Integrated Ichnology and Sedimentology of Mixed River- and Wave-Influenced Delta Complexes, Upper Cretaceous Basal Belly River Formation, Central Alberta, Canada

by

Brittan M. Jones
B.Sc. (Hons.), Brandon University, 2008

Thesis Submitted In Partial Fulfillment of the Requirements for the Degree of Master of Science

in the Department of Earth Sciences Faculty of Science

© Brittan M. Jones 2013

SIMON FRASER UNIVERSITY

Summer 2013

All rights reserved. However, in accordance with the Copyright Act of Canada, this work may be reproduced, without authorization, under the conditions for “Fair Dealing.” Therefore, limited reproduction of this work for the purposes of private study, research, criticism, review and news reporting is likely to be in accordance with the law, particularly if cited appropriately.
Approval

Name: Brittan M. Jones
Degree: Master of Science (Earth Sciences)
Title of Thesis: Integrated Ichnology and Sedimentology of Mixed River- and Wave-Influenced Delta Complexes, Upper Cretaceous Basal Belly River Formation, Central Alberta, Canada

Examining Committee: Chair: Dr. Dan Gibson
Associate Professor

Dr. James MacEachern
Senior Supervisor
Professor

Dr. Shahin Dashtgard
Supervisor
Associate Professor

Dr. Kerrie Bann
Supervisor
Adjunct Professor

Dr. Brent Ward
External Examiner
Associate Professor

Date Defended/Approved: May 16, 2013
Partial Copyright Licence

The author, whose copyright is declared on the title page of this work, has granted to Simon Fraser University the right to lend this thesis, project or extended essay to users of the Simon Fraser University Library, and to make partial or single copies only for such users or in response to a request from the library of any other university, or other educational institution, on its own behalf or for one of its users.

The author has further granted permission to Simon Fraser University to keep or make a digital copy for use in its circulating collection (currently available to the public at the “Institutional Repository” link of the SFU Library website (www.lib.sfu.ca) at http://summit.sfu.ca and, without changing the content, to translate the thesis/project or extended essays, if technically possible, to any medium or format for the purpose of preservation of the digital work.

The author has further agreed that permission for multiple copying of this work for scholarly purposes may be granted by either the author or the Dean of Graduate Studies.

It is understood that copying or publication of this work for financial gain shall not be allowed without the author’s written permission.

Permission for public performance, or limited permission for private scholarly use, of any multimedia materials forming part of this work, may have been granted by the author. This information may be found on the separately catalogued multimedia material and in the signed Partial Copyright Licence.

While licensing SFU to permit the above uses, the author retains copyright in the thesis, project or extended essays, including the right to change the work for subsequent purposes, including editing and publishing the work in whole or in part, and licensing other parties, as the author may desire.

The original Partial Copyright Licence attesting to these terms, and signed by this author, may be found in the original bound copy of this work, retained in the Simon Fraser University Archive.

Simon Fraser University Library
Burnaby, British Columbia, Canada

revised Fall 2011
Abstract

Marine-generated bounding discontinuities subdivide the basal Belly River cycles into 3 allomembers (D, E, and G). Detailed sedimentological and ichnological analysis of allomembers D and E of the Upper Cretaceous basal Belly River Formation (central Alberta) reveals 13 discrete facies. Sedimentary facies are grouped into 6 mappable facies associations. Depositional environments are interpreted to record a variety of marginal-marine, paralic, and coastal environments, including: river-dominated, storm-influenced deltas (FA1); storm-dominated, mixed river- and wave-influenced deltas (FA2); fluvial channels (FA3); fluvio-estuarine distributary channels (FA4); marine-influenced, lower delta plains (FA5); and delta/coastal plains (FA6).

Based on the integration of data from cored intervals, multiple dip- and strike oriented cross-sections, and net-sand isopach maps; no lateral variations in facies distribution, consistent with the asymmetric delta model, are identified. Correlations indicate that the deposits of Allomember D are exclusively linked to FA1 successions, whereas the deposits of Allomember E are exclusively linked to FA2 successions.

Keywords: Sedimentological; Ichnological; Basal Belly River Formation; Deltas; Asymmetric Model.
For my parents.
Acknowledgements

I would like to sincerely thank James MacEachern and Shahin Dashtgard for their seemingly unlimited patience, knowledge and support over the past two and a half years. Their dedication to the success of the ARISE group goes above and beyond, and for that I am truly grateful.

Kerrie Bann is thanked for taking the time out of her busy schedule to introduce proper core-logging techniques, as well as providing excellent suggestions towards the improvement of this thesis. Special thanks are also expressed to Brent Ward for his participation as the external examiner.

Furthermore, I would like to acknowledge the help, comradery, friendship and support of my fellow ARISE members: Korhan Aryanci, Joanna Czarneckie, Andrew LaCroix, Stacy Johnson, Adam Montgomery, Alireza Morshedian, Liam Ricci, and Chad Sisulak. It’s a great feeling to know that we will not only be career-long colleagues, but lifetime friends also.

Finally, I would like to thank my family for their endless support, as well as my beautiful fiancé, Melecia, for her unwavering love and understanding throughout this entire post-secondary journey.
# Table of Contents

1. **An Introduction to the Geology of the Upper Cretaceous Basal Belly River Formation, Central Alberta, Canada** ................................................. 1  
   1.1. INTRODUCTION................................................................................................. 1  
   1.2. OBJECTIVES..................................................................................................... 2  
   1.3. STUDY AREA / DATABASE / METHODS .......................................................... 4  
   1.4. REGIONAL GEOLOGY AND PALEOGEOGRAPHY........................................... 7  
   1.5. REGIONAL STRATIGRAPHY............................................................................ 11  
      1.5.1. Lithostratigraphy...................................................................................... 11  
      1.5.2. Allostratigraphy..................................................................................... 13  
      1.5.3. Sequence Stratigraphy........................................................................... 15  
   1.6. PREVIOUS WORK ............................................................................................ 17  

2. **Concepts: Classification of Mixed River- and Wave-Influenced Delta Complexes and the Evolution of the Asymmetric Delta Model** .................. 20  
   2.1. CLASSIFICATION OF MIXED RIVER- AND WAVE-INFLUENCED DELTA SYSTEMS ............................................................................................................. 20  
   2.2. EVOLUTION AND CONCEPTUAL DEVELOPMENT OF THE ASYMMETRIC DELTA MODEL................................................................................. 27  

3. **Facies Descriptions** ...................................................................................... 35  
   3.1. INTRODUCTION................................................................................................ 35  
   3.2. Facies 1: Interstratified Sandstone, Siltstone, and Mudstone.......................... 39  
      3.2.1. Facies 1a: Sporadically Bioturbated, Interstratified Sandstone, Siltstone, Mudstone and Organic-Rich Claystone......................................................... 39  
      3.2.2. Facies 1b: Moderately Bioturbated, Interstratified Sandstone, Siltstone, Mudstone and Organic-Rich Claystone......................................................... 44  
   3.3. Facies 2: Graded and Soft-Sediment Deformed, Interstratified Silty Sandstone, Siltstone and Organic-Rich Claystone.............................................. 48  
   3.4. Facies 3: Sandstone ....................................................................................... 52  
      3.4.1. Facies 3a: Apparently Structureless (Massive) to Planar Parallel Laminated Sandstone .............................................................................................. 52  
      3.4.2. Facies 3b: Cryptically Bioturbated to Bioturbated Sandstone ................. 56  
      3.4.3. Facies 3c: Cross-Stratified to Rippled Sandstone .................................... 60  
   3.5. Facies 4: Pebbley Sandstone to Pebble Conglomerate................................... 64  
   3.6. Facies 5: Cross-Bedded Sandstone ............................................................... 67  
   3.7. Facies 6: Cross-Bedded Sandstone with Sporadically Bioturbated Mudstone Laminae ................................................................................................. 70  
   3.8. Facies 7: Current-Ripple Laminated Sandstone............................................. 74
3.9. Facies 8: Root-Bearing and Sporadically Bioturbated, Interstratified Sandstone and Siltstone ................................................................. 78
3.10. Facies 9: Fining-Upward, Interstratified Sandstone and Siltstone and Apparently Structureless (Massive) Mudstone ........................................ 82
3.11. Facies 10: Apparently Structureless (Massive) Mudstone to Sporadically Bioturbated, Shell-Bearing Muddy Heterolithic Units ....................... 86
3.12. Facies 11: Sporadically Bioturbated, Thinly Interstratified Sandstone, Clayey Siltstone, and Mudstone ......................................................... 90

4. Facies Associations ................................................................................. 101
4.1. INTRODUCTION ...................................................................................... 101
4.2. Facies Association 1: River-Dominated, Storm-Influenced Delta Deposits ..... 106
   4.2.1. Discussion: ...................................................................................... 106
4.3. Facies Association 2: Storm-Dominated, Mixed River- and Wave-Influenced Delta Deposits ............................................................... 113
   4.3.1. Discussion: ...................................................................................... 114
4.4. Facies Association 3: Fluvial Channel Deposits ...................................... 121
   4.4.1. Discussion: ...................................................................................... 121
4.5. Facies Association 4: Fluvio-Estuarine Distributary Channel Deposits ..... 126
   4.5.1. Discussion: ...................................................................................... 126
4.6. Facies Association 5: Marine-Influenced, Lower Delta Plain Deposits ....... 129
   4.6.1. Discussion: ...................................................................................... 130
4.7. Facies Association 6: Delta Plain / Coastal Plain Deposits ...................... 134
   4.7.1. Discussion: ...................................................................................... 135

5. Application of the WAVE Classification Scheme: Examples from Cycles D and E of the Basal Belly River Formation ........................................ 141
5.1. INTRODUCTION ...................................................................................... 141
5.2. APPLYING THE WAVE CLASSIFICATION TO FACIES ASSOCIATION 1 .... 142
   5.2.1. Discussion: ...................................................................................... 144
5.3. APPLYING THE WAVE CLASSIFICATION TO FACIES ASSOCIATION 2 .... 147
   5.3.1. Discussion: ...................................................................................... 149

6.1. INTRODUCTION ...................................................................................... 152
6.2. STRATIGRAPHIC FRAMEWORK ............................................................ 154
   6.2.1. Stratigraphic Surfaces ..................................................................... 154
   6.2.2. Correlation Concepts ..................................................................... 159
   6.2.3. Datum ............................................................................................ 159
6.3. DIP-ORIENTED CROSS-SECTIONS ...................................................... 162
   6.3.1. Cross-Section AA’ ......................................................................... 162
   6.3.2. Cross-Section BB’ ......................................................................... 165
   6.3.3. Cross-Section CC’ ......................................................................... 167
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4.</td>
<td>STRIKE-ORIENTED CROSS-SECTIONS</td>
<td>170</td>
</tr>
<tr>
<td>6.4.1.</td>
<td>Cross-Section DD’</td>
<td>170</td>
</tr>
<tr>
<td>6.4.2.</td>
<td>Cross-Section EE’</td>
<td>173</td>
</tr>
<tr>
<td>6.5.</td>
<td>STRATIGRAPHIC DISCUSSION AND DEPOSITIONAL INTERPRETATION</td>
<td>175</td>
</tr>
<tr>
<td>6.6.</td>
<td>ASSESSMENT OF ALONG-STRIKE VARIATIONS IN FACIES DISTRIBUTIONS</td>
<td>178</td>
</tr>
<tr>
<td>6.6.1.</td>
<td>Allomember D</td>
<td>178</td>
</tr>
<tr>
<td>6.6.2.</td>
<td>Allomember E</td>
<td>182</td>
</tr>
<tr>
<td>6.7.</td>
<td>SUMMARY AND DEPOSITIONAL MODELS</td>
<td>185</td>
</tr>
<tr>
<td>7.</td>
<td>Conclusions</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>Appendices</td>
<td>203</td>
</tr>
<tr>
<td></td>
<td>Appendix A. CD-ROM LITHOLOG DATA</td>
<td>204</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1.1. Location map with the major Belly River fields in central Alberta (modified after Power and Walker, 1996). The red border outlines the study area for this thesis. The green border outlines the study area of Hansen (2007). ................................................................. 3

Figure 1.2. List of subsurface cores intersecting the basal Belly River Formation, which were logged and analyzed in the study................................................ 5

Figure 1.3. Visual representation and comparison of Bioturbation Index (BI) values within mudstone and sandstone dominated facies (modified after Bann et al., 2008). .......................................................................... 6

Figure 1.4. Cretaceous sedimentary basins and mountain ranges of western Canada and northwestern USA (modified after DesRoches, 2008). .......... 8

Figure 1.5. Idealized cross-section of the Western Canada Sedimentary Basin (modified after DesRoches, 2008). Note the asymmetrical appearance of the basin. The thickness of the black arrows represents the relative amount subsidence or isostatic rebound experienced across the WCSB. .................................................................................. 9

Figure 1.6. Paleogeography of the Western Interior Cretaceous Seaway in (A) the Early Campanian, and (B) the Middle Campanian (modified after Williams and Stelck, 1975). Note that the province of Alberta is highlighted in yellow for reference.............................. 10

Figure 1.7. Lithostratigraphy of the Belly River and Lea Park formations (modified after Hansen, 2007). The red, dashed border outlines the interval of interest. ........................................................................................... 12

Figure 1.8. Schematic, dip-oriented cross-section showing the proposed allostratigraphy of the Lea Park – Belly River transition (modified after Power and Walker, 1996). Note the intertonguing and diachronous relationship between the two formations.............................................. 14

Figure 1.9. Simplified diagram comparing the basal Belly River cycles as defined by (A) Power and Walker (1996), and (B) Hansen (2007) (modified after Hansen, 2007). The latter method is used in this thesis. Abbreviations: RSME (regressive surface of marine erosion); FS (flooding surface); IFS (initial flooding surface); MjFS (major flooding surface); and WRS (wave ravinement surface). .................................................. 16
Figure 1.10. Gross-sand isopach map of Cycle G (from Hansen, 2007). The Hansen (2007) study area is outlined in orange. Note that FA1 successions, predominant in the southeast, are interpreted to represent wave-dominated (updrift) deposits; whereas FA2 successions, predominant in the NW, are interpreted to represent river-dominated (downdrift) deposits. The areas dominated by the two FAs are separated by the solid purple line. ................................................... 19

Figure 2.1. Tripartite delta classification model (modified after Bhattacharya and Giosan, 2003), showing the three delta end-member types: wave-, river-, and tide-dominated. Delta-front sand-body morphologies (isopach diagrams) are from Coleman and Wright (1975). ........................... 21

Figure 2.2. WAVE classification scheme (from Ainsworth et al., 2011). Non-fluvialite coastlines are represented along the base of triangles A and B. Triangle A shows the 15 possible classification categories. Triangle B depicts how percentages of sedimentary structures are used to characterize each category. F = Fluvial dominated; W = Wave dominated; T = Tide dominated; Fw = Fluvial dominated, wave influenced; Ft = Fluvial dominated, tide influenced; Tf = Tide dominated, fluvial influenced; Tw = Tide dominated, wave influenced; Wt = Wave dominated, tide influenced; Wf = Wave dominated, fluvial influenced; Ftw = Fluvial dominated, tide influenced, wave affected; Tfw = Tide dominated, fluvial influenced, wave affected; Wtf = Tide dominated, wave influenced, fluvial affected; Wft = Wave dominated, tide influenced, fluvial affected; Wtf = Wave dominated, fluvial influenced, tide affected. .................................................................................................. 24

Figure 2.3. Representative plan-view models, showing depositional geometries for each of the 15 coastal classification categories (from Ainsworth et al., 2011). Note the difference in depositional architecture between the different categories. ................................................................................. 25

Figure 2.4. The asymmetric delta model (modified after Bhattacharya and Giosan, 2003). The model indicates that a strong groyne effect generated at the distributary mouth tends to block sediment being transported alongshore. As a result, greater amounts of fine-grained, heterolithic deposits are associated with downdrift and prodelta areas, whereas thicker, more mature sands are deposited in updrift areas. .......................... 29

Figure 2.5. (A) Location map of the Sf. Gheorghe lobe of the Danube River delta (image courtesy of Google Earth). The delta lobe is located in southeast Romania and builds into the Black Sea. (B) A schematic close-up of the Sf. Gheorghe lobe (modified after Bhattacharya and Giosan, 2003). Sandbodies are coloured in yellow; delta plain silts and muds are grey; bay-head delta sediments are brown. Longshore drift (represented by the small arrow) is southward. ................................. 30
Figure 2.6. Conceptual evolution model for the asymmetric, Sf. Gheorghe lobe of the Danube River Delta (modified after Bhattacharya and Giosan, 2003). (A) Strong discharge at the distributary mouth acts as a barrier to along strike sediment transport, leading to sand deposition on the updrift flank of the delta front. Fluvial-sourced sediment is deflected preferentially downdrift and deposited into the subaqueous part of the delta. (B) A middle-ground bar forms at the distributary mouth, causing bifurcation of the distributary channel. Sediment in the subaqueous, part of the delta is reworked by basinal processes (e.g., waves) to form shore-parallel barrier bars. (C) The shore-parallel barrier bars coalesce to form a barrier island. A bay-head delta and lagoon may form landward of the barrier island. Longshore drift (represented by the arrow) is southward................................. 33

Figure 3.1. Summary of depositional facies recognized within cycles D and E of the basal Belly River Formation. ................................................................. 36

Figure 3.2. Ethology of traces observed within the facies of the basal Belly River Formation. Behavioural interpretation based on the summary of Gingras et al. (2007). .................................................. 38

Figure 3.3. Facies 1a: Sporadically bioturbated, interstratified sandstone, siltstone, mudstone, and organic-rich claystone. (A) Very fine- to fine-grained sandstone, interbedded/interlaminated with muddy siltstone and organic-rich claystone. Units show BI 1-4. Physical structures include local curvilinear lamination. Ichnogenera include Rhizocorallium (Rh), Diplocraterion (Di), Planolites (P), Chondrites (Ch), Siphonichnus (Si), Asterosoma (As), Palaeophycus tubularis (Pt), and Helminthopsis (H). Well 6-16-42-6W5, 1598.04m. (B) Very fine- to fine-grained sandstone, interbedded/interlaminated with muddy siltstone, and organic-rich claystone. Units show BI 0-1. Physical structures include wavy bedding, curvilinear lamination, syneresis cracks (syn), and normally and inversely graded beds. Ichnogenera include Palaeophycus tubularis (Pt), Siphonichnus (Si), Planolites (P), and Phycosiphon (Ph). Note the siderite band in the center of the photo. Well 6-16-42-6W5, 1598.75m. (C) Fine-grained sandstone interstratified with silty mudstone (BI 0-1). Sandstone layers are sharp based, apparently structureless (massive), and contain Phycosiphon (Ph). Muddy siltstone layers drape the sandstones and contain isolated Planolites (P) and navichnia (na). Well 15-34-42-6W5, 1507.0m. (D) Very fine- to fine-grained sandstone, interbedded with silty mudstone, muddy siltstone, and organic-rich claystone. Units exemplify the sporadic distribution of bioturbation, displaying BI 0-4. Ichnogenera include Teichichnus (T), Planolites (P), and Phycosiphon (Ph). Well 6-16-42-6W5, 1599.6m......... 42
Figure 3.4. Facies 1b: Moderately bioturbated, interstratified sandstone, siltstone, mudstone, and organic-rich claystone. (A) Sandstone with interlaminated organic-rich claystone. Physical structures include low-angle to horizontal planar parallel lamination and curvilinear lamination. Ichnogenera include Trichichnus (Tr), Arenicolites (Ar), Asterosoma (As), Planolites (P), and Phycosiphon (Ph). Well 14-28-42-4W5, 1289.34m. (B) Very fine- to upper fine-grained sandstone, interbedded/interlaminated with muddy siltstone and organic-rich claystone. Unit shows BI 1-3. Ichnogenera include Cylindrichnus (Cy), Phycosiphon (Ph), Palaeophycus tubularis (Pt), and Planolites (P). Well 16-20-42-4W5, 1301.22m. (C) Sandstone, interlaminated/interbedded with organic-rich claystone and sandy mudstone. Physical structures include wavy bedding, horizontal to curvilinear lamination, and load casts (base of uppermost sandstone bed). Unit shows BI 0-3. Ichnogenera include Planolites (P), Thalassinoides (Th), Chondrites (Ch), Cylindrichnus (Cy), and navichnia (na). Well 14-28-42-4W5, 1288.93m. (D) Localized sandstone bed displaying Rhizocorallium (Rh). Well 12-31-42-3W5, 1298.0m. (E) Sandy mudstone overlying organic-rich claystone. Unit shows BI 1-2. Ichnogenera include Thalassinoides (Th) and Planolites (P). Well 14-28-42-4W5, 1289.19m. ............................................................. 47

Figure 3.5. Facies 2: Graded and soft-sediment deformed, interstratified silty sandstone, siltstone, and organic-rich claystone. (A) Silty sandstone with abundant soft-sediment deformation. Well 1-19-43-2W5, 1136.57m. (B) Thinly interlaminated silty sandstone, siltstone, and muddy siltstone. Note the pinstriped appearance, as normally and inversely graded laminations rhythmically alternate to form graded composite bedsets. Ichnogenera include Palaeophycus tubularis (Pt) and fugichnia. Well 8-2-43-5W5, 1324.0m. (C) Interlaminated muddy siltstone, sandy siltstone, and silty sandstone. Physical structures include a composite, normally and inversely graded bedset, as well as curvilinear lamination, starved current ripples, current ripples, and combined-flow ripples. Well 8-2-43-5W5, 1324.05m. (D) Sandy siltstone with pervasive soft-sediment deformation. Well 16-16-41-6W5, 1587.92m. ............................................................................................ 51

Figure 3.6. Facies 3a: Apparently structureless (massive) to planar parallel laminated sandstone. (A) Apparently structureless (massive) sandstone with an allochthonous Rosselia mud ball (Ro). Well 14-28-42-4W5, 1282.42m. (B) Apparently structureless (massive) sandstone with a single mudstone rip-up clast (ruc). Well 16-20-42-4W5, 1302.2m. (C) Apparently structureless (massive) sandstone. Well 14-28-42-4W5, 1287.32m. (D) Low-angle planar parallel laminated sandstone with an escape structure (fugichnia) disrupting laminae. Well 16-20-42-4W5, 1295.59m. ............................................................................................ 55
Figure 3.7. Facies 3b: Cryptically bioturbated to bioturbated sandstone. (A) Cryptically bioturbated sandstone. Well 6-31-42-4W5, 1293.56m. (B) Bioturbated sandstone with visible *Macaronichnus segregatis* (Ma). The unit shows BI 4-5. Well 16-20-42-4W5, 1289.55m. (C) Bioturbated sandstone with visible *Macaronichnus segregatis* (Ma). The unit shows BI 3-5. Well 14-28-42-4W5, 1277.86m. (D) Apparently structureless (massive) sandstone with root traces (Rt). Well 6-31-42-4W5, 1288.75m.

Figure 3.8. Facies 3c: Cross-stratified to rippled sandstone. (A) Fine- to lower medium-grained sandstone. Physical structures include current ripples, combined-flow ripples, and curvilinear lamination. Foresets are marked by organic detritus. Well 8-2-43-5W5, 1322.05m. (B) Low-angle, cross-stratified sandstone. Note the presence of spherulitic siderite. Well 15-34-42-6W5, 1503.83m. (C) Thinly interlaminated sandstone and muddy siltstone (BI 0-1). Physical structures include curvilinear lamination, current ripples, starved current ripples, combined-flow ripples, and micro-faults (mf). Ichnogenera include *Chondrites* (Ch), *Palaeophycus tubularis* (Pt), and *Planolites* (P). Well 15-34-42-6W5, 1500.6m. (D) Erosive base of Facies 3c. Note the presence of slightly coarser-grained sediment, as well as the abundance of mudstone rip-up clasts and siderite nodules. Well 8-2-43-5W5, 1322.67m.

Figure 3.9. Facies 4: Pebby sandstone to pebble conglomerate. (A) Cross-stratified pebbly sandstone with compositionally variable clasts delineating the foresets. Well 2-3-42-9W5, 1679.5m. (B) Same description as previous. Well 6-13-42-6W5, 1453.32m. (C) Same description as previous. Well 14-33-42-8W5, 1548.96m. (D) Pebble conglomerate to pebbly sandstone. Note the sharp basal contact and the presence of coal fragments. Well 11-17-44-9W5, 1578.57m.

Figure 3.10. Facies 5: Cross-bedded sandstone. (A) Trough cross-bedded sandstone. Yellow arrows denote potentially paired drapes of millimetre-diameter mudstone rip-up clasts and organic detritus. Well 16-16-41-6W5, 1584.93m. (B) Trough cross-bedded sandstone. Millimetre-diameter mudstone rip-up clasts and organic detritus mark foresets. Well 8-17-42-6W5, 1598.50m. (C) Planar-tabular cross-bedded sandstone. Well 12-13-43-6W5, 1401.22m. (D) Trough cross-bedded sandstone with centimetre-scale diameter siderite nodules. Carbonaceous debris and millimetre-diameter mudstone rip-up clasts mark foresets. Well 16-16-41-6W5, 1581.23m.
Figure 3.11. Facies 6: Cross-bedded sandstone with sporadically bioturbated mudstone laminae. (A) Lower fine- to lower medium-grained sandstone with interlaminated sandy mudstone. Units show BI 0-3. Physical structures include wavy bedding, curvilinear lamination, and apparently structureless (massive) bedding. Trace fossil suite is dominated by *Cylindrichnus* (Cy), but also includes *Planolites* (P), *Palaeophycus tubularis* (Pt), and *Lockeia* (Lo). Well 16-35-42-5W5, 1320.84m. (B) Low-angle, cross-stratified sandstone. Note the abundance of carbonaceous debris marking foresets. Well 8-2-43-5W5, 1315.25m. (C) Apparently structureless (massive) sandstone with an isolated sandy siltstone bed. Note the root traces (Rt). Well 16-35-42-5W5, 1318.57m. (D) Apparently structureless (massive) sandstone. Well 8-2-43-5W5, 1313.03m.

Figure 3.12. Facies 7: Current-ripple laminated sandstone. (A) Upper very fine- to upper fine-grained sandstone. Physical structures include current-ripple lamination, curvilinear lamination, and aggradational current ripples. Ichnogenera include abundant root traces (Rt). Well 6-16-42-6W5, 1575.78m. (B) Lower fine- to upper fine-grained sandstone with siltstone laminae. Physical structures include curvilinear lamination and small-scale soft-sediment deformation (ssd). A single, mud-lined *Skolithos* (S) is present. Well 8-24-42-7W5, 1568.28m. (C) Upper fine- to lower medium-grained sandstone. Note the abundance of organic detritus marking the foresets of current ripples. Well 2-3-42-9W5, 1669.10m. (D) Upper very fine- to lower fine-grained sandstone. Physical structures include current-ripple lamination, curvilinear lamination, and small-scale convolute bedding. Well 10-32-41-4W5, 1287.20m.
Figure 3.13. Facies 8: Root-bearing and sporadically bioturbated, interstratified sandstone and siltstone. (A) Lower fine- to lower medium-grained sandstone with interlaminated muddy siltstone. Physical structures include curvilinear lamination, current ripples, and small-scale convolute bedding. Note the variable grain size between beds. Units display BI 0. Well 16-34-41-5W5, 1373.79m. (B) Heterolithic interval of thinly interstratified sandstone and muddy siltstone. Units show BI 0-2. Physical structures include small-scale convolute bedding and curvilinear lamination. Ichnogenera include *Taenidium* (Ta). Well 8-24-42-7W5, 1567.0m. (C) Upper very fine- to upper fine-grained sandstone interlaminated/interbedded with muddy siltstone. Units show BI 0-3. Physical structures include curvilinear lamination and local intervals of apparently structureless (massive) bedding. Ichnogenera include common root traces (Rt), *Naktodemasis* (Nk) and possible *Taenidium* (Ta). Well 6-16-42-6W5, 1575.62m. (D) Heterolithic, composite bedset of interlaminated/interbedded sandstone and muddy siltstone. Units show BI 0-2. Physical structures include small-scale convolute bedding and curvilinear lamination. Ichnogenera include possible *Planolites* (P) and *Thalassinoides* (Th), as well as root traces. Well 14-2-42-6W5, 1481.16m.

Figure 3.14. Facies 9: Fining-upward, interstratified succession of sandstone and siltstone and apparently structureless (massive) mudstone. (A) Lower to upper fine-grained sandstone, with moderate amounts of carbonaceous detritus. Physical structures include current ripples, aggradational current-ripples and curvilinear lamination. Well 6-31-42-4W5, 1302.28m. (B) Heterolithic interval, comprising thinly interstratified sandstone and silty mudstone. Units display BI 0-3. Physical structures include curvilinear lamination and combined-flow ripples. Trace-fossil suite consists of *Diplocraterion* (D), *Arenicolites* (Ar), *Palaeophycus tubularis* (Pt), *Cylindrichnus* (Cy), *Planolites* (P), and navichnia (na). Well 6-19-43-4W5, 1298.35m. (C) Silty sandstone with curvilinear lamination and current-ripples. Note the allochthonous coal fragment that contains *Teredolites* (Td). Well 1-19-43-2W5, 1135.44m. (D) Horizontal lamination, rhythmically alternating between very fine-grained sandstone and siltstone. Well 16-31-42-4W5, 1290.85m. (E) Lower to upper fine-grained sandstone with interlaminated siltstone and organic-rich claystone. Units show BI 0-2. Physical structures include curvilinear lamination and small-scale convolute bedding. Ichnogenera include *Skolithos* (S), *Trichichnus* (Tr), *Palaeophycus tubularis* (Pt), and *Planolites* (P). Well 6-31-42-4W5, 1301.26m.
Figure 3.15. Facies 10: Apparently structureless (massive) mudstone to sporadically bioturbated, shell-bearing muddy heterolithic units. (A) Heterolithic interval, comprising thinly interlaminated sandstone and siltstone (BI 0-2). Wavy bedding and curvilinear lamination are prevalent. Note the centimetre-thick shell lag. Well 14-19-42-4W5, 1318.18m. (B) Apparently structureless (massive) silty mudstone. Note the abundance of shell fragments. Well 8-2-42-5W5, 1353.30m. (C) Apparently structureless (massive) silty mudstone. Well 14-19-42-4W5, 1318.40m. (D) Coarsening-upward succession of thinly interstratified sandstone and siltstone. Units display BI 0-2. Physical structures include wavy bedding, curvilinear lamination, and small-scale convolute bedding. Note the abundance of carbonaceous debris, coal fragments, and mudstone rip-up clasts (ruc). Ichnogenera include Skolithos (S), Teichichnus (T), Cylindrichnus (Cy), Planolites (P), and possibly Rosselia (R). Well 16-35-42-5W5, 1323.74m.

Figure 3.16. Facies 11: Sporadically bioturbated, thinly interstratified sandstone, clayey siltstone and mudstone. (A) Fine-grained sandstone with interlaminated muddy siltstone and silty mudstone. Unit shows BI 0-2. Curvilinear lamination is prevalent. Labeled traces include Arenicolites (Ar), Diplocraterion habichi (Dh), Trichichnus (Tr), and Planolites (P). Well 14-19-42-4W5, 1304.26m. (B) Heterolithic, composite bedset of interlaminated very fine-grained sandstone and silty mudstone. This photo highlights the presence of rare Cylindrichnus (Cy). Well 7-7-43-4W5, 1288.29m. (C) Similar heterolithic interval, showing syneresis cracks (syn) within organic-rich claystone laminae. Well 14-19-42-4W5, 1305.22m. (D) Interlaminated very fine-grained sandstone, silty mudstone, and organic-rich claystone. Units display BI 0-3. Physical structures include wavy bedding and curvilinear lamination. Labeled ichnogenera include Planolites (P), Cylindrichnus (Cy), Palaeophycus tubularis (Pt), Lockeia (Lo), and Trichichnus (Tr). Well 6-31-42-4W5, 1287.80m.

