrent orientations measured from dune foresets are oriented toward the north and northeast (Table 4.1).

Interpretation

DU2 is dominated by high-energy deposition, as evidenced by the scale of cross-bedding, the abundance of internal erosion surfaces, and the lack of silty sediment throughout this unit. Given the consistent unimodal sediment transport directions, the sand is ascribed to sedimentation under unidirectional flow. When sediment transport direction is compared



Figure 4.6: Facies plate showing the sedimentology of DU2. **A)** Metre- to decimetre-scale planar-tabular cross-bedding. **B)** Decimetre-scale planar-tabular cross-bedding with abundant organic detritus in the bottomsets of the dunes. **C)** Coal fragments scattered throughout massively-appearing sand. **D)** Organic detritus lining the foresets of a decimetre-scale dune.

with the accretionary direction of bedding planes, a high angular divergence suggests that the sand is a laterally-accreting unit (Table 4.1; *e.g.* Miall, 2010; Olariu *et al.* 2012a). The lack of bioturbation, lack of any discernable tidal influence, and abundance of organic detritus lining the dune foresets strongly supports an interpretation of a fluvially dominated point-bar (*cf.* Shchepetkina *et al.* 2016b). As such, DU2 is interpreted as a fluvial lateral accretion point-bar deposit that is laterally equivalent to the channel deposits of DU1.

DEPOSITIONAL UNIT 3: FLUVIAL LEVEE

Description

Depositional Unit 3 (DU3) is a gently-dipping heterolithic facies sharply overlying the planar and current rippled sand facies of DU1 in the northern region of the outcrop (Table 4.1). The sand beds are fine-grained and range in thickness from 5-40 centimetres, but are typically 15-20 centimetres thick (Fig. 4.7). The sand beds are characterized mainly by sharp-based current and climbing ripples with occasional wavy bedding. Muddy interbeds are on the scale of 1-5 centimetres thick. Both the sand and mud beds are bounded by sharp contacts. Notably, this facies is completely devoid of bioturbation. Large siderite nodules are distributed randomly throughout the heterolithic facies of DU3. The sand beds often show iron staining near their bases. Locally, entire 30 centimetre beds are sideritized for up to 20 metres laterally (Fig. 4.7D). Bedding planes typically dip gently (less than 5°), but dips between 5-10° may be present locally (Table 4.1). Overall, DU3 extends laterally for at least 200 metres, and shows evidence of slumping toward the south until it becomes obscured by cover. Toward the south, DU3 incises into and inter-fingers with the sand comprising DU1 (Fig. 4.7C).

Interpretation

The heterolithic facies comprising DU3 displays several sedimentological features consistent with deposition in an overbank environment flanking a fluvial channel. Rhyth-

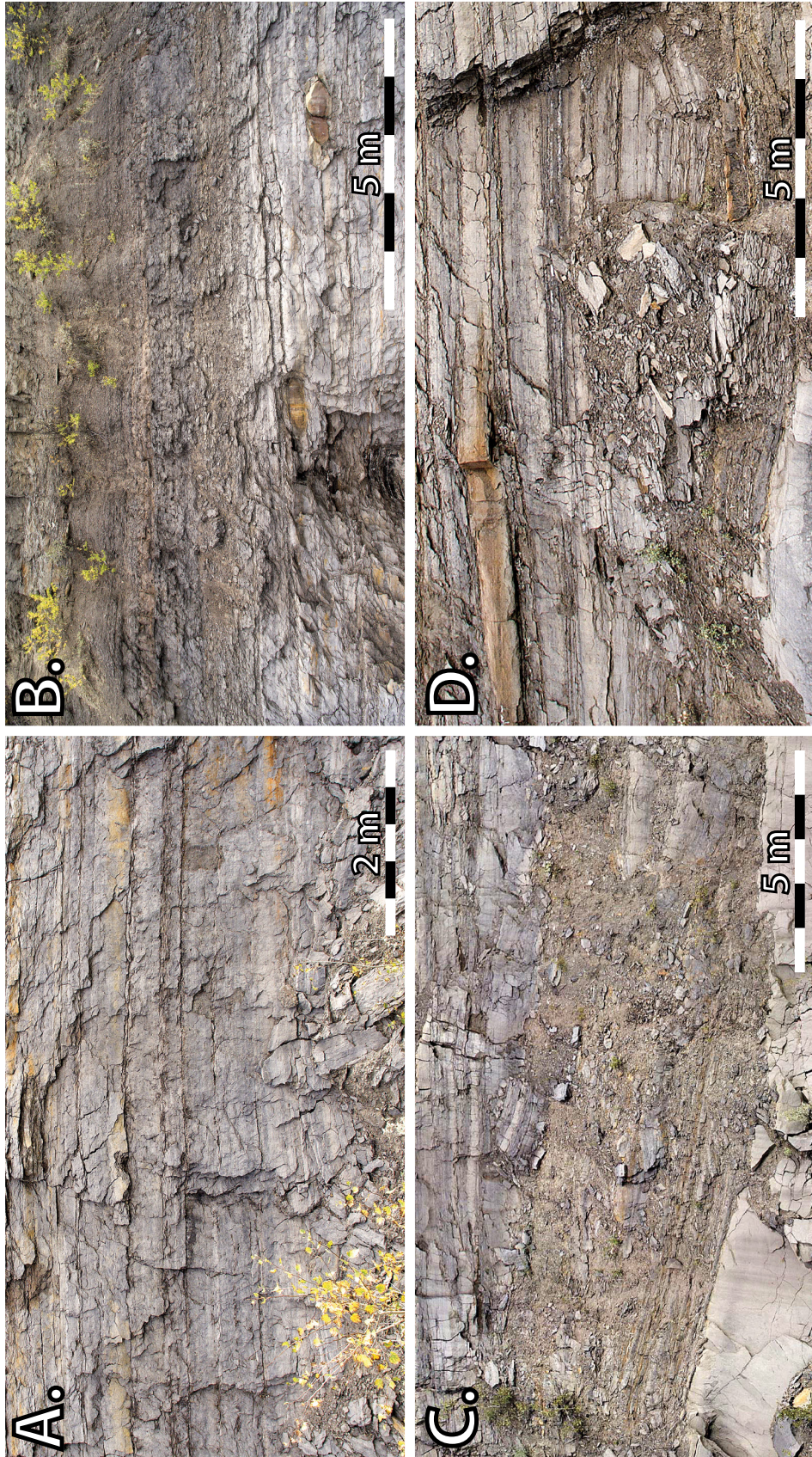


Figure 4.7: Facies plate showing the sedimentology of DU3. DU3 consists of decimetre-scale, current and climbing current rippled sandstone rhythmically interbedded with centimetre-scale silt beds. Large sideritized nodules (B) and laterally extensive sideritized sand beds (D) are common throughout DU3.

mically bedded sand and mud couplets consisting of decimetre-scale sand beds and centimetre-scale mud beds are consistent with individual river flood deposits on levees (Miall, 1996). Rising- and waning-stage deposits are reflected as individual rhythmites on the levee (Fielding, 1986; Farrell, 1987; Brierley *et al.* 1997). Within the sand beds, the presence of sharp-based current ripples and climbing ripples suggest deposition in a high-energy setting with abundant sediment supply, such as a sheet flood during the river flood stage. These sedimentary structures are commonly associated with levee deposits (*e.g.* Reineck and Singh, 1980; Tyler and Ethridge, 1983; Fielding *et al.* 1993; Brierley *et al.* 1997). Notably, due to the lack of bioturbation and presence of well-developed rhythmites, the levee was likely proximal to the fluvial channel (Farrell, 1987). A potential chute channel is observed at the base of DU3 (Fig. 4.7C), but the fill is mainly obscured so this could not be interpreted confidently.

Considering that levees are subjected to repeated wetting and drying cycles, oxidation is common within these deposits (Galloway and Hobday, 1983). As such, many authors have observed siderite nodules in association with levee deposits in the rock record (*e.g.* Ethridge *et al.* 1981; Flores, 1981; Fielding, 1986; Fielding *et al.* 1993). Furthermore, the gently-dipping bedding within the heterolithic facies is consistent with the geometry of levee deposits studied by Bown and Kraus (1987) and Fielding *et al.* (1993). These authors suggest the dip of levee-associated bedding is anywhere from 2-5°, although up to 10° dips are possible.