Figure 3.17. Facies 12: Carbonaceous mudstone, siltstone, sandstone, and coal. (A) Silty mudstone/muddy siltstone. Lithologic accessories include abundant coal fragments and minor siderite granules. Well 7-34-42-6W5, 1492.12m. (B) Convolute bedded sandy siltstone. Note the root traces (Rt). Well 6-16-42-6W5, 1563.69m. (C) Coal bed. Well 12-13-43-6W5, 1404.70m. (D) Carbonate-cemented breccia with coal fragments. Well 7-34-42-6W5, 1490.20m. (E) Silty to sandy mudstone. Unit shows BI 0-2. Physical structures include convolute bedding and curvilinear lamination. Ichnogenera include Naktodemasis (Nk). A centimetre-diameter siderite nodule is also present near the top of the photo. Well 12-13-43-6W5, 1406.80m.
Figure 3.18. Facies 13: Root-bearing silty mudstone and muddy siltstone. (A) Mottled muddy siltstone with abundant root traces (Rt). Note the pale colour. Well 14-2-42-6W5, 1480.56m. (B) Mottled muddy to sandy siltstone with root traces (Rt). Note the pale colour. Well 10-32-41-4W5, 1276.66m. (C) Sandy siltstone with moderate amounts of disseminated carbonaceous debris. Well 16-34-41-5W5, 1372.79m.

Figure 4.1. Summary of facies associations recognized within cycles D and E of the basal Belly River Formation. Facies within each association are listed in ascending order (bottom to top) and correlate to typical expressions observed in box cores.

Figure 4.2. Ethologies indicated by trace fossils in the facies associations of the Basal Belly River Formation. Behavioural interpretation based on the summary of Gingras et al. (2007).

Figure 4.3. Legend of symbols used in the facies association lithologs.

Figure 4.4. Litholog of representative well 8-2-43-5W5, illustrating the various facies that comprise FA1. Legend for strip log in Fig. 4.3.

Figure 4.5. Box core photograph of Facies Association 1 in well 8-2-43-5W5 (1318.90 to 1327.47 m). The interval displays a coarsening upward succession, interpreted to reflect shallowing-upward, with sporadically bioturbated heterolithic units (Facies 1a) passing progressively into intervals of graded bedding and soft-sediment deformation (Facies 2), cross-stratified to rippled sandstone (Facies 3c), and fining-upward heterolithic intervals (Facies 9). Overall, the association is interpreted to represent the progradation of a river-dominated, storm-influenced delta.

Figure 4.6. Litholog of representative well 14-28-42-4W5, illustrating the various facies that comprise FA2. Legend for strip log in Fig. 4.3.

Figure 4.7. Box core photograph of Facies Association 2 in well 14-28-42-4W5 (1284.84 to 1290.00 m). The interval displays a coarsening-upward succession, interpreted to reflect shallowing-upward, characterized by upward transitioning from moderately bioturbated heterolithic bedsets (Facies 1b) into thick intervals of apparently structureless (massive) to planar parallel laminated sandstone (Facies 3a), capped by bioturbated sandstone (Facies 3b). Overall, the association is interpreted to represent the progradation of a storm dominated, mixed river- and wave-influenced delta complex.

Figure 4.8. Litholog of representative well 10-15-42-8W5, illustrating the various facies that comprise FA3. Legend for strip log in Fig. 4.3.
Figure 4.9. Box core photograph of Facies Association 3 in well 10-15-42-8W5 (1511.34 to 1516.25 m). The succession displays cross-bedded (Facies 5) and current-ripple laminated sandstone (Facies 7), capped by intervals of root-bearing and sporadically bioturbated, interstratified sandstone and siltstone (Facies 8). The association is interpreted to represent fluvial channel deposits.

Figure 4.10. Litholog of representative well 8-2-43-5W5, showing FA4. Legend for strip log in Fig. 4.3.

Figure 4.11. Box core photograph of Facies Association 4 in well 8-2-43-5W5 (1311.52 to 1318.17 m). Deposits comprise a single, erosionally based and fining-upward succession of cross-stratified sandstone with sporadically distributed mudstone laminae (Facies 6). Overall, the association is interpreted to represent a fluvio-estuarine distributary channel deposit.

Figure 4.12. Litholog of representative well 14-19-42-4W5, illustrating the two distinct facies that comprise FA5. Legend for strip log in Fig. 4.3.

Figure 4.13. Two distinct expressions of Facies Association 5 in well 14-19-42-4W5. A) Transition from structureless mudstone into sporadically bioturbated, shell-bearing muddy heterolithic units (Facies 10; 1317.78 to 1318.50 m). These deposits typically overlie FA1 where present in core. B) Sporadically bioturbated, thinly interlaminated heterolithic units (Facies 11; 1303.90 to 1306.80 m). These deposits typically overlie FA2 where present in core. Overall, the association is interpreted to represent marine-influenced, lower delta plain deposits.

Figure 4.14. Litholog of representative well 12-13-43-6W5, illustrating the various facies that comprise FA6. Legend for strip log in Fig. 4.3.

Figure 4.15. Box core photograph of Facies Association 6 in well 12-13-43-6W5 (1404.04 to 1414.50 m). The interval is dominated by lithologically variable, organic-rich deposits (Facies 12) and paleosols (Facies 13). An erosionally based and fining-upward sandstone unit is also present (Facies 5). Overall, the association is interpreted to represent upper delta plain / coastal plain deposits.

Figure 5.1. Application of the WAVE classification to FA1. Litholog shows an interval of FA1, contained within well 8-2-43-5W5. The figure illustrates the percentage of sedimentary structures generated by fluvial (92%), wave (7%), and tidal (1%) processes. The interval is therefore designated as a fluvial-dominated, wave-influenced, and tide-affected (Fw) element complex. Legend for strip log in Fig. 4.3.

Figure 5.2. WAVE classification scheme (modified after Ainsworth et al., 2011). Red dots mark the location where FA1 (well 8-2-43-5W5) plots within the ternary diagram. The yellow, dashed outline denotes the range of variability for FA1 successions.
Figure 5.3. Representative plan-view models, showing depositional geometries for each of the 15 coastal classification categories (modified after Ainsworth et al., 2011). The solid red box marks the Fwt system, which appears to represent the FA1 succession as observed in well 8-2-43-5W5. The dashed border denotes the Fw system, which is characterized in other cored examples of FA1.................................146

Figure 5.4. Application of the WAVE classification to FA2. Litholog shows an interval of FA2 from well 14-28-42-4W5. The figure illustrates the percentage of sedimentary structures generated by wave (95%) and fluvial (5%) processes. On that basis, the interval is designated as a wave-dominated, fluvial-influenced (Wf) element complex. Legend for strip log in Fig. 4.3.................................................................148

Figure 5.5. WAVE classification scheme (modified after Ainsworth et al., 2011). Red dots mark the location where FA2 (well 14-28-42-4W5) plots in the ternary diagram. The red dashed line denotes the range of variability for FA2 successions..................................................................150

Figure 5.6. Representative plan-view models, showing depositional geometries for each of the 15 coastal classification categories (modified after Ainsworth et al., 2011). The solid red box outlines the Wf system, designated by the FA2 succession observed in well 14-28-42-4W5. This system characterizes all cored expressions of FA2. ..............................151

Figure 6.1. Location map showing the position of cross-sections AA' - EE'. The red border outlines the study area of this thesis. The green border outlines the study area of Hansen (2007). ..................................................153

Figure 6.2. Allostratigraphic bounding discontinuities. (A) A major marine flooding surface (MjFS) separates Allomember E from the underlying Allomember D, placing prodelta deposits (Facies 1b) of FA2 above mouth-bar/distributary channel complexes (Facies 3c) of FA1. Well 00/14-28-42-4W5, 1290.14m. (B) A wave ravinement surface (WRS) produces a similar juxtaposition of facies along the Allomember D (below) / Allomember E (above) contact. Well 00/14-7-43-4W5, 1295.90m. .................................................................................155

Figure 6.3. Subtle expression of the Glossifungites Ichnofacies. (A) Box shot showing the upper portion of Allomember E. A wave ravinement surface (WRS) places delta-front deposits (Facies 3a) of FA2 above interdistributary bay deposits (Facies 11) of FA5. (B) The WRS is demarcated by a palimpsest trace-fossil suite consisting of firmground Thalassinoides (Th), attributable to the Glossifungites Ichnofacies. Note the syneresis crack (syn) present in the underlying FA5 layer. Well 00/12-31-42-3W5, 1296.09m. .................................................................156
Figure 6.4. Minor marine flooding surfaces (MnFS). The cored interval depicts 2 MnFSs, which separate FA2 successions within the upper portion of Allomember E. These surfaces are interpreted to be autogenic in origin. Well 00/12-31-42-3W5. .......................................................................................... 158

Figure 6.5. The Milk River Shoulder (MRS) datum, represented by the red dashed line, separates the upper Lea Park Formation (Pakowki) from the underlying lower Lea Park Formation (Milk River equivalent). Note the petrophysical signature on the resistivity log (right) and the gamma-ray log (left). Allomember D is truncated by MjFS2/WRS2, which is overlain by thick sandstones of Allomember E. Note: petrophysical logs for well 00/14-16-43-04W5 were obtained using IHS Accumap software.................................................................................................................. 161

Figure 6.6. Cross-section AA' represents a dip-oriented transect through allomembers D, E, and G of the basal Belly River Formation. The correlation is approximately 75 km in length. Allomember D comprises 5 river-dominated, storm-influenced deltaic successions (FA1); Allomember E consists of 3 storm-dominated, mixed river- and wave-influenced deltaic successions (FA2); and Allomember G exhibits 1 FA2 succession within the cross-section. Fluvial channels (FA3), distributary channels (FA4), marine-influenced lower delta plains (FA5), and delta/coastal plains (FA6) dominate in landwards (SW) and overlying stratigraphic positions. A legend of the symbols and colours used within cross-sections AA' - EE' is included. .......................... 164

Figure 6.7. Cross-section BB' represents a dip-oriented transect through allomembers D, E, and G of the basal Belly River Formation. The correlation is approximately 43 km in length and extends into the study area of Hansen (2007). Within the correlation: Allomember D contains 3 FA1 cycles; Allomember E contains 3 FA2 cycles; and Allomember G is interpreted to comprise 3 successions, similar to FA2. All cored intervals penetrating Allomember G were logged and interpreted by Hansen (2007). Fluvial channel (FA3) and delta/coastal plain (FA6) deposits overlie the allomembers in proximal (SW) regions, whereas Allomember H is present above Allomember G in more distal regions.......................................................................................................................... 166
Figure 6.8. Cross-section CC’ represents a dip-oriented transect through allomembers D, E, and G of the basal Belly River Formation. The correlation is approximately 61 km in length and extends from the current study area into the Hansen (2007) study area. Within the correlation: Allomember D contains 4 FA1 cycles; Allomember E contains 3 FA2 cycles; and Allomember G comprises 3 successions similar to FA1. All cored intervals penetrating Allomember G were logged and interpreted by Hansen (2007). Fluvial channels (FA3), distributary channels (FA4), marine-influenced lower delta plains (FA5), and delta/coastal plains (FA6) dominate landwards (SW) and overlying stratigraphic positions. Allomember H is present in distal (NE) regions.

Figure 6.9. Cross-section DD’ is a strike-oriented transect, which intersects Allomember D of the basal Belly River Formation. The correlation is approximately 70 km in length and represents the most proximal correlation of facies associations within the study area. The correlation illustrates the dominance of FA1 successions within Allomember D. Fluvial channel (FA3) and delta/coastal plain (FA6) deposits dominate stratigraphic positions above the deltaic units.

Figure 6.10. Cross-section EE’ represents a strike-oriented transect, which intersects allomembers D and E of the basal Belly River Formation. The correlation is approximately 77 km in length and shows the exclusivity of FA1 successions within Allomember D, and FA2 successions within Allomember E. Marine-influenced, lower delta plain accumulations (FA5) cap each allomember. Fluvial channel (FA3) and delta/coastal plain (FA6) deposits dominate overlying positions of the correlation.

Figure 6.11. Net sand isopach map of Allomember D deposits. Locations of two strike-oriented cross-sections (DD’ and EE’) are also shown. Note the lobate sand-body geometries. Dots indicate data points.

Figure 6.12. Net sand isopach map of Allomember E deposits. Location of strike-oriented cross-section BB’ is also shown. Note the arcuate to cuspatate, and overall more strike-elongate, sand-body geometries. Dots indicate data points.

Figure 6.13. Paleogeographic reconstruction of the depositional setting for allomembers D and E. (A) Illustrates the river-dominated delta system of Allomember D (modified after Ainsworth et al., 2011). (B) Depicts the more wave-influenced delta system of Allomember E (modified after Ainsworth et al., 2011). Figures not drawn to scale.
1. An Introduction to the Geology of the Upper Cretaceous Basal Belly River Formation, Central Alberta, Canada

1.1. INTRODUCTION

Research conducted on modern, mixed wave- and river-influenced deltas (cf. Dominguez et al., 1987; Dominguez, 1996; Bhattacharya and Giosan, 2003) demonstrates the potential for asymmetric delta-lobe development where both fluvial discharge and net longshore drift components are strong. Bhattacharya and Giosan (2003) developed a process-based facies model for such asymmetric, wave-influenced deltas based on research from the modern Sfantu Gheorghe lobe of the Danube River delta. The model predicts higher quality (i.e., thicker, better winnowed, and/or more homogeneous) sandstones in updrift delta front areas and greater amounts of fine-grained, heterolithic deposits in downdrift delta front and prodelta areas.

This thesis focuses on assessing whether along-strike asymmetry can be recognized and mapped within mixed river- and wave-influenced delta complexes in the basal Belly River Formation, central Alberta. Previous work on the basal Belly River Formation detailed the ichnology and sedimentology of cycles D – H (cf. Power and Walker, 1996; Coates, 2001; Coates and MacEachern, 2007), and the deposits were interpreted as mixed river- and wave-influenced deltaic successions. A subsequent subsurface study of the basal Belly River Formation (Hansen, 2007; Hansen and MacEachern, 2007), focused on Cycle G, revealed predictable and mappable facies associations that varied along depositional strike, consistent with the asymmetric delta model.

Based on the findings of Hansen and MacEachern (2007) and the similar depositional interpretation for cycles D and E, the possibility exists that asymmetric development may also be present and recognizable in these similarly mixed-influence,
underlying deltaic successions. A detailed subsurface analysis of cycles D and E was initiated within the Ferrier, Willesden Green, Gilby and Wilson Creek fields of central Alberta (Fig. 1.1), in order to compliment the research completed by Hansen (2007) on the Ferrybank and Keystone fields. Ichnology is integrated with the sedimentology and stratigraphy of each succession, in order to complete high-resolution facies analysis and assess along-strike variations in facies distributions. Facies associations were evaluated using a semiquantitative, process-based approach developed by Ainsworth et al. (2011). The results were compared with the asymmetric delta model proposed by Bhattacharya and Giosan (2003). Data from this study serves to further the understanding of facies architecture within ancient, mixed river- and wave-influenced deltaic systems, and enhance the predictability of their reservoir heterogeneities.

1.2. OBJECTIVES

1. Characterize and interpret the depositional environments of the basal Belly River Formation (cycles D and E) within the Ferrier, Willesden Green, Gilby and Wilson Creek fields of central Alberta (Fig. 1.1). A high-resolution facies framework (both facies and facies associations) is utilized to accomplish this task. Facies associations are also analyzed using the WAVE classification scheme (Ainsworth et al., 2011). More specifically, ichnology is integrated with the physical sedimentological characteristics of each association to determine the relative influence of fluvial, wave, and tidal processes on sediment deposition.

2. Construct and correlate facies-based stratigraphic cross-sections of the study interval, showing strike- and dip-oriented variations in depositional architecture. Criteria for differentiating between autogenic and allogenic surfaces are proposed, and are tested against core-based facies associations.

3. Integrate facies characteristics with depositional architectures to construct an accurate depositional model of the basal Belly River Formation within the study area.

4. Test the depositional model for the basal Belly River Formation within the study area (red box, Fig. 1.1), against the modern asymmetric delta model of Bhattacharya and Giosan (2003). The results of this research will also be integrated with those of Hansen (2007; green outline, Fig. 1.1).
Figure 1.1. Location map with the major Belly River fields in central Alberta (modified after Power and Walker, 1996). The red border outlines the study area for this thesis. The green border outlines the study area of Hansen (2007).
1.3. STUDY AREA / DATABASE / METHODS

The study focuses on subsurface data from cycles D and E of the basal Belly River Formation in central Alberta. The study area is positioned between Townships 39-45 and Ranges 01W5-10W5 (2317.5 km²), which encompasses the Ferrier, Willesden Green, Gilby, and Wilson Creek hydrocarbon fields (Fig. 1.1).

Fifty subsurface cores intersecting the basal Belly River Formation in the study area were selected for analysis (Fig. 1.2). Intersections averaged 13.5 metres in length, and the total logged interval was 916.4 metres. Cores were logged and evaluated using physical sedimentology and ichnology in order to assess facies relationships, identify recurring facies associations, and interpret depositional environments. Facies were defined by unique combinations of lithologic, sedimentologic, and biogenic characteristics, which allowed them to be differentiated from overlying, underlying, and laterally adjacent facies (cf. Walker, 1992). Sedimentological analysis focused on textures, sediment calibre, physical sedimentary structures, bed thicknesses, bedding contacts, and lithologic accessories. Ichnological evaluation concentrated on bioturbation intensities, trace-fossil distributions, ichnogenera identification, and assessment of trace-fossil diversities. Bioturbation intensities were assigned a Bioturbation Index (BI) value (cf. Taylor and Goldring, 1993), with 0 defining the absence of bioturbation and 6 reflecting complete bioturbation (Fig. 1.3).

A digital photographic database was created for each of the cored intervals. Each box of subsurface core was systematically photographed using whole-box and close-up techniques. Close-up photos placed particular emphasis on detailing sedimentary and biogenic structures, lithologic accessories, reoccurring facies and facies associations, as well as facies contacts for facies characterization. Whole-box photos, for each cored interval, were merged together in Adobe Photoshop© to digitally reconstruct the succession. Such photo-mosaics aided in continued analysis of the cores, as well as the overall presentation of data.

A collection of petrophysical well logs was also acquired for the study area. Over 200 well logs were used to assist in the construction of 7 depositional strike- and dip-oriented stratigraphic cross-sections, as well as the development of net-sand isopach
<table>
<thead>
<tr>
<th>WELL LOCATION</th>
<th>CORED INTERVAL(S)</th>
<th>FIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-27-40-7 W5</td>
<td>1584.6 - 1603.0m</td>
<td>Ferrier</td>
</tr>
<tr>
<td>8-35-40-9 W5</td>
<td>1745.0 - 1763.0m</td>
<td>Ferrier</td>
</tr>
<tr>
<td>1-36-40-9 W5</td>
<td>1714.0 - 1729.2m</td>
<td>Ferrier</td>
</tr>
<tr>
<td>10-6-41-8 W5</td>
<td>1672.1-1690.4; 1690.4-1694.7m</td>
<td>Ferrier</td>
</tr>
<tr>
<td>12-21-41-8 W5</td>
<td>1648.2-1650.6; 1650.6-1669; 1669-1674.1m</td>
<td>Ferrier</td>
</tr>
<tr>
<td>2-3-42-9 W5</td>
<td>1668.0 - 1681.5m</td>
<td>Ferrier</td>
</tr>
<tr>
<td>16-34-41-5 W5</td>
<td>1371.0 - 1389.0m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>16-16 BR 41-6 W5</td>
<td>1579.0 - 1588.4m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>16-20-42-5 W5</td>
<td>1319-1336.5; 1381-1389.6m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>14-2-42-6 W5</td>
<td>1480-1-1492.3; 1526.4- 1538.6m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>6-13-42-6 W5</td>
<td>1444.0 - 1456.0m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>6-16-42-6 W5</td>
<td>1541.1-1555.4; 1556-1569.7; 1573.1-1588; 1588.3-1603.3m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>8-17-42-6 W5</td>
<td>1596.9 - 1608.1m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>7-34-42-6 W5</td>
<td>1484.4 - 1502.4m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>15-34-42-6 W5</td>
<td>1473.0-1481.0; 1499-1507.5m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>8-24-42-7 W5</td>
<td>1532-1536; 1536-1544; 1561.7-1575m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>10-15-42-8 W5</td>
<td>1499.6-1517.3; 1517.6-1529.8m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>14-33-42-8 W5</td>
<td>1540.0-1547.6; 1547.6-1554.1m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>12-13-43-6 W5</td>
<td>1396.0 - 1414.5m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>3-21-43-8 W5</td>
<td>1522.0 - 1530.0m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>6-15-44-7 W5</td>
<td>1376.3 - 1389.5m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>7-16-44-9 W5</td>
<td>1573.0 - 1591.2m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>11-17-44-9 W5</td>
<td>1565.0 - 1583.0m</td>
<td>Willesden Green</td>
</tr>
<tr>
<td>11-29-40-3 W5</td>
<td>1254.0 - 1270.5m</td>
<td>Gilby</td>
</tr>
<tr>
<td>10-32 BR 41-4 W5</td>
<td>1275.6 - 1290.8m</td>
<td>Gilby</td>
</tr>
<tr>
<td>4-34-41-4 W5</td>
<td>1289-1295.5; 1295.5-1301.5m</td>
<td>Gilby</td>
</tr>
<tr>
<td>8-2-42-5 W5</td>
<td>1377.0 - 1358.0m</td>
<td>Gilby</td>
</tr>
<tr>
<td>12-31-42-3 W5</td>
<td>1291-1292.6; 1292.6-1304.4m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>15-17-42-4 W5</td>
<td>1265.8 - 1279.1m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>14-19-42-4 W5</td>
<td>1301.0 - 1319.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>16-20-42-4 W5</td>
<td>1285.0 - 1303.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>14-28-42-4 W5</td>
<td>1277.0 - 1295.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>6-31-42-4 W5</td>
<td>1285.0 - 1303.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>16-31-42-4 W5</td>
<td>1277.0 - 1295.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>14-34-42-4 W5</td>
<td>1270.0 - 1288.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>10-27-42-5 W5</td>
<td>1316.7 - 1336.6m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>16-35-42-5 W5</td>
<td>1314.0 - 1332.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>7-7-43-4 W5</td>
<td>1288-1296; 1296-1301.4m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>14-7-43-4 W5</td>
<td>1283.0 - 1301.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>14-16-43-4 W5</td>
<td>1264.0 - 1282.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>6-19-43-4 W5</td>
<td>1287-1294.9; 1294.9-1300.2m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>8-29-43-4 W5</td>
<td>1278.0 - 1296.7m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>2-32-43-4 W5</td>
<td>1271.0 - 1289.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>6-1-43-5 W5</td>
<td>1298.8 - 1316.8m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>8-2-43-5 W5</td>
<td>1310.0 - 1328.0m</td>
<td>Wilson Creek</td>
</tr>
<tr>
<td>14-7-43-2 W5</td>
<td>1145.0 - 1163.5m</td>
<td>Wrotes</td>
</tr>
<tr>
<td>3-15-43-2 W5</td>
<td>1087.5 - 1105.5</td>
<td>Wrotes</td>
</tr>
<tr>
<td>16-18-43-2 W5</td>
<td>1139-1148.2; 1148.2-1157.2m</td>
<td>Wrotes</td>
</tr>
<tr>
<td>1-19-43-2 W5</td>
<td>1118.0 - 1136.6m</td>
<td>Wrotes</td>
</tr>
<tr>
<td>14-36-43-3 W5</td>
<td>1130.0 - 1148.0m</td>
<td>Wrotes</td>
</tr>
</tbody>
</table>

Figure 1.2. List of subsurface cores intersecting the basal Belly River Formation, which were logged and analyzed in the study.
<table>
<thead>
<tr>
<th>BI</th>
<th>Visual Representation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>Bioturbation absent</td>
</tr>
<tr>
<td>1</td>
<td>Sparse bioturbation, bedding distinct, few discrete traces</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Rare bioturbation, bedding distinct, low trace density</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Moderate bioturbation, bedding boundaries sharp, traces discrete with rare overlap</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Common bioturbation, bedding boundaries indistinct, high trace density with common overlap</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Abundant bioturbation, bedding just visible, although completely disturbed</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Complete bioturbation, total biogenic homogenization of sediment</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1.3. Visual representation and comparison of Bioturbation Index (BI) values within mudstone and sandstone dominated facies (modified after Bann et al., 2008).
maps for cycle D and E successions. These maps detail along-strike variations in sedimentological and ichnological characteristics within the delta complex, delineate the depositional architecture of the two cycles, and form the basis for characterizing the paleoshoreline of the basal Belly River in central Alberta.

1.4. REGIONAL GEOLOGY AND PALEOGEOGRAPHY

The Upper Cretaceous (early-mid Campanian) basal Belly River Formation is contained within the Western Canada Sedimentary Basin (WCSB) of Alberta, Canada (Fig. 1.4). The WCSB represents an ancient foreland basin, constrained between the Rocky Mountains to the west and the Canadian Shield to the east and northeast (Stott, 1984). Basin development was initiated with the accretion of allochthonous Intermontane terranes associated with the Columbian Orogeny (Early Jurassic to Early Cretaceous), and continued through the early phases of the Laramide Orogeny (Late Cretaceous to Paleocene) as the Insular Superterranne collided with the North American craton (Leckie and Smith, 1992). During this period, western Canada was transformed from a large, stable platform in the Triassic, into a rapidly subsiding, retro-arc foredeep basin (Smith, 1994). The sedimentary basin was asymmetric in east-west cross-section, as subsidence and sedimentation rates were greatest adjacent to the western Cordillera where thrust loading was most pronounced (Fig. 1.5). The majority of basin-fill was derived from the active orogenic belt to the west, though minor amounts of sediment were also sourced from the eastern craton (Porter et al., 1982; Leckie and Smith, 1992; Morshedian, 2012). This resulted in the deposition of stacked, eastward-thinning clastic wedges (Leckie and Smith, 1992).

Throughout the Cretaceous, the WCSB was periodically flooded from the north (Boreal Seaway) and south (Gulfian Sea), periodically meeting to form the Western Interior Cretaceous Seaway (WIS; cf. Williams and Stelck, 1975; Kauffman, 1984; Leckie and Smith, 1992; Smith, 1994; Blakey, 2006; Morshedian, 2012). At maximum transgression, the WIS extended from the Canadian Arctic to the Gulf of Mexico, with periodic connection to Hudson’s Bay (Kauffman, 1984). During an early Campanian transgression (Fig. 1.6a), the Pakowki/Nomad Sea inundated the Alberta region, and the widespread marine shales of the Lea Park Formation were deposited (Stott, 1984;
Figure 1.4. Cretaceous sedimentary basins and mountain ranges of western Canada and northwestern USA (modified after DesRoches, 2008).
Figure 1.5. Idealized cross-section of the Western Canada Sedimentary Basin (modified after DesRoches, 2008). Note the asymmetrical appearance of the basin. The thickness of the black arrows represents the relative amount subsidence or isostatic rebound experienced across the WCSB.
Figure 1.6. Paleogeography of the Western Interior Cretaceous Seaway in (A) the Early Campanian, and (B) the Middle Campanian (modified after Williams and Stelck, 1975). Note that the province of Alberta is highlighted in yellow for reference.
This transgression was terminated when orogenesis, associated with early phases of the Laramide Orogeny, led to Belly River sedimentation into the basin (Stott, 1984). The major influx of Cordillera-derived clastics induced marked progradation of coastal systems (Fig. 1.6b), and shifted the shoreline eastward as far as Saskatoon, Saskatchewan during maximum regression (Dawson et al., 1994).

1.5. REGIONAL STRATIGRAPHY

1.5.1. Lithostratigraphy

The Belly River Formation grades upwards out of the marine shales of the Lea Park Formation, and is capped by the marine shales of the Bearpaw Formation (Fig. 1.7). The Belly River Fm comprises an eastward-thinning clastic wedge, characterized by basal deltaic successions progressively overlain by coastal plain and alluvial complexes (Smith, 1994). The clastic wedge is thickest along the Alberta foothills, and decreases to its depositional edge in southeast Saskatchewan (Eberth et al., 1990). The thick sandstone units of the lower Belly River Formation are referred to informally as the “basal Belly River” by workers in the oil and gas industry (Hamblin and Abrahamson, 1996). The base of the basal Belly River Formation is lithostratigraphically defined as the base of the first major sandstone overlying the Lea Park shales (Dawson et al., 1994), a criterion that is quite subjective. The contact is also strongly diachronous, as successive allomembers young to the east-northeast.
Figure 1.7. Lithostratigraphy of the Belly River and Lea Park formations (modified after Hansen, 2007). The red, dashed border outlines the interval of interest.
1.5.2. **Allostratigraphy**

Power and Walker (1996) subdivided the basal Belly River Formation into mappable units (allomembers), defined and delineated on the basis of bounding discontinuities. More specifically, regressive surfaces of marine erosion (RSME) and non-marine subaerial unconformities (SU) were employed to identify individual allomembers. RSMEs were interpreted to originate from forced regressions caused by high-frequency relative sea level falls, which rapidly shifted shorelines basinward and led to the progradation of deltaic allomembers. Landward of the deltaic successions, SUs underlie fluvial channels and associated delta-plain deposits. Power and Walker (1996) maintained that the RSME and SU surfaces were induced by the same base-level falls and are, therefore, genetically related.

The correlation of the RSMEs and SUs permitted greater mappability and enabled Power and Walker (1996) to establish an allostratigraphic framework for the interval. Their framework comprises eight offlapping, regressive-transgressive allomembers (A-H), which intertongue northeastward with the marine shales of the Lea Park Formation (Fig. 1.8).

The use of RSMEs as bounding discontinuities becomes problematic when applied to high-resolution, allostratigraphic correlations of deltas. Hansen (2007) notes that this method of subdivision places a stratigraphic break within each progradational wedge containing an RSME, implying that the facies above and below the boundary have no genetic affinity. In actuality, however, the RSMEs only represent minor basinward shifts in environment (e.g., diastems), which separate prodelta mudstones (underlying the RSME) from more rapidly prograded delta-front sandstones (overlying the RSME) of the same deltaic lobe. Consequently, Hansen (2007) concluded that the allostratigraphic approach employed by Power and Walker (1996) is unsuitable for high-resolution correlations and facies analysis within deltaic complexes of the basal Belly River Formation.
Figure 1.8. Schematic, dip-oriented cross-section showing the proposed allostratigraphy of the Lea Park – Belly River transition (modified after Power and Walker, 1996). Note the intertonguing and diachronous relationship between the two formations.
1.5.3. **Sequence Stratigraphy**

Historically, researchers conducting high-resolution correlations within deltaic successions have utilized marine flooding surfaces to subdivide the complexes into genetically related successions (e.g., Galloway, 1989a, b; Bhattacharya and Walker, 1991; Hansen, 2007; Hansen and MacEachern, 2007; Li et al., 2011). Sequence stratigraphy is a framework with chronostratigraphic affinities, which delineates stratal stacking patterns caused by changes in accommodation and sediment supply through time (Dalrymple, 2010; Catuneanu, 2011). The most basic and fundamental building block within this type of framework is the parasequence. A parasequence represents “a relatively conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces” (Posamentier et al., 1988, p. 110). By subdividing stratigraphic units into distinct, genetically related entities, the established framework allows detailed correlations and the interpretation of lateral facies relationships to be determined along a single depositional surface (Hansen, 2007).

In an effort to facilitate high-resolution, stratigraphic analysis that is both compatible and complimentary to the research completed in the adjacent Ferrybank and eastern Pembina/Keystone fields (cf. Hansen, 2007; Hansen and MacEachern, 2007), each basal Belly River “cycle” or “allomember” is herein defined using the sequence stratigraphic parameters of a parasequence. Therefore, each basal Belly River cycle defined in this thesis is bound by marine flooding surfaces (Fig. 1.9).
Figure 1.9. Simplified diagram comparing the basal Belly River cycles as defined by (A) Power and Walker (1996), and (B) Hansen (2007) (modified after Hansen, 2007). The latter method is used in this thesis. Abbreviations: RSME (regressive surface of marine erosion); FS (flooding surface); IFS (initial flooding surface); MjFS (major flooding surface); and WRS (wave ravinement surface).
1.6. PREVIOUS WORK

The majority of previous research completed on the basal Belly River Formation was regional in extent. Wasser (1988) conducted a geological evaluation of the Judith River Formation (= Belly River Formation) in the Pembina area of central Alberta. The study focused on stratigraphic analysis and depositional architecture, with minor petrographic analysis. Eight coarsening-upwards cycles, recognized within the Foremost interval (basal Belly River Formation), were interpreted as being deposited in shallow-marine, deltaic and nearshore environments.

Al-Rawahi (1993) focused on the sedimentology and allostratigraphy of the subsurface transitional zone between the Lea Park and the basal Belly River formations of central Alberta (Red Deer area). Deposits were subdivided into three, informal allomembers (A1 to A3) bounded by erosional discontinuities. Allomember A1 sediments were interpreted as mixed fluvial- and wave-influenced delta deposits; A2 deposits were interpreted as non-marine, channel sandstones; and A3 successions were interpreted to contain both transgressive, open-bay sediments, and regressive, mixed fluvial- and wave-influenced delta deposits.

Hamblin and Abrahamson (1996) conducted a regional-scale subsurface correlation of the basal Belly River stratigraphy throughout southern Alberta and Saskatchewan. Analysis focused on stratigraphic architecture and plan-view geometries of individual cycles. They concluded that the basal Belly River Formation could be subdivided into at least seven stacked, predominantly regressive cycles that thin to the east. Overall, the interval was interpreted to consist of a central core of stacked shoreline sandstones that pass westwards into continental deposits.

Power and Walker (1996) studied the Lea Park-Belly River transition in central Alberta, and subdivided the basal Belly River Formation into eight regressive-transgressive shoreline allomembers (A-H) based on bounding discontinuities (Fig. 1.8). Three types of bounding discontinuities were recognized: (1) regressive surfaces of marine erosion (RSMEs) formed during base-level fall; (2) subaerial unconformities (SUs) produced when base-level fall induced subaerial exposure; and (3) marine flooding surfaces (FSs) associated with a rise of base level. RSMEs and SUs formed
the basis of defining allomembers because they are laterally extensive and easy to identify in core and on well logs. In Power and Walker’s (1996) stratigraphic framework, each allomember is construed as a stratigraphic sequence (cf. Van Wagoner et al., 1990; Posamentier et al., 1992), and together the eight allomembers form a progradational sequence set. Power and Walker (1996) interpreted the basal Belly River Formation as representing the progradation of a river-influenced delta “shoreface”.

Coates (2001) and Coates and MacEachern (2007) focused on allomembers D–H of the basal Belly River Formation in west-central Alberta. Their research concentrated on the integration of ichnology with sedimentology, in order to characterize the various subenvironments of wave- and river-dominated delta deposits. The Belly River cycles were interpreted to represent mixed river- and wave-influenced deltaic successions, based on vertical and lateral variations in the relative importance of storm beds, wave-generated structures, soft-sediment deformation features, and reduced proportions of burrows of inferred suspension-feeding organisms versus deposit-feeding infauna.

Hansen (2007) and Hansen and MacEachern (2007) examined Cycle G (Allomember G) of the basal Belly River Formation in the Ferrybank and eastern Pembina/Keystone fields of central Alberta (Fig. 1.1). They focused on along-strike variations in facies distributions within a single, mixed river- and wave-influenced delta lobe, in order to determine whether the facies distribution patterns were consistent with those observed in the asymmetric delta model of Bhattacharya and Giosan (2003). Integration of ichnological and sedimentological characteristics permitted the discrimination of two distinct facies associations, interpreted to represent wave-dominated (FA1, updrift) and river-dominated (FA2, downdrift) settings, respectively (Fig. 1.10). Hansen (2007) concluded that Cycle G showed predictable and mappable facies associations that varied along depositional strike, which was consistent with the asymmetric delta model of Bhattacharya and Giosan (2003).
Figure 1.10. Gross-sand isopach map of Cycle G (from Hansen, 2007). The Hansen (2007) study area is outlined in orange. Note that FA1 successions, predominant in the southeast, are interpreted to represent wave-dominated (updrift) deposits; whereas FA2 successions, predominant in the NW, are interpreted to represent river-dominated (downdrift) deposits. The areas dominated by the two FAs are separated by the solid purple line.
2. Concepts: Classification of Mixed River- and Wave-Influenced Delta Complexes and the Evolution of the Asymmetric Delta Model

2.1. CLASSIFICATION OF MIXED RIVER- AND WAVE-INFLUENCED DELTA SYSTEMS

Prevailing models for deltas emphasize the interaction of wave, tide and fluvial influence as it affects the distribution, orientation, and internal geometry of deltaic deposits (cf. Coleman and Wright, 1975; Galloway, 1975; Elliot, 1986; Bhattacharya and Walker, 1992; Bhattacharya, 2010). Other models also incorporate grain size (cf. Orton and Reading, 1993; Reading and Collinson, 1996). Ternary or tripartite diagrams subdivide deltas in terms of three end-member types: river dominated; wave dominated; and tide dominated (Fig. 2.1). Each end-member type is characterized by a distinctive sand-body morphology that is based on studies of modern deltas (cf. Wright and Coleman, 1973; Coleman and Wright, 1975). Individual deltas are plotted qualitatively within the diagram, closest to the end member that exhibits similar sand-body morphology. A sand body whose morphology displays similarities to multiple end-member types (e.g., mixed-influence deltas) is qualitatively placed somewhere between the end members, based on an approximation of its most likely position.

Although the tripartite, depositional-energy framework provides a valid means of classifying deltaic systems, multiple problems can arise. For example, there is a general proclivity to force-fit deltas into an end-member type, or to place complex deltaic systems that may contain multiple lobes with variable end-member influences (e.g., the Danube River delta) at a single point on such a ternary diagram (Bhattacharyya and Giosan, 2003). Another problem encountered is that different environments within the same delta lobe may exhibit domination by different processes characteristic of the different end-member types. For example, the delta front of the Rhone delta is wave-
Figure 2.1. Tripartite delta classification model (modified after Bhattacharya and Giosan, 2003), showing the three delta end-member types: wave-, river-, and tide-dominated. Delta-front sand-body morphologies (isopach diagrams) are from Coleman and Wright (1975).
dominated, whereas the delta plain is largely fluvially dominated (Elliot, 1986). These problems are only exacerbated in subsurface studies, where limited sample points force the extrapolation and interpretation of potentially unrepresentative data (Bhattacharya and Walker, 1992; Bhattacharya and Giosan, 2003).

A new process-based framework, referred to as the WAVE classification scheme, is presented by Ainsworth et al. (2011). This scheme (Fig. 2.2) expands on the previously described tripartite model by incorporating non-deltaic coastal systems. The WAVE classification allows for coastal regimes to potentially show the effects of fluvial, wave and tidal processes, and so subdivides the ternary plot into nine discrete fields based on the relative proportion of controlling depositional processes. Process categories are evaluated as to whether they constitute a dominant, secondary, or tertiary effect on sedimentation. In categories where three processes are involved, the processes are said to “dominate”, “influence”, and “affect” deposition, respectively, in order of decreasing importance. This new framework, therefore, permits a semi-quantitative (rather than qualitative) classification of marginal-marine systems, where subtle differences in the controlling depositional processes can be more readily and precisely communicated (Ainsworth et al., 2011). For example, on the left margin of the WAVE classification triangle (Fig. 2.2), a coastline can be wave dominated (W); wave dominated and fluvial influenced (Wf); fluvial dominated and wave influenced (Fw); or wholly fluvial dominated (F). When tidal influence is also incorporated, a total of fifteen process combinations are possible. An example of a system wherein three processes control sedimentation is an “FWt”, or a fluvial-dominated, wave-influenced, tide-affected coastline. Representative plan-view models showing depositional geometries for each coastal system in the scheme are also included on a separate diagram (Fig. 2.3).

In order to apply the WAVE framework to cycles D and E of the basal Belly River Formation, a depositional-process designation must be assigned to each facies association. Facies associations are equivalent to element complexes (EC) in the WAVE classification system. Each classification category is based on the relative proportion of wave-, fluvial and tidal-generated sedimentary structures. The sedimentary structures must be attributed to a specific process in order to accurately plot the system within the ternary diagram and assign the proper name (Ainsworth et al., 2011). It is,
Figure 2.2. WAVE classification scheme (from Ainsworth et al., 2011). Non-fluvialite coastlines are represented along the base of triangles A and B. Triangle A shows the 15 possible classification categories. Triangle B depicts how percentages of sedimentary structures are used to characterize each category. 

F = Fluvial dominated; W = Wave dominated; T = Tide dominated; Fw = Fluvial dominated, wave influenced; Ft = Fluvial dominated, tide influenced; Tf = Tide dominated, fluvial influenced; Tw = Tide dominated, wave influenced; Wt = Wave dominated, tide influenced; Wf = Wave dominated, fluvial influenced; Fwt = Fluvial dominated, wave influenced, tide affected; Ftw = Fluvial dominated, tide influenced, wave affected; Tfw = Tide dominated, fluvial influenced, wave affected; Twf = Tide dominated, wave influenced, fluvial affected; Wtf = Wave dominated, tide influenced, fluvial affected; Wft = Wave dominated, fluvial influenced, tide affected.
Figure 2.3. Representative plan-view models, showing depositional geometries for each of the 15 coastal classification categories (from Ainsworth et al., 2011). Note the difference in depositional architecture between the different categories.
therefore, paramount to ascribe each preserved sedimentary structure to its proper formative process.

The following groups of physical sedimentary structures are commonly ascribed to wave, tidal, and fluvial processes, respectively. Wave-generated structures include: hummocky cross-stratification (HCS); swaley cross-stratification (SCS); horizontal planar parallel lamination; planar tabular and trough cross-stratification; wave-ripples; and low-angle curvilinear lamination (cf. Clifton et al., 1971; Leckie, 1988; Bhattacharya and Walker, 1991; Walker and Plint, 1992; Bann et al., 2008; Plint, 2010). Tide-generated structures include: double mud drapes; tidal rhythmites; reactivation surfaces; flaser bedding; and bidirectional ripples (e.g., Boersma and Terwindt, 1981; Dashtgard et al., 2009; Dashtgard et al., 2012; Vakarelov et al., 2012). Fluvial-generated structures include: current-ripples; combined-flow ripples; aggradational current ripples; planar tabular and trough cross-stratification; drapes of inferred fluid mud origin; carbonaceous beds; normal and inverse grading; syneresis cracks; and soft-sediment deformation features (e.g., Bhattacharya and Walker, 1991; MacEachern et al., 2005; Hansen, 2007; Bhattacharya and MacEachern, 2009). Numerous structures, however, are formed by multiple processes (e.g., trough cross-stratification, planar parallel lamination), and are therefore not diagnostic. The WAVE classification system also enables evaluation of uncertainty by allowing the facies successions to be considered in light of different causative processes. Other lines of evidence (e.g., associated sedimentary structures, paleogeographic setting, and ichnological data) must be incorporated in order to select the most likely depositional process (Ainsworth et al., 2011).

The WAVE classification scheme provides an expanded framework, which allows users to semi-quantify and more accurately compare subtle differences between various mixed-influence, marginal-marine systems. An a priori assumption when applying this framework to the ancient record (core- and outcrop-based studies) is that the dominant process influencing sediment deposition will have been responsible for the majority of the preserved sedimentary structures (Ainsworth et al., 2011). One potential issue could develop in storm-influenced depositional environments, wherein erosively emplaced tempestites have truncated and removed ambient deposits that reflect the prevailing conditions of the setting. This creates a preferential bias towards the preservation of catastrophic and episodic deposits, despite the fact that they do not correspond to the
dominant processes operating within the setting. It should be noted that storm influence is not limited to wave-dominated environments and, therefore should not be used to underpin the theory of associated wave domination. Storm influence and affiliated tempestites can occur in all shallow-marine settings, regardless of the degree of river, wave, or tidal influence (cf. Bhattacharya and Walker, 1991; Power and Walker, 1996; Gingras et al., 1998; Coates, 2001; MacEachern et al., 2005; Buatois et al., 2012). Despite the potential for such limitations, the WAVE classification scheme is reasonably predicated on the principle that successions can only be characterized using the preserved features (not inferred), and that these features must be employed to deduce the most reasonable formative process(es) affecting deposition. Currently, this represents the most accurate, semi-quantitative approach available for characterizing the rock record.

2.2. EVOLUTION AND CONCEPTUAL DEVELOPMENT OF THE ASYMMETRIC DELTA MODEL

Historical models for wave-influenced deltas depict quasi-shore-parallel, prograding beach-ridge complexes (cf. Wright and Coleman, 1973; Coleman and Wright, 1975; Bhattacharya and Walker, 1992; Reading and Collinson, 1996). The sand bodies display lobate, arcuate, cuspatate and strike-elongate morphologies, respectively, as the degree of wave influence increases (Reading and Collinson, 1996). Plan-view models typically show depositional complexes symmetrically arranged around the distributary channel, and assume that sediment is supplied solely from fluvial sources. More recent analyses of modern, wave-influenced deltas (cf. Dominguez et al., 1987; Dominguez, 1996; Bhattacharya and Giosan, 2003) have demonstrated that such models are reasonably accurate where net longshore drift at the distributary mouth is negligible; however, these models are not appropriate where net longshore drift is pronounced (Bhattacharya and Giosan, 2003).

Strong net longshore drift results where oblique waves consistently approach the shoreline from a single direction or where incoming waves from one direction predominate over those from other directions (Li et al., 2011a). Longshore currents transport sediment downdrift parallel to the shoreline, and can lead to asymmetric
development of wave-influenced deltas (cf. Reading and Collinson, 1996; Bhattacharya and Giosan, 2003; Li et al., 2011a). Historical studies recognized the significance of longshore currents in the evolution of delta asymmetry (cf. Wright and Coleman, 1973; Coleman and Wright; 1975), but assumed that strong longshore drift resulted in total downdrift deflection of distributary mouths. Dominguez (1996) proposed an alternative model, suggesting that in wave-influenced deltas, the fluvial effluent behaves effectively as a groyne or barrier, forcing the updrift retention of longshore-transported sediment. Periodic decreases in fluvial discharge may result in downdrift migration of the distributary mouth, but total downdrift deflection will only occur when fluvial discharge is insufficient to produce a groyne effect.

Building on this concept, Bhattacharya and Giosan (2003) created a process-based facies model for asymmetric, mixed river- and wave-influenced deltas (Fig. 2.4). The model is based on analysis of the Sfantu Gheorghe lobe of the Danube River delta (Fig. 2.5), and predicts thick accumulations of sand deposited in updrift areas and greater amounts of fine-grained, heterolithic deposits lying in downdrift and prodelta areas. Amalgamated beach ridges form updrift of distributary channels when fluvial discharge is of sufficient magnitude to operate as a groyne, impeding alongshore sediment transport. Consequently, updrift, sand-rich deposits are not derivatives of the adjacent fluvial channel but are, in fact, texturally and compositionally more mature than other sands within the delta complex. Downdrift deposits are sourced directly from the fluvial channel and are characteristically more heterolithic. Various subenvironments may form in downdrift areas, including bayhead deltas, lagoons and barrier islands. Bhattacharya and Giosan (2003) identified four requirements for asymmetric development within mixed river- and wave-influenced delta complexes: (1) strong net longshore sediment transport; (2) an updrift source of sand; (3) high fluvial discharge for most of the year; and (4) significant sediment input into the mouth bar. A strong longshore drift component is critical for initiating downdrift deflection of the distributary mouth during periods of waning fluvial discharge and imposing sediment transport alongshore. An updrift source for this sediment is necessary. This could include another active distributary mouth or an older deltaic lobe undergoing net erosion. High fluvial discharge is also necessary to produce the groyne effect, blocking sediment transport alongshore.
Figure 2.4. The asymmetric delta model (modified after Bhattacharya and Giosan, 2003). The model indicates that a strong groyne effect generated at the distributary mouth tends to block sediment being transported alongshore. As a result, greater amounts of fine-grained, heterolithic deposits are associated with downdrift and prodelta areas, whereas thicker, more mature sands are deposited in updrift areas.
Figure 2.5. (A) Location map of the Sf. Gheorghe lobe of the Danube River delta (image courtesy of Google Earth). The delta lobe is located in southeast Romania and builds into the Black Sea. (B) A schematic close-up of the Sf. Gheorghe lobe (modified after Bhattacharya and Giosan, 2003). Sandbodies are coloured in yellow; delta plain silts and muds are grey; bay-head delta sediments are brown. Longshore drift (represented by the small arrow) is southward.
and forcing deposition updrift of the fluvial channel. Finally, significant sediment input into the distributary mouth bar provides siliciclastic material that can later be reworked by basinal processes, potentially leading to the formation of barrier islands with associated lagoons and bay-head deltas (Fig. 2.6).

The asymmetric delta model predicts significant, along-strike variations in facies distributions between updrift and downdrift portions of a mixed river- and wave-influenced delta (Bhattacharya and Giosan, 2003). Further research has refined this paradigm (cf. Coates and MacEachern, 2007; Hansen and MacEachern, 2007; Li et al., 2011b), by establishing updrift deposits as wave- to storm-dominated, sand-rich successions showing minor evidence of fluvial influence, and downdrift deposits as river-dominated, heterolithic successions that exhibit an abundance of fluvially generated features (e.g., soft-sediment deformation, syneresis cracks, normal and inversely graded beds, current-generated structures, and drapes of inferred fluid mud origin; MacEachern et al., 2005). Along-strike heterogeneity is not limited to lithology and physical sedimentary structures: ichnological differences are also pronounced between wave- and river-dominated depositional environments (Moslow and Pemberton, 1988; Gingras et al., 1998; Coates and MacEachern, 1999; MacEachern et al., 2005; Hansen and MacEachern, 2007). Updrift deposits tend to contain more robust and diverse ichnological suites, attributable to slightly stressed to unstressed expressions of the Cruziana and Skolithos ichnofacies. In contrast, downdrift deposits display marked reductions in bioturbation intensity, ichnogeneric diversity, and the range of ethological groupings. Ichnological suites are dominated by morphologically simple, facies-crossing, inferred deposit-feeding structures, with a noticeable paucity of structures generated by inferred suspension/filter-feeding organisms (cf. Moslow and Pemberton, 1988; Gingras et al., 1998; Coates and MacEachern, 2007; Hansen and MacEachern, 2007). Overall, downdrift suites are attributable to a stressed expression of the distal to proximal Cruziana Ichnofacies.

Variations in the distribution patterns of the aforementioned sedimentologic and ichnologic features are interpreted to result from the interaction of physico-chemical stresses within the depositional environment (MacEachern et al., 2007b). The majority of these stresses are directly related to the degree of fluvial influence, which can induce
Conceptual evolution model for the asymmetric, Sf. Gheorghe lobe of the Danube River Delta (modified after Bhattacharya and Giosan, 2003). (A) Strong discharge at the distributary mouth acts as a barrier to along strike sediment transport, leading to sand deposition on the updrift flank of the delta front. Fluvial-sourced sediment is deflected preferentially downdrift and deposited into the subaqueous part of the delta. (B) A middle-ground bar forms at the distributary mouth, causing bifurcation of the distributary channel. Sediment in the subaqueous part of the delta is reworked by basinal processes (e.g., waves) to form shore-parallel barrier bars. (C) The shore-parallel barrier bars coalesce to form a barrier island. A bayhead delta and lagoon may form landward of the barrier island. Longshore drift (represented by the arrow) is southward.
salinity fluctuations, increased depositional rates, heightened water turbidity, episodic deposition, and reduced oxygenation near the bed (Gingras et al., 1998; MacEachern et al., 2005; Coates and MacEachern, 2007; Hansen and MacEachern, 2007; MacEachern et al., 2007b; Li et al., 2011b). It is reasonable, therefore, to infer that the influence of fluvial influx on biogenic colonization and sedimentary processes will be strongest at distributary mouths and will decrease laterally. Deposits downdrift of the distributary channel will possess distinct indications of fluvial influence, whereas deposits updrift of the distributary channel will display marked reductions in river-generated features, as the depositional environment transitions towards stronger overall wave domination (MacEachern et al., 2005).

The distinction between updrift and downdrift characteristics outlined in the asymmetric delta model and other studies focusing on asymmetry in ancient mixed river- and wave-influence deltas (cf. Hansen and MacEachern, 2007; Li et al., 2011b), allows (at a minimum) the subdivision of such complexes into two separate facies associations. Facies associations represent updrift and downdrift areas. Along-strike heterogeneities observed between the two associations act as a continuum, passing progressively from river-dominated deltaic environments (downdrift) to wave-dominated strandplain environments (updrift). Careful integration of the sedimentological and ichnological characteristics observed at any one location within the delta complex permits an accurate prediction of the depositional position with respect to updrift or downdrift position, as well as the proximity to the distributary mouth (MacEachern et al., 2005; Hansen and MacEachern, 2007; Li et al., 2011b).
3. Facies Descriptions

3.1. INTRODUCTION

Fifty subsurface cores, totalling 916.4 m of interval, were logged and evaluated on the basis of their sedimentology and ichnology. Integration of the preserved sedimentologic, ichnologic and biogenic characteristics reveal 13 discrete and recurring facies (Fig. 3.1). Facies are systematically detailed using 3 descriptive categories: (i) sedimentology; (ii) ichnology; and (iii) depositional interpretation. Sedimentologic descriptions include textures, sediment calibre (grain size), physical sedimentary structures, bed thicknesses, bedding contacts, and lithologic accessories. Ichnologic characterization includes bioturbation intensities, trace-fossil distributions, ichnogenera identification, and assessment of trace-fossil diversities. Depositional interpretations are based on process-response implications of the dominant facies characteristics (sedimentologic, ichnologic and biogenic aspects), leading to the proposal of potential depositional environments.

Bioturbation intensities are assessed using Bioturbation Index (BI) (cf. Taylor and Goldring, 1993; Fig. 1.2), with zero defining absent bioturbation and six reflecting complete bioturbation. BI values constitute grades of bioturbation deemed to be discernible to the human eye, and derive from the original neoichnological work of Reineck (1963). Ichnologic descriptions reference the relative abundances of individual traces as: very rare (vr); rare (r); moderate (m); common (c); and abundant (a). Interpreted ethologies (i.e., behaviours) associated with the particular ichnogenera of each facies are based on Gingras et al. (2007), and are organized in Figure 3.02. Photo plates are also included to fully illustrate the differences between the individual facies.
<table>
<thead>
<tr>
<th>Facies #</th>
<th>Description</th>
<th>Sedimentology</th>
<th>Lithologic Accessories</th>
<th>Trace Fossil Suite</th>
<th>B.I.</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Sparsely bioturbated, intensitated sandstone, siltstone, mudstone, and organic-rich claystone</td>
<td>Mud-dominated heterolithic unit; common ways to lamellar bedding; sandstones contain low-angle planar parallel and wavy-parallel lamination (micro-SCS); oscillation ripples, combined-flow ripples, loading structures, and small-scale convolute bedding; siltsstones commonly display normal, as well as inverse grading, and typically show underlying sandstone units; organic-rich claystones are present and are usually associated with sand-filled syneresis cracks</td>
<td>Moderately abundant amounts of carbonaceous detritus and plant fragments; common mm-scale siltstone bands; local mudstone rip-up clasts</td>
<td>Planolites, Thalassinoides, Teichichnus, Cylindrichnus, Palaeophycus, Cheiroleike,903, Phosphatichnus, Hameolites, navicularis and rugatihir.</td>
<td>B.I. - 2</td>
<td>Distal to Provisional Product</td>
</tr>
<tr>
<td>1b</td>
<td>Moderately bioturbated, intensitated sandstones, siltstones, mudstones, and organic-rich claystones</td>
<td>Mud-dominated heterolithic unit; similar physical sedimentary structures to those in 1a; however, syneretic cracks are not as well developed; siltstone layers are less common</td>
<td>Moderately abundant amounts of carbonaceous detritus and mudstone rip-up clasts; local cm-scale siltstone bands</td>
<td>Planolites, Thalassinoides, Teichichnus, Boreichnus, Antasichnus, Palaeophycus, Cylindrichnus, Phosphatichnus, Skolithos, Ammoskolithos, Skolithos, Rhamphotheca, Carbonicula, Phosphatichnus, Nematolithus, Loculites, navicularis, and rugatihir.</td>
<td>B.I. - 4</td>
<td>Distal to Provisional Product</td>
</tr>
<tr>
<td>2</td>
<td>Graded and soft-sediment deformed, intensitated clype средне, siltstone, and organic-rich claystone</td>
<td>Heterolithic unit; sandstones display low-angle and horizontal planar parallel lamination, convolute lamination, soft-sediment deformation, apparently structureless (massive) bedding, internal current ripples, and synsedimentary deformation; siltsstones contain well-developed normal grading, soft-sediment deformation, micro-flushing, and horizontal to convolute lamination; local intervals display graded bedding; organic-rich claystones are sparsely distributed and commonly contain syneretic cracks</td>
<td>Moderately abundant amounts of carbonaceous detritus; minor siltstone and fine sandstone</td>
<td>Planolites, Palaeophycus, Chondrites, Skolithos, Loculites, and rugatihir.</td>
<td>B.I. - 1</td>
<td>Proximal Product to Distal Delta Front</td>
</tr>
<tr>
<td>3a</td>
<td>Apparently structureless (massive) to planar parallel to massive sandstone</td>
<td>Anomalous simple bodies; apparently structureless (massive) bedding and horizontal to low-angle planar parallel lamination and planar subaerial cross-stratification</td>
<td>Moderately abundant amounts of organic detritus, mudstone/siltstone rip-up clasts, and coal fragments; minor pyritic nodules, plant fragments, and siltstone fragments</td>
<td>Rhamphotheca, Dilophichnus, Rhizocorallium, Ophiomorpha, Cyclidichnus, Thalassemnus, Planolites, Macaronichnus, and rugatihir.</td>
<td>B.I. - 3</td>
<td>Distal to Proximal Delta Front</td>
</tr>
<tr>
<td>3b</td>
<td>Cylotically bioturbated to bioturbated sandstone</td>
<td>Anomalous simple bodies; common apparently structureless (massive) appearance; local horizontal to low-angle planar parallel lamination and planar subaerial cross-stratification</td>
<td>Moderately abundant amounts of disseminated organic detritus and minor occurrence of test structures</td>
<td>Macaronichnus aggregatus, cryptic benthos, and local occurrence of test structures</td>
<td>B.I. - 5</td>
<td>Proximal Delta Front: Foreshore</td>
</tr>
<tr>
<td>3c</td>
<td>Cross-stratified to rippled sandstone</td>
<td>Common trough and planar subaerial cross-stratification, as well as current ripples; lamination, local undulatory current ripples, oscillation ripples, combined flow ripples, apparently structureless bedding, and cm-scale convolute bedding; minor mm-thick organic-rich claystone and siltstone are associated with syneretic cracks</td>
<td>Moderately abundant amounts of carbonaceous detritus and pyrite (rarely thin); common mudstone rip-up clasts, and coal fragments</td>
<td>Planolites, Planolites, Chondrites, Skolithos, Antasichnus, Dilophichnus, Cyclidichnus, Palaeophycus, and Macaronichnus</td>
<td>B.I. - 2</td>
<td>Active Terminal Distributary Channel: Mouth-Bar Complexes</td>
</tr>
<tr>
<td>4</td>
<td>Pebble sandstone to pebble conglomerate</td>
<td>Poorly to moderately well sorted, subrounded to rounded pebble clasts of variable composition; lower medium- to upper course-grained sandstone and pebbly sandstone with very thick and planar subaerial cross-stratification; apparently structureless (massive) bedding</td>
<td>Moderately disseminated carbonaceous detritus, mudstone rip-up clasts, and coal fragments</td>
<td>No trace fossils observed</td>
<td>B.I. - 0</td>
<td>Channel Base</td>
</tr>
<tr>
<td>5</td>
<td>Cross-beded sandstone</td>
<td>Anomalous simple bodies; low- to high-angle planar subaerial and trough cross-stratification; local occurrences of apparently structureless (massive) bedding, low-angle planar parallel lamination, convolute lamination and small-scale convolute bedding</td>
<td>Moderately abundant organic detritus (commonly marking laminae); dispersed pebbles, siltstone nodules, coal fragments, and mudstone rip-up clasts</td>
<td>Reefs structures (possibly the top of the facies)</td>
<td>B.I. - 0</td>
<td>Lower to Middle Portion of Channel</td>
</tr>
</tbody>
</table>

Figure 3.1. Summary of depositional facies recognized within cycles D and E of the basal Belly River Formation.
<table>
<thead>
<tr>
<th>No.</th>
<th>Depositional Environment</th>
<th>Depositional Features</th>
<th>Depositional Features</th>
<th>Sedimentary Structures and Textures</th>
<th>Refer to Channel (Stratigraphy)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Cross-bedded sandstone with speculatively bioturbated mudstone laminae</td>
<td>Common low-angle planar tabular and trough cross-stratification, as well as apparently structureless massive bedding; local current-ripple laminae, horizontal plane parallel lamination, curved planar lamination, and small-scale convolute bedding; rare double mud drapes and intervals of very fine grained mud.</td>
<td>Low to moderate organic detritus (commonly marking fossils); local calcareous nodules, coal fragments, mudstone rip-up clasts, and shell fragments.</td>
<td>Cylindrical, Planar, Planar/Planar, and root structures (restricted to the top of the facies)</td>
<td>0 - 3</td>
<td>Fluvio-Extensive Distributary Channel</td>
</tr>
<tr>
<td>7</td>
<td>Current-ripple laminated sandstone</td>
<td>Abundant current-ripple laminae; local current-laminated, aggradational current ripple-laminated, trough cross-stratification, and small-scale convolute bedding; rare double mud drapes and intervals of very fine grained mud.</td>
<td>Moderately to abundant organic detritus (commonly marking fossils); coal fragments, and mudstone rip-up clasts.</td>
<td>Nodular/Planar, Planar, Planar/Planar, and root structures.</td>
<td>0 - 2 TYPICAL 0 - 1</td>
<td>Lower to Middle Portion of Channel</td>
</tr>
<tr>
<td>8</td>
<td>Rock-boring and speculatively bioturbated, interbedded sandstone and silts.</td>
<td>Heterolithic unit; sandstone commonly contains current-ripples, current parallel laminae, trough cross-stratification, low-angle planar parallel laminae, and small-scale convolute bedding; silts contain droplets and intervals of bioturbated horizons.</td>
<td>Moderately to abundant disseminated organic detritus, coal fragments, and mudstone rip-up clasts.</td>
<td>Nodular/Planar, Planar, Planar/Planar, and root structures.</td>
<td>0 - 4 TYPICAL 1 - 3</td>
<td>Upper Channel Margin or Lower</td>
</tr>
<tr>
<td>9</td>
<td>Fining-upward, interbedded sandstone, silts, and apparently structureless (massive) sandstone</td>
<td>Lithologically variable, but forms fining-upward successions; sandstones contain current-ripple laminae, very-parallel laminae, aggradational current ripples, and small-scale convolute bedding; mudstones and silts are dominated by all-sediment deformation and appear structureless (massive) bedding; organic-rich mudstones are common and contain cyanobacterial stromatolites.</td>
<td>Moderately to abundant carbonaceous detritus and silty detritus nodules.</td>
<td>Nodular/Planar, Planar, Planar/Planar, and root structures.</td>
<td>0 - 3 TYPICAL 0 - 2</td>
<td>Abandoned Terminal Distributary Channel/Mouth-Bar Complex</td>
</tr>
<tr>
<td>10</td>
<td>Apparently structureless (massive) mudstone to speculatively bioturbated, shell-bearing muddy heterolithic units</td>
<td>Mid-dominated unit with locally calcified silts and sand; local heterolithic intervals; abundant massive bedding and all-sediment deformation; local sandstone laminae display very-parallel laminae, oscillation ripples, and current ripples.</td>
<td>Moderately carbonaceous detritus, plant material, and coal fragments; common bi-valve shell fragments; minor siliciclastic bands.</td>
<td>Planar, Planar, Planar, Planar, and root structures.</td>
<td>0 - 2</td>
<td>Restricted Bay or Lagoon</td>
</tr>
<tr>
<td>11</td>
<td>Speculatively bioturbated, thinly intercalated sandstone, clayey silts, and mudstone</td>
<td>Heterolithic unit; highly variable silts to mudstone matrix; common very-parallel bedding with local current-ripple and flow bedding; abundant convex parallel laminae and oscillation ripples; common synechoctonic units associated with clayey silts and mudstone matrix; local current ripples, aggradational current ripples, and combined-flow ripples.</td>
<td>Moderately organic detritus, plant remains, and coal fragments; common moss on thin siliciclastic bands.</td>
<td>Planar, Planar, Planar, Planar, and root structures.</td>
<td>0 - 2 TYPICAL 0 - 2</td>
<td>Interfluvial Bay</td>
</tr>
<tr>
<td>12</td>
<td>Carbonaceous mudstones, silts, sandstone, and coal</td>
<td>Lithologically variable; intercalated coal; common horizontal plane parallel laminae, apparently structureless massive bedding and convolute bedding; local sandstone laminae with current ripples, horizontal plane parallel laminae, curved planar lamination, and massive bedding.</td>
<td>Anomalous high concentrations of intercalated carbonaceous debris, plant fragments, and leaf imprints; moderate amounts of coal fragments, coal beds, and siliciclastic bands.</td>
<td>Planar, Planar, Planar, and root structures.</td>
<td>0 - 1</td>
<td>Floodplain, Swamp, Bog, and/or Marsh</td>
</tr>
<tr>
<td>13</td>
<td>Root-bearing silty mudstone and muddy silts</td>
<td>Lithologically variable; primary sedimentary structures are commonly absent or appear as indistinct nodules; local horizontal lamination, apparently structureless massive bedding, and pedogenic slickenstones; intercalated sandstone laminae display horizontal plane parallel to curved planar lamination.</td>
<td>Moderately organic detritus and coal fragments; new coal laminae.</td>
<td>Nodular/Planar, Planar, Planar, and root structures.</td>
<td>0 - 1</td>
<td>Floodplain to Piedmont</td>
</tr>
</tbody>
</table>

Figure 3.1. Summary of depositional facies continued.
### Figure 3.2

Ethology of traces observed within the facies of the basal Belly River Formation. Behavioural interpretation based on the summary of Gingras et al. (2007).
3.2. Facies 1: Interstratified Sandstone, Siltstone, and Mudstone

Facies 1 comprises heterolithic, composite bedsets of interstratified sandstone, siltstone, mudstone, and organic-rich claystone. Deposits vary from mud-dominant to subequally proportioned mudstone and sandstone. Sandstone beds are largely centimetre-scale in thickness and are dominated by oscillation-generated structures. Siltstone and mudstone beds are also generally centimetre-scale in thickness, and commonly display normal and inverse grading. Organic-rich claystone layers are sporadically distributed, and contain isolated syneresis cracks. Facies 1 is subdivided into two subfacies, based on discrete sedimentologic and ichnologic features.