DEPOSITIONAL UNIT 4: FLUVIAL COUNTER POINT-BAR

Description

Depositional unit 4 (DU4) is similar sedimentologically to DU2. It incises into DU2 in the central region of the outcrop, and completely erodes older McMurray strata toward the south until it unconformably overlies and downlaps on the Waterways Formation. Internal stratigraphic surfaces within DU4 can be traced laterally for hundreds of metres. Overall, DU4 thickens from a zero edge in the central region of the outcrop to 30 metres at the south-

ern end. The thickening trend corresponds to the progressive southward thinning of the underlying DU2.

Exposed DU4 strata can be differentiated into two facies: a lowermost sand-dominated facies and an upper heterolithic facies. Importantly, these two facies are observed to interdigitate with one another over the span of 50-100 metres (Fig. 4.8A). The sand-dominated facies is fine-grained and contains low angle planar tabular cross-bedding, planar bedding, and current ripples (Fig. 4.8B). Similar to DU2, organic detritus and coal fragments are common throughout the sand facies. Bedding in the sand facies is typically on a decimetre-scale, thinning to centimetre-scale, current-rippled beds upward. Master bedding accretion is dominantly oriented west to southwest within the sand unit (Table 4.1). No palaeocurrent data is collected from the outcrop model of DU4 due to the lack of visibly dipping dune foresets and the lack of relief along the dunes where visible.

The heterolithic facies above consists of inclined, interbedded sand and silt beds (Figs. 4.8C and 4.8D). The sand beds are fine- to very fine-grained, current rippled, and range in thickness from 1-20 centimetres. Occasionally, planar bedding is observed in the sandy beds. Silty interbeds are typically 1-5 centimetres thick, and commonly contain organic detritus. Siderite nodules and sideritized beds are common. The master bedding within the heterolithic facies follows a similar trend to the underlying sand facies: accretionary surfaces of beds are oriented southwest to west.

Interpretation

The upward transition from sand-dominated low angle cross-bedding and planar bedding to heterolithic current rippled sand interbedded with silt represents an overall decrease in depositional energy levels upward (Allen, 1970; Walker and Cant, 1982). The presence of organic detritus and coal fragments throughout the entire depositional unit suggests sediment

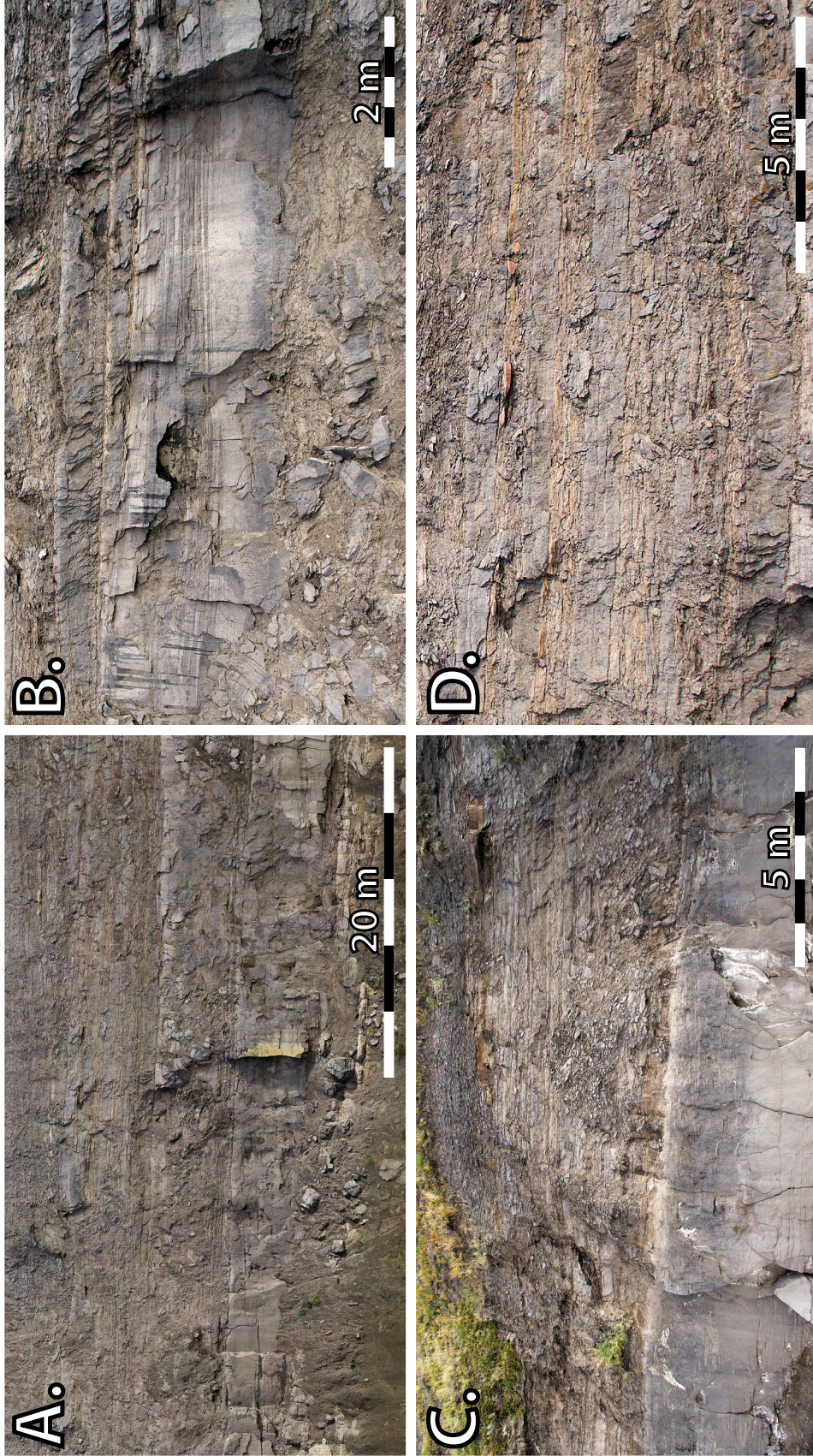


Figure 4.8: Facies plate showing the sedimentology of DU4. **A)** The interfingering relationship between cross- and planar-bedded sand and the overlying IHS. **B)** Cross- and planar-bedded sand sharply overlain by IHS strata. **C)** Planar-bedded sand sharply overlain by IHS with large sideritized beds common throughout. **D)** Fluviially-dominated IHS. Note the relative thickness of sand beds (decimetre-scale) in comparison to mud beds (centimetre-scale), in addition of the lack of bioturbation and abundance of sideritized sand beds.

is sourced from a continental setting. Consistent with the older DU2, the lack of bioturbation and lack of tidal indicators place DU4 in a freshwater, fluvial environment. Despite the lack of palaeocurrent data obtained from the 3D outcrop model, evidence such as the unidirectional depositional dip direction of the heterolithic beds is consistent with sedimentation on a point-bar (e.g. De Mowbray, 1983; Thomas *et al.* 1987; Miall, 1996; Strobl *et al.* 1997). Coupled with the unequivocal evidence of interdigitating between the lowermost sand and overlying heterolithic facies in DU4, this unit is interpreted as a fluvial point-bar with preserved lower (sand facies) and upper point-bar (inclined heterolithic facies) deposits. The abundance of silty IHS deposits, organic detritus, and planar laminae observed in DU4 conform to counter point-bar lithofacies (Smith *et al.* 2009), and therefore it is likely that the unit as a whole represents a counter point-bar deposit accreting toward the southwest.

DEPOSITIONAL UNIT 5: BRACKISH-WATER ASSOCIATED PRODELTA

Description

Depositional unit 5 (DU5) is a 10 metre thick, horizontally-bedded unit that is laterally extensive across the entire extent of the Crooked Rapids outcrop exposure. It overlies DU3, DU2, and DU4 in the northern, central, and southern regions of the outcrop, respectively. Notably, the horizontal beds truncate the underlying DU2-DU4 deposits, as evidenced by the angular disconformity observed in the central and southern regions of the outcrop. This unit is composed of fine-grained sandy siltstone near the base, and coarsens upward into a silty sandstone. Sand beds are typically 5-10 centimetres thick, separated by 1-3 centimetre silt beds. Centimetre-scale cross-bedding is apparent in the sand beds. Due to the high silt content in DU5, much of the unit is covered by scree. Despite this, bioturbation is observed throughout DU5, with bioturbation index ranging from 1-3. The most common trace fossils in the unit are *Cylindrichnus*. Locally, small siderite nodules are scattered throughout the upper three metres of DU5.