3.2.1. Facies 1a: Sporadically Bioturbated, Interstratified Sandstone, Siltstone, Mudstone and Organic-Rich Claystone

Sedimentology:

Facies 1a ranges from 0.7 to 6.3 metres in thickness. The mudstone-dominated, heterolithic unit comprises a composite bedset of interlaminated to thinly interbedded silty mudstone, muddy siltstone, very fine- to fine-grained sandstone, and organic-rich claystone (Fig. 3.3a-d). Wavy to lenticular bedding is common, and the mudstone/siltstone to sandstone ratio typically ranges from 9:1 to 7:3. Sandstone units are primarily centimetre-scale in thickness, but millimetre- and decimetre-thick intervals are also present. Decimetre-thick intervals comprise amalgamated, simple bedsets. Basal contacts are sharp, show local evidence of scouring, and commonly display load structures. Sedimentary structures include horizontal to low-angle planar parallel lamination, curvilinear parallel lamination, local combined-flow ripples, and small-scale soft-sediment deformation. Centimetre-thick, normally graded sandstone beds are also common. Silty mudstone and muddy siltstone layers are millimetre- to decimetre-scale in thickness and locally display either sharp or gradational basal contacts. These layers commonly display normal grading, as well as normal to inverse grading, and typically drape underlying sandstone units (Fig. 3.3b). Millimetre- to centimetre-thick, organic-rich claystone units also constitute common features of the facies (Fig. 3.3a, b, d). These sharp-based units are sporadically distributed and regularly associated with sand-filled
syneresis cracks. Lithologic accessories include moderate amounts of organic detritus and plant fragments, as well as common, millimetre- to centimetre-thick siderite bands.

**Ichnology:**

Bioturbation is sporadically distributed throughout Facies 1a, and burrowing intensities are generally low (Fig. 3.3b, c). Many intervals are completely devoid of bioturbation. Silty mudstone and muddy siltstone beds typically possess bioturbation intensities that range from absent to rare (BI 0-2); however, isolated centimetre-thick intervals may show more extensive burrowing (BI 2-4). The trace-fossil suite commonly includes *Planolites*, *Thalassinoides*, *Teichichnus*, *Chondrites*, *Lockeia*, and *Phycosiphon*. Aforementioned zones of higher-intensity burrowing (Fig. 3.3a, d) may also include small numbers of *Asterosoma*, *Rosselia*, *Siphonichnus*, and *Helminthoida*. Sandstone units generally exhibit lower intensities of burrowing, ranging from absent to sparse (BI 0-1). The trace-fossil suite includes: rare *Phycosiphon*, *Arenicolites*, *Cylindrichnus*, *Palaeophybus*, *Lockeia* and fugichnia. Localized zones of higher-intensity burrowing may also include robust *Diplocraterion* and *Rhizocorallium* (Fig. 3.3a). Bioturbation in organic-rich claystone laminations/beds is primarily absent (BI 0). However, isolated *Planolites*, *Chondrites*, and navichnia are locally present. Overall, the trace-fossil suites are low diversity. Biogenic structures predominantly reflect deposit-feeding behaviours, with subordinate amounts of dwelling structures of inferred suspension-/filter-feeders and passive carnivores, as well as grazing structures. This suite reflects a stressed, archetypal expression of the *Cruziana* Ichnofacies (*cf.* MacEachern and Bann, 2008; MacEachern et al., 2012).

**Interpretation:**

The heterolithic character of Facies 1a reflects deposition in an environment with fluctuating energy and sedimentation rates. Siltstones and mudstones represent periods of suspension-sediment settling and/or clay flocculation, whereas sandstone units represent periods of coarser sediment influx. Sandstones are dominated by horizontal to low-angle planar parallel lamination and curvilinear lamination, interpreted to
Figure 3.3. Facies 1a: Sporadically bioturbated, interstratified sandstone, siltstone, mudstone, and organic-rich claystone. (A) Very fine- to fine-grained sandstone, interbedded/interlaminated with muddy siltstone and organic-rich claystone. Units show BI 1-4. Physical structures include local curvilinear lamination. Ichnogenera include Rhizocorallium (Rh), Diplocraterion (Di), Planolites (P), Chondrites (Ch), Siphonichnus (Si), Asterosoma (As), Palaeophycus tubularis (Pt), and Helminthopsis (H). Well 6-16-42-6W5, 1598.04m. (B) Very fine- to fine-grained sandstone, interbedded/interlaminated with muddy siltstone, and organic-rich claystone. Units show BI 0-1. Physical structures include wavy bedding, curvilinear lamination, syneresis cracks (syn), and normally and inversely graded beds. Ichnogenera include Palaeophycus tubularis (Pt), Siphonichnus (Si), Planolites (P), and Phycosiphon (Ph). Note the siderite band in the center of the photo. Well 6-16-42-6W5, 1598.75m. (C) Fine-grained sandstone interstratified with silty mudstone (BI 0-1). Sandstone layers are sharp based, apparently structureless (massive), and contain Phycosiphon (Ph). Muddy siltstone layers drape the sandstones and contain isolated Planolites (P) and navichnia (na). Well 15-34-42-6W5, 1507.0m. (D) Very fine- to fine-grained sandstone, interbedded with silty mudstone, muddy siltstone, and organic-rich claystone. Units exemplify the sporadic distribution of bioturbation, displaying BI 0-4. Ichnogenera include Teichichnus (T), Planolites (P), and Phycosiphon (Ph). Well 6-16-42-6W5, 1599.6m.
represent micro-hummocky cross-stratification (mHCS) generated by periodic storms and their associated wave processes (e.g., Dott and Bourgeois, 1982). Sharp bases of sandstone units, combined with locally observed mudstone rip-up clasts and loading structures, support the interpretation of high-energy, rapid deposition. Rare combined-flow ripples indicate the sporadic influence of subordinate, unidirectional sediment transport processes. Load casts and flame structures indicate that the sands were periodically emplaced onto less dense, water-saturated mud layers, resulting in differential loading and deformation of the underlying muds. Based on the presence of storm beds (tempestites), it is interpreted that deposition occurred above storm-weather wave-base. Normally graded sandstone and siltstone beds may record flood-generated hyperpycnal flows (e.g., Bhattacharya and MacEachern, 2009). Organic-rich claystone laminae are consistent with the bedload transport of fluid muds, wherein the muds accumulated via flocculation in the zone of fresh water and marine water mixing. Such bedload transport of mud may be consistent with longshore drift, tidal flow, or storm-induced geostrophic flow (e.g., Vakarelov et al., 2012; Dashtgard et al., 2012; Plint et al., 2012). Syneresis cracks are present, and reflect short-lived salinity changes immediately above the sea floor (e.g., Plummer and Gostin, 1981; Gingras et al., 1998; MacEachern et al., 2005). Common siderite banding is interpreted to reflect brackish-water conditions, generated by nearby fluvial discharge (e.g., Bhattacharya and Walker, 1991; Bhattacharya and MacEachern, 2009). Moderate amounts of organic detritus further support the hypothesis of enhanced fluvial influence in the marine realm (e.g., Leckie et al., 1989).

The sporadic distribution of bioturbation and overall low intensity of burrowing may be a result of high-energy conditions, elevated sedimentation rates, and/or periodic salinity reductions. Low diversity trace-fossil suites and reduced sizes of ichnogenera may also indicate salinity fluctuations (cf. Beynon et al., 1988; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; MacEachern and Gingras, 2007). The presence of navichnia (sediment-swimming structures; cf. Gingras et al., 2007) or mantle-and-swirl structures (Lobza and Schieber, 1999) within organic-rich claystone laminae supports a fluid-mud interpretation, and indicates the presence of soupground conditions at the sea floor. Based on sedimentology and ichnology, Facies 1a is interpreted to represent deposition within the distal to proximal prodelta of a river-dominated delta.
3.2.2. Facies 1b: Moderately Bioturbated, Interstratified Sandstone, Siltstone, Mudstone and Organic-Rich Claystone

Sedimentology:

Facies 1b ranges from about 0.8 to 1.1 metres in thickness, and comprises heterolithic, composite bedsets of lower very fine- to upper fine-grained sandstone, interbedded/interlaminated with silty mudstone, muddy siltstone, sandy siltstone and organic-rich claystone (Fig. 3.4a-e). Wavy to lenticular bedding is common, and the mudstone/siltstone to sandstone ratio ranges from 17:3 to subequal proportions, forming a sanding-upward succession. Sandstones vary from millimetre- to centimetre-scale thicknesses. Basal contacts are sharp with local evidence of scouring. Rare loading structures are present along sandstone-claystone contacts. Physical sedimentary structures include curvilinear parallel lamination, oscillation ripples, low-angle to horizontal planar parallel lamination, and very rare combined-flow ripples. Local expressions of the facies may contain centimetre-thick sandstone beds with normal grading. Silty mudstone, muddy siltstone, and sandy siltstone units are millimetre- to centimetre-scale in thickness with sharp basal contacts. These layers drape underlying sandstone beds and locally display zones of normal grading. Isolated, organic-rich claystone laminae are also present (Fig. 3.4a-c). These sporadically distributed units are sharp based with local evidence of scouring, and contain rare syneresis cracks. Lithologic accessories include moderate amounts of organic detritus, and millimetre-diameter mudstone rip-up clasts observed exclusively above the bases of some sandstone beds. Millimetre- to centimetre-thick siderite bands are also observed.

Ichnology:

Facies 1b displays variable bioturbation intensities at the bed scale. Bioturbation is sporadically distributed, with higher burrowing intensities associated with lithologically variable mudstones and siltstones (Fig. 3.4e), and lower intensities associated with sandstones and organic-rich claystone drapes (Fig. 3.4a). Silty mudstones, muddy siltstones and sandy siltstones display bioturbation intensities ranging from sparse to common (BI 1-4), but more typically are sparse to moderate (BI 1-3). Ichnogenera include Planolites, Thalassinoides, Teichichnus, Cylindrichnus, Siphonichnus, Chondrites, Zoophycos, Asterosoma, Rosselia, Rhizocorallium, Palaeophycus, Lockeia,
Phycosiphon, Helminthopsis, and Helminthoida. By comparison, sandstones exhibit reduced bioturbation intensities that range from absent to moderate (BI 0-3), but generally are absent to uncommon (BI 0-2). Trace-fossil suites contain common Cylindrichnus and Phycosiphon; subordinate Arenicolites, Palaeophycus, Lockeia and fugichnia, and rare Rhizocorallium, Asterosoma, Skolithos and Bergaueria. The majority of traces within sandstone units display top-down burrowing. Organic-rich claystone laminations are also present, and possess absent to sparse bioturbation (BI 0-1). Trace-fossil suites in organic-rich claystones consist of isolated Planolites, Chondrites and rare navichnia. Overall, the facies is characterized by low to moderate burrowing intensity (BI 0-4) with low to moderate diversities of ichnogenera. Biogenic structures predominantly reflect deposit-feeding behaviours, with subordinate numbers of dwelling structures of inferred suspension/filter-feeders, as well as rare grazing structures. This suite reflects a stressed, archetypal to proximal expression of the Cruziana Ichnofacies (cf. MacEachern and Bann, 2008; MacEachern et al., 2012).

Interpretation:

Facies 1b is lithologically and sedimentologically comparable to Facies 1a, indicating deposition in a broadly similar physical environment. However, subtle ichnological differences exist. The heterolithic character of the facies indicates deposition in an environment with alternating energy conditions and sedimentation rates. Lithologically variable mudstone and siltstone layers are consistent with suspension-sediment settling. These units display increased intensities of burrowing relative to Facies 1a, which is typical of slow, continuous sedimentation below fairweather wave-base (e.g., Bann et al., 2008). Sharp-based sandstones are interpreted as tempestites generated by periodic storms (Dott and Bourgeois, 1982). This indicates that deposition was above storm wave base.

Isolated organic-rich claystone laminae are consistent with fluid-mud layers and may be indicative of a nearby zone of fresh water and salt water mixing (Hovikoski et al., 2008). Syneresis cracks are ubiquitously associated with these layers, suggesting that concomitant salinity fluctuations occurred during fluid-mud deposition; such conditions suggest mud deposition associated with buoyant (hypopycnal) plumes (e.g., MacEachern et al., 2005, 2007). Normally graded sandstone and siltstone beds may
Figure 3.4. Facies 1b: Moderately bioturbated, interstratified sandstone, siltstone, mudstone, and organic-rich claystone. (A) Sandstone with interlaminated organic-rich claystone. Physical structures include low-angle to horizontal planar parallel lamination and curvilinear lamination. Ichnogenera include *Trichichnus* (Tr), *Arenicolites* (Ar), *Asterosoma* (As), *Planolites* (P), and *Phycosiphon* (Ph). Well 14-28-42-4W5, 1289.34m. (B) Very fine- to upper fine-grained sandstone, interbedded/interlaminated with muddy siltstone and organic-rich claystone. Unit shows BI 1-3. Ichnogenera include *Cylindrichnus* (Cy), *Phycosiphon* (Ph), *Palaeophycus tubularis* (Pt), and *Planolites* (P). Well 16-20-42-4W5, 1301.22m. (C) Sandstone, interlaminated/interbedded with organic-rich claystone and sandy mudstone. Physical structures include wavy bedding, horizontal to curvilinear lamination, and load casts (base of uppermost sandstone bed). Unit shows BI 0-3. Ichnogenera include *Planolites* (P), *Thalassinoides* (Th), *Chondrites* (Ch), *Cylindrichnus* (Cy), and navichnia (na). Well 14-28-42-4W5, 1288.93m. (D) Localized sandstone bed displaying *Rhizocorallium* (Rh). Well 12-31-42-3W5, 1298.0m. (E) Sandy mudstone overlying organic-rich claystone. Unit shows BI 1-2. Ichnogenera include *Thalassinoides* (Th) and *Planolites* (P). Well 14-28-42-4W5, 1289.19m.
record periodic, flood-generated hyperpycnal flows (*cf.* Bhattacharya and MacEachern, 2009). Moderate amounts of organic detritus provide further evidence of periodic fluvial influx (*e.g.*, Leckie et al., 1989). Increased bioturbation intensities with sporadic distributions are consistent with fluctuations in energy conditions and sedimentation rates. Reductions in ichnological diversity may indicate fluctuating salinity levels. Facies 1b is consistent with deposition in the distal to proximal prodelta of a mixed river- and wave-influenced delta.

### 3.3. Facies 2: Graded and Soft-Sediment Deformed, Interstratified Silty Sandstone, Siltstone and Organic-Rich Claystone

*Sedimentology:*

Facies 2 is gradationally based and ranges from 0.3 to 2.8 metres in thickness. The heterolithic unit is lithologically variable, consisting of varying proportions of interbedded silty sandstone, sandy siltstone and siltstone, with sporadically distributed organic-rich claystone laminae and thin beds (Fig. 3.5a-d). Siltstone to sandstone ratios are also highly variable, ranging from 7:3 to 3:17; but more typically 3:2 to 2:3 (*i.e.*, subequal proportions). In addition, both coarsening- and fining-upward successions are observed in separate expressions of the facies. Silty sandstone layers are sharp-based and range from millimetres to decimeters in thickness, though typically centimetre scale. Low-angle to horizontal, planar-parallel lamination, curvilinear-parallel lamination, soft-sediment deformation, apparently structureless (massive) bedding, starved current ripples, and current-ripple lamination comprise the dominant physical sedimentary structures. Sandy siltstone and siltstone layers are millimetres to decimeters thick, and display both sharp and gradational, basal contacts. Well-developed normal grading, soft-sediment deformation (Fig. 3.5a, d), micro-faulting, and horizontal planar parallel to curvilinear parallel lamination constitute the dominant physical sedimentary structures in these layers. Local decimetre-thick intervals display a pinstriped appearance, as normally and inversely graded, millimetre- to centimetre-thick layers rhythmically alternate, to form graded composite bedsets and laminations (Fig. 3.5b, c). Organic-rich claystones are sporadically distributed throughout the facies, typically increasing in
abundance upwards. Claystones are millimetres to centimetres thick, and are commonly associated with subaqueous shrinkage cracks (syneresis cracks). Lithologic accessories include moderate to abundant amounts of carbonaceous detritus and minor siderite cement.

**Ichnology:**

Facies 2 displays a general paucity in burrowing. Bioturbation is sporadically distributed, with intensities ranging from absent to sparse (BI 0-1). Ichnogenera include diminutive *Skolithos, Planolites, Palaeophycus, Chondrites, Lockeia*, and fugichnia. The common soft-sediment deformation in the facies commonly inhibits the identification of biogenic structures. Nevertheless, the trace-fossil suite is of low diversity, and consists primarily of facies-crossing, feeding and dwelling structures of inferred deposit feeders, suspension feeders and passive carnivores (in order of decreasing abundance). This is consistent with a stressed, archetypal to proximal expression of the *Cruziana* Ichnofacies (*cf.* MacEachern and Bann, 2008; MacEachern et al., 2012).

**Interpretation:**

Facies 2 reflects deposition in an environment with fluctuating energy conditions and/or sedimentation rates (*cf.* Gingras et al., 1998; Hansen and MacEachern, 2007; Bann et al., 2008). Local silty sandstone beds containing low-angle to horizontal planar parallel lamination and curvilinear parallel lamination are interpreted as episodically emplaced tempestites. This demonstrates that deposition occurred above storm wave base. Local starved-, combined-flow- and current-ripple lamination indicates the additional influence of current sediment transport processes. Soft-sediment deformation is common to the facies, and is attributed to rapid dewatering due to high sedimentation rates, degassing due to the burial of organic material, and/or slope failure in a delta-front setting (Gingras et al., 1998). Some normally graded siltstone and sandstone beds are interpreted to record hyperpycnal density underflows (e.g., Bhattacharya et al., 2007). Normally to inversely graded beds are interpreted as hyperpycnites (*cf.* Mulder et al., 2002; Bhattacharya and MacEachern, 2009), deposited during waxing and waning fluvial-driven sediment-gravity flows. Organic-rich claystone laminae and drapes are interpreted as fluid-mud layers. Syneresis cracks are common and support the probable
Figure 3.5. Facies 2: Graded and soft-sediment deformed, interstratified silty sandstone, siltstone, and organic-rich claystone. (A) Silty sandstone with abundant soft-sediment deformation. Well 1-19-43-2W5, 1136.57m. (B) Thinly interlaminated silty sandstone, siltstone, and muddy siltstone. Note the pinstriped appearance, as normally and inversely graded laminations rhythmically alternate to form graded composite bedsets. Ichnogenera include *Palaeophycus tubularis* (Pt) and fugichnia. Well 8-2-43-5W5, 1324.0m. (C) Interlaminated muddy siltstone, sandy siltstone, and silty sandstone. Physical structures include a composite, normally and inversely graded bedset, as well as curvilinear lamination, starved current ripples, current ripples, and combined-flow ripples. Well 8-2-43-5W5, 1324.05m. (D) Sandy siltstone with pervasive soft-sediment deformation. Well 16-16-41-6W5, 1587.92m.
hyperpycnal emplacement of local sand and mud layers (MacEachern et al., 2005; Bann et al., 2008; Bhattacharya and MacEachern, 2009). The near absence of biogenic structures is likely the result of a combination of stresses, including high-energy, heightened rates of deposition, soupground conditions associated with fluid mud, and salinity reductions. Where present, the ichnological assemblage is dominated by facies-crossing biogenic structures (cf. Gingras et al., 2007), consistent with stressed marginal-marine environments. Facies 2 is interpreted to represent deposition in a fluvially influenced, proximal prodelta to distal delta-front environment.

3.4. Facies 3: Sandstone

Facies 3 units consist of lower fine- to lower medium-grained sandstone. Beds are commonly amalgamated into simple, decimetre- to metre-thick bedsets, dominated by apparently structureless (massive) bedding, horizontal to low-angle planar parallel lamination (HCS), planar tabular and trough cross-stratification, and current-ripple lamination. Facies 3 has been subdivided into three subfacies, based on sedimentologic and ichnologic features.

3.4.1. Facies 3a: Apparently Structureless (Massive) to Planar Parallel Laminated Sandstone

Sedimentology:

Facies 3a ranges from 1.3 to 7.8 metres in thickness. The facies is predominantly sharp based, and comprises coarsening-upwards successions of moderately well-sorted, lower fine- to lower medium-grained sandstone (Fig. 3.6a-d). Beds are amalgamated into simple bedsets that range from decimetres to metres thick. Basal contacts are sharp and show local evidence of scouring. Apparently structureless (massive) bedding (Fig. 3.6a-c) and horizontal to low-angle planar parallel lamination (Fig. 3.6d) dominate the facies. Curvilinear-parallel- and oscillation-ripple-lamination are present in lesser abundances within lower portions of the succession. Rare trough and planar tabular cross-stratification are observed in centimetre- to decimetre-thick beds. Local occurrences of current ripples, soft-sediment deformation, and micro-faults are
also present. Millimetre- to centimetre-thick, organic-rich claystone partings may occur between some laminated units, but are relatively rare. These layers display sharp basal contacts and are commonly associated with subaqueous shrinkage cracks (i.e., syneresis cracks). Lithologic accessories include moderate to abundant amounts of organic detritus, millimetre- to centimetre-diameter mudstone rip-up clasts, and coal fragments. Organic detritus is mainly disseminated throughout sandstone beds, but also occurs as concentrated, millimetre- to centimetre-thick layers demarcating laminae. Less common pyrite nodules, shell fragments, and plant fragments are also present.

**Ichnology:**

Facies 3a displays sporadically distributed bioturbation, with intensities ranging from absent to moderate (BI 0-3), but more typically absent to rare (BI 0-2). Ichnogenera include *Macaronichnus*, *Rosselia*, *Diplocraterion*, *Rhizocorallium*, *Ophiomorpha*, *Cylindrichnus*, *Thalassinoides*, *Planolites*, and *fugichnia*. *Planolites* and *Thalassinoides* are exclusively associated with localized mudstone layers. *Rosselia* dwelling tubes (“stalks”) are typically in situ; however, mudballs are generally truncated and locally occur as rip-up clasts (Fig. 3.6a). Overall, the facies is characterized by a low diversity of ichnogenera. Biogenic structures are dominated by those associated with deposit-feeding behaviours, with rare dwelling structures of inferred suspension/filter-feeders. This suite reflects a stressed, proximal expression of the *Cruziana* Ichnofacies (*cf.* MacEachern and Bann, 2008; MacEachern et al., 2012).

**Interpretation:**

Apparently structureless (massive) intervals are common and may reflect high sedimentation rates with subsequent loading and dewatering, and/or storm-induced liquefaction (*cf.* Pettijohn and Potter, 1964; Blatt et al., 1980; Collinson and Thompson, 1982). Moderate amounts of soft-sediment deformation and micro-faulting support this interpretation. Amalgamated beds of horizontal to low-angle planar-parallel lamination are interpreted as hummocky cross-stratification (*cf.* Dott and Bourgeois, 1982). These sharp to erosively based units indicate that deposition occurred well above storm wave-base in a high-energy environment. Mudstone rip-up clasts, likely derived from erosion of buried fluid-mud layers, further support the interpretation of a high-energy, erosive
Figure 3.6. Facies 3a: Apparently structureless (massive) to planar parallel laminated sandstone. (A) Apparently structureless (massive) sandstone with an allochthonous *Rosselia* mud ball (Ro). Well 14-28-42-4W5, 1282.42m. (B) Apparently structureless (massive) sandstone with a single mudstone rip-up clast (ruc). Well 16-20-42-4W5, 1302.2m. (C) Apparently structureless (massive) sandstone. Well 14-28-42-4W5, 1287.32m. (D) Low-angle planar parallel laminated sandstone with an escape structure (fugichnia) disrupting laminae. Well 16-20-42-4W5, 1295.59m.
environment. Localized oscillation ripples are present near the tops of beds, reflecting deposition during waning storm conditions. Rare current-generated structures (e.g., trough and planar tabular cross-stratification) are indicative of migration of dune-scale bedforms. Claystone laminae draping beds are interpreted as fluid muds (e.g., Lobza and Schieber, 1999; Schieber, 2003) and indicate relative proximity to a source of freshwater and saltwater mixing (e.g., distributary discharge). Rare syneresis cracks associated with these layers may indicate short-lived salinity changes at or near the bed (e.g., Plummer and Gostin, 1981; Gingras et al., 1998). Local concentrations of carbonaceous material are interpreted as phytodetrital pulses (cf. Rice et al., 1986), considered to have been deposited by distributary discharge (MacEachern et al., 2005; Hansen, 2007; Bann et al., 2008). Moderate to abundant amounts of organic detritus, coal fragments, and plant fragments also support the presence of a nearby terrestrial sediment source (e.g., Leckie et al., 1989). Low intensities of bioturbation may indicate a combination of stresses, including elevated rates of sedimentation, increased energy conditions, and fluctuating salinities. Facies 3a is interpreted to represent deposition within a distal to proximal delta-front environment.

**3.4.2. Facies 3b: Cryptically Bioturbated to Bioturbated Sandstone**

*Sedimentology:*

Facies 3b (Fig. 3.7a-d) ranges from 0.4 to 5.8 metres in thickness, and displays both sharp and gradational basal contacts. Beds are amalgamated, forming simple, decimetre- to metre-scale bedsets consisting of upper fine- to lower medium-grained, moderately well-sorted sandstone. Apparently structureless (massive) bedding dominates the facies. Local, centimetre- to decimetre-thick intervals may display low-angle to horizontal planar parallel lamination, as well as trough and planar tabular cross-stratification. Laminae within stratified intervals commonly possess a “fuzzy” fabric imparting a slightly blurred appearance. Lithologic accessories include moderate amounts of carbonaceous detritus, disseminated throughout sandstone beds and locally demarcating laminae.

*Ichnology:*

56
Bioturbation is sporadically distributed and intensities are highly variable, ranging from sparse to abundant (BI 1-5). Monospecific assemblages of *Macaronichnus* are a distinct feature of the facies (Fig. 3.7b, c), and commonly result in complete obliteration of primary sedimentary structures. Root structures may also occur near the top of the facies (Fig. 3.7d).

**Interpretation:**

Apparently structureless (massive) bedding may be the result of high sedimentation rates with subsequent loading and dewatering, storm-induced liquefaction, and/or complete biogenic reworking (Reading and Collinson, 1996). Given the lack of associated soft-sediment deformation, biogenic homogenization may be most likely cause of the structureless appearance. Intercalated layers of low-angle cross-stratification are indicative of traction transport by a unidirectional flow and the migration of low-amplitude dune-scale bedforms (*cf*. Boggs, 2001). Parallel lamination also suggests unidirectional flow and represents periodic decreases in water depth or increases in overall flow velocity. Stratified intervals displaying a “fuzzy” or slightly blurred appearance are interpreted to represent cryptobioturbation (Fig. 3.7a), resulting from intense reworking by meiofauna with subtle disruption of the original sedimentary fabric (*cf*. Howard and Frey, 1973, 1975; Pemberton et al., 2008). *Macaronichnus segregatis* is representative of deep-tier, deposit-feeding behaviours, commonly associated with higher energy regimes (Coates, 2001; Bann et al., 2008). Previous authors characterize this suite as a “toe-of-the-beach” assemblage (*cf*. Saunders et al., 1994; MacEachern et al., 1999; Pemberton et al., 2001). Root traces are observed exclusively near the top of the facies and indicate subsequent subaerial exposure. This facies is consistent with deposition in the swash and backwash zone of the foreshore environment of shorefaces and proximal delta fronts.
Figure 3.7. Facies 3b: Cryptically bioturbated to bioturbated sandstone. (A) Cryptically bioturbated sandstone. Well 6-31-42-4W5, 1293.56m. (B) Bioturbated sandstone with visible *Macaronichnus segregatis* (Ma). The unit shows BI 4-5. Well 16-20-42-4W5, 1289.55m. (C) Bioturbated sandstone with visible *Macaronichnus segregatis* (Ma). The unit shows BI 3-5. Well 14-28-42-4W5, 1277.86m. (D) Apparently structureless (massive) sandstone with root traces (Rt). Well 6-31-42-4W5, 1288.75m.
3.4.3. Facies 3c: Cross-Stratified to Rippled Sandstone

Sedimentology:

Facies 3c (Fig. 3.8a-d) ranges from 0.4 to 5.3 metres in thickness and displays sharp, erosive basal contacts. The unit comprises lower fine- to lower medium-grained sandstones that commonly coarsen-upwards; however, fining-upward successions occur locally. Siltstone and organic-rich claystone layers are also moderately common (Fig. 3.8c). Individual, centimetre- to decimetre-thick sandstone beds are typically erosionally amalgamated into simple bedsets. Internal scour surfaces may be delineated by slightly coarser-grained sediment, millimetre- to centimetre-diameter mudstone rip-up clasts and siderite nodules, as well as truncation of underlying laminae (Fig. 3.8d). Physical sedimentary structures are dominated by trough and planar tabular cross-stratification, as well as current-ripple lamination. Aggradational current ripples, starved current ripples, oscillation ripples, combined-flow ripples, apparently structureless (massive) layers, micro-faults, and small-scale convolute bedding are also present in lesser amounts. Lithologic accessories include moderate to abundant amounts of carbonaceous debris (Fig. 3.8a) and spherulitic siderite (Fig. 3.8b), typically marking foresets of ripple- and dune-scale cross-stratification. Millimetre- to centimetre-diameter mudstone rip-up clasts and coal fragments are also very common. Thin organic-rich claystone drapes locally contain rare syneresis cracks.

Ichnology:

Bioturbation is sporadically distributed, and intensities range from absent to rare (BI 0-2). Burrowing is most prevalent within siltstone and claystone layers, with common ichnogenera including Planolites, Thalassinoides, and Chondrites. Burrowing is much less common in sandstone units, and ichnogenera include very rare Skolithos, Arenicolites, Diplocraterion, Cylindrichnus, Palaeophycus and Macaronichnus. Overall, the trace-fossil suite displays low diversity, and is dominated by facies-crossing ichnogenera. The assemblage is attributable to a stressed, proximal expression of the Cruziana Ichnofacies (cf. MacEachern and Bann, 2008; MacEachern et al., 2012).

Interpretation:
Sharp to erosive basal contacts, combined with the abundance of sandstone, point to a high-energy environment characterized by elevated flow velocities. Cross-stratification and current-ripple lamination dominates, illustrating the prevalence of traction-sediment transport by quasi-steady unidirectional flows and the migration of dune- and ripple-scale bedforms, respectively. Aggradational current-ripples indicate periodic increases in sedimentation rate. Local, apparently structureless (massive) layers and convolute bedding further support rapid sedimentation and deposition, with subsequent loading and dewatering. Oscillation and combined-flow ripples are also present and demonstrate the influence of basinal processes (e.g., waves) on deposition (at least periodically). Thinly interbedded siltstone layers are interpreted to reflect rare preservation of sediments deposited by suspension settling during periods of decreased energy conditions. Organic-rich claystone laminae are consistent with fluid mud layers (e.g., Lobza and Schieber, 1999; Schieber, 2003; MacEachern et al., 2005; Hovikoski et al., 2008) and may indicate the mixing of freshwater with marine water resulting in mud flocculation. Syneresis cracks are also present and reflect short-lived salinity changes within the depositional setting (Plummer and Gostin, 1981; Gingras et al., 1998). Moderate to abundant amounts of organic detritus and spherulitic siderite point to a nearby terrestrial sediment source (e.g. Leckie et al., 1989). The lack of bioturbation corresponds to a stressed depositional setting (e.g., salinity fluctuations, high sedimentation rates, high-energy conditions, and episodic deposition, among others). Based on sedimentology and ichnology, Facies 3c is interpreted to represent deposition within a terminal distributary channel/mouth-bar complex.
Figure 3.8. Facies 3c: Cross-stratified to rippled sandstone. (A) Fine- to lower medium-grained sandstone. Physical structures include current ripples, combined-flow ripples, and curvilinear lamination. Foresets are marked by organic detritus. Well 8-2-43-5W5, 1322.05m. (B) Low-angle, cross-stratified sandstone. Note the presence of spherulitic siderite. Well 15-34-42-6W5, 1503.83m. (C) thinly interlaminated sandstone and muddy siltstone (BI 0-1). Physical structures include curvilinear lamination, current ripples, starved current ripples, combined-flow ripples, and microfaults (mf). Ichnogenera include Chondrites (Ch), Palaeophycus tubularis (Pt), and Planolites (P). Well 15-34-42-6W5, 1500.6m. (D) Erosive base of Facies 3c. Note the presence of slightly coarser-grained sediment, as well as the abundance of mudstone rip-up clasts and siderite nodules. Well 8-2-43-5W5, 1322.67m.
3.5. Facies 4: Pebbly Sandstone to Pebble Conglomerate

*Sedimentology / Ichnology:*

Facies 4 ranges from 0.1 to 1.5 metres in thickness and displays sharp and erosional basal contacts. The unit is moderately well to well sorted and comprises a continuum from pebbly sandstone to clast-supported pebble conglomerate (Fig. 3.9a-d). Consequently, pebble contents are highly variable, ranging from 5 to 40% within centimetre- to decimetre-thick beds. Individual beds display evidence of scouring at their bases, and are amalgamated into simple bedsets. Pebble clasts are millimetre- to centimetre-scale in diameter (long axis), predominantly subrounded to rounded, and display moderate to high sphericity. Clast compositions are variable, comprising chert, argillite, mudstone, sandstone, siderite and coal. Sand within the pebbly sandstones and conglomerate matrix ranges from lower medium to upper coarse grained. Planar tabular cross-stratification, trough cross-stratification, and apparently structureless (massive) bedding dominate the facies. Pebbles commonly mark or delineate bedform foresets (Fig. 3.9a-c). Lithologic accessories include moderate amounts of disseminated organic detritus and millimetre- to centimetre-diameter mudstone rip-up clasts and coal fragments (Fig. 3.9d). This facies shows no evidence of bioturbation (BI 0).

*Interpretation:*

Sharp to erosive basal contacts, combined with a dominance of pebble-sized clasts and coarse-grained sediment, indicate deposition under high-energy conditions. Flow velocities were sufficiently high to entrain the large-diameter clasts, and periodically winnow fine and intermediate sediment calibres from the bed (cf. Boggs, 2001; Kleinhans, 2005). The subrounded to rounded nature of pebble clasts support long-transport distances from the source terrain, likely by rivers. Common trough- and planar-tabular cross-stratification indicates traction transport by a quasi-steady unidirectional flow, and the migration of dune-scale bedforms. Moderate amounts of organic detritus and coal fragments suggest a nearby terrestrial source (e.g., Leckie et al., 1989). The absence of bioturbation supports the interpretation of a high-energy,
Figure 3.9. Facies 4: Pebbly sandstone to pebble conglomerate. (A) Cross-stratified pebbly sandstone with compositionally variable clasts delineating the foresets. Well 2-3-42-9W5, 1679.5m. (B) Same description as previous. Well 6-13-42-6W5, 1453.32m. (C) Same description as previous. Well 14-33-42-8W5, 1548.96m. (D) Pebble conglomerate to pebbly sandstone. Note the sharp basal contact and the presence of coal fragments. Well 11-17-44-9W5, 1578.57m.
highly stressed, depositional environment. Facies 4 is interpreted to represent channel-floor lags and/or the lower sandy deposits of active fluvial channels.

3.6. Facies 5: Cross-Bedded Sandstone

Sedimentology / Ichnology:

Facies 5 ranges from 0.7 to 10.0 metres in thickness and displays sharp, erosional basal contacts. The unit consists of centimetre- to decimetre-thick beds of moderately well-sorted sandstone. Sediment calibres range from upper fine- to lower coarse-grained, and generally fine upwards. Individual beds display sharp and locally scoured contacts, and are amalgamated into simple bedsets. Low- to high-angle, planar tabular and trough cross-stratification are the dominant sedimentary structures (Fig. 3.10a-d). Locally, centimetre- to decimetre-thick beds appear structureless (massive), or locally show current-ripple lamination, horizontal planar-parallel lamination, curvilinear lamination, and/or small-scale convolute bedding. Moderate to abundant amounts of organic detritus are dispersed throughout the facies, commonly marking laminae (Fig. 3.10a, b, d). Dispersed pebbles may also be present, particularly where the unit overlies Facies 4. Millimetre- to centimetre-scale siderite nodules (Fig. 3.10d), coal fragments and mudstone rip-up clasts are sporadically distributed. They occur as isolated stringers, as clasts marking laminae, or as centimetre- to decimetre-thick beds of mudstone-clast breccia. Drapes of millimetre-diameter mudstone rip-up clasts and organic detritus are locally paired, and separated by a thin sandstone layer (Fig. 3.10a). Such drapes are sporadically distributed, isolated, and present in very low abundances. Bioturbation is absent in this facies (BI 0). Root structures are observed locally, restricted to the top of the facies interval.

Interpretation:

The unit is dominated by trough- and planar-tabular cross-stratification, indicating traction sediment transport by quasi-steady unidirectional flow, and the migration of dune-scale bedforms. The sharp to erosional base of the unit, combined with the predominance of a coarse sediment calibre, dune-scale structures, coal fragments,
Figure 3.10. Facies 5: Cross-bedded sandstone. (A) Trough cross-bedded sandstone. Yellow arrows denote potentially paired drapes of millimetre-diameter mudstone rip-up clasts and organic detritus. Well 16-16-41-6W5, 1584.93m. (B) Trough cross-bedded sandstone. Millimetre-diameter mudstone rip-up clasts and organic detritus mark foresets. Well 8-17-42-6W5, 1598.50m. (C) Planar-tabular cross-bedded sandstone. Well 12-13-43-6W5, 1401.22m. (D) Trough cross-bedded sandstone with centimetre-scale diameter siderite nodules. Carbonaceous debris and millimetre-diameter mudstone rip-up clasts mark foresets. Well 16-16-41-6W5, 1581.23m.
dispersed pebbles, and mudstone rip-up clasts, indicates a high-energy environment with high flow velocities. Horizontal planar-parallel lamination reflect unidirectional sheet-flow conditions, and indicates periodic decreases in water depth or increases in overall flow velocity. Localized current-ripple lamination may indicate periodic decreases in flow velocity. The fining-upward tendency of the facies implies that energy conditions decreased over the period of deposition. Moderate to abundant amounts of organic detritus, spherulitic siderite, and siderite nodules are considered indicative of a nearby terrestrial sediment source (e.g., Leckie et al., 1989). Paired drapes that are separated by thin sandstone layers are interpreted as mud couplets, and may indicate tidal influence within the depositional environment (cf. Visser, 1980; Nio and Yang, 1991). The lack of bioturbation is interpreted as a response to a highly stressed depositional setting (e.g., low salinity, high sedimentation rates). Root structures demonstrate that subaerial exposure occurred following deposition. Facies 5 is interpreted to represent the migration of dune-scale bedforms within fluvial or crevasse channels.

3.7. Facies 6: Cross-Bedded Sandstone with Sporadically Bioturbated Mudstone Laminae

**Sedimentology:**

Facies 6 (Fig. 3.11a-d) ranges from 4.5 to 5.0 metres in thickness and overlies an erosional basal contact. Sediment calibres range from lower fine- to lower medium-grained, and fine upward. Individual beds display sharp basal contacts with local evidence of scouring, and are amalgamated into composite bedsets. Low-angle, planar tabular and trough cross-stratification, as well as, apparently structureless (massive) bedding are common. Centimetre- to decimetre-thick beds also display current-ripple lamination, horizontal planar-parallel lamination, curvilinear lamination, and small-scale convolute bedding. Low to moderate amounts of organic detritus are dispersed throughout the facies, commonly marking laminae (Fig. 3.11b). Millimetre- to centimetre-scale siderite nodules, coal fragments, mudstone rip-up clasts, and shell fragments are sporadically distributed. Millimetre-diameter mudstone rip-up clasts and organic detritus, locally paired and separated by a thin sandstone layer, periodically mantle stratification. These are present in low abundances, however. Millimetre- to
centimetre-thick (up to 2 cm), silty to sandy mudstone beds are sporadically distributed within the facies, locally constituting centimetre-scale intervals of wavy-bedding (Fig. 3.11a). These layers tend to increase in abundance upwards and contain isolated syneresis cracks. Root structures are observed locally, and are restricted to the top of the facies (Fig. 3.11c).

**Ichnology:**

Bioturbation is sporadically distributed, with burrowing restricted to the mudstone layers and close-proximity sandstone beds. Bioturbation intensities range from absent to moderate (BI 0-3), and ichnogenera include *Cylindrichnus, Palaeophycus, Planolites* and *Lockeia*. Rarely, bioturbation is represented by a mottled fabric, and discrete trace fossils are not apparent. Overall, the trace-fossil suite displays low diversity and contains traces that comprise facies-crossing forms (cf. MacEachern and Bann, 2008; MacEachern et al., 2012).

**Interpretation:**

The presence of planar tabular and trough cross-stratification indicates traction transport by quasi-steady, unidirectional flows, and the migration of dune-scale bedforms. Apparently structureless and convolute bedded intervals suggest periods of rapid sedimentation/deposition with subsequent loading and dewatering. The erosional base of the facies, combined with dune-scale structures, coal fragments and mudstone rip-up clasts, indicates a high-energy environment with high flow velocities. Silty and sandy mudstone layers support deposition via suspension sediment settling and/or clay flocculation, and may imply periodic decreases in flow velocity. Syneresis cracks are locally present within these units and support short-lived salinity changes (e.g., Plummer and Gostin, 1981; Gingras et al., 1998; MacEachern and Gingras, 2007), possibly through the mixing of salt- and fresh-water. The fining-upwards profile suggests overall decreasing flow conditions during deposition. Low to moderate amounts of organic detritus and siderite nodules are indicative of a terrestrial sediment source (e.g., Leckie et al., 1989). Paired mudstone drapes separated by thin sandstone layers are interpreted as double drapes and support tidal influence (cf. Visser, 1980; Nio and Yang, 1991). The low-diversity trace-fossil suite, consisting of facies-crossing elements, also
Figure 3.11. Facies 6: Cross-bedded sandstone with sporadically bioturbated mudstone laminae. (A) Lower fine- to lower medium-grained sandstone with interlaminated sandy mudstone. Units show BI 0-3. Physical structures include wavy bedding, curvilinear lamination, and apparently structureless (massive) bedding. Trace fossil suite is dominated by *Cylindrichnus* (Cy), but also includes *Planolites* (P), *Palaeophycus tubularis* (Pt), and *Lockeia* (Lo). Well 16-35-42-5W5, 1320.84m. (B) Low-angle, cross-stratified sandstone. Note the abundance of carbonaceous debris marking foresets. Well 8-2-43-5W5, 1315.25m. (C) Apparently structureless (massive) sandstone with an isolated sandy siltstone bed. Note the root traces (Rt). Well 16-35-42-5W5, 1318.57m. (D) Apparently structureless (massive) sandstone. Well 8-2-43-5W5, 1313.03m.
indicates brackish-water conditions (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern and Gingras, 2007). Facies 6 is interpreted to represent deposition within fluvio-estuarine distributary channels.

### 3.8. Facies 7: Current-Ripple Laminated Sandstone

**Sedimentology:**

Facies 7 (Fig. 3.12a-d) ranges from 0.6 to 1.8 metres in thickness, and displays both sharp and erosional basal contacts. The unit is characterized by amalgamated beds of current-ripple laminated sandstone (Fig. 3.12a, c, d). Rare siltstone or silty mudstone interbeds are locally present (Fig. 3.12b). Sandstones range from upper very fine- to lower medium-grained, and locally form successions that fine upwards. Individual beds are centimetre- to decimetre-thick, display sharp basal contacts, and commonly form simple bedsets. In addition to current-ripple lamination, sandstone beds display minor amounts of curvilinear lamination, trough cross-stratification, aggradational current-ripple lamination and small-scale convolute bedding. Isolated couplets of siltstone and carbonaceous drapes locally mark the foresets of current ripples. Rare flasers are also observed within ripple troughs, although these are present in low abundances. Siltstone and silty mudstone beds are centimetre-scale in thickness and display gradational or sharp basal contacts. The layers drape underlying sandstone beds and locally exhibit parallel and curvilinear lamination, as well as small-scale convolute bedding. Lithologic accessories include moderate to abundant amounts of organic detritus that commonly mark foresets of current ripples, as well as elongate, millimetre- to centimetre-scale mudstone rip-up clasts.

**Ichnology:**

Facies 7 is characterized by sporadically distributed bioturbation, with intensities ranging from absent to rare (BI 0-2), but more typically absent to sparse (BI 0-1). Ichnogenera include common *Naktodemasis* and root structures (Fig. 3.12a); rare *Planolites*; and very rare *Skolithos* (Fig. 3.12b) and *Palaeophycus*. Burrowing is predominantly restricted to siltstone and silty mudstone layers; however, *Naktodemasis*
and root structures can transect all lithologies. Overall, the ichnological assemblage displays low diversities and contains elements consistent with the *Scoyenia* Ichnofacies.

*Interpretation:*

The dominant sedimentary structures reflect traction transport and deposition resulting from quasi-steady, unidirectional currents. Current-ripple lamination indicates the migration of ripples under lower flow regime conditions. Aggradational current-ripple lamination points to traction transport coupled with increases in sedimentation rates at the bed. Local trough cross-stratification suggests the periodic migration of dune-scale bedforms. Silty mudstone drapes are interpreted as rare periods of decreased energy conditions that allowed suspension sediment settling and/or clay flocculation and accumulation. Moderate to abundant amounts of organic detritus may reflect a terrestrial sediment source (e.g., Leckie et al., 1989). Mud couplets are interpreted as double mudstone drapes and coupled with isolated occurrences of flaser bedding, may be indicative of tidal influence (cf. Visser, 1980; Nio and Yang, 1991). The designation of the *Scoyenia* Ichnofacies implies deposition in a low-energy continental environment characterized by alternating subaerial and subaqueous conditions (Buatois and Mángano, 1995; MacEachern et al., 2007b; MacEachern et al., 2010; Buatois and Mángano, 2011). Common root traces and *Naktodemasis* are indicative of subaerial exposure, growth of vegetation, and incipient soil development (cf. Smith et al., 2008; Counts and Hasiotis, 2009). Potential depositional environments for Facies 7 include lower to middle portions of fluvial, distributary, or crevasse channels, channel-bar complexes, and crevasse splays.
Figure 3.12.  Facies 7: Current-ripple laminated sandstone. (A) Upper very fine- to upper fine-grained sandstone. Physical structures include current-ripple lamination, curvilinear lamination, and aggradational current ripples. Ichnogenera include abundant root traces (Rt). Well 6-16-42-6W5, 1575.78m. (B) Lower fine- to upper fine-grained sandstone with siltstone laminae. Physical structures include curvilinear lamination and small-scale soft-sediment deformation (ssd). A single, mud-lined *Skolithos* (S) is present. Well 8-24-42-7W5, 1568.28m. (C) Upper fine- to lower medium-grained sandstone. Note the abundance of organic detritus marking the foresets of current ripples. Well 2-3-42-9W5, 1669.10m. (D) Upper very fine- to lower fine-grained sandstone. Physical structures include current-ripple lamination, curvilinear lamination, and small-scale convolute bedding. Well 10-32-41-4W5, 1287.20m.
3.9. Facies 8: Root-Bearing and Sporadically Bioturbated, Interstratified Sandstone and Siltstone

**Sedimentology:**

Facies 8 ranges from 0.2 to 1.2 metres in thickness and locally displays either gradational or sharp-based contacts. Units comprise heterolithic, composite bedsets of thinly interstratified sandstones and siltstones (Fig. 3.13a-d). More specifically, the units comprise sandstone, silty sandstone, sandy siltstone and clayey siltstone layers. Sandstone to siltstone ratios range from 9:1 to subequal proportions, and fine upwards. Sandstone grain sizes are variable and range from lower very fine- to upper medium-grained, locally alternating within individual beds (Fig. 3.13a). Sandstone and silty sandstone units range from centimetre- to decimetre-scale in thickness, displaying sharp basal contacts with local evidence of scouring and loading. Current ripples, curvilinear lamination, and convolute bedding are common, with rare trough cross-stratification and low-angle planar parallel lamination. Sandy siltstone and clayey siltstone units are millimetre- to centimetre-scale in thickness with sharp basal contacts. The layers drape underlying sandstone/silty sandstone beds and display horizontal planar parallel to curvilinear laminae, apparently structureless (massive) bedding, and convolute bedding. Convolute-bedded intervals result in thin, discontinuous, and irregularly oriented laminae. Lithologic accessories include moderate to abundant amounts of disseminated organic detritus, coal fragments, and mudstone rip-up clasts.

**Ichnology:**

Bioturbation within Facies 8 is sporadically distributed. Intensities range from absent to common (BI 0-4), but are more typically sparse to moderate (BI 1-3). Root structures, *Taenidium* and *Naktodemasis* dominate the trace-fossil suite (Fig. 3.13b-c), with very rare *Planolites, Thalassinoides* and *Palaeophycus* present locally. Overall, the ichnological assemblage is characterized by low diversity, and dominated by elements consistent with the *Scoyenia* Ichnofacies.

**Interpretation:**
The heterolithic character of this facies implies deposition in an environment with alternating periods of suspension sediment settling and/or clay flocculation (clayey and sandy silt deposition), as well as periods of coarser sediment influx (silty sandstone and sandstone deposition). The sharp bases of sandstone units support the interpretation of intermittent rapid deposition, whereas the draping of siltstone units supports the interpretation of periodic relative quiescence. Current ripples and trough cross-stratification demonstrate traction transport by a quasi-steady unidirectional flow and the migration of ripple- and dune-scale bedforms, respectively. Low-angle planar parallel lamination is also suggestive of unidirectional flow, and indicates periodic decreases in water depth or increases in overall flow velocity. Moderate to abundant amounts of mudstone rip-up clasts also indicate a high-energy environment with associated scour. Convolute bedding demonstrates periods of rapid sedimentation and deposition with subsequent loading and dewatering. Moderate to abundant amounts of organic detritus may reflect a terrestrial sediment source (e.g., Leckie et al., 1989). The designation of the *Scoyenia* Ichnofacies implies deposition in a low-energy continental environment, characterized by alternating subaerial and subaqueous conditions (Buatois and Mángano, 1995, 2011; MacEachern et al., 2007b; MacEachern et al., 2010). Abundant amounts of root traces and *Naktodemasis* indicate subaerial exposure, growth of vegetation, and incipient soil development (cf. Smith et al., 2008; Counts and Hasiotis, 2009). Facies 8 is interpreted to represent upper channel-margin or levee deposits, subaerially exposed and locally pedogenically modified.
Figure 3.13. Facies 8: Root-bearing and sporadically bioturbated, interstratified sandstone and siltstone. **(A)** Lower fine- to lower medium-grained sandstone with interlaminated muddy siltstone. Physical structures include curvilinear lamination, current ripples, and small-scale convolute bedding. Note the variable grain size between beds. Units display BI 0. Well 16-34-41-5W5, 1373.79m. **(B)** Heterolithic interval of thinly interstratified sandstone and muddy siltstone. Units show BI 0-2. Physical structures include small-scale convolute bedding and curvilinear lamination. Ichnogenera include *Taenidium* (Ta). Well 8-24-42-7W5, 1567.0m. **(C)** Upper very fine- to upper fine-grained sandstone interlaminated/interbedded with muddy siltstone. Units show BI 0-3. Physical structures include curvilinear lamination and local intervals of apparently structureless (massive) bedding. Ichnogenera include common root traces (Rt), *Naktodemasis* (Nk) and possible *Taenidium* (Ta). Well 6-16-42-6W5, 1575.62m. **(D)** Heterolithic, composite bedset of interlaminated/interbedded sandstone and muddy siltstone. Units show BI 0-2. Physical structures include small-scale convolute bedding and curvilinear lamination. Ichnogenera include possible *Planolites* (P) and *Thalassinoides* (Th), as well as root traces. Well 14-2-42-6W5, 1481.16m.
3.10. Facies 9: Fining-Upward, Interstratified Sandstone and Siltstone and Apparently Structureless (Massive) Mudstone

*Sedimentology:*

Facies 9 (Fig. 3.14a-e) ranges from 0.5 to 2.9 metres in thickness and predominantly displays gradational basal contacts, although occurrences with sharp-based contacts are also observed locally. The unit is lithologically variable, but repeatedly forms fining-upward successions. Very fine- to upper fine-grained sandstones pass upwards intergradationally into siltstones, silty mudstones and carbonaceous-rich mudstones. Transitional intervals include interbedded to interlaminated sandstones and mudstones (Fig. 3.14b, e), as well as various admixtures of interstitial sand, silt and mud. Sandstone layers are sharp-based, with local evidence of scouring and loading. Units are millimetres to decimetres in thickness. Sedimentary structures are dominated by current-ripple lamination, with common curvilinear lamination, combined-flow ripples, aggradational current ripples, and small-scale convolute bedding. Mudstone and siltstone layers are also sharp based with local evidence of scouring and loading, and are millimetres to decimetres in thickness. Apparently structureless (massive) bedding and soft-sediment deformation dominate these units. One expression of the facies contains a decimetre- to metre-thick interval of horizontal lamination that consists of rhythmic alternations of very fine-grained sandstone and siltstone/mudstone (Fig. 3.14d). Organic-rich claystone laminae are also a common feature of the facies (Fig. 3.14e). These sharp-based units are sporadically distributed and locally associated with sand-filled syneresis cracks. Lithologic accessories include irregularly shaped siderite nodules within mudstone intervals, and moderate amounts of carbonaceous detritus dispersed throughout the facies.

*Ichnology:*

Facies 9 contains sporadically distributed bioturbation, with intensities ranging from absent to moderate (BI 0-3); but more typically absent to uncommon (BI 0-2). Burrowing appears to be confined to the sandstone and heterolithic intervals, although this may be a reflection of the massive- and convolute-bedded character of the thicker
mudstone layers, which makes it difficult to distinguish any biogenic structures. Sandstone layers contain rare to locally common abundances of mud-lined *Skolithos* and *Diplocraterion*, mud-filled *Cylindrichnus* and *Trichichnus*, as well as *Palaeophycus* and *Arenicolites*. The majority of these burrows are diminutive and subtend from overlying siltstone and mudstone layers. Local beds may display monospecific assemblages of mud-filled *Trichichnus*. In addition, *Teredolites* occurs locally in allochthonous coal fragments (Fig. 3.14c). Siltstone and mudstone layers contain common *Planolites*, with rare *Cylindrichnus* and *Lockeia*. Additionally, a single occurrence of a trace-fossil suite attributable to the *Glossifungites* Ichnofacies marks the boundary between a sandstone unit and the underlying mudstones. Firmground *Skolithos* and *Arenicolites* constitute the dominant ichnogenera. The trace-fossil suite displays low diversity, and is dominated by elements of the *Skolithos* Ichnofacies with subordinate elements of *Cruziana* Ichnofacies. This suite is attributable to a stressed, distal expression of the *Skolithos* Ichnofacies (cf. MacEachern and Bann, 2008; MacEachern et al., 2010; MacEachern et al., 2012).

**Interpretation:**

The heterolithic character of this facies implies deposition in an environment with alternating periods of suspension sediment settling and/or clay flocculation (silty mud and mud deposition) with periods of coarser sediment influx (sandstone deposition). The fining-upwards tendency of the facies, combined with the relative absence of sandstones in middle to upper portions, is indicative of marked reductions in energy over the period of deposition. Local sandstones are sharp based, supporting the interpretation of rapid deposition. Current ripples dominate these units, and indicate traction transport by quasi-steady unidirectional flows and the migration of ripple-scale bedforms. Aggradational current ripples illustrate temporary increases in sedimentation rates at the bed. Curvilinear lamination and combined-flow ripples point to the periodic influence of oscillatory processes on deposition. Siltstones and mudstones thicken upwards, suggesting a transition to a quiet-water setting. Convolute bedding is common throughout the facies and points to rapid sedimentation and deposition with subsequent loading and dewatering. Organic-rich claystone laminae are consistent with fluid muds (e.g., Lobza and Schieber, 1999; Schieber, 2003; MacEachern et al., 2005; Hovikoski et
Figure 3.14. Facies 9: Fining-upward, interstratified succession of sandstone and siltstone and apparently structureless (massive) mudstone. (A) Lower to upper fine-grained sandstone, with moderate amounts of carbonaceous detritus. Physical structures include current ripples, aggradational current-ripples and curvilinear lamination. Well 6-31-42-4W5, 1302.28m. (B) Heterolithic interval, comprising thinly interstratified sandstone and silty mudstone. Units display BI 0-3. Physical structures include curvilinear lamination and combined-flow ripples. Trace-fossil suite consists of Diplocraterion (D), Arenicolites (Ar), Palaeophycus tubularis (Pt), Cylindrichnus (Cy), Planolites (P), and navichnia (na). Well 6-19-43-4W5, 1298.35m. (C) Silty sandstone with curvilinear lamination and current-ripples. Note the allochthonous coal fragment that contains Teredolites (Td). Well 1-19-43-2W5, 1135.44m. (D) Horizontal lamination, rhythmically alternating between very fine-grained sandstone and siltstone. Well 16-31-42-4W5, 1290.85m. (E) Lower to upper fine-grained sandstone with interlaminated siltstone and organic-rich claystone. Units show BI 0-2. Physical structures include curvilinear lamination and small-scale convolute bedding. Ichnogenera include Skolithos (S), Trichichnus (Tr), Palaeophycus tubularis (Pt), and Planolites (P). Well 6-31-42-4W5, 1301.26m.
al., 2008) and may indicate the mixing of freshwater with marine water, promoting mud flocculation. Syneresis cracks are also present and may indicate short-lived salinity changes within the setting (e.g., Plummer and Gostin, 1981; Gingras et al., 1998; MacEachern et al., 2005). The low-diversity trace-fossil suite consisting of relatively diminutive traces may indicate brackish-water conditions (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern et al., 2005; MacEachern and Gingras, 2007). Where present, rhythmic alternations of horizontally laminated sandstone and siltstone are interpreted to be tidal rhythmites (cf. Dalrymple, 2010). The firmground Glossifungites Ichnofacies indicates erosional exhumation of the substrate, and demarcates a discontinuity (cf. MacEachern et al., 2007b; MacEachern et al., 2010; MacEachern et al., 2012). Facies 9 is interpreted to reflect the gradual abandonment of terminal distributary channel/mouth-bar complexes or fluvio-estuarine distributary channels.

3.11. Facies 10: Apparently Structureless (Massive) Mudstone to Sporadically Bioturbated, Shell-Bearing Muddy Heterolithic Units

Sedimentology:

Facies 10 ranges from 0.2 to 1.8 metres in thickness and locally displays gradational or sharp basal contacts. The unit is lithologically variable, ranging from carbonaceous-rich mudstones, mudstones with locally admixed silt and very fine-grained sand, and heterolithic intervals of interstratified siltstone and very fine- to upper fine-grained sandstone (Fig. 3.15a-d). Wavy to lenticular bedding is locally present and mudstone/siltstone to sandstone ratios range from 49:1 to 7:3; typically becoming sandier upwards. Apparently structureless (massive) bedding and soft-sediment deformation comprise the dominant structures within the mudstones. Sandstone layers are sharp-based, with local evidence of scouring, and predominantly range from millimetres to centimetres thick. Sedimentary structures in these beds include common curvilinear lamination and oscillation ripples, with rare current ripples, and small-scale convolute bedding. Lithological accessories include moderate amounts of carbonaceous detritus, plant material, and millimetre- to centimetre-diameter coal fragments, as well as
very rare siderite bands. A distinctive feature of this facies is the common presence of bivalve (pelecypod) shell fragments (Fig. 3.15a, b). The shell fragments may be dispersed throughout the facies, or locally concentrated into lags that are typically less than 2 centimetres thick.

Ichnology:

Facies 10 contains sporadically distributed bioturbation, with intensities ranging from absent to uncommon (BI 0-2). Burrowing is largely confined to the more heterolithic intervals, although this may be a preservational bias, where biogenic structures cannot be distinguished in massive- and convolute-bedded, thicker mudstone layers. Ichnogenera include common Planolites, Thalassinoides and Palaeophycus, rare Cylindrichnus and Skolithos, and very rare Teichichnus, Arenicolites, Rosselia, navichnia and fugichnia. The trace-fossil suite displays low diversity and is dominated by facies-crossing elements otherwise common to the Cruziana Ichnofacies, with subordinate amounts of facies-crossing elements of the Skolithos Ichnofacies (cf. MacEachern and Bann, 2008). The suite is attributable to a stressed and proximal expression of the Cruziana Ichnofacies (cf. MacEachern et al., 2010; MacEachern et al., 2012).