Interpretation

The most notable difference between DU5 and the older DU1-DU4 strata is the presence of pervasive bioturbation and horizontally-bedded strata in DU5. Notably, DU5 contains a monospecific assemblage of *Cylindrichnus*, suggesting these strata were likely deposited under stressed conditions in the presence of brackish water (e.g. Pemberton *et al.* 1982; Gingras *et al.* 2016). As such, the base of the unit represents a significant flooding surface, separating continental fluvial deposits from marginal marine strata above. Past workers have interpreted similar deposits as mixed wave/fluvial influenced bayhead deltas in a partially closed brackish seaway (Caplan and Ranger, 2001).

DEPOSITIONAL UNIT 6: MARINE-ASSOCIATED SHOREFACE

Description

Similar to DU5, Depositional Unit 6 (DU6) is an 8 metre thick, horizontally-bedded unit extending across the entire outcrop face. DU6 is composed of fine- and very fine-grained sand interbedded with mud near the base, with an overall increase in sand content upward. Sand beds are 5-15 centimetres thick, with 1-3 centimetre wavy mud interbeds. Low angle cross-beds, oscillation ripples, and planar bedding are common within sand beds. Bioturbation is abundant throughout the entire unit, with bioturbation indices between 1-4. Trace fossils within DU6 include *Conichnus*, *Ophiomorpha*, and *Cylindrichnus*. Toward the top of the unit, small depositional cycles on the order of 1-2 metres thick are apparent, with a transition from cross-bedding at the base of the cycle, to oscillation rippled sand and planar bedded sand at the top of each cycle. No bed orientation data is collected from DU6 since the bedding is discontinuous and the outcrop face lacks relief in this unit.

Interpretation

Based on sedimentological and ichnological features observed in DU6, this unit is highly influenced by marine depositional processes. Oscillation ripples are abundant through-

out many of the sand beds, suggesting wave modulation. DU6 is the only unit at the Crooked Rapids outcrop that displays pervasive bioturbation consistent with deposition in brackish to stressed marine waters. The ichnological assemblage is more diverse than the underlying DU5, containing *Conichnus*, *Cylindrichnus*, and *Ophiomorpha*. Of note, *Conichnus* is a trace fossil found only in water with marine salinities since the tracemaker is considered to be a sea anemone (Frey and Howard, 1981), and these organisms are generally intolerant of reduced salinity conditions (Davison and MacEachern, 2009; Ranger and Gingras, 2010).

4.5 DISCUSSION

DEPOSITIONAL HISTORY OF THE CROOKED RAPIDS OUTCROP

The depositional history of the Crooked Rapids outcrop can be broken down into two separate events of point-bar deposition. Point-bar 1 (PB1) consists of DU1-DU3. Together these strata represent a complete point-bar succession from channel (DU1) to lateral accretion (DU2) and levee (DU3) architectural elements. Based on the gentle variance of bedding dip direction laterally from 43 degrees in the north to 109 degrees in the south, the scrolls of an eastward-accreting point-bar can be reconstructed in plan-view (Fig. 4.9A). Based on Figure 4.9, the width of the original meander loop can be reasonably estimated to be at least one kilometre based on these data. Unlike many McMurray Formation point-bar deposits, PB1 at Crooked Rapids is predominantly sand and completely devoid of bioturbation, similar to the fluvial reaches of the Fraser River (La Croix and Dashtgard, 2015). Importantly, these authors show that heterolithic bedding (*i.e.* flaser, wavy, and lenticular bedding) is only observed in the brackish-water reaches of the lower Fraser River, whereas mud deposition is absent in the freshwater reach of the river. Point-bar 1 is ultimately capped by levee deposits (DU3) associated with the banks of the fluvial channel. The lack of an observable mud plug or deposits consistent with channel abandonment (*i.e.* evidence of waning flow; Toonen *et al.* 2012) suggest that the point-bar continued expanding laterally eastward away from the

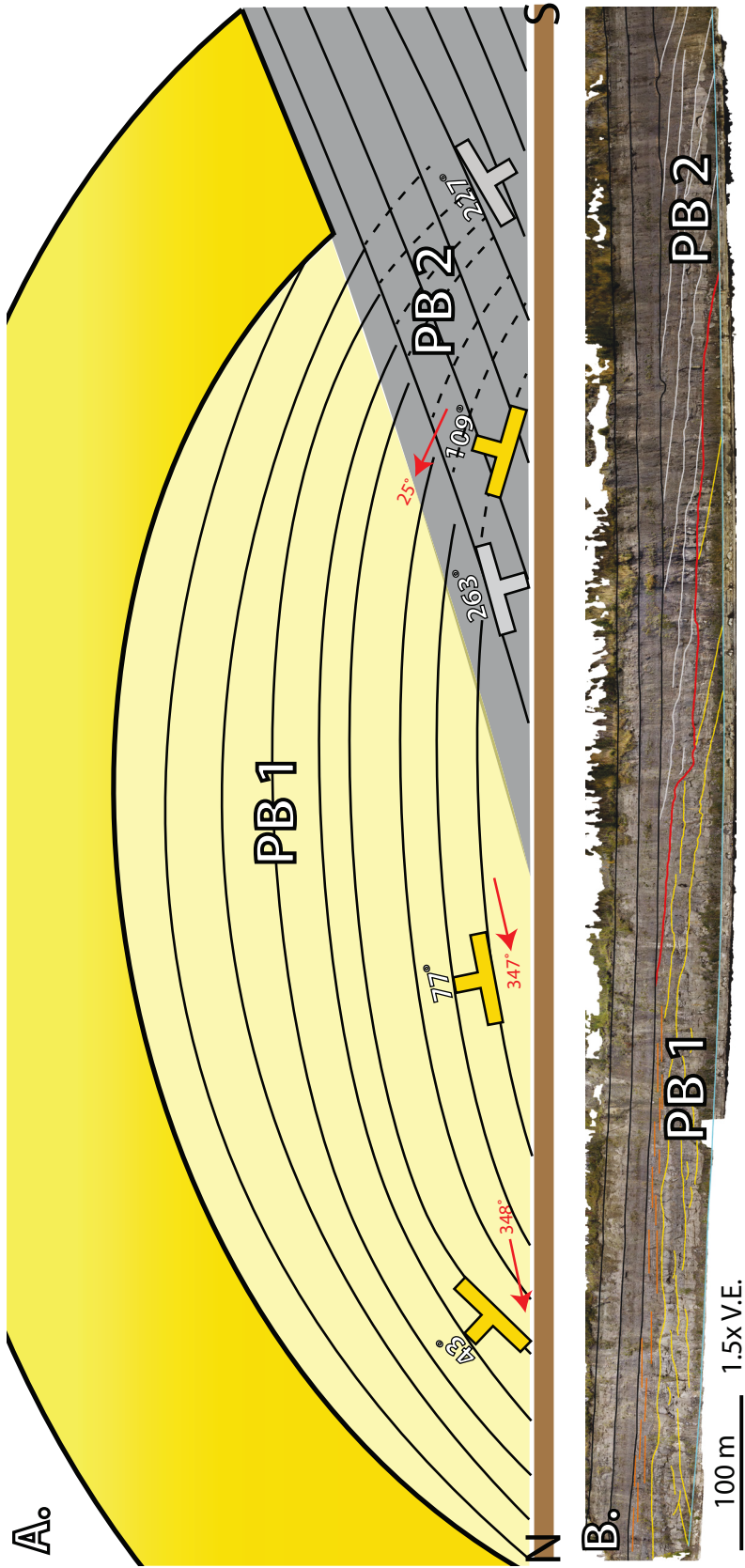


Figure 4.9: Depositional model for the Crooked Rapids outcrop. **A)** Plan-view interpretation of the Crooked Rapids outcrop. Point-bar 1 (PB1) accretes towards the east, with master bedding surfaces evolving laterally along the outcrop from an average dip direction of 43° (n=32) in the north, to 77° (n=18) in the central and 109° (n=27) in the southern regions of the outcrop. Red arrows indicate the approximate palaeocurrent orientation at the marked location along the outcrop face in PB1 strata. Average palaeocurrent orientation changes laterally from 348° (n=49) in the north, to 347° (n=25) in the central and 25° (n=12) in the southern regions of the outcrop. Note the oblique relationship between master bedding and palaeocurrent in the north (average divergence of 55°) when compared to the orthogonal relationship observed in the central (average divergence of 90°) and southern (average divergence of 84°) regions of PB1. Point-bar 2 (PB2) is shaded grey, with accretion surfaces oriented 263° in the central region of the outcrop and 227° toward the south. **B)** Interpretation of the outcrop annotated on the orthomosaic of the 3D model. The red line marks the erosion surface between the interpreted point-bars. Note the apparent dip of both PB1 and PB2 is toward the south, despite the ~180° difference in bedding orientation as shown in Figure 4.9A. Refer to the Appendix for a larger outcrop mosaic.

outcrop prior to the eventual abandonment of the meander loop.