Interpretation:

The lower and middle portions of Facies 10 are dominated by fine-grained deposits, which indicate accumulation in quiet-water settings with energy levels sufficiently low to allow suspended sediment settling and/or clay flocculation. In contrast, the transition to heterolithic deposits in the upper parts of the unit suggests a shift to higher-energy conditions, with millimetre- to centimetre-thick sandstone layers recording periodic influx of coarse-grained material. Bases of these layers are sharp and commonly show evidence of scouring, further supporting high-energy emplacement. The dominance of oscillation ripples and curvilinear lamination suggests deposition by wave processes. Commonly associated bivalve fragments also point to significant marine influence within the depositional environment. Moderate amounts of organic detritus, plant remains, and coal fragments point to a nearby terrestrial sediment source (e.g., Leckie et al., 1989). Rare siderite bands are interpreted to reflect brackish-water
Figure 3.15. Facies 10: Apparently structureless (massive) mudstone to sporadically bioturbated, shell-bearing muddy heterolithic units. (A) Heterolithic interval, comprising thinly interlaminated sandstone and siltstone (BI 0-2). Wavy bedding and curvilinear lamination are prevalent. Note the centimetre-thick shell lag. Well 14-19-42-4W5, 1318.18m. (B) Apparently structureless (massive) silty mudstone. Note the abundance of shell fragments. Well 8-2-42-5W5, 1353.30m. (C) Apparently structureless (massive) silty mudstone. Well 14-19-42-4W5, 1318.40m. (D) Coarsening-upward succession of thinly interstratified sandstone and siltstone. Units display BI 0-2. Physical structures include wavy bedding, curvilinear lamination, and small-scale convolute bedding. Note the abundance of carbonaceous debris, coal fragments, and mudstone rip-up clasts (ruc). Ichnogenera include *Skolithos* (S), *Teichichnus* (T), *Cylindrichnus* (Cy), *Planolites* (P), and possibly *Rosselia* (R). Well 16-35-42-5W5, 1323.74m.
conditions (e.g., Bhattacharya and Walker, 1991; Bhattacharya and MacEachern, 2009). The low-diversity trace-fossil suite, consisting of facies-crossing elements, also indicates brackish-water conditions (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern and Gingras, 2007). The reduction in bioturbation intensity and ichnological diversity likely reflects the stressed depositional setting (e.g., low salinity, high energy deposition, episodic deposition, etc.). Overall, Facies 10 is interpreted to represent deposition within a restricted bay or lagoon.


*Sedimentology:*

Facies 11 is sharp based, ranges from 0.5 to 3.6 metres in thickness, and comprises a heterolithic, composite bedset of interlaminated to very thinly interbedded, very fine-grained sandstone, clayey siltstone, and mudstone (Fig. 3.16a-d). The sandstone to clayey siltstone/mudstone ratios are highly variable (3:17 to 9:1), but successions typically coarsen upward. Fining-upward expressions are, nevertheless, also observed locally. Common wavy bedding with localized lenticular and flaser bedding are predominant. Sandstone units are sharp based and vary from millimetres to centimetres in thickness (typically 0.5 - 3.0 cm). Sedimentary structures are dominated by curvilinear lamination and oscillation ripples. Current-ripple lamination, aggradational current ripples, and combined-flow ripples are also present in rare to moderate amounts, but are generally more common in the upper, sandier intervals. Clayey siltstone and mudstone laminae are sharp based, and range from millimetres to a maximum of 2.0 centimetres thick. These layers commonly drape sandstone units and locally mark toesets of current and combined-flow ripples. Organic-rich claystone laminae are present locally. Syneresis cracks are common to abundant, and exclusively associated with the organic-rich claystone laminae (Fig. 3.16c). Lithologic accessories include moderate amounts of organic detritus, plant remains, and coal fragments. Siderite bands are also common, reaching thicknesses of 2.0 centimetres.
Ichnology:

Bioturbation is sporadically distributed, with intensities varying slightly between the different lithologic bedding types. Clayey siltstone and mudstone layers tend to display slightly higher intensities of burrowing, ranging from absent to moderate (BI 0-3), but typically absent to uncommon (BI 0-2). Ichnogenera include Planolites, Teichichnus, Rosselia, Thalassinoides and rare Cylindrichnus (Fig. 3.16b). Sandstone layers exhibit bioturbation intensities ranging from absent to uncommon (BI 0-2), but generally absent to sparse (BI 0-1). The majority of burrows are simple, vertical to inclined structures that subtend from overlying clayey siltstone or mudstone layers. Ichnogenera include mud-filled Cylindrichnus, Skolithos and Trichichnus, as well as Arenicolites, Diplocraterion habichi, Palaeophycus, Rosselia, Lockeia and fugichnia. Overall, trace-fossil suites display low diversity and are characterized by diminutive biogenic structures. This suite represents stressed and proximal expressions of the Cruziana Ichnofacies to distal expressions of the Skolithos Ichnofacies (cf. MacEachern and Bann, 2008; MacEachern et al., 2010; MacEachern et al., 2012).

Interpretation:

Marine traces and oscillatory-generated structures (e.g., curvilinear lamination and oscillation ripples) indicate a subaqueous environment subjected to periodic wave agitation. The heterolithic character of the facies suggests deposition in an environment that experienced alternating periods of suspended sediment settling and/or clay flocculation (clayey silt and mud deposition) and high-energy, coarser sediment influx (e.g., very fine-grained sand deposition). The sharp basal contacts of the sandstone units support the interpretation of periods of rapid deposition, whereas the siltstone and mudstone drapes support the interpretation of relatively quiet-water conditions. Local occurrences of current ripples are indicative of periodic traction transport by quasi-steady, unidirectional flows (lower flow regime) and the migration of ripple-scale bedforms. Aggradational current-ripples indicate traction transport coupled with increases in sedimentation rates at the bed. Organic-rich claystone laminae and drapes are consistent with fluid-mud layers (e.g., Lobza and Schieber, 1999; Schieber, 2003; MacEachern et al., 2005; Bhattacharya and MacEachern, 2009) and may indicate the mixing of freshwater with saltwater, promoting mud flocculation. Syneresis cracks may
Figure 3.16. Facies 11: Sporadically bioturbated, thinly interstratified sandstone, clayey siltstone and mudstone. (A) Fine-grained sandstone with interlaminated muddy siltstone and silty mudstone. Unit shows BI 0-2. Curvilinear lamination is prevalent. Labeled traces include Arenicolites (Ar), Diplocraterion habichi (Dh), Trichichnus (Tr), and Planolites (P). Well 14-19-42-4W5, 1304.26m. (B) Heterolithic, composite bedset of interlaminated very fine-grained sandstone and silty mudstone. This photo highlights the presence of rare Cylindrichnus (Cy). Well 7-7-43-4W5, 1288.29m. (C) Similar heterolithic interval, showing syneresis cracks (syn) within organic-rich claystone laminae. Well 14-19-42-4W5, 1305.22m. (D) Interlaminated very fine-grained sandstone, silty mudstone, and organic-rich claystone. Units display BI 0-3. Physical structures include wavy bedding and curvilinear lamination. Labeled ichnogenera include Planolites (P), Cylindrichnus (Cy), Palaeophycus tubularis (Pt), Lockeia (Lo), and Trichichnus (Tr). Well 6-31-42-4W5, 1287.80m.
indicate short-lived salinity changes at or near the bed (Plummer and Gostin, 1981; Gingras et al., 1998). Moderate amounts of organic detritus, plant remains, and coal fragments are consistent with a nearby source of terrestrial sediment (e.g., Leckie et al., 1989). Common occurrences of siderite bands are regarded to reflect brackish-water conditions, generated by nearby fluvial discharge (e.g., Bhattacharya and Walker, 1991). The low-diversity trace-fossil suite, consisting of diminutive, facies-crossing elements also supports brackish-water conditions (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern et al., 2005; MacEachern and Gingras, 2007). The common recurrence of flaser, wavy, and lenticular bedding may indicate a tidal influence within the depositional setting (cf. van Straaten, 1954; Reineck, 1967; Reineck and Wunderlich, 1968; Terwindt, 1971; Terwindt and Breusers, 1972). Based on sedimentology and ichnology, Facies 11 is interpreted to represent deposition within brackish-water, interdistributary bays.

3.13. Facies 12: Carbonaceous Mudstone, Siltstone, Sandstone and Coal

*Sedimentology:*

Facies 12 ranges from 0.3 to 3.8 metres in thickness with occurrences displaying gradational or sharp-based facies contacts. The unit is lithologically variable, locally consisting of mudstone, silty mudstone, sandy mudstone, clayey siltstone, siltstone, muddy sandstone, silty sandstone, and coal (Fig. 3.17a-e). Concentrations of carbonaceous material also vary locally, imparting colors that range between black, brownish-black, brown, dark grey, and grey. Overall, the unit is dominated by dark siltstones and mudstones (Fig. 3.17a), which display horizontal planar-parallel lamination and massive (apparently structureless) bedding. Convolute bedding is locally abundant, comprising various admixtures of mudstone and siltstone, with 5 to 40% intercalated sand (Fig. 3.17b). Isolated micro-faults are also present. Millimetre- to centimetre-thick, upper very fine- to upper fine-grained sandstone stringers are intercalated sporadically and, locally produce wavy bedding. These layers can display horizontal planar-parallel to curvilinear lamination, current ripples, and apparently structureless (massive) bedding. Centimetre- to decimetre-thick coal beds (Fig. 3.17c) also are intercalated sporadically
within the facies. The coals are dense, black to brownish-black in color, and exhibit silky to vitreous lustres. Lithologic accessories include moderate to abundant amounts of disseminated organic detritus, plant fragments, and leaf imprints preserved on bedding planes. In addition, moderate amounts of coal fragments, siderite nodules, and brecciated intervals (Fig. 3.17d) are also common. Facies 12 commonly possesses a friable to rubbly expression within the core.

**Ichnology:**

Bioturbation is predominantly absent (BI 0) within Facies 12. Root traces are locally common to abundant; however, other ichnofossils generally are not. Sporadically distributed *Naktodemasis* (Fig. 3.17e) and *Planolites* are present, but are exceedingly rare in this facies. Overall, the ichnologic assemblage is characterized by superlatively low diversity, and contains elements consistent with the *Scoyenia* Ichnofacies.

**Interpretation:**

The predominance of fine-grained sediment (e.g., mudstone and siltstone) indicates deposition in a quiet-water setting, with energy levels sufficiently low to allow suspended-sediment settling. High concentrations of carbonaceous material (e.g., organic detritus, plant and coal fragments, and *in situ* coal) point to an environment capable of accumulating considerable amounts of organic material. Intercalated sandstone stringers are sharp based, reflecting periodic influxes of coarser-grained sediment. Current ripples indicate traction transport by a quasi-steady, unidirectional flow (lower flow regime) and the migration of ripple-scale bedforms. Horizontal planar-parallel lamination also demonstrates unidirectional flow, and may exemplify periodic sheet-flow conditions. The abundance of soft-sediment deformation is interpreted to result from either the rapid deposition of sand onto a water-saturated, soupy substrate, or by degassing of trapped methane generated through the burial and decay of organic material. Siderite nodules and brecciated fabrics are characteristic of permanently saturated soils in swampy areas (e.g., Retallack, 2001). Common root traces and rare *Naktodemasis* indicate subaerial exposure, growth of vegetation, and incipient soil development (*cf.* Smith et al., 2008; Counts and Hasiotis, 2009). The presence of *Scoyenia* Ichnofacies elements implies deposition in a low-energy continental
Figure 3.17. Facies 12: Carbonaceous mudstone, siltstone, sandstone, and coal. (A) Silty mudstone/muddy siltstone. Lithologic accessories include abundant coal fragments and minor siderite granules. Well 7-34-42-6W5, 1492.12m. (B) Convolute bedded sandy siltstone. Note the root traces (Rt). Well 6-16-42-6W5, 1563.69m. (C) Coal bed. Well 12-13-43-6W5, 1404.70m. (D) Carbonate-cemented breccia with coal fragments. Well 7-34-42-6W5, 1490.20m. (E) Silty to sandy mudstone. Unit shows BI 0-2. Physical structures include convolute bedding and curvilinear lamination. Ichnogenera include *Naktodemasis* (Nk). A centimetre-diameter siderite nodule is also present near the top of the photo. Well 12-13-43-6W5, 1406.80m.
environment, characterized by alternating wet and dry conditions (Buatois and Mángano, 1995; Counts and Hasiotis, 2009; Buatois and Mángano, 2011). Facies 12 may represent vertically accreted deposition within floodplains, swamps, bogs, and/or marshes.


*Sedimentology / Ichnology:*

Facies 13 ranges from 0.2 to 4.9 metres in thickness and displays gradational basal contacts. The unit consists of silty mudstones and muddy siltstones exhibiting pale green, grey, and tan colours (Fig. 3.18a-c). Primary sedimentary structures are commonly absent, or are present as cryptic deformation features displayed as indistinct mottles (Fig. 3.18a, b). Horizontal planar-parallel lamination and apparently structureless (massive) bedding occur locally. Millimetre- to centimetre-thick, upper very fine- to upper fine-grained sandstone stringers are sporadically intercalated, and locally display horizontal planar-parallel to curvilinear lamination. Moderate amounts of organic detritus, coal fragments, and rare coal laminations are present. Pedogenic slickensides also occur. Facies 13 commonly possesses a friable to blocky appearance in core. With the exception of root traces, which dominate the facies, biogenic structures are exceedingly rare. *Naktodemasis* occur locally but are sporadically distributed, displaying intensities that vary from absent to sparse (BI 0-1).

*Interpretation:*

Facies 13 is dominated by fine-grained units, indicating accumulation within a quiet-water environment with energy levels sufficiently low to allow suspended sediment settling. Moderate amounts of organic detritus, coal fragments, and *in situ* coal laminae suggest a setting with the potential to accumulate substantial amounts of plant material. Intercalated sandstone stringers display horizontal to curvilinear lamination and reflect infrequent, event-style deposition. Root traces and visible slickensides suggest subaerial exposure following deposition, with subsequent pedogenic modification. The
Figure 3.18. Facies 13: Root-bearing silty mudstone and muddy siltstone. (A) Mottled muddy siltstone with abundant root traces (Rt). Note the pale colour. Well 14-2-42-6W5, 1480.56m. (B) Mottled muddy to sandy siltstone with root traces (Rt). Note the pale colour. Well 10-32-41-4W5, 1276.66m. (C) Sandy siltstone with moderate amounts of disseminated carbonaceous debris. Well 16-34-41-5W5, 1372.79m.
predominantly pale color of the facies, combined with the presence of mottling, may indicate gleying of the substrate during soil/paleosol development (Leckie et al., 1989). *Naktodemasis* is produced by soil-dwelling insect larvae (e.g., beetle larvae; Counts and Hasiotis, 2009), which further supports subaerial exposure and incipient soil formation. Facies 13 is interpreted to represent vertically accreted paleosols within a floodplain setting.
4. Facies Associations

4.1. INTRODUCTION

Facies associations are recurring combinations of genetically related facies (Collinson, 1969), which group deposits into specific categories that reflect an overriding depositional setting. Facies associations are considered the fundamental underpinning for facies analysis (Reading and Levell, 1996), as paleoenvironmental interpretations are more accurately achieved when individual facies are rationalized in concert with over- and underlying deposits, and their spatial distributions are considered. Facies within a particular succession commonly pass upwards in a semi-predictable manner. However, seemingly random facies occurrences are not atypical. Although localized discontinuities may be present, Walther’s Law remains largely applicable within each individual facies association.

Based on these principles, the 13 individual facies recognized within the basal Belly River deposits (Cycles D and E) can be grouped into 6 mappable facies associations (FA1-FA6; Fig. 4.1). Ethologies (interpreted organism behaviours) reflected by the affiliated ichnogenera within each association are described and organized in Figure 4.2. Lithologs and representative box-core photographs are also included to illustrate the arrangement of facies within each association. A legend for the lithologs is provided in Figure 4.3.
<table>
<thead>
<tr>
<th>Facies Association</th>
<th>Facies #</th>
<th>Description</th>
<th>Sedimentology</th>
<th>Lithologic Accessories</th>
<th>Trace Fossil Suite</th>
<th>B.L.</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Cross-stratified to rippled sandstone</td>
<td>Common trough and planar tabular cross- stratification, as well as current- ripple lamination, local aggradational current ripples, oscillation ripples, and eddy ripples, as well as sheet ripples, as well as sheet ripples, cross- ripples, and cross- lamination.</td>
<td>Moderate amounts of carbonaceous detritus and siderite nodules</td>
<td></td>
<td>0–3</td>
<td>Abandoned Channel/Mesohabitate Complex</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Apparently structures (massive to planar) laminated sandstone</td>
<td>An amalgamated simple bed; common apparent structures (massive to planar) laminated sandstone; local cross- ripples, as well as cross- lamination, as well as cross- lamination, as well as cross- ripples, cross- lamination, as well as cross- lamination.</td>
<td>Moderate amounts of carbonaceous detritus and siderite nodules</td>
<td></td>
<td>0–2</td>
<td>Active Channel/Mesohabitate Complex</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Graded and sub- sediment deflated, interstratified silty sandstone, siltstone, and organo- rich claystone</td>
<td>Heterolithic unit; sandstone with small- scale ripple lamination, as well as sheet ripples, cross- ripples, as well as sheet ripples, cross- ripples, as well as sheet ripples, cross- ripples, as well as sheet ripples, cross- ripples.</td>
<td>Moderate amounts of organic detritus and siderite nodules, as well as organic detritus and siderite nodules, as well as organic detritus and siderite nodules, as well as organic detritus and siderite nodules.</td>
<td></td>
<td>0–2</td>
<td>Proximal Delta Front</td>
<td></td>
</tr>
<tr>
<td>1a</td>
<td>Sparsely bioturbation, interstratified sandstone, siltstone, mudstone, and organo- rich claystone</td>
<td>Mostly detrital heterolithic unit; common reworking by bioturbation, bioturbation, bioturbation, bioturbation, bioturbation, bioturbation, bioturbation, bioturbation, bioturbation.</td>
<td>Moderate amounts of carbonaceous detritus and siderite nodules</td>
<td></td>
<td>0–2</td>
<td>Proximal Delta Front</td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>Cyclically bioturbation to bioturbation sands</td>
<td>An amalgamated simple bed; common apparently structures (massive to planar) laminated sandstone; local cross- ripples, cross- lamination, as well as cross- lamination, as well as cross- lamination, as well as cross- lamination, as well as cross- lamination, as well as cross- lamination.</td>
<td>Moderate amounts of carbonaceous detritus and siderite nodules</td>
<td></td>
<td>1–5</td>
<td>Proximal Delta-Front Forests</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Apparently structures (massive to planar) laminated sandstone</td>
<td>An amalgamated simple bed; common apparent structures (massive to planar) laminated sandstone; local cross- ripples, cross- lamination, as well as cross- lamination, as well as cross- lamination, as well as cross- lamination, as well as cross- lamination.</td>
<td>Moderate amounts of disconformable organic detritus and siderite nodules, as well as organic detritus and siderite nodules, as well as organic detritus and siderite nodules, as well as organic detritus and siderite nodules.</td>
<td></td>
<td>0–3</td>
<td>Proximal Delta Front</td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>Moderately bioturbation, interstratified sandstone, siltstone, mudstone, and organo- rich claystone</td>
<td>Mostly detrital heterolithic unit; common apparent structures (massive to planar) laminated sandstone; local cross- ripples, cross- lamination, as well as cross- lamination, as well as cross- lamination, as well as cross- lamination, as well as cross- lamination.</td>
<td>Moderate amounts of carbonaceous detritus and siderite nodules</td>
<td></td>
<td>0–4</td>
<td>Proximal Delta Front</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.1. Summary of facies associations recognized within cycles D and E of the basaii Belly River Formation. Facies within each association are listed in ascending order (bottom to top) and correlate to typical expressions observed in box cores.
<table>
<thead>
<tr>
<th>Figure 4.1. Summary of facies associations continued.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(3) Fluvial Distributary Channel Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(4) Fluvio-Littoral Distributary Channel Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(5) Marine-Influenced, Lower Delta Plain Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(6) Delta Plain / Coastal Plain Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>
Figure 4.2. Ethologies indicated by trace fossils in the facies associations of the Basal Belly River Formation. Behavioural interpretation based on the summary of Gingras et al. (2007).
Figure 4.3. Legend of symbols used in the facies association lithologs.
4.2. Facies Association 1: River-Dominated, Storm-Influenced Delta Deposits

Facies Association 1 (FA1) constitutes a coarsening-upward succession, ascribed to upward shallowing, and is characterized by markedly heterolithic, fully marine to marginal-marine deposits (Figs. 4.4 and 4.5). Successions are differentiated by an abundance of river-produced features, such as stacked current-generated structures, normal-graded bedding, syneresis cracks, soft-sediment deformation, and drapes of inferred fluid-mud origin. Lesser amounts of wave- and storm-generated physical sedimentary structures are locally present. Bioturbation is sporadically distributed with generally low intensities (BI 0-2), and trace-fossil suites display low diversities with abundant facies-crossing elements (cf. Gingras et al., 2007; MacEachern and Gingras, 2007). The lowermost division of the association comprises sporadically bioturbated heterolithic units (Facies 1a), locally capped by intervals of graded bedding and soft-sediment deformation (Facies 2). Deposits pass upwards into apparently structureless (massive) to planar-parallel laminated sandstone (Facies 3a), and cross-stratified to rippled sandstone (Facies 3c). Fining-upward heterolithic accumulations commonly cap these successions (Facies 9). FA1 successions range from 8.5 to 11.0 metres in thickness and are typically associated with Cycle D deposits.

4.2.1. Discussion:

Overall, the association is interpreted to represent the progradation of a river-dominated, storm-influenced delta. Facies 1a corresponds to distal to proximal prodelta deposition. The heterolithic character reflects fluctuating sedimentation rates and energy conditions (cf. Gingras et al., 1998; Hansen and MacEachern, 2007; Bann et al., 2008), consistent with deposition above storm wave base, but below fairweather wave base (cf. Gingras et al., 1998; Coates, 2001; MacEachern et al., 2005; Bann et al., 2008; MacEachern et al., 2010). A prevalence of diffusely stratified, normally and inversely graded siltstone and silty mudstone beds (Fig. 3.3b) reflects prolonged fluvial influx, and is characteristic of rapid sedimentation by waxing and waning hyperpycnal flows (e.g., Bhattacharya et al., 2007). Normally to inversely graded beds are interpreted as hyperpycnites (cf. Mulder et al., 2002; Bhattacharya and MacEachern, 2009) and sandstone layers are interpreted as tempestites. The association of these units
suggests a linkage between large storms and the generation of hyperpycnal flows (Wheatcroft, 2000). High-magnitude events such as hurricanes and tropical storms can affect both the drainage basin and nearshore shelf simultaneously, resulting in increased fluvial output that deposits sediment across a concomitantly stormy shelf (Bhattacharya and MacEachern, 2009).

Organic-rich claystones (Fig. 3.3b) typically mantle tempestites, producing a distinctive sandy heterolithic expression to the units. The claystones are interpreted as preserved accumulations of flocculated fluid mud, and serve as additional indicators of fluvial influence (cf. MacEachern et al., 2005; Bhattacharya and MacEachern, 2009). Deposition of fluid muds may be associated with heightened levels of precipitation and river discharge generated concomitantly with, and subsequent to, storm events (MacEachern et al., 2005; Bann et al., 2008; Bhattacharya and MacEachern, 2009). Large volumes of suspended sediment and phytodetritus are discharged to the prodelta and delta-front environment as hypopycnal (buoyant) plumes or via hyperpycnal flows (cf. Rice et al., 1986; Raychaudhuri and Pemberton, 1992; MacEachern et al., 2005; Bann et al., 2008; Bhattacharya and MacEachern, 2009). The common presence of syneresis cracks within these layers may support a hyperpycnal hypothesis, as bottom-hugging freshwater plumes can cause short-lived salinity changes immediately above the sea floor (cf. Plummer and Gostin, 1981; Gingras et al., 1998; MacEachern et al., 2005; Bann et al., 2008; Bhattacharya and MacEachern, 2009). Alternatively, the flocculation of clays within buoyant plumes may encapsulate freshwater, transporting it to the bed with the fluid mud, resulting in salinity changes with subsequent syneresis development. The relatively unburrowed character of these claystone drapes may be linked to soupground conditions at the sea floor (cf. Lobza and Schieber, 1999), but may also reflect periodic dysaerobic conditions produced by the oxidation of anomalous concentrations of land-derived organic material (e.g., Savrda and Bottjer, 1987, 1989; Wignall and Pickering, 1993). Such conditions would be limited to the subrate, inhibiting benthic colonization and also shielding underlying beds from opportunistic fauna (Leithold, 1989; Raychaudhuri and Pemberton, 1992; Leithold and Dean, 1998; Coates and MacEachern, 1999; MacEachern et al., 2005; Hansen and MacEachern, 2007). Locally observed navichnia (sediment-swimming structures; cf. Gingras et al., 2007) or mantle-
and-swirl structures (Lobza and Schieber, 1999) support intermittent soupground conditions.

The dominance of facies-crossing ichnogenera reflects a high degree of infaunal opportunism, and is typical of prodelta settings prone to recurring fluvial influence (cf. Bhattacharya and Walker, 1991; Coates, 2001; Coates and MacEachern, 2007; Hansen, 2007). Low-diversity trace-fossil suites and reduced sizes of ichnogenera characterize the facies and suggest persistent salinity fluctuations, likely caused by river-floods (c.f. Beynon et al., 1988; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; MacEachern and Gingras, 2007; Tonkin, 2012). The sporadically distributed character and overall low-intensity of bioturbation (typically BI 0-2) is presumably a result of multiple physico-chemical stresses, including increased rates of sedimentation, episodic deposition, and salinity reductions and fluctuations. Intervals that display increases in bioturbation intensity, trace-fossil diversity and overall sizes of ichnogenera are sporadically distributed, and may record short-lived returns to ambient conditions, probably related to pauses in fluvial influx. The ichnological assemblage reflects a stressed expression of the archetypal *Cruziana* Ichnofacies (cf., MacEachern and Bann, 2008).

Facies 2 locally caps the prodelta deposits of Facies 1a. The deposits are gradationally based and show an increase in fluvial signature (e.g., current-generated structures, graded bedding and soft-sediment deformation). Abundant convolute-bedded intervals (Fig. 3.5a, d) record repeated episodes of slope failure and slumping in proximal prodelta and distal delta-front settings, as high sedimentation rates with elevated concentrations of organic material led to rapid dewatering and degassing (cf. Reading and Collinson, 1996). Additional deformational features include load casts and micro-faults. The continued prevalence of graded beds and mudstone beds of inferred fluid mud origin, combined with the development of graded beds in composite bedsets (Fig. 3.5b, c), supports prolonged periods of rapid sedimentation by hyperpycnal density underflows (Bhattacharya, 2010). Syneresis cracks are also an enduring component of the facies and suggest that salinity reductions occurred as a result of fluvial discharge events and hyperpycnal-emplaced turbidites (Hansen and MacEachern, 2007).
Figure 4.4. Litholog of representative well 8-2-43-5W5, illustrating the various facies that comprise FA1. Legend for strip log in Fig. 4.3.
Figure 4.5. Box core photograph of Facies Association 1 in well 8-2-43-5W5 (1318.90 to 1327.47 m). The interval displays a coarsening upward succession, interpreted to reflect shallowing-upward, with sporadically bioturbated heterolithic units (Facies 1a) passing progressively into intervals of graded bedding and soft-sediment deformation (Facies 2), cross-stratified to rippled sandstone (Facies 3c), and fining-upward heterolithic intervals (Facies 9). Overall, the association is interpreted to represent the progradation of a river-dominated, storm-influenced delta.
Facies 3a is a sharp-based sandstone unit dominated by apparently structureless (massive) intervals and HCS. The unit commonly rests directly on Facies 1a (in the absence of Facies 2); however, it is also observed overlying Facies 2, or interbedded within the overlying deposits of Facies 3c. Massively bedded intervals (Fig. 3.6b, c) are attributed to increased depositional rates with subsequent loading and dewatering, or to storm-induced liquefaction (cf. Pettijohn and Potter, 1964; Coates and MacEachern, 2007; Hansen and MacEachern, 2007; Bann et al., 2008). Both processes are typical of deposition at, or above, fairweather wave base within the distal reaches of delta fronts (cf. Reading and Collinson, 1996; Bhattacharya, 2010). The increased thickness and local amalgamation of HCS beds (Fig. 3.6d) demonstrates the amplified effect of storms in shallower water.

Facies 3c is a sharp- to erosionally based sandstone unit that is dominated by current-generated sedimentary structures (e.g., trough and planar tabular cross-stratification, current ripple lamination, and aggradational current ripples), overprinted by oscillatory-induced structures (e.g., combined-flow ripples, oscillation ripples, and hummocky cross-stratification). The facies is consistent with terminal distributary channel/mouth-bar deposits (cf. Bhattacharya and Walker, 1991; Gingras et al., 1998; Olariu and Bhattacharya, 2006; Hansen, 2007; Hansen and MacEachern, 2007; Bhattacharya, 2010), which are influenced by fluvial, as well as basinal processes (e.g., waves). Terminal distributary channels and mouth-bars are intimately associated, comprising the foremost constituents of river-dominated delta fronts (Olariu and Bhattacharya, 2006). Terminal distributary channels develop near the margins separating the lower delta plain and the delta front, and extend to channelized expressions on the subaqueous delta front. Mouth-bars serve to infill the channels through aggradation as well as lateral or upstream migration, which autogenically controls the evolution of the overall complex (Olariu and Bhattacharya, 2006). Moderate to abundant spherulitic siderite (Fig. 3.8b), carbonaceous detritus, and coal fragments suggest that sediments were derived from soils and associated fine-grained units on the delta plain, liberated through floods, and/or the autogenic migration of channels (cf. Leckie et al., 1989). Fluid muds with associated syneresis cracks are persistent elements of the facies, illustrating repeated periods of fluvially induced physico-chemical stress. Facies 3c displays sporadically distributed burrowing with exceedingly low
bioturbation intensities (typically 0-2), reflecting the highly stressed setting prone to increased sedimentation rates and heightened fluvial discharge. Burrowing is most prevalent within thinly interbedded siltstone and claystone layers, interpreted to represent periods of low discharge (cf. Olariu et al., 2005). The ichnological assemblage reflects a stressed, proximal expression of the *Cruziana* Ichnofacies (cf. MacEachern and Bann, 2008).

Facies 9 commonly caps FA1 successions, recording the gradual abandonment of terminal distributary channel/mouth-bar complexes during autogenically induced channel avulsion and/or lobe switching. Thickening-upward mudstones and siltstones point to suspension sediment fallout in a quiet-water environment, whereas current ripple-laminated sandstones illustrate periodic, weak traction currents. This fining-upwards tendency, combined with the relative absence of sandstones in middle to upper portions of the facies, indicates that clastic bedload sedimentation ceased over time (Reading and Collinson, 1996). Sedimentologic and ichnologic characteristics are comparable to those of the underlying deposits (e.g., abundant river-generated structures, low bioturbation intensities, and low-diversity assemblages with diminutive traces), representing the continued influence of physico-chemical stresses within a marginal-marine environment. Tidal rhythmites are locally present (Fig. 3.14d), developing as a result of variations in diurnal and neap-spring tidal currents. Such structures are more common to sheltered settings where wave action and fluvial input are restricted, but tidal processes can continue to operate (Dalrymple, 2010). The presence of tide-generated structures (e.g., tidal rhythmites) also demonstrates the continued influence of saline (marine) waters.

### 4.3. Facies Association 2: Storm-Dominated, Mixed River- and Wave-Influenced Delta Deposits

Facies Association 2 (FA2) comprises coarsening- and shallowing-upward successions, characterized by relatively sand-rich, fully marine to marginal-marine facies (Figs. 4.6 and 4.7). Successions are dominated by an abundance of wave- and storm-generated physical sedimentary structures, with subordinate amounts of the river-generated features common to FA1 (e.g., current-generated structures, graded bedding,
syneresis cracks, soft-sediment deformation, and fine-grained drapes of inferred fluid mud origin). Like FA1, burrowing within FA2 remains sporadically distributed; however, increases in bioturbation intensity and trace-fossil diversity are distinctive. Distal portions of the association consist of moderately bioturbated, heterolithic deposits (Facies 1b), which pass upwards into thick intervals of apparently structureless (massive) and planar-parallel laminated sandstone (Facies 3a), capped by cryptically bioturbated to bioturbated sandstone (Facies 3b). FA2 successions range from 9.0 to 16.0 metres in thickness and are typically associated with Cycle E deposits where present in core.

4.3.1. Discussion:

Overall, FA2 is interpreted to represent the progradation of a storm-dominated, mixed river- and wave-influenced delta. Facies 1b corresponds to distal to proximal prodelta deposition, and is lithologically and bathymetrically (i.e., above storm wave base but below fairweather wave base) analogous to the lower portions of FA1 (e.g., Facies 1a). Similarly, the heterolithic character of the facies indicates alternating energy conditions and sedimentation rates (cf. Ainsworth, 1994; Gingras et al., 1998; Hansen and MacEachern, 2007; Bann et al., 2008; Buatois et al., 2012). A characteristic difference, however, is reflected by the decreased abundance of river-generated features (e.g., graded beds, fine-grained drapes of inferred fluid mud origin, and syneresis cracks). This indicates a diminished fluvial signal within the depositional environment, as well as a decrease in the effects of associated physico-chemical stresses.