Continued migration of the fluvial channel in the meander belt led to a shift in the channel trajectory, where a younger channel ultimately truncated the strata of PB1 at the southern end of the outcrop. The younger channel deposits consisting solely of DU4 strata are interpreted as the deposition of a second point-bar (PB2) for several reasons: 1) there is a stark difference in the direction of point-bar accretion, where PB1 accretes toward the east and PB2 accretes westward (Figs. 4.9 and 4.10); 2) PB2 has a much lower sand-mud ratio and is notably more heterolithic than PB1; and 3) PB2 lacks evidence for high energy flow conditions such as metre-scale trough and planar-tabular cross-bedding that are abundant in the deposits of PB1. It should also be noted that contemporaneous point-bar and counter point-bars belonging to the same meander loop will accrete in the same direction (Smith *et al.* 2009). Therefore, the most parsimonious interpretation of PB2 based on these observations is that it is composed of counter point-bar strata.

The exposed strata at the Crooked Rapids outcrop has previously been interpreted as the deposition of a single, southward-accreting point-bar that becomes progressively muddier toward the south until the eventual abandonment of the meander loop (Mossop and Flach, 1983). This is because bedding data show that the apparent dip of both PB1 and PB2 are oriented toward the south (Fig. 4.9B). Because of this, the contact between PB1 and PB2 is obscured in outcrop, and is difficult to identify without the accurate placement of bedding orientation measurements and careful sedimentological observation (Fig. 4.10). Similar relationships are observed in other examples of outcropping fluvial strata, and such contacts are typically interpreted as two genetically separate, but adjacent point-bar deposits sitting on opposite sides of a channel (Bridge *et al.* 2000; Donselaar and Overeem, 2008; Ghinassi *et al.* 2013).

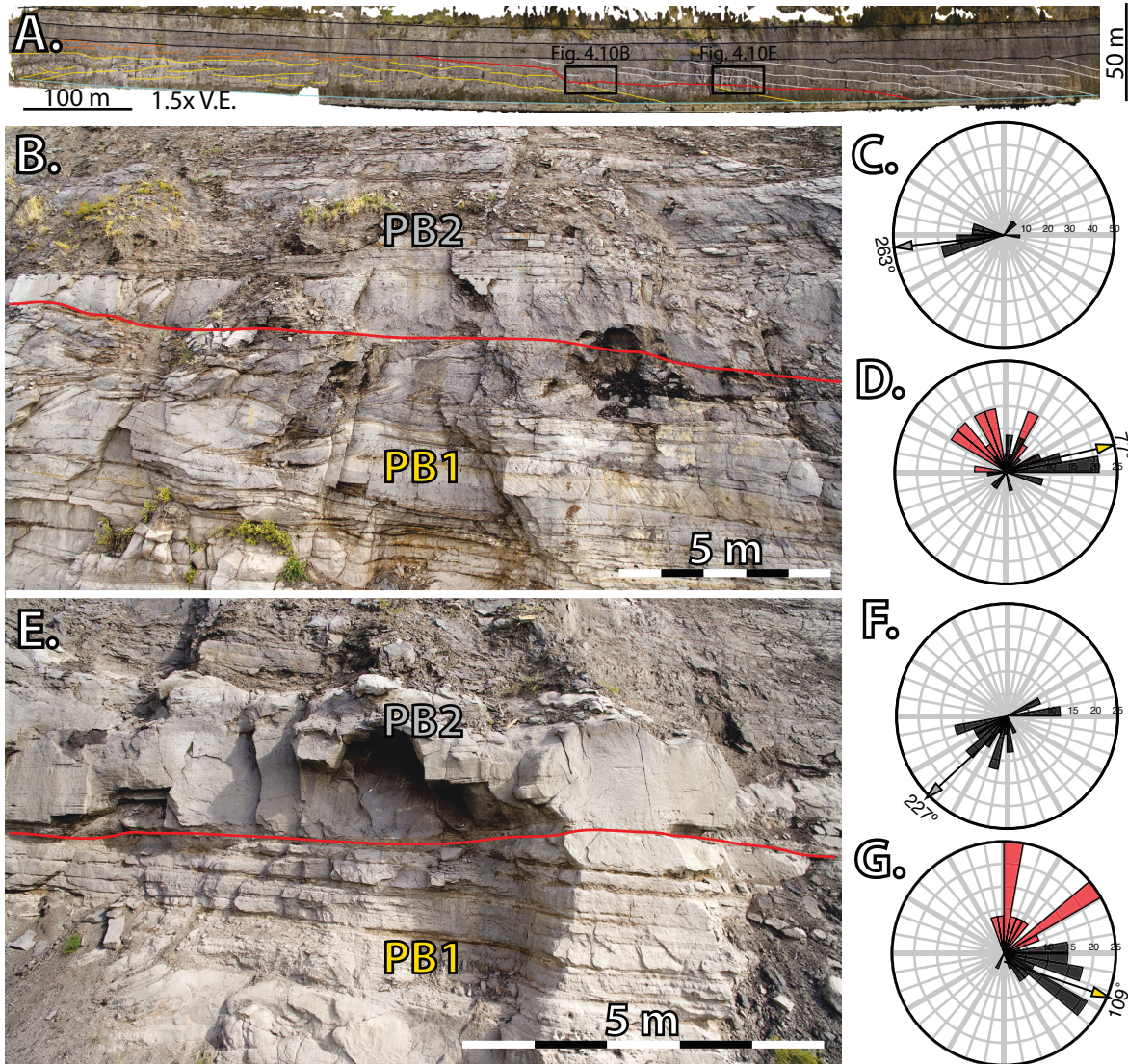


Figure 4.10: Images of the erosional contact between PB1 and PB2. **A)** Interpreted outcrop and location of the close-up images. **B)** Close-up image of the interpreted contact in the central region of the outcrop. Beneath the contact, deformed cross-beds are common, in addition to a minor sideritized lag at the contact. **C)** Rose diagram for the overlying PB2. Average accretion direction is 263° (n=14). **D)** Rose diagram for the underlying PB1. Average accretion direction is 77° (n=18). Black petals indicate master bedding orientation, and red petals indicate the palaeocurrent orientation. **E)** Close-up image of the contact toward the south. A change in apparent dip is evident between PB1 and PB2. **F)** Rose diagram for the overlying PB2, with the average master bedding orientation at 227° (n=26). **G)** Rose diagram for the underlying PB1, with master bedding oriented at 109° (n=27) on average. Black petals are master bedding orientations, and red petals are palaeocurrent. Rose diagrams are generated using Stereonet (© R.W. Allmendinger; Allmendinger *et al.* 2013; Cardozo and Allmendinger, 2013).

Another plausible interpretation is that the change in direction of point-bar migration may be significant within a single bar owing to internal discordant surfaces that can dramatically alter the accretion direction as a result of high-energy flooding events (Durkin *et al.* 2015). These authors show that a single point-bar can rotate up to 50° across the discordant surfaces. Over the lifespan of an actively accreting point-bar, this may lead to significant orientation differences between the initial deposition and final abandonment of a meander loop. Despite this, the most appropriate interpretation of the outcrop in this study is that it consists of two point-bar geobodies. Of note, if any highly discordant contacts were present in the Crooked Rapids outcrop, there would be a much more gradual shift from eastward-accreting (DU2; PB1) to south westward-accreting (DU4; PB2) strata (refer to the rose diagrams in Table 4.1). In all likelihood, intermediate stages of point-bar accretion toward the southeast and south would preclude a final west to southwestward accreting scroll pattern on a single bar. In the central region of the outcrop, the change in average bed orientation across the contact separating PB1 and PB2 is 186° (Figs. 4.10C and 4.10D). Therefore, we instead favour the two point-bar depositional model for the Crooked Rapids outcrop (Fig. 4.9).

Following the deposition of the two point-bars, the fluvial strata were transgressed and Depositional Units 5 and 6 were deposited above the meander belt deposits. As evidenced by robust ichnogenera including *Cylindrichnus*, *Conichnus*, *Ophiomorpha*, in addition to oscillation ripples, these units are consistent with deposition in a marine environment. Depositional Unit 5 represents a marginal marine Upper McMurray parasequence (sensu Caplan and Ranger, 2001), while DU6 is interpreted to be the Wabiskaw Member of the overlying Clearwater Formation.

SEDIMENTOLOGICAL AND ARCHITECTURAL COMPARISON TO OTHER FLUVIAL STRATA

The sedimentology and depositional architecture of fluvially dominated strata has been well-studied in modern (*e.g.* Farrell, 1987; Smith, 1987; Smith *et al.* 2009) and ancient

(e.g. Bridge *et al.* 2000; Donselaar and Overeem, 2008; Ghinassi *et al.* 2013; Ielpi and Ghinassi, 2014; Durkin *et al.* 2015) depositional systems. Early sedimentological facies models established that on a large-scale (*i.e.* entire point-bar scale) a fining-upward trend is characteristic of meandering fluvial deposits (Allen, 1970; Walker and Cant, 1982). In sand-dominated laterally-accreting meandering systems, the base of the channel and the lower point-bar is marked by large-scale trough cross-stratified sandstone with dunes oriented downstream or oblique to the flow direction. The overlying middle and upper point-bar successions are characterized by planar cross-stratified sandstone and IHS consisting of current-rippled sand and mud couplets. The overall upward decrease in grain-size, increase in mud abundance, and transition from high flow regime to low flow regime bedforms represents decreasing energy levels upward on the point-bars, which is likely associated with decreasing water depth. Sedimentation is terminated on the point-bar surface as the channel continues to migrate or avulse, with the top of the point-bar marked by palaeosols, rooted horizons, or sediments ascribed to overbank deposition such as levee or crevasse splay sandstone and mudstone. In this study, many of the facies recognized in each of the defined fluvial depositional units (DU1-DU4) are consistent with the fluvial facies model described above.

Recent studies of meandering fluvial successions (Donselaar and Overeem, 2008; Smith *et al.* 2009; Ghinassi *et al.* 2013; Ielpi and Ghinassi, 2014; Durkin *et al.* 2015; Wang and Bhattacharya, 2018) have focused more on the morphodynamical evolution of point-bar elements. Work by these authors, among others has shown that fluvial meander belts in outcrop and/or plan view may show symmetrical or asymmetrical expansion, rotation, downstream migration, or a combination of these processes related to point-bar growth. Importantly, these processes control sediment deposition on the point-bar, as well as the preservation potential of upstream, central, and downstream portions of the bar. All of these factors combine to complicate the upward-fining fluvial facies model described above (Allen, 1970; Walker and Cant, 1982). At the Crooked Rapids outcrop, the lack of a sufficient

three-dimensional and plan view of the strata hinder specific interpretations regarding the morphodynamics of the point-bars. However, when viewed laterally along the extent of the exposure, bedding dip and palaeocurrent remain more or less orthogonal to each other, which is diagnostic of laterally-accreting units (Fig. 4.9A) (Miall, 2010). Additionally, the presence of an interpreted counter point-bar (PB2) suggests there may be an element of downstream accretion influencing deposition of the strata at the outcrop. Other than these broad conclusions, there is insufficient evidence to interpret the morphodynamical evolution of the point-bars any further.

The thicknesses of the cross-beds in the outcrop (up to 2 metres thick, but typically 1-1.5 metres thick) can be used to estimate channel dimensions. Leclair and Bridge (2001) proposed a method whereby the mean dune height is approximately 2.9 times the mean cross-bed thickness, and that bankfull channel depths are 6-10 times the height of the dunes. In DU1, an average dune thickness of 1.5 metres yields an original dune height of 4.42 metres. This suggests that the channel depth is 26.5-44.2 metres thick (Bridge and Tye, 2000; Leclair and Bridge, 2001). Given the thickness of the exposed strata in DU1, and the presence of levee deposits overlying the sandy point-bar below, it is reasonable to assume that most of the bar has been preserved at this location. Including the levee deposits, the strata is approximately 23 metres thick, and therefore the channel depth is likely close to the lower end of the estimate at 26.5 metres. Furthermore, Ethridge and Schumm (1977) show that mean bankfull depth is approximately half of the maximum bankfull channel depth. Using this value, calculated to be 11.5 metres, the channel width can be estimated using an equation from Bridge and MacKey (1993). The result is a channel estimated to be 757 metres wide.

COMPARISON TO OTHER McMURRAY FORMATION OUTCROPS

The depositional architecture of the defined depositional units at the Crooked Rapids outcrop become significant when placed into the same context as other outcrops in the Mc-

Murray Formation. Importantly, Crooked Rapids is the only locale that shows widespread sedimentological, ichnological, and architectural evidence for fluvial deposition on a large scale. Despite the differences between estuarine and fluvial strata (*e.g.* Fig. 4.11), one common observation in both estuarine and fluvial McMurray outcrops is the presence of a decimetre- to metre-scale cross bedded sand unit overlain by an inclined heterolithic (IHS) unit. However, as discussed below, there are several ways to interpret this relationship at different outcrop locales.

Estuary Outcrops

The depositional origin of the basal cross-bedded sand units and the overlying IHS units at many McMurray Formation outcrops can be ascribed to specific sub-environments within an estuary. Early studies of the Steepbank #3 outcrops (*e.g.* Pemberton *et al.* 1982) placed the exposed strata in an estuary channel setting, whereby the cross-bedded sand represented thalweg to lower point-bar sandstones and the overlying IHS represented deposition on the middle and upper point-bar. A recent study of these outcrops by Hayes *et al.* (in press) interpreted the cross-bedded sand as a fluvially-dominated unit (based on the abundance of simple dunes, unimodal transport directions, and absence of bioturbation) abruptly overlain by a genetically separate IHS unit of estuarine origin owing to the presence of an ichnological assemblage consistent with brackish-water deposition (*i.e.* low diversity suites, suites containing marine-derived ichnogenera, and diminutive traces, among others; Pemberton *et al.* 1982; MacEachern and Gingras, 2007; Gingras *et al.* 2016) and the abundance of muddy interbeds, which are common elements of estuarine point-bar lithofacies models (Fig. 4.11A) (Smith, 1987; Allen, 1991; MacEachern *et al.* 2010). At the Amphitheatre outcrop, Wightman and Pemberton (1997) and Hayes *et al.* (in press) observed a brackish water ichnological assemblage and large-scale flow reversals in both the cross-bedded sand and IHS channel filling units, placing these geobodies in a middle estuary compound dune setting and an inner estuary channel fill environment, respectively. Finally, the Christina River outcrop

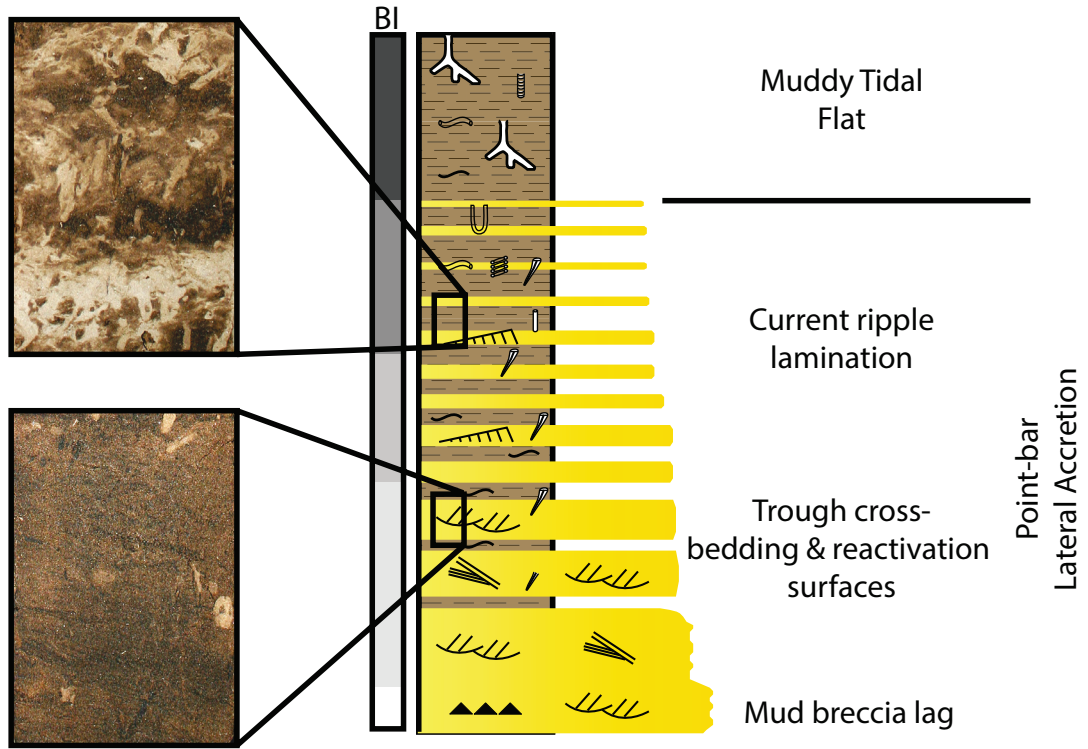
displays a monospecific assemblage of *Cylindrichnus* in the toesets of the cross-bedded sand and a semi-diurnal synodic tidal cyclicity within the dune foresets (Hayes *et al.* 2017). The described features at all of these outcrops are all emblematic of deposition in an estuarine setting, save for the sand dunes at the base of the Steepbank #3 outcrops which are fluvial in origin.