The ichnological suite reflects a stressed, archetypal to proximal expression of the Cruziana Ichnofacies (cf. MacEachern and Bann, 2008). Although the trace-fossil suite displays a departure from the archetypal ichnofacies like FA1, the increase in bioturbation intensities and trace-fossil diversities suggests increased wave energy, which acts to moderate or mitigate the environmental stresses imparted by fluvial influx, and/or a reduction in the degree of river-sediment influx. Lithologically variable mudstones and siltstones record ambient or fairweather conditions. These units display low to moderate bioturbation intensities (typically BI 1-4; Fig. 3.4a, b, c), with low to moderate trace-fossil diversities, reflecting colonization by K-selected organisms,
adapted to equilibrium conditions (cf. Jumars, 1993). Sharp-based sandstone layers are interpreted as erosionally emplaced tempestites. Physical sedimentary structures are oscillatory-generated and are consistent with storm deposition (e.g., curvilinear parallel lamination, oscillation ripples and micro-hummocky cross-stratification); however, isolated combined-flow ripples demonstrate the presence of subordinate, unidirectional currents (e.g., river- or tide-generated currents). Sandstone layers exhibit reduced bioturbation intensities (typically BI 0-2) compared with intercalated fairweather deposits; however, they possess much higher bioturbation intensities than their FA1 counterparts. This observation preserves the marked decrease in river-generated stresses, including the supply of fluid-muds that mantle these layers. The majority of trace fossils within sandstone units represent top-down burrowing, and are assigned to opportunistic (r-selected) organisms, which tend to rapidly recolonize newly available substrates following storms (e.g., approximately two months; cf. Boesch et al., 1976; Rees et al., 1977; Berry, 1989). The bioturbation in sandstone units most likely records conventional colonization through seasonally timed larval dispersion (cf. Rees et al., 1977; Hagerman and Rieger, 1981; Dobbs and Vozarik, 1983; Butman, 1987); however isolated examples of storm-transported organisms or “doomed pioneers” (cf. Follmi and Grimm, 1990) also may be present.

Facies 3a rests sharply on Facies 1b. The unit comprises thick intervals of sandstone, representing storm domination and high rates of deposition. Apparently structureless (massive) bedding (Fig. 3.6b, c) is common and further supports high sedimentation rates with subsequent loading and dewatering, or storm-induced liquefaction (cf. Pettijohn and Potter, 1964; Coates and MacEachern, 2007; Hansen and MacEachern, 2007; Bann et al., 2008). Moderate amounts of associated soft-sediment deformation and micro-fault formation support this interpretation. These features are typical of deposition within the distal portions of delta fronts (Reading and Collinson, 1996). Amalgamated beds of hummocky cross-stratification (cf. Dott and Bourgeois, 1982) signal the increasing influence and frequency of storm events. Mudstone rip-up clasts (Fig. 3.6b) likely derive from the erosion of compacted fluid-mud layers, and further support high-energy, erosional conditions at least periodically within the environment. Rare current-generated structures (e.g., trough and planar tabular cross-stratification) are assigned to wave-induced currents, initiated as waves break in shallow
waters (Hunter et al., 1979; Walker and Plint, 1992; Bann et al., 2008). Such processes are consistent with deposition in a more proximal delta-front setting.

Bioturbation is sporadically distributed and intensities are, in general, low (BI 0-3). The trace-fossil suite of Facies 3a reflects a stressed, proximal expression of the *Cruziana* Ichnofacies (cf. MacEachern and Bann, 2008). Despite the sand-dominated character of the facies, only rare traces attributable to the *Skolithos* Ichnofacies are present (e.g., *Diplocraterion* and *Ophiomorpha*). This overall paucity of inferred suspension-feeding structures is interpreted to be the result of turbid water conditions and increased amounts of suspended load (cf. Moslow and Pemberton, 1988; Gingras et al., 1998; Coates and MacEachern, 1999; MacEachern et al., 2005; MacEachern et al., 2007; Bann et al., 2008). Heightened levels of water turbidity are believed to clog the filter-feeding apparatus of suspension-feeding organisms, decrease the relative amount of available food particles, and inhibit primary productivity (e.g., reductions in proportions of phytoplankton), making it difficult for such organisms to persist in the setting (Moslow and Pemberton, 1988; Gingras et al., 1998; MacEachern et al., 2005). The overall impoverishment of inferred suspension-feeding structures (*Skolithos* Ichnofacies), combined with an overwhelming majority of biogenic structures reflecting deposit feeding (*Cruziana* Ichnofacies) constitutes one of the main diagnostic indicators of delta-front conditions (cf. Moslow and Pemberton, 1988; Gingras et al., 1998; MacEachern et al., 2005; Tonkin, 2012).

As observed in the underlying prodeltaic deposits of Facies 1b, river-generated features impart a markedly reduced ichnological signal, both in terms of abundance and diversity. Laminae, consisting of concentrations of carbonaceous detritus, occur locally. They are interpreted to represent phytodetrital pulses, deposited concomitantly with distributary flood discharges (cf. Rice et al., 1986; Raychaudhuri and Pemberton, 1992; MacEachern et al., 2005). Oxidation of these anomalous concentrations of organic carbon may have depleted oxygen levels at the sea floor, temporarily leading to dysaerobic conditions at the substrate and imposing environmental stresses on infaunal communities. Isolated fluid mud layers also would have induced soupground conditions at the sea floor, making inhabitation difficult for deposit-feeders and precluding suspension-feeding organisms (e.g., Lobza and Schieber, 1999; MacEachern et al., 2005). Such fluid mud
Figure 4.6. Litholog of representative well 14-28-42-4W5, illustrating the various facies that comprise FA2. Legend for strip log in Fig. 4.3.
Figure 4.7. Box core photograph of Facies Association 2 in well 14-28-42-4W5 (1284.84 to 1290.00 m). The interval displays a coarsening-upward succession, interpreted to reflect shallowing-upward, characterized by upward transitioning from moderately bioturbated heterolithic bedsets (Facies 1b) into thick intervals of apparently structureless (massive) to planar parallel laminated sandstone (Facies 3a), capped by bioturbated sandstone (Facies 3b). Overall, the association is interpreted to represent the progradation of a storm dominated, mixed river- and wave-influenced delta complex.
layers also drape underlying deposits, essentially shielding them from infaunal colonization (MacEachern et al., 2005; Hansen, 2007).

Storm influence and episodic deposition of resulting tempestites (Fig. 3.6d) are interpreted to be responsible for the sporadically distributed nature of bioturbation and the reductions in bioturbation intensity. Storm-induced sedimentation scourcs the substrate, destroying or modifying fair-weather paleocommunities and altering the consistency of the substrate compared to ambient conditions. The introduction of phytodetritus caused by elevated levels of precipitation and associated river floods, also affects paleocommunities by reducing food availability (MacEachern et al., 2005). Fairweather deposits (and their associated trace fossil suites) are truncated by storm-induced erosion, leading to marked defaunation of the substrate and creating successions characterized by storm-bed amalgamation. Such successions do not adequately reflect the biogenic activity that surely persisted during ambient conditions and therefore represent a preservational bias. High-frequency storms reduce the colonization window, and limit faunal burrowing further. Fugichnia (escape structures), locally observed in the tempestites, represent the upward movement of organisms entrained in or buried by the rapidly emplaced layers (cf. Ekdale et al., 1984; Frey, 1990).

Facies 3b caps the FA2 succession and is also dominated by apparently structureless (massive) sandstone. However, unlike Facies 3a, its massive appearance is more likely the result of biogenic reworking rather than rapid sedimentation or storm-induced liquefaction. Horizontal lamination and low-angle cross-stratification are locally present within the beds. When interpreted in the context of the underlying distal to proximal delta front deposits, such beds are indicative of sheet flow conditions in the swash and backwash zone of the foreshore. Stratified intervals commonly exhibit a “fuzzy” or slightly blurred appearance. This subtle fabric is interpreted as cryptic bioturbation (Fig. 3.7a), resulting from intense reworking by meiofauna with little disruption to the original sedimentary fabric (cf. Howard and Frey, 1973, 1975; Bromley, 1990; Pemberton et al., 2008). Monospecific assemblages of *Macaronichnus segregatis* (Fig. 3.7b, c) are also a distinct feature of the facies, commonly resulting in complete obliteration of primary sedimentary structures. *Macaronichnus segregatis* is representative of a deep-tier, deposit-feeding behaviour, associated with higher energy
regimes (Saunders and Pemberton, 1990; MacEachern and Pemberton, 1992; Saunders et al., 1994; Bann et al., 2008). Previous authors characterize this suite as a “toe-of-the-beach” assemblage (cf. Saunders et al., 1994; MacEachern et al., 1999; Pemberton et al., 2001), consistent with high-energy and shallow-water environments such as the foreshore. Root traces are observed near the top of the facies and indicate subsequent subaerial exposure through continued progradation of the environment.

4.4. Facies Association 3: Fluvial Channel Deposits

Facies Association 3 (FA3) comprises erosionally based and fining-upwards successions with multistory fills; typical of channelized deposits (Figs. 4.8 and 4.9). Facies successions are dominated by current-generated structures, including planar tabular and trough cross-stratification, current-ripple lamination, and horizontal planar-parallel lamination. Minor structures reminiscent of tidal influence (e.g., double drapes and flaser bedding) are sporadically distributed. Pebbly sandstones and pebble conglomerates (Facies 4) locally overlie basal erosion surfaces, and pass upwards into cross-bedded (Facies 5) and current-ripple laminated sandstones (Facies 7), which are capped by root-bearing intervals of interstratified sandstone and siltstone (Facies 8). Bioturbation is absent (BI 0) in lower to middle portions of the succession (Facies 4 and 5). The uppermost deposits (Facies 7 and 8) display sporadically distributed bioturbation, with intensities ranging from absent to common (BI 0-4). Trace-fossil suites are of low diversity and attributed to the Scoyenia Ichnofacies. FA3 ranges from 3.4 to 15.4 metres in thickness; but is generally 5.0 to 10.0 metres-thick when observed in core. Successions are typically overlain and underlain by FA6.

4.4.1. Discussion:

Overall, FA3 is interpreted to represent fluvial-channel deposits. Facies 4 comprises pebbly sandstones and pebble conglomerates (Fig. 3.9a-d) that constitute lags or thalweg accumulations, deposited at or near the base of active channels. Abundant cross-stratification (e.g., planar tabular and trough cross-stratification) supports deposition through traction transport processes, induced by turbulent quasi-steady currents, rather than rapid emplacement by sediment-gravity flows (cf. Miall,
Pebble-sized clasts are subrounded to rounded, which also implies some degree of fluvial transport. Where present, Facies 4 passes gradationally into Facies 5. Where absent, Facies 5 is erosionally based and forms the basal part of FA3 successions.

Facies 5 and Facies 7 comprise the thickest intervals of FA3 successions, and are interpreted to reflect the lower to middle portions of fluvial-channel deposits, respectively. The units are dominated by cross-stratified (e.g., planar tabular and trough-cross stratification; Fig 3.10a-c) and current-ripple laminated sandstones (Fig. 3.12a, c). Such structures reflect current-dominated environments, with flow velocities capable of mobilizing relatively coarse sediment and fashioning it into dune-scale bedforms. Mudstone rip-up clasts also indicate that flow velocities were sufficiently high to erode and transport blocks of cohesive sediment. Rare mudstone-clast breccias likely record slumping from nearby cutbanks. The angular character of the clasts suggests that transport distances were not great. The fining-upwards profile, combined with a switch from dune- to ripple-scale bedforms (e.g., cross-stratification to current-ripple lamination), indicates decreasing or waning energy conditions over time, which is deemed typical of channel deposits (cf. Miall, 1996, 2010). Moderate to abundant amounts of organic detritus, spherulitic siderite, and siderite nodules (Fig. 3.10d) indicate a nearby terrestrial sediment source (e.g., Leckie et al., 1989).

Low abundances of double drapes (Fig. 3.10a) and flaser bedding are contained within the deposits, and may indicate tidal influence (cf. Visser, 1980; Nio and Yang, 1991). Tidal currents can strongly influence the character of fluvial-channel deposition well inland of salt-water invasion (e.g., tens to hundreds of kilometres landward of the shoreline; cf. Dalrymple and Choi, 2007; Dalrymple, 2010), up to a point where tidal action is just sufficient to produce a record (tidal limit; cf. Dalrymple and Choi, 2007). Landward of this limit, no effective tidal influence is experienced. However, pseudo-tidal features (e.g., double mud drapes, herringbone cross-bedding, and flaser bedding) may still develop solely through fluvial processes (Dalrymple and Choi, 2007); therefore, it is crucial to not over-interpret such structures as tidally generated (Dalrymple, 2010). Based on their sporadic distributions, low abundances, and lack of cyclicity, deposition is interpreted to have occurred landward of the tidal limit (e.g., fluvial channels).
Figure 4.8. Litholog of representative well 10-15-42-8W5, illustrating the various facies that comprise FA3. Legend for strip log in Fig. 4.3.
Figure 4.9. Box core photograph of Facies Association 3 in well 10-15-42-8W5 (1511.34 to 1516.25 m). The succession displays cross-bedded (Facies 5) and current-ripple laminated sandstone (Facies 7), capped by intervals of root-bearing and sporadically bioturbated, interstratified sandstone and siltstone (Facies 8). The association is interpreted to represent fluvial channel deposits.
Facies 8 forms the uppermost portion of FA3 successions and may pass
gradationally or sharply out of Facies 5 or 7. The unit consists of thinly interstratified
siltstones and sandstones (Fig. 3.13a-d), which reflect alternating periods of suspension
sediment settling and coarser sediment influx along upper channel margins (e.g.,
levees). Levee accumulations develop at the margins of channels as successive river-
floods overtop the banks and deposit sediment in adjacent areas (Collinson, 1996).
Coarse-grained sediment is transferred over the channel banks during flood stage and
deposited through traction transport processes. Finer-grained material is deposited out
of suspension as turbulence diminishes (Fielding, 1986; Miall, 1996). The sharp bases
of sandstone units support the interpretation of periods of rapid deposition, whereas the
draping of siltstone units supports the interpretation of relative quiescence. Current
ripples and trough cross-stratification are indicative of traction transport by a quasi-
steady unidirectional flow and the migration of ripple- and dune-scale bedforms,
respectively.

Bioturbation is sporadically distributed within FA3 and typically restricted to the
uppermost units (e.g., Facies 7 and 8). The trace-fossil suites display low diversities and
consist of abundant root structures, *Naktodemasis*, and *Taenidium* (Fig. 3.13c),
consistent with the *Scoyenia* Ichnofacies. This designation implies deposition in a low-
energy continental setting, characterized by alternating subaerial and subaqueous
conditions (Seilacher, 1967; Buatois and Mangano, 1995, 2011; MacEachern et al.,
2007b). Localized *Skolithos* are interpreted to represent simple vertical dwellings of
continental organisms (e.g. insects) rather than suspension-feeding organisms typical of
marginal-marine and marine settings. *Naktodemasis* records meniscate backfilled
burrows produced by soil-dwelling insect larvae (e.g., beetle larvae; Counts and
Hasiotis, 2009). These burrows have only been found in paleosol and terrestrial flood-
plain deposits (*cf.* Smith et al., 2008; Counts and Hasiotis, 2009), and their presence
supports the interpretation of subsequent subaerial exposure and incipient soil formation
following deposition. These traits are all consistent with deposition along the margins of
4.5. Facies Association 4: Fluvio-Estuarine Distributary Channel Deposits

Facies Association 4 (FA4) comprises a single facies, characterized by an erosional base and a fining-upward succession (Figs. 4.10 and 4.11) of cross-stratified, current-ripple laminated, and apparently structureless sandstones (Facies 6). Like FA3, the deposits reflect deposition within channels (e.g., erosionally based, fining-upward sandstone successions dominated by current-generated structures) and contain minor amounts of features (e.g., double drapes) commonly ascribed to tidal flow. Unlike FA3, additional facies elements also demonstrate the presence of brackish-water conditions during deposition (e.g., inferred fluid-mud drapes, syneresis cracks, and trace-fossil suites typical of brackish-water settings). Bioturbation is sporadically distributed, with intensities ranging from absent to moderate (BI 0-3). Trace fossil suites display low diversity with abundant facies-crossing elements. FA4 ranges from 4.5 to 5.0 metres in thickness where observed in core. Successions typically erosionally overlie FA5 and are overlain by FA6.

4.5.1. Discussion:

Overall, the association is interpreted to represent fluvio-estuarine distributary channel deposits. FA4 successions are characteristic of channel fill. An abundance of current-generated structures (e.g., planar and tabular cross-stratification, as well as current ripple lamination) and massive intervals support deposition through traction transport processes with frequent periods of rapid sedimentation. The presence of brackish-water trace-fossil assemblages demonstrates some degree of marine influence within the channels. During low-flow stages, it is not uncommon for marine waters to penetrate distributary channels within the lower reaches of the delta plain (cf. Reading and Collinson, 1996; Bhattacharya, 2010). The denser salt water forms a salt wedge along the channel floor and the lighter freshwater flows overtop, typically initiating some degree of estuarine circulation (Dalrymple, 2010). Within this zone of mixing, flocculation and residual circulation trap suspended sediment, which in turn may be deposited during slack-water periods to form fluid muds (Dalrymple and Choi, 2007; Dalrymple, 2010). Localized silty and sandy mudstone laminae represent such layers (Fig. 3.11a), and imply periodic decreases in flow velocity. Isolated syneresis cracks
Figure 4.10. Litholog of representative well 8-2-43-5W5, showing FA4. Legend for strip log in Fig. 4.3.
Figure 4.11. Box core photograph of Facies Association 4 in well 8-2-43-5W5 (1311.52 to 1318.17 m). Deposits comprise a single, erosionally based and fining-upward succession of cross-stratified sandstone with sporadically distributed mudstone laminae (Facies 6). Overall, the association is interpreted to represent a fluvio-estuarine distributary channel deposit.
also illustrate intermittent salinity fluctuations (cf. Plummer and Gostin, 1981), generated through the mixing of fresh and salt water. The presence of double mud drapes, some of which consist of millimetre-scale mudstone rip-up clasts and organic detritus, provides evidence that supports tidal influence (cf. Visser, 1980; Nio and Yang, 1991). The fragmentation of the mudstone drapes suggests that the mud layers (deposited during slack-water) were eroded by the reversing current or disaggregated by the dominant current (Visser, 1980). Low to moderate amounts of organic detritus are indicative of a nearby terrestrial sediment source (e.g., fluvial source; Leckie et al., 1989).

Bioturbation is sporadically distributed, with intensities ranging from absent to moderate (BI 0-3), and trace-fossil assemblages displaying low diversity with a preponderance of facies-crossing elements (Fig. 3.11a). These traits are compatible with fundamental characteristics of the brackish-water ichnological model (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern and Gingras, 2007; MacEachern et al., 2007c, 2010). The paradigm is succinctly outlined in MacEachern et al. (2010), and includes ichnologic suites characterized by: reduced numbers and diversities of ichnogenera; diminutive sizes of traces; a predominance of simple, horizontal or vertical structures; common alternation between horizontal and vertical structures; variable levels of bioturbation (BI 0-6) fluctuating at the bed scale; and the local development of monospecific suites. Such traits are representative of settings prone to persistent physico-chemical stresses, which may include variations in substrate consistency and sedimentation rate, increased water turbidity, salinity fluctuations, and salinity reductions (cf. MacEachern et al., 2007c, 2010). This is consistent with the environmental conditions encountered within a fluvio-estuarine distributary channel.

4.6. Facies Association 5: Marine-Influenced, Lower Delta Plain Deposits

Facies Association 5 (FA5) embodies sanding-upward successions characterized by markedly heterolithic, paralic and marginal-marine units (Figs. 4.12 and 4.13). Successions are dominated by wave-and storm-generated sedimentary structures (e.g., curvilinear parallel lamination and oscillation ripples), with minor abundances of current-
induced features (e.g., current-ripples, aggradational current ripples, and combined-flow ripples). Moderate to abundant amounts of terrigenous material (e.g., organic detritus, plant remains, and coal fragments) and siderite bands are also intercalated. Burrowing is sporadically distributed, with intensities ranging from absent to moderate (BI 0-3). Trace-fossil suites display low diversities and consist of diminutive, facies-crossing ichnogenera. Two separate expressions of the association exist: the first grades from structureless mudstone into shell-bearing heterolithic intervals (Facies 10); whereas the second comprises intervals of wavy-bedded heterolithic bedsets (Facies 11). FA5 successions range from 0.2 to 3.6 metres in thickness, and typically overlie FA1 and FA2 where present in core.

4.6.1. Discussion:

Overall, FA5 is interpreted to represent marine-influenced lower delta plain deposits. Facies 10 is a gradationally based to sharp-based unit, commonly observed overlying FA1 successions. Deposits are mud-prone, reflecting the dominance of low-energy conditions and passive sedimentation within restricted bays or lagoons. Such environments characteristically develop parallel to the shoreline, separated from the sea by spits or barriers, and tend to be wave-dominated with little fluvial input (Reading and Collinson, 1996). Highly carbonaceous mudstones (in lower portions of the facies; Fig. 3.15c) are likely indicative of temporary anoxic conditions, created by restricted water circulation. In contrast, the upward transition into heterolithic units (Fig. 3.15d) demonstrates a shift to higher energy conditions, with associated water-column mixing, as millimetre- to centimetre-thick sandstone layers mark periodic influxes of coarse-grained material. The dominance of oscillation ripples and curvilinear parallel lamination (Fig. 3.15a, d) in thin sandstone beds points to wave-induced processes and, therefore, demonstrates (at least) intermittent communication with, or connection to, a water body. Sandstone layers are interpreted as washover accumulations, deposited as sediment over-topped barriers during storms. Commonly associated bivalve fragments (Fig. 3.15a, b) are interpreted to originate from brackish-water fauna (e.g., oysters). Oyster beds were likely eroded, transported, and reworked into shell lags during storm-induced, high-energy pulses, consistent with those responsible for deposition of the sandstone.
layers. Moderate amounts of organic detritus, plant remains, and coal fragments may suggest some degree of fluvial input into the depositional setting (cf. Leckie et al., 1989).

Ichnologic data supports deposition within a restricted bay or lagoon. Bioturbation is sporadically distributed within the deposits and intensities are low (BI 0-2). Burrowing is notably absent from carbonaceous mudstones, potentially indicating short-lived periods of anoxia. However, the apparent absence of bioturbation could also correlate to a lack of lithologic contrast between trace outlines and the sediment infill (cf. Schieber, 2003). Heterolithic intervals contain low-diversity trace-fossil suites, consisting of facies-crossing elements, and are characteristic of brackish-water conditions (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern et al., 2005; MacEachern and Gingras, 2007). Salinity variations are common to such settings, as freshwater input increases during wet periods and marine inundation is supplemented during storms (Reading and Collinson, 1996). Overall, the lack of bioturbation is interpreted to reflect the stressed nature of the depositional setting (e.g., low salinity, reduced oxygenation, episodic deposition, etc.).

Facies 11 is a sharp-based unit, commonly overlying FA2 successions. Accumulations comprise relatively thin (< 4 metres thick), coarsening- or fining-upward successions of heterolithic strata, consistent with the infilling of interdistributary bays on the lower delta plain (cf. Elliot, 1974; Reading and Collinson, 1996; Bhattacharya, 2010). Interdistributary bays occupy the regions between deltaic distributaries and may be enclosed, partially enclosed, or open to the sea (Coleman et al., 1964). Oscillatory-generated structures dominate sandstone layers within the heterolithic intervals of Facies 11 (Fig. 3.16a-d), recording storm-induced sedimentation or wave action associated with strong winds. Upper portions of the facies are commonly sandier and display a prevalence of current-generated structures (e.g., current-ripple lamination, aggradational current ripples, and combined-flow ripples), marking a switch to deposition through traction transport and the migration of ripple-scale bedforms. Coarser-grained material is diverted from adjacent distributaries during floods, such as overbank flooding, crevassing, and avulsion (Elliot, 1974). Through these processes, features such as levees, crevasse channels, crevasse splays, and minor deltas may ultimately fill interdistributary areas (Reading and Collinson, 1996). Moderate amounts of organic
Figure 4.12. Litholog of representative well 14-19-42-4W5, illustrating the two distinct facies that comprise FA5. Legend for strip log in Fig. 4.3.
Figure 4.13. Two distinct expressions of Facies Association 5 in well 14-19-42-4W5. A) Transition from structureless mudstone into sporadically bioturbated, shell-bearing muddy heterolithic units (Facies 10; 1317.78 to 1318.50 m). These deposits typically overlie FA1 where present in core. B) Sporadically bioturbated, thinly interlaminated heterolithic units (Facies 11; 1303.90 to 1306.80 m). These deposits typically overlie FA2 where present in core. Overall, the association is interpreted to represent marine-influenced, lower delta plain deposits.
detritus, plant remains, and coal fragments support sedimentation from nearby a terrestrial source (e.g., fluvial source; Leckie et al., 1989).

Mudstone beds of inferred fluid-mud origin are present in moderate amounts and contain syneresis cracks (Fig. 3.16c). The combination of these structures is indicative of salinity fluctuations generated through the mixing of freshwater with salt water, indicating some degree of connection to marine environments. Common presence of siderite bands further supports brackish-water conditions (cf. Bhattacharya and Walker, 1991; Bhattacharya and MacEachern, 2009). The persistence of flaser, wavy, and lenticular bedding also points to some degree of tidal influence on deposition (cf. Dalrymple, 2010). Small-amplitude tides can regularly affect large areas of the lower delta plain that are inundated by brackish water (Reading and Collinson, 1996).

Bioturbation is sporadically distributed, with intensities ranging from absent to moderate (BI 0-3). Trace-fossil suites display low diversity with an abundance of facies-crossing elements. These traits, combined with the prevalence of a mixture of elements common to the Cruziana or Skolithos ichnofacies, are interpreted to indicate brackish-water conditions (cf. Beynon et al., 1988; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; MacEachern and Gingras, 2007; MacEachern et al., 2007c, 2010). This is consistent with interdistributary bays, wherein fluvial influx, combined with the mixing of fresh and marine waters can generate various physico-chemical stresses (e.g., variations in substrate consistency and sedimentation rate, increased water turbidity, and salinity fluctuations; cf. MacEachern et al., 2007c, 2010).

4.7. Facies Association 6: Delta Plain / Coastal Plain Deposits

Facies Association 6 (FA6) constitutes lithologically variable successions of fine-grained units (Figs. 4.14 and 4.15). The deposits contain an abundance of mudstone and siltstone, and are characterized by anomalously high concentrations of intercalated carbonaceous debris, coal fragments, siderite-cemented nodules, and pedogenic features (e.g., root structures). Horizontal lamination, apparently structureless (massive) intervals, and convolute bedding are common. Sporadically interbedded sandstones are
also a common characteristic, and are dominated by cross-stratification and current-ripple lamination. With the exception of root traces, biogenic structures are exceedingly rare. Trace-fossil suites display low diversity and are assigned to the Scoyenia Ichnofacies. Facies occurrences are seemingly randomly distributed in comparison to other associations. Nonetheless, successions are dominated by lithologically variable, organic-rich deposits (Facies 12) and paleosols (Facies 13), with subordinate amounts of interbedded sandstones (Facies 5 and 7). FA6 ranges from 1.1 to 13.2 metres in thickness. FA6 successions overlie all other facies associations.

4.7.1. Discussion:

Overall, FA6 is interpreted to represent delta plain / coastal plain deposits. Facies 12 ranges from gradational to sharp-based, and constitutes a lithologically variable unit, consisting of carbonaceous mudstones, siltstones, sandstones, and coal. The prevalence of mud and silt accumulation (Fig. 3.17a, b, e) is indicative of deposition within quiet-water settings that permitted suspended sediment settling. High concentrations of carbonaceous detritus and coal fragments combined with the presence of \textit{in situ} coal beds (Fig. 3.17c) point to fluvial and delta-plain environments such as floodplains, swamps, bogs, and/or marshes (cf. Collinson, 1996; Miall, 1996). In such settings, considerable amounts of terrigenous material accumulates and is periodically wetted, as adjacent channels introduce sediment during overbank flooding events (Miall, 1996). Intercalated sandstone stringers further support periodic influx of coarse-grained material, interpreted as crevasse splays (cf. Elliot, 1986). Convolute bedding (Fig. 3.17b) likely developed in response to the event-style deposition, with sand rapidly loaded onto a presumably water-saturated or soupy substrate. Another possibility for the development of convolute bedding is that deformational features formed through the degassing of trapped methane, which is commonly generated in such settings by the burial and decay of organic material. Siderite nodules (Fig. 3.17e) are characteristic of permanently waterlogged soils (Retallack, 2001). Their common occurrence and sporadic distribution exemplifies the repetitive nature of subaqueous conditions within the depositional environment. Common root traces (Fig. 3.17b) and rare \textit{Naktodemasis} (Fig. 3.17e) record fluctuating water levels and periods of subaerial exposure, with
Figure 4.14. Litholog of representative well 12-13-43-6W5, illustrating the various facies that comprise FA6. Legend for strip log in Fig. 4.3.
Figure 4.15. Box core photograph of Facies Association 6 in well 12-13-43-6W5 (1404.04 to 1414.50 m). The interval is dominated by lithologically variable, organic-rich deposits (Facies 12) and paleosols (Facies 13). An erosionally based and fining-upward sandstone unit is also present (Facies 5). Overall, the association is interpreted to represent upper delta plain / coastal plain deposits.
associated growth of vegetation, incipient soil development, and beetle larvae burrowing (cf. Smith et al., 2008; Counts and Hasiotis, 2009).

Facies 13 is also a common feature of FA6. The unit grades upwards out of underlying units, and consists of pale-coloured mudstones and siltstones (Fig. 3.18a, b). Like Facies 12, deposits are consistent with accumulation in delta plain or coastal plain settings, and reflect continuous sedimentation in low-lying environments (e.g., floodplains, swamps, bogs, and/or marshes). Nevertheless, an abundance of pedogenic features (e.g., root structures, pale colours, scalloped and discontinuous waxy to glossy slickensides, mottled textures, and ichnological elements of the Scoyenia Ichnofacies) are interpreted to record prevailing subaerial conditions and the development of paleosols. The predominantly pale color of the facies, combined with mottling, indicates gleying of the substrate during soil/paleosol development (Leckie et al., 1989). Gleization is characteristic of organic-rich, waterlogged soils that accumulate under anaerobic conditions, allowing micro-organisms to chemically reduce oxidized minerals (Retallack, 2001). Slickensides are also common and represent the expansion and contraction of swelling clays (e.g., smectite), during intermittent wet (e.g., seasonal rainfall) and dry conditions (Retallack, 2001). The presence of Naktodemasis further supports subaerial exposure with concomitant paleosol development (cf. Smith et al., 2008; Counts and Hasiotis, 2009). It also indicates that soil moisture contents, on average, were below saturation but above the wilting point for a particular soil (Counts and Hasiotis, 2009).