All of the estuarine outcrops listed above show a large-scale depositional architecture commonality that is not observed at Crooked Rapids. The contact between the discussed cross-bedded sand and overlying IHS units is sharp, abrupt, and locally erosional (Hayes *et al.* in press; Fig. 4.12B and 4.12C), representing a disconformity in most cases. The nature of this contact, as well as the drastic changes in depositional environments between the sand and IHS (*i.e.* fluvial sand overlain by estuarine IHS at the Steepbank #3 outcrops; middle estuary compound dunes incised into by an inner estuary IHS channel-fill succession at Amphitheatre) suggest that these two large-scale units are separate architectural elements at several outcrops interpreted to be estuarine in origin. This is significant – there is no inter-fingering of the cross-bedded sand and IHS observed at any outcrop exposure with estuarine IHS deposits, however, as discussed below, an interdigitating relationship is present at the fluvially dominated Crooked Rapids outcrop.

Fluvial Outcrop

Inclined Heterolithic Stratification in fluvial settings differs significantly from IHS in estuarine environments. Fluvial IHS forms sand-mud couplets as a result of two-stage sedimentation: 1) sand beds are deposited during times of high fluvial discharge, usually as bedload during seasonal flooding events; and 2) mud beds deposited during waning flow conditions, sourced from a silt-dominated, often organic rich suspended load (Sisulak and Dashtgard, 2012). Often times, the deposition and preservation of the silty waning-flow deposits may be dependent on the position of the point-bar in the fluvial-tidal transition zone

A.



B.

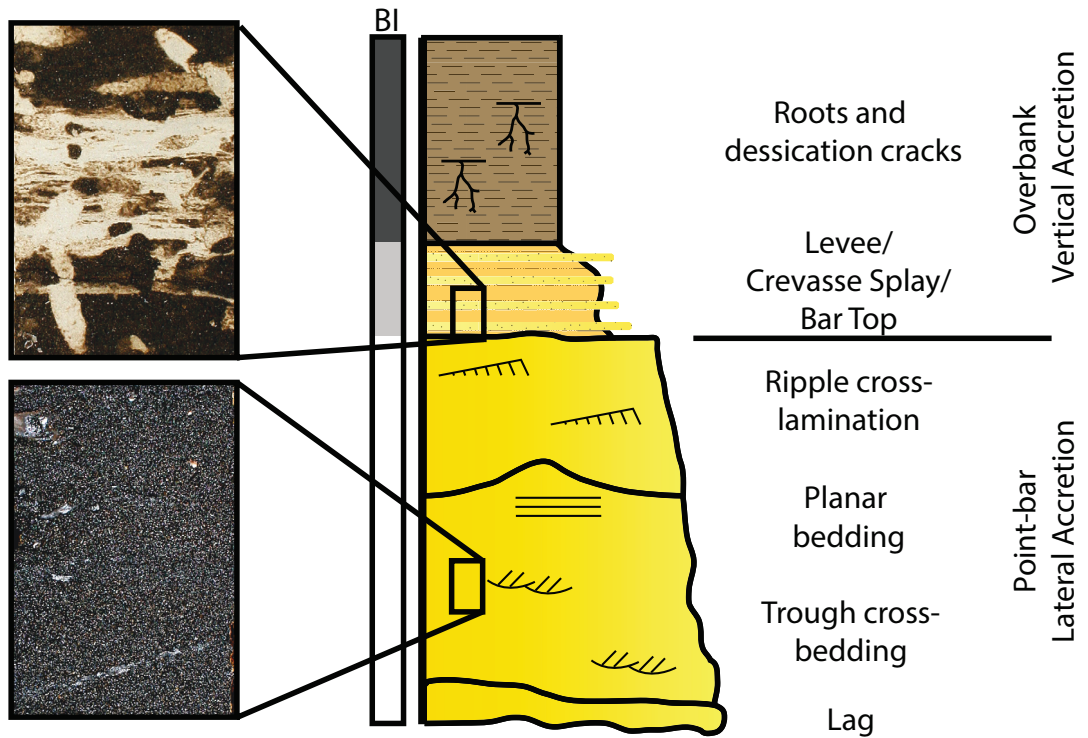


Figure 4.11 (previous page): Idealized vertical sections of estuarine and fluvial point-bar strata. All core photos shown are 7cm wide. **A)** Vertical estuarine point-bar succession after Smith (1987) and MacEachern *et al.* (2010). Sandy lateral accretion beds are characteristically thinner than fluvial lateral accretion deposits, and muddy strata is abundant throughout the bar. Bioturbation is dominated by a low-diversity assemblage in the channel (BI of 1-3) with an increase in BI upward. Core photos are from the 16-21-95-11W4 core. **B)** Vertical fluvial point-bar model after Allen (1970). Modified from Donselaar and Overeem, 2008. Note the abundance of sand in lateral accretion deposits, as well as the lack of bioturbation and fining-upward trend in channelized deposits. Bioturbation in overbank deposits may be variable, but consists of meniscate traces created by insects. Core photos are from the 13-22-95-11W4 well.

(La Croix and Dashtgard, 2015) or the energy level of the succeeding freshet phase. Because river discharge is the main driver of deposition in fluvial environments in contrast to both fluvial discharge and the extent of the tidal prism in estuarine environments (Letley *et al.* 2005a), seasonal flooding events in fluvially dominated settings are more destructive than in estuarine settings. This leads to the low preservation potential of silty IHS beds on fluvial point-bars (if deposited at all) (Fig. 4.11B) in comparison to estuarine point-bars (Fig. 4.11A), where mud still flocculates and is deposited at the position of the turbidity maximum during both high and low river discharge. In the freshwater reach of the Fraser River, La Croix and Dashtgard (2015) observe channel bars dominated by thick trough and planar cross-bedded sand beds with rare, very thin mud beds, similar to what is observed on the PB1 strata at Crooked Rapids.

From a depositional architecture point of view, the lateral and vertical relationship between cross-bedded sand and IHS at Crooked Rapids is stratigraphically significant within DU4. Notably, this is the only point-bar element that has both cross-bedded sand and IHS preserved, and these are interpreted to represent lower and upper point-bar environments, respectively. Based on bed orientation trends, the implication is that because both the sand and IHS within DU4 accrete west-southwest, they are genetically related and belong to the same counter point-bar (PB2). Extensive oblique dip-oriented sections of the outcrop show an inter-fingering relationship between the lower and upper point-bar units, providing unequivocal proof of this geometry (Fig. 4.12A). Past outcrop studies (*e.g.* Mossop and Flach,

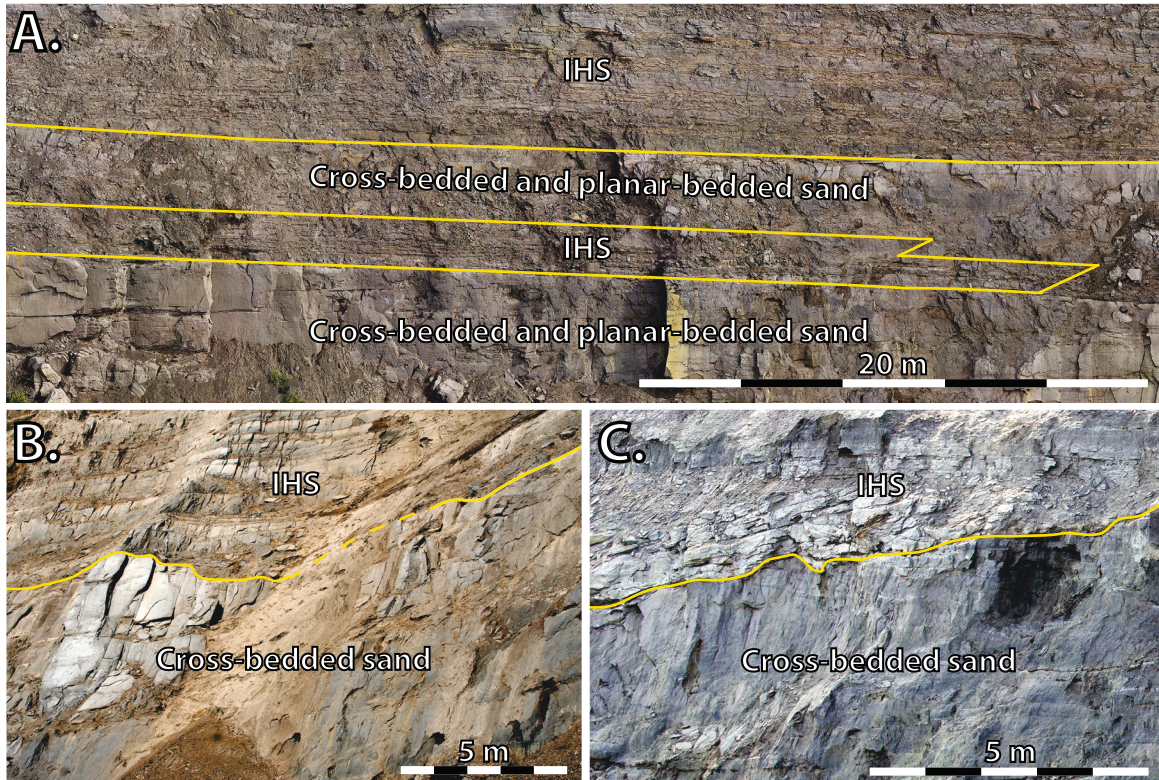


Figure 4.12: Comparison of the cross-bedded sand-IHS contact at the Crooked Rapids outcrop (A) to the Steepbank #3 outcrops (B) and Amphitheatre outcrop (C). An interdigitating relationship between the cross-bedded sand and IHS at the fluvial Crooked Rapids outcrop is apparent, and this relationship is not observed at other McMurray Formation outcrops interpreted to be estuarine in origin.

1983; Wightman and Pemberton, 1997; Strobl *et al.* 1997; Musial *et al.* 2012; Jablonski and Dalrymple, 2016) on the McMurray Formation have interpreted a similar architectural relationship between cross-bedded sand and IHS geobodies, despite the lack of observable evidence of inter-fingering at the studied outcrops (Figs. 4.12B and 4.12C) (Hayes *et al.* in press).

Ichnologically, the laterally accreting strata (IHS) is completely devoid of bioturbation at Crooked Rapids, which is a significant component of laterally-accreting geobodies exposed at other outcrops as discussed above. The notable absence of ichnofauna at Crooked Rapids can be explained in two ways: 1) the IHS was deposited below the water line on a fluvial point-bar landward of the salt wedge and tidal limit; or 2) the IHS was subjected to extreme conditions such as a salinity stress or unstable substrates in a brackish-water envi-

ronment, both of which may inhibit colonization of the sediment or erode existing traces. Because high bioturbation intensities in IHS associated with brackish-water conditions are ubiquitous at all other McMurray Formation outcrops, the latter interpretation here is unlikely. Sedimentologically, the presence of abundant organic detritus and coal fragments, although not unequivocal evidence of deposition in fluvial environments, still suggests higher riverine input in the IHS at Crooked Rapids when contrasted with the IHS in other outcrops. In addition, the presence of overbank levee deposits and the lack of sedimentary structures commonly observed in tidally influenced environments such as metre-scale flow reversals, double mud drapes, and reactivation surfaces adds credibility to a fluvial interpretation.

The ichnology of meandering rivers is not as well studied as the sedimentological aspects of these systems, however, bioturbation intensities in the fluvial reaches of modern estuaries are very low and often absent in subtidal and intertidal point-bar units (Hauck *et al.* 2009; La Croix *et al.* 2015; Shchepetkina *et al.* 2016b; Shchepetkina *et al.* 2016c). Importantly, much of the bioturbation in fluvial systems occurs on channel margins and in overbank environments rather than in the channel, with insects producing meniscate ichnogenera such as *Taenidium*, *Naktodemasis*, *Scoyenia*, or *Beaconites* (Gingras *et al.* 2016). The types of traces preserved in these environments depend on a number of factors including frequency of inundation, water table level, and the nature of biota present (Hasiotis, 2002; Hasiotis, 2007), which contrasts with in-channel stresses such as high energy flow conditions, unstable substrates, and brackish-water incursion. In addition to this, Gingras *et al.* (2016) note that burrows below the water line in fluvial settings are rare. As such, from an ichnological standpoint, the lack of bioturbation in the IHS at the Crooked Rapids outcrop may be explained by deposition on a fluvial point-bar below the water line. Combining the ichnological reasoning with the sedimentological observations at the outcrop, placing the Crooked Rapids outcrop in a purely fluvial depositional environment is the best interpretation of the strata.

4.6 CONCLUSION

This study investigates the sedimentology, ichnology, and depositional architecture of a number of depositional units interpreted to be fluvial in origin at the Crooked Rapids outcrop using an unmanned aerial vehicle and Structure-from-Motion photogrammetry. In particular, each Depositional Unit (DU) is ascribed to either channel, lateral accretion, or levee fluvial architectural elements according to the classification scheme by Miall (1996). Sedimentologically, the strata at the Crooked Rapids outcrop conform to fluvial facies models: a fining-upward sediment profile with energy levels decreasing upward as evidenced by the transition from thickly-bedded trough to planar tabular cross-beds to thinly-bedded planar beds and rippled sand upward. Within the preserved strata, the amalgamation of sand beds (and therefore the lack of mud beds), abundance of organic detritus in dune foresets and bottomsets, coal debris, and laterally extensive sideritized beds (for tens of metres) all point toward deposition in a fluvially dominated environment. Combined with the lack of a discernable tidal influence and complete absence of bioturbation emblematic of deposition in brackish water (which is pervasive at all other McMurray Formation outcrops), Crooked Rapids as a whole is interpreted to be positioned much further paleo-landward than all other McMurray Formation outcrops in published literature.

On a large-scale, the Crooked Rapids outcrop is similar lithologically to other outcrops in the McMurray Formation - the base of the preserved strata is a cross-bedded sand unit that is overlain by inclined heterolithic stratal (IHS) units. The interpretation of data collected from the 3D outcrop model in this study leads to two main conclusions: 1) the outcrop is characterized by a kilometre-scale, eastward accreting, dominantly sandy lateral accretion point-bar (PB1) that is truncated by a younger, southwest accreting counter point-bar (PB2); and 2) an inter-digitating relationship between cross-bedded sand and IHS units belonging to PB2, combined with a consistent bedding dip toward the southwest shows an architectural

relationship not observed at any other McMurray Formation outcrop. Importantly, this geometry provides unequivocal evidence that both the cross-bedded sand and IHS are genetically related to deposition on the same point-bar, an interpretation that can not be applied to many estuarine outcrops including the Steepbank #3, Amphitheatre, and Christina River outcrops, among others.

Overall, this study provides clarity in the recent debate among researchers regarding the physiographic location of McMurray point-bars in a fluvial-tidal transition zone. Most notably, a fluvial baseline for McMurray Formation outcrops is established, and therefore fluvially dominated deposits in subsurface reservoirs should conform to the sedimentological (and lack of ichnological) observations made at the Crooked Rapids outcrop. For a point-bar to be interpreted as fluvial in the McMurray, the following observations should be noted: 1) the point-bar is overwhelmingly sandy with very insignificant silty interbeds (if at all present); and 2) the entire point-bar deposit (both sand and mud lithosomes) is devoid of bioturbation until the bar-top, overbank strata is encountered, after which any bioturbation is considered to be continental. Given the overall rarity of these observations in the McMurray Formation, the preserved point-bars are dominantly estuarine – however, estuarine and fluvial point-bars do coexist in McMurray strata.

CHAPTER FIVE: CONCLUSION

The inherent depositional complexity within the Aptian-aged McMurray Formation makes correlation between wells only hundreds of metres apart problematic (*e.g.* Ranger and Pemberton, 1997). As a result, the interpretation of the depositional history of the McMurray Formation has often times been oversimplified. Specifically, many workers still interpret all occurrences of cross-bedded sand overlain by Inclined Heterolithic Stratification (IHS) to represent single, 35-40 metre thick point-bars in outcrop and the subsurface, despite observations by a handful of researchers that have interpreted a regional discontinuity between the dune sand and IHS in outcrop (*e.g.* Ranger *et al.* 2008; Ranger and Gingras, 2010; Hayes *et al.* in press). Indeed, laterally-accreting point-bar geobodies are relatively widespread throughout the McMurray Formation, but they are not ubiquitous. Broadly speaking, the research in this dissertation expands on the recognized regional discontinuity in outcrop, while still identifying and interpreting large-scale point-bars whenever the geological observations suffice. Coupled with the recent debate amongst researchers regarding the physiographic location of point-bar strata in tidal-fluvial channels, the working hypothesis for the depositional architecture and stratigraphy of the McMurray Formation has never been so contested.

Specific to the McMurray Formation itself, the contributions of this research to McMurray workers are simple: at least three important reservoir-quality geobodies are present in the McMurray Formation, and these are not only constrained to channel thalweg or lower point-bar sand. Beginning with Chapter 2, the metre-scale sand dunes along the Christina River are placed in a tidally-dominated depositional environment by way of a strong semi-diurnal, synodic cyclicity recognized by analyzing the foreset thickness variations in the dunes. A similar reservoir-quality sand body is interpreted at the Amphitheatre outcrop in Chapter 3, whereby metre-scale flow reversals, the tendency for sediment transport to be oriented parallel to master bedding, and a low-diversity ichnological assemblage consistent with depo-

sition in brackish-water strongly suggest deposition in a middle estuary, compound dune environment. When these sand units are contrasted with the basal dune sand at the Steepbank #3 outcrops (as described in Chapter 3) or the Crooked Rapids outcrop in Chapter 4, both interpreted to be fluvial, it becomes clear that the depositional origin of cross-bedded sand geobodies may vary significantly in the McMurray Formation. Architecturally, the interpreted fluvial cross-bedded sand bodies show no preferred direction of accretion, a more-or-less unimodal sediment transport direction, and are devoid of bioturbation and sedimentary structures that commonly indicate the presence of tides. Importantly, each of these described sand units, whether they are estuarine or fluvial, may reach thicknesses of upwards of 15-20 metres, thereby representing significant reservoir units in the subsurface.

In a stratigraphic context, the 3D outcrop models provide insight into not only the architectural differences between the dune sand and overlying IHS, but also the large-scale relationship between these two genetic units. At the Steepbank #3 outcrops studied in Chapter 3, a sharp, abrupt contact between the fluvial dune sand and estuarine IHS is clearly visible on 3D models and orthomosaics. A similar contact is recognized at the Amphitheatre outcrop, where an interpreted inner estuary IHS-filled channel incises into a middle estuary compound dune complex. Across these contacts, an abrupt decrease in grain size is apparent, in addition to pervasively bioturbated IHS overlying unbioturbated (Steepbank #3) fluvial sand or sparsely bioturbated (Amphitheatre) estuarine sand. Given the sedimentological, ichnological, and architectural differences between the cross-bedded strata and overlying IHS at these outcrops, it is feasible to suggest that the contacts between the units at both outcrop locations are disconformable, and therefore may represent important stratigraphic surfaces. In contrast, the nature of the observed contact at the fluvial Crooked Rapids outcrop, studied in Chapter 4, presents a different story. Most notably, there is an interdigitating relationship between the cross-bedded sand and IHS facies at the outcrop. Coupled with consistently southwestward accreting bedding data in both the sand and IHS facies obtained from the 3D model, the

interfingering relationship between the dune sand and IHS show unequivocal evidence that together, the two units are genetically related, and therefore are deposited on the same fluvial point-bar.

The successful application of 3D photogrammetry techniques for outcrop analysis employed in this thesis should become a common practice moving forward in field geology. If the expense of a LiDAR-based 3D modelling approach in comparison to a UAV-based approach is ignored, the main limitation in prior outcrop studies is the lack of high-resolution textured outcrop models for bedding contacts to be traced laterally. To combat this, often times low-resolution photomosaics created from images captured during a helicopter fly-by of the outcrop were used for an outcrop-scale view, but the resolution is not sufficient to trace bedding, identify subtle facies contacts, or investigate important features preserved in the outcrop such as scouring or slumping. The value in having a high-resolution view orthogonal to an outcrop face at any location cannot be understated: not only is bias from perspective distortion removed, but the view of the outcrop is comparable to capturing an image with a camera while logging the outcrop at a specific location. By supplementing traditional logging methods in the field with 3D photogrammetry techniques, a more robust interpretation of the large-scale depositional processes can be applied to the exposed strata at a fraction of the cost of a LiDAR-based approach.

Not only have the 3D photogrammetry outcrop models been proven useful for centimetre-scale outcrop resolution, but they also provide a means of acquiring bed orientation and palaeocurrent data with extreme precision. Using the Steepbank 3B outcrop in Chapter 3 as an example (Fig. 3.8C), the subdivision of stacked, smaller scale point-bars in the IHS is accomplished using the 3D models based on: 1) identification of large-scale cross-cutting or incising relationships; 2) visual analysis of sand-bed thickness trends within the IHS; or 3) the IHS bed orientation data indicates subtle variations in the average bed dip direction

between LAS B1, LAS B2, LAS B3, and LAS B4. Recognition of these subtle changes in bed orientation among stacked lateral accretion sets is made possible only by using 3D models to acquire the data, since the acquired data is much more accurate than data from a compass in the field. This is because: 1) bedding surfaces are traced laterally instead of acquiring orientations from a point along a section; 2) more 3D relief along the face of the outcrop is used to fit a plane to the placed data points, thereby increasing the accuracy of the orientation of the plane; and 3) acquiring a bedding measurement in the field while abseiling the outcrop introduces an order of uncertainty to the dataset. When coupled with sedimentological and ichnological descriptions acquired by logging the outcrop, an interpretation of stacked, smaller scale point-bars rather than a single, 30 metre thick point-bar can be made with ample evidence to do so.

Collectively, the three studies presented in this thesis use 3D outcrop models as an additional tool to characterize a number of McMurray Formation outcrops in both fluvial and tidal depositional environments. The sedimentological complexity of rivers, estuaries, and the brackish- to fresh-water transition zone, along with its limited lateral extent in modern studies (approximately 10 kilometres at the Ogeechee River estuary (Shchepetkina *et al.* 2016b), 20 kilometres in the Fraser River, and 7 kilometres at Kouchibouguac National Park (La Croix *et al.* 2015)) makes the interpretation of ancient tidal-fluvial deposits increasingly difficult. Additionally, autogenic processes such as sea level fluctuations during the Aptian and allogenic processes such as the interplay between deposition and preservation of point-bars in meander belt systems (*e.g.* Durkin *et al.* 2017) add to the complexity of the spatial distribution of fluvial and estuarine deposits in the rock record, compounding the issue. By using very precise bed orientation data in conjunction with sedimentology and ichnology, geobodies that are both genetically related and genetically unrelated to each other are quickly and efficiently interpreted, which provides clarity into the scale and origin of deposition in a physiographic sense. In turn, this increases our overall knowledge and understanding of the

complex transition from fluvial to estuarine deposition in the rock record, particularly when sea level fluctuates.

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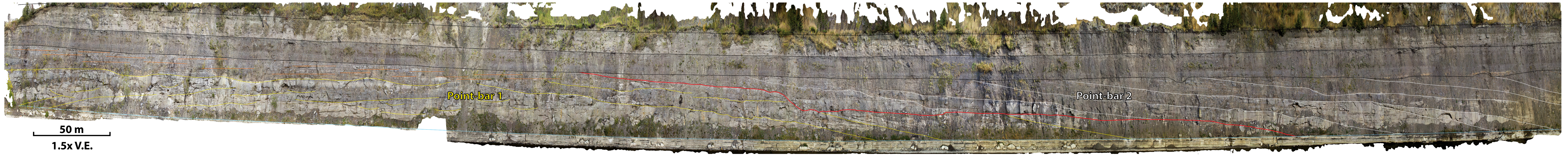
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APPENDIX



Point-bar 1

Point-bar 2

50 m
1.5x V.E.

Crooked Rapids outcrop as shown in Figure 4.9B (previous page): Interpretation of the outcrop annotated on the orthomosaic of the 3D model. The red line marks the erosion surface between the interpreted point-bars. Note the apparent dip of both PB1 and PB2 is toward the south, despite the $\sim 180^\circ$ difference in bedding orientation as shown in Figure 4.9A (link).