Facies 5 and 7 are locally interbedded within FA6 successions. These erosionally based, decimetre- to metre-thick sandstones are interpreted as crevasse channels or splay sands, episodically emplaced into adjacent floodplain environments. Crevasse channels are associated with most meandering-river successions, and form when levees are breached during periods of high runoff. Once the levee is breached, water and associated sediment are deflected through the channel and deposited into overbank areas as crevasse splays (Miall, 2010). Such units are dominated by cross-stratification (Facies 5) and current-ripple lamination (Facies 7), indicating traction transport by quasi-steady unidirectional flow and the migration of dune- and ripple-scale bedforms, respectively. Deposits typically fine-upwards, recording gradual abandonment and deposition under waning-flow conditions. Bioturbation is generally
absent from these deposits, reflecting the episodic and energetic nature of deposition. Isolated ichnogenera attributable to the *Scoyenia* Ichnofacies (e.g., *Naktodemasis*) and roots are consistent with subaerially exposed and periodically wetted delta plain / coastal plain environments (Buatois and Mangano, 1995, 2011; MacEachern et al., 2010).
5. Application of the WAVE Classification Scheme: Examples from Cycles D and E of the Basal Belly River Formation

5.1. INTRODUCTION

The WAVE classification ideology (cf. Ainsworth et al., 2011) was introduced and detailed in Chapter 2 (Section 2.1). This scheme allows semi-quantitative classification of marginal- to shallow-marine environments and facilitates accurate comparisons between varying systems. Chapters 3 and 4 focused on the analysis and characterization of deposits comprising Cycles D and E of the basal Belly River Formation. Thirteen distinct facies were differentiated and grouped into 6 recurring facies associations (FA1-FA6). Of these, only FA1 and FA2 represent coastal systems and, therefore, have suitable application within the WAVE framework. FA1 is affiliated with Cycle D deposits, and interpreted to represent the progradation of a river-dominated, storm-influenced delta (Fw Lobe Element Complex (EC)). FA2 correlates to Cycle E deposits, and is interpreted to represent the progradation of a storm-dominated, mixed river- and wave-influenced delta (Wf Lobe EC).

At present, there is a dearth of case studies attempting to apply the WAVE approach to ancient deposits (cf. Ainsworth et al., 2010, 2011; Vakarelov et al., 2011). This chapter provides a simple rock-record example that employs this approach. Representative intervals of FA1 and FA2 are characterized within the WAVE classification, in order to semi-quantify the effects of fluvial, wave, and tidal processes in each depositional system. Workflow follows the guidelines established by Ainsworth et al. (2011), and each facies association is assigned a formal classification category (e.g., Wtf). Schematic plan-view models showing potential coastal geometries for each category are also included.
5.2. APPLYING THE WAVE CLASSIFICATION TO FACIES ASSOCIATION 1

The first step in applying the WAVE classification to ancient deposits is to semi-quantify the relative influence of fluvial, wave, and tidal processes on sediment deposition (Ainsworth et al., 2011). In order to do this, an estimated percentage of the structures generated by each process must be calculated for the beds of interest. Consider the Facies Association 1 (FA1) example detailed in Chapter 4 (Figs. 4.04 and 4.05). Well 8-2-43-5W5 demonstrates a complete succession of FA1 (Facies 1a, 2, 3c, and 9). The succession displays an abundance of fluvial-generated features, including current-generated structures (e.g., current ripples, combined-flow ripples, aggradational current ripples, both planar tabular and trough cross-stratification), normal and inverse grading, syneresis cracks, soft-sediment deformation, carbonaceous beds, and drapes of inferred fluid mud origin. Wave-induced structures are present in lesser amounts and comprise micro-hummocky cross-stratification, wave ripples, and curvilinear parallel lamination. Tide-generated structures are also locally present, although only in very minor abundances. These consist of tidal rhythmites and flaser bedding.

The FA1 interval within well 8-2-43-5W5 is 9.50 metres thick. The combined thickness of fluvial-generated structures is calculated to be 8.75 metres; the combined thickness of wave-generated structures is calculated to be 0.66 metres; and the combined thickness of tide-generated structures is calculated to be 0.09 metres (Fig. 5.1). Therefore, 92% of the sedimentary structures are attributed to fluvial processes, 7% to wave processes, and 1% are ascribed to tidal processes. Using the WAVE classification, the facies association is categorized as a fluvial-dominated, wave-influenced, tide-affected element complex (Fwt EC), and can be plotted graphically within the WAVE ternary diagram (see Fig. 5.2a, b). The Fwt EC designation also allows for an approximation of the potential geometries of the system, through the use of a schematic plan-view model (Fig. 5.3). Each representative model is formulated through observation of modern coastal systems and portrays the different architectures that result from various combinations of processes (Ainsworth et al., 2011).
Figure 5.1. Application of the WAVE classification to FA1. Litholog shows an interval of FA1, contained within well 8-2-43-5W5. The figure illustrates the percentage of sedimentary structures generated by fluvial (92%), wave (7%), and tidal (1%) processes. The interval is therefore designated as a fluvial-dominated, wave-influenced, and tide-affected (Fwt) element complex. Legend for strip log in Fig. 4.3.
5.2.1. **Discussion:**

The deposits contained in well 8-2-43-5W5 reflect a particularly fluvial-dominated expression of FA1. Although FA1 is consistently characterized by fluvial dominance, other examples show increased proportions of secondary, wave-induced structures. Consequently, these examples plot slightly closer to the W apex of the WAVE ternary diagram (Fig. 5.2b). Tide-generated structures persist as tertiary elements in most occurrences of FA1; however, in some cases evidence of tides is absent. In such instances, the deposits are categorized as fluvial dominated, wave influenced (Fw EC), and plot along the Fw line of the ternary diagram (Fig. 5.2). As there is no defined percentage which necessitates a primary, secondary, tertiary or absent element classification, tidal influence is still commonly reflected in the element complex name despite its reduced relative abundances. Perhaps future workers using the WAVE classification scheme can delineate quantitative values that may consistently be applied to allow accurate comparisons between the depositional processes operating in different marginal-marine systems. Thus, a tertiary element in one deltaic system will have comparable abundances to a tertiary element in another system.

The representative model of the Fw t coastal system (Fig. 5.3) predicts a lobate morphology. Isolated beach-ridge complexes are present in the upper delta front and constitute the main sand bodies in the modern representation of the system. Multiple tidal and fluvial channels are active within the lower reaches of the delta plain, with tidal flats locally contained in interdistributary areas. Within a Fw EC (Fig. 5.3), the model also predicts a lobate coastal morphology. However, individual beach-ridge complexes are amalgamated into sets, tidal channels and tidal flats are no longer present, and the system is influenced by a single distributary channel with multiple abandoned remnants occupying the delta plain.

Preliminary observations indicate that FA1 successions correlate directly to cycle D deposits within the study area. Chapter 6 focuses on the stratigraphy of the basal Belly River cycles and facilitates the comparison between the representative models and the actual subsurface correlations of Cycle D.
Figure 5.2.  WAVE classification scheme (modified after Ainsworth et al., 2011). Red dots mark the location where FA1 (well 8-2-43-5W5) plots within the ternary diagram. The yellow, dashed outline denotes the range of variability for FA1 successions.
Representative plan-view models, showing depositional geometries for each of the 15 coastal classification categories (modified after Ainsworth et al., 2011). The solid red box marks the Fwt system, which appears to represent the FA1 succession as observed in well 8-2-43-5W5. The dashed border denotes the Fw system, which is characterized in other cored examples of FA1.
5.3. APPLYING THE WAVE CLASSIFICATION TO FACIES ASSOCIATION 2

Facies Association 2 (FA2) can also be cataloged within the WAVE classification framework. Consider the example given in Chapter 4 (Figs. 4.6 and 4.7). Well 14-28-42-4W5 contains a complete succession of FA2 (Facies 1b, 3a, and 3b). Wave-generated structures, including hummocky cross-stratification, apparently structureless (massive) bedding, and curvilinear parallel lamination, dominate the deposits, whereas fluvial-generated structures such as normal and inverse grading, syneresis cracks, carbonaceous beds, and drapes of inferred fluid mud origin, are present only in subordinate amounts. Tide-generated structures are not observed within the FA2 succession.

The FA2 interval in well 14-28-42-4W5 is 7.73 metres thick. The combined thickness of wave-generated structures is calculated to be 7.35 metres and the combined thickness of fluvial-generated structures is 0.38 metres (Fig. 5.4). Hence, 95% of the sedimentary structures are attributed to wave processes and 5% are attributed to fluvial processes. Using the WAVE classification, the facies association is therefore categorized as a wave-dominated, fluvial-influenced element complex (Wf EC), and can be represented graphically within the WAVE ternary plot (see Fig. 5.5a, b). The Wf EC designation can also be used to determine potential architectural elements typical of such systems (Fig. 5.6).
Figure 5.4. Application of the WAVE classification to FA2. Litholog shows an interval of FA2 from well 14-28-42-4W5. The figure illustrates the percentage of sedimentary structures generated by wave (95%) and fluvial (5%) processes. On that basis, the interval is designated as a wave-dominated, fluvial-influenced (Wf) element complex. Legend for strip log in Fig. 4.3.
5.3.1. **Discussion:**

Well 14-28-42-4W5 depicts a typical example of FA2. Thick sandstone intervals dominate the succession and are characterized by apparently structureless (massive) bedding and hummocky cross-stratification. Such structures are interpreted as inherently storm-induced, created by wave action and liquefaction during storms, but reflect a potential preservational bias. Storm-dominated environments support a predisposition towards the preservation of tempestites through the erosional truncation of fairweather deposits. Therefore, the preservation potential of fluvial- and tide-generated structures in such settings is low, whereas the preservation potential of wave/storm-generated structures is high. Such conditions explain why the concentration of fluvial-generated structures exponentially decreases as the succession passes upwards from prodelta heterolithic units (Facies 1b) into delta-front sandstones (Facies 3a and 3b). In settings where this preservational bias is mitigated (e.g., embayed or sheltered shorelines, protected from direct wave approach; Ainsworth et al., 2011), the overall percentage of fluvial-generated structures increases and the system plots slightly closer to F apex along the Wf line of the ternary diagram (Fig. 5.5b).

The schematic model of the Wf coastal system (Fig. 5.6) depicts a strike-elongate morphology. Amalgamated beach-ridge sets are quasi-shore-parallel, and represent the main sandstone deposits. A single distributary channel supplies sediment to the system, and abandoned remnants develop within the delta plain owing to channel avulsion. Preliminary observations suggest that FA2 successions correlate to Cycle E deposits within the study area. Correspondingly, the following chapter provides an opportunity to test the accuracy of this modern-based model against subsurface correlations and sandstone-distribution maps of Cycle E. Comparing the Wf interpretation of Cycle E with similar ancient deposits could lead to further refinement of the model.
Figure 5.5. WAVE classification scheme (modified after Ainsworth et al., 2011). Red dots mark the location where FA2 (well 14-28-42-4W5) plots in the ternary diagram. The red dashed line denotes the range of variability for FA2 successions.
Figure 5.6. Representative plan-view models, showing depositional geometries for each of the 15 coastal classification categories (modified after Ainsworth et al., 2011). The solid red box outlines the Wf system, designated by the FA2 succession observed in well 14-28-42-4W5. This system characterizes all cored expressions of FA2.

6.1. INTRODUCTION

This thesis investigates whether the along-strike asymmetry recognized within Cycle G of the basal Belly River Formation (Hansen, 2007) is a characteristic expression of the underlying deposits of Cycles D and E. Integration of ichnology with physical sedimentological characteristics permitted the differentiation of 13 depositional facies within the study area (detailed in Chapter 3). The recurrent character of particular combinations of these facies facilitated the construction of 6 facies associations, each representing a distinct depositional setting (detailed in Chapter 4). Through the analysis of 50 subsurface cores, a petrophysical signature for each association was determined using the geophysical well-log dataset, and the major stratigraphic surfaces were identified. Over 200 additional well logs were interpreted, in order to accurately correlate the “key” surfaces throughout the study area. Using this dataset, three dip-oriented and two strike-oriented cross sections (Fig. 6.1) were constructed to showcase the stratigraphic architecture of allomembers D and E. Dip-oriented cross-sections (AA’, BB’, CC’) trend southwest to northeast and focus on differentiating the main sand-bodies of Cycles D and E, as well as characterizing their progradational and offlapping relationships. The lines of section also extend eastward into the adjacent study area of Hanson (2007), in order to “tie-in” the stratigraphic position of the overlying Cycle G deposits. Strike-oriented cross-sections (DD’, EE’) trend northwest to southeast and depict limited lateral variations in facies distribution within each cycle. Consequently, these sections provide the most conclusive and diagnostic evidence for the assessment
Figure 6.1. Location map showing the position of cross-sections AA' - EE'. The red border outlines the study area of this thesis. The green border outlines the study area of Hansen (2007).
of along-strike asymmetry. Isopach maps illustrate the net-sand thicknesses of each cycle, and are included to compare plan-view geometries with cross-section correlations and depositional interpretations. Representative depositional models, characterizing the overall deltaic system of each basal Belly River cycle, are also included.

6.2. STRATIGRAPHIC FRAMEWORK

6.2.1. Stratigraphic Surfaces

An allostratigraphic approach (detailed in Chapter 1; Section 1.5.3) was chosen to subdivide the stratigraphic interval into distinct and genetically related units, following the approach of Powers and Walker (1996). Within this framework, each basal Belly River cycle equates to an allomember, bounded above and below by a marine-generated discontinuity. The discontinuities are typically interpreted as major marine flooding surfaces (MjFS; Fig. 6.2a); however, where evidence of erosion is present, they are designated as wave ravinement surfaces (WRSs; Fig. 6.2b). In distal settings, discontinuities are characterized by prodelta deposits sharply overlying delta-front or terminal distributary channel/mouth-bar deposits of the previous allomembers. In more proximal locales, discontinuities are characterized by delta-front deposits backstepped and sharply overlying various delta plain/coastal plain successions. Locally, such surfaces are demarcated by palimpsest firmground suites attributable to the Glossifungites Ichnofacies (Fig. 6.3). These palimpsest suites are typically associated with erosionally exhumed (dewatered and compacted) substrates, and commonly represent stratigraphically significant surfaces (see MacEachern et al., 2007b; MacEachern et al., 2010 for a review).

Each MjFS/WRS differentiated within the study interval is regionally correlatable and easily distinguished in petrophysical well logs. Hence, they are interpreted to represent transgressive surfaces, most likely allogenic in origin (related to a relative rise in sea level). Allogenic processes occur external to the sedimentary basin and are interpreted to regulate accommodation space (e.g., eustatic fluctuations, tectonism, and climate change; see Catuneanu et al., 2011 for a review). Such surfaces are utilized within conventional sequence stratigraphy, in order to partition depositional packages.
Figure 6.2. Allostratigraphic bounding discontinuities. (A) A major marine flooding surface (MjFS) separates Allomember E from the underlying Allomember D, placing prodelta deposits (Facies 1b) of FA2 above mouth-bar/distributary channel complexes (Facies 3c) of FA1. Well 00/14-28-42-4W5, 1290.14m. (B) A wave ravinement surface (WRS) produces a similar juxaposition of facies along the Allomember D (below) / Allomember E (above) contact. Well 00/14-7-43-4W5, 1295.90m.
Figure 6.3. Subtle expression of the Glossifungites Ichnofacies. (A) Box shot showing the upper portion of Allomember E. A wave ravinement surface (WRS) places delta-front deposits (Facies 3a) of FA2 above interdistributary bay deposits (Facies 11) of FA5. (B) The WRS is demarcated by a palimpsest trace-fossil suite consisting of firmground *Thalassinoides* (Th), attributable to the Glossifungites Ichnofacies. Note the syneresis crack (syn) present in the underlying FA5 layer. Well 00/12-31-42-3W5, 1296.09m.
and determine stratal stacking patterns. An alternative possibility is that each MjFS/WRS was generated by large-scale autogenic changes, which occurred under steady dynamic conditions within the depositional system (e.g., constant sediment supply and sea-level rise; Muto et al., 2007). This hypothesis is based on the principles of autostratigraphy (cf. Muto et al., 2007; Muto et al., 2012), which advocates that fluvio-deltaic systems can exhibit non-equilibrium and non-linear responses to steady-state (equilibrium) conditions. Correspondingly, their stratigraphic architectures can be explained without appealing to allogenic controls.

In order to definitively ascertain the origin of each MjFS/WRS (e.g., allogenic vs. autogenic), allogenically induced flooding surfaces from outside the delta complex (e.g., strandplain shoreface environment) need to be identified and tied back to the deltaic depositional architecture, to determine if they are correlatable with a MjFS/WRS. If correlatable, the MjFS/WRS are best regarded as allogenic. If not, they are likely autogenic. Given the scope of the project, combined with the fact that none of the logged intervals from the study area were interpreted to have been deposited outside of the overall delta complex, sufficient data was not available to pursue this methodology. Therefore, the implications of both possibilities must be considered when interpreting the depositional history of the study area.

Multiple minor marine flooding surfaces (MnFS; Fig. 6.4) are also recognized within the allomembers. These stratigraphic surfaces are much more difficult to correlate regionally; they appear to die out both down depositional dip and along strike on the scale of kilometres, and therefore are considered autogenic. Autogenic processes such as channel avulsion and delta lobe switching are common within deltaic settings and can generate stratigraphic signatures similar to those produced by allogenic mechanisms (Muto and Steel, 2001, 2004; Muto et al., 2007). The resulting coarsening-upward lobes or cycles are bounded above and below by autogenically induced MnFSs, which control the internal architecture of each allomember.
Figure 6.4. Minor marine flooding surfaces (MnFS). The cored interval depicts 2 MnFSs, which separate FA2 successions within the upper portion of Allomember E. These surfaces are interpreted to be autogenic in origin. Well 00/12-31-42-3W5.
6.2.2. **Correlation Concepts**

Correlations were focused on the major bounding discontinuities (MjFS/WRS) rather than the individual lobes per se, owing to the magnitude of spacing between adjacent wells and cored intervals. Nevertheless, an attempt was made to correlate the secondary MnFSs, in order to map-out and ascertain the relationships between adjacent autogenic lobes. This proved to be much more feasible in the wave-dominated successions (e.g., Allomember E), as MnFS are more clearly defined on gamma-ray logs. Adversely, within the river-dominated intervals (e.g., Allomember D), gamma-ray signatures routinely showed considerable degrees of heterogeneity, and correlating the MnFS was more problematic.

The resulting correlations (cross-sections AA’ through EE’) employ a combination of both allostratigraphic and lithostratigraphic principles, as the deltaic deposits of each allomember are partitioned using flooding surfaces as bounding discontinuities (e.g., MjFS, WRS, and MnFS), whereas the overlying delta plain/coastal plain successions (FA3/FA4/FA5/FA6) are predominantly mapped lithostratigraphically. This approach clearly defines each allomember in the marginal-marine realm, displaying the spatial relationships of deposits in strike- and dip-oriented directions, and allowing for an accurate assessment of along-strike variations in facies distributions (the main goal of the study). Correlating transgressive surfaces into the continental realm becomes problematic and is beyond the scope of this investigation. Thus, thick delta plain/coastal plain accumulations are simply correlated together, to portray their overlying stratigraphic position, and cannot be definitively linked to any particular allomember.

6.2.3. **Datum**

The Milk River Shoulder (MRS) was chosen as the datum for all correlations. This is consistent with previous studies that focused on correlating the deposits of the basal Belly River Formation (e.g., Wasser, 1988; Al-Rawahi, 1993; Hamblin and Abrahamson, 1996; Power and Walker, 1996; Hansen, 2007; Hansen and MacEachern, 2007). The MRS represents a regional marine transgression, which deposited finer-grained facies of the Pakowki Formation above coarser-grained facies of the Milk River Formation in southern Alberta (Dawson et al., 1994). Within the study area, deposits of
the upper Lea Park Formation (Pakowki equivalent) are indistinguishable from deposits of the lower Lea Park Formation (Milk River equivalent); however, a distinct petrophysical “kick” can be recognized on both resistivity and gamma-ray logs (Fig. 6.5), clearly marking the distal expression of this flooding surface (Dawson et al., 1994).

The MRS is laterally continuous across the entire study area and is located approximately 25 to 50 metres stratigraphically below the MjFS delineating the top of Allomember D. Although an ideal datum should occur stratigraphically above an interval of interest, the MRS represents the most suitable choice within the study area because it is easily recognized on petrophysical well logs, is widespread and laterally continuous, is stratigraphically close to allomembers D and E, and is regarded to represent a relatively horizontal stratigraphic surface (Dawson et al., 1994).

One problem encountered through the use of an underlying stratigraphic surface as a datum was that multiple wells did not penetrate sufficiently deep to intersect the MRS. In many instances, this problem was averted by carefully choosing representative wells that intersected the datum along the line of section. However, in certain cases, specific wells were utilized in the cross-sections because they contained a logged interval of core. If these wells did not intersect the MRS, their petrophysical signature was compared to those of an adjacent well that did intersect the MRS, and an approximation of the proper stratigraphic position was made based on the position of distinctive sandstone or coal marker beds.
Figure 6.5. The Milk River Shoulder (MRS) datum, represented by the red dashed line, separates the upper Lea Park Formation (Pakowki) from the underlying lower Lea Park Formation (Milk River equivalent). Note the petrophysical signature on the resistivity log (right) and the gamma-ray log (left). Allomember D is truncated by MjFS2/WRS2, which is overlain by thick sandstones of Allomember E. Note: petrophysical logs for well 00/14-16-43-04W5 were obtained using IHS Accumap software.
6.3. DIP-ORIENTED CROSS-SECTIONS

6.3.1. Cross-Section AA’

Cross-section AA’ (Fig. 6.6) is oriented roughly parallel to the inferred depositional dip of allomembers D and E. The cross-section is approximately 75 km in length, extending southwest to northeast across the Ferrier, Willesden Green, Gilby, Wilson Creek, and Westerose South fields. The section has been correlated using data from dozens of wells across the study area. Ten petrophysical well logs and 10 cores were selected to showcase these relationships. Collectively, cored intervals penetrate the upper cycles of Allomember D (D3-D5), all of Allomember E (E1-E3), and the basal lobe of Allomember G (G1). Cross-sections show the gamma-ray signature for each well, and the stratigraphic position of each cored interval is represented by an AppleCORE litholog. As with all correlations, the stratigraphic datum is represented by the Milk River Shoulder (MRS).

Cross-section AA’ (Fig. 6.6) illustrates the overall progradation of allomembers D and E. The base of Allomember D is identified by a subtle increase in radioactivity shown on gamma-ray logs, as well as a sharp decrease in conductivity depicted on resistivity logs (not shown in the cross-section). This signature is correlatable across the study area and is interpreted to represent either a major marine flooding surface or wave ravinement surface (MjFS1/WRS1). No cores intersect this surface within the study area. Allomember D in Figure 6.6 is interpreted to contain 5 coarsening- and shallowing-upward successions (D1-D5), each of which represents a period of progradation followed by minor transgression (marked by MnFS). Sandstone units within each cycle downlap and thin to the northeast (basinward), collectively forming a progradational stacking pattern. D3, D4 and D5 are each intersected by cores. Successions are dominated by cross-stratified to current-rippled sandstones (Facies 3c), interpreted as terminal distributary channel/mouth-bar complexes within a river-dominated, storm-influenced deltaic setting (FA1). An underlying, centimetre- to decimetre-thick layer of distal to proximal prodelta deposits (Facies 1a) is also present in well 02/16-16-41-6W5, further supporting the FA1 interpretation. In proximal regions (e.g., well 02/16-16-41-6W5), FA1 intervals pass upward into fluvial channel (FA3) and delta/coastal plain (FA6) accumulations. In slightly more basinward locations (e.g., well 00/14-19-42-4W5), FA1
deposits are capped by mud-rich, shell-bearing layers (Facies 10), interpreted to have accumulated on the lower delta plain within restricted bays or lagoons (FA5). These deposits are sharply truncated and overlain by Allomember E (MjFS2/WRS2).

Allomember E on cross-section AA’ (Fig. 6.6) comprises a depositional package that consists of 3 coarsening-upward lobes (E1-E3), which grade from moderately bioturbated, interstratified sandstone, siltstone, mudstone, and organic-rich claystone (Facies 1b), into apparently structureless or planar parallel laminated sandstone (Facies 3a), and cryptically bioturbated to bioturbated sandstone (Facies 3b). Cumulatively, these facies comprise FA2, and are interpreted to represent deposition within a storm-dominated, mixed river- and wave-influenced deltaic setting. Sandstone units correlate across the study area, downlapping and thinning basinwards (east to northeast) to form a progradational stacking pattern similar to that of Allomember D. Each progradational unit is terminated by a minor transgression that places prodelta deposits over delta-front deposits in distal locations, and distal delta-front deposits over proximal delta-front deposits in more proximal settings. Allomember E is locally capped by coals and passes upwards into sporadically bioturbated composite bedsets consisting of thinly interstratified sandstone, clayey siltstone, and mudstone (Facies 11), characteristic of marine-influenced, lower delta plain environments (FA5). More specifically, the facies is interpreted to represent interdistributary bay deposits. FA5 accumulations pass into thick layers of FA3 and FA6. Fluvio-estuarine distributary channels (FA4) are also present in eastern regions of the study area (e.g., well 02/14-7-43-2W5). These successions are incised into the previously deposited FA5 layers, are dominated by cross-bedded sandstone up to 10 m thick, with sporadically distributed bioturbated mudstone laminae.
Figure 6.6. Cross-section AA' represents a dip-oriented transect through allomembers D, E, and G of the basal Belly River Formation. The correlation is approximately 75 km in length. Allomember D comprises 5 river-dominated, storm-influenced deltaic successions (FA1); Allomember E consists of 3 storm-dominated, mixed river- and wave-influenced deltaic successions (FA2); and Allomember G exhibits 1 FA2 succession within the cross-section. Fluvial channels (FA3), distributary channels (FA4), marine-influenced lower delta plains (FA5), and delta/coastal plains (FA6) dominate in landwards (SW) and overlying stratigraphic positions. A legend of the symbols and colours used within cross-sections AA' - EE' is included.
6.3.2. **Cross-Section BB’**

Cross-section BB’ (Fig. 6.7) is also oriented roughly parallel to the inferred depositional dip of allomembers D and E, and acts as an extension of cross-section AA’. Cross-section BB’ is approximately 43 km long, and is oriented southwest to northeast across the Westerose South, Homeglen-Rimbey, Ferrybank, and Anthony fields. Ten petrophysical well logs and six cores are included in the correlation, which extends eastward (beyond the study area) in order to incorporate the previous observations of Hansen (2007). Only the core litholog for well 00/3-15-43-2W5 was collected in this study. The remaining five lithologs were generated by Hansen (2007) and are interpreted to intersect the overlying Allomember G.

Cross-section BB’ (Fig. 6.7) illustrates the continued progradation of Allomembers D, E, and G. The internal lobes of allomembers D and E extend across the correlation, and sandstone units successively pinch-out as the lobes dip gently basinward (eastward). The base of Allomember G is marked by MjFS3/WRS3, which is penetrated by well 00/3-15-43-2W5. The cored interval records the transgression, reflected by the juxtaposition of distal prodelta deposits associated with Allomember G above proximal delta-front deposits of Allomember E. Allomember G is interpreted to comprise 3 coarsening- and shallowing-upward successions (G1-G3), separated by MnFS, forming a progradational stacking pattern. Five cored intervals intersect Allomember G across the cross section. The deposits were interpreted by Hansen (2007) to represent deposition within a prograding, mixed wave- and storm-influenced delta, broadly similar to Allomember E. Observations in this study concur with that interpretation. The character of these deposits is consistent with deposition in the updrift portion of a mixed river- and wave-influenced, asymmetric delta complex.
Figure 6.7. Cross-section BB’ represents a dip-oriented transect through allomembers D, E, and G of the basal Belly River Formation. The correlation is approximately 43 km in length and extends into the study area of Hansen (2007). Within the correlation: Allomember D contains 3 FA1 cycles; Allomember E contains 3 FA2 cycles; and Allomember G is interpreted to comprise 3 successions, similar to FA2. All cored intervals penetrating Allomember G were logged and interpreted by Hansen (2007). Fluvial channel (FA3) and delta/coastal plain (FA6) deposits overlie the allomembers in proximal (SW) regions, whereas Allomember H is present above Allomember G in more distal regions.
6.3.3. **Cross-Section CC’**

Cross-section CC’ (Fig. 6.8) likewise is dip oriented. The line of section is approximately 61 km in length, extending from southwest to northeast, and is positioned north of cross sections AA’ and BB’. The correlation strikes across the Wilson Creek, Westerose South, and Westerose fields, and uses data from ten petrophysical well logs and five cores. Collectively, cored intervals penetrate the upper cycles of Allomember D (D3-D4), all of Allomember E (E1-E3), and the upper cycles of Allomember G (G2-G3). Lithologs for the cores that intersect allomembers D and E were generated in this study. The two lithologs (wells 00/6-11-45-2W5 and 00/4-14-46-1W5) that penetrate Allomember G were generated by Hansen (2007).

Cross-sectional CC’ (Fig. 6.8) illustrates the progradation of allomembers D, E, and G. The allomembers are bounded above and below by major transgressive surfaces, and consist of multiple autogenically bound lobes that exhibit an overall progradational stacking pattern, consistent with the geometries observed in sections AA’ and BB’. Cycles D2 to D5 are present within Allomember D along the line of section. Successions comprise FA1 deposits, consistent with deposition in a river-dominated, storm-influenced delta. FA1 intervals are overlain by FA5 accumulations (Facies 10) in proximal regions (e.g., well 00/8-2-43-5W5), and are truncated by MjFS2/WRS2 in more distal locales (e.g., well 00/14-16-43-4W5). A fluvio-estuarine distributary channel (FA4) is also intersected by well 00/8-2-43-5W5. The succession is approximately 5 m in thickness, sits erosionally on FA5 deposits, and passes upward into FA6 and FA3 accumulations.

The architecture of Allomember E in cross section CC’ (Fig. 6.8) is likewise consistent with previous correlations (AA’ and BB’). The depositional package consists of 3 progradational cycles (E1-E3), and is bounded above and below by MjFS3/WRS3 and MjFS2/WRS2, respectively. Cored intervals display sand-rich successions, interpreted to represent deposition within the proximal reaches of a storm-dominated, mixed river- and wave-influenced delta (FA2). Allomember E is locally capped by centimetre- to decimetre-thick coals (e.g., well 00/14-7-43-4W5), which are sharply overlain by interdistributary bay deposits (Facies 11), characteristic of a marine-influenced, lower delta plain environment (FA5). The FA5 layers pass upwards into FA3 and FA6.
The base of Allomember G in CC’ is marked by MjFS3/WRS3. The internal architecture of Allomember G is compatible with previous correlations, consisting of 3 coarsening-upward and progradational successions (G1-G3). Contrary to cross-section BB’, however, the 2 cored intervals display an abundance of inferred river-generated features. These deposits were interpreted by Hansen (2007) to represent the progradation of a storm-influenced, river-dominated delta lobe, similar to Allomember D. Observations in this study indicate that such deposits are more consistent with deposition in the downdrift portion of a mixed river- and wave-influenced, asymmetric delta complex.
Figure 6.8. Cross-section CC’ represents a dip-oriented transect through allomembers D, E, and G of the basal Belly River Formation. The correlation is approximately 61 km in length and extends from the current study area into the Hansen (2007) study area. Within the correlation: Allomember D contains 4 FA1 cycles; Allomember E contains 3 FA2 cycles; and Allomember G comprises 3 successions similar to FA1. All cored intervals penetrating Allomember G were logged and interpreted by Hansen (2007). Fluvial channels (FA3), distributary channels (FA4), marine-influenced lower delta plains (FA5), and delta/coastal plains (FA6) dominate landwards (SW) and overlying stratigraphic positions. Allomember H is present in distal (NE) regions.
6.4. STRIKE-ORIENTED CROSS-SECTIONS

6.4.1. Cross-Section DD’

Cross-section DD’ (Fig. 6.9) is oriented roughly parallel to the inferred paleoshoreline of Allomember D. The cross-section is approximately 70 km long, striking northwest to southeast within the Willesden Green field, and has been correlated using ten petrophysical well logs, as well as data collected from six cores. Cross-section DD’ presents the most proximal (landward) correlation of facies associations within the study area and, consequently, only intersects Allomember D. The base of Allomember D (MjFS1/WRS1) is identified by a subtle increase in radioactivity shown on gamma-ray logs, and is correlatable across the study area. No cored intervals intersect this surface within the study area. MjFS2/WRS2 is not present, as the transgressive surface does not extend sufficiently far westward to intersect the cross-section.

Four cored intervals intersect cycles of Allomember D (D3-D4) across the line of section CC’ (Fig. 6.9). In core, these successions are characterized by distal to proximal prodelta deposits (Facies 1a), which pass upwards into distal to proximal delta-front (Facies 3a) and terminal distributary channel/mouth-bar complex deposits (Facies 3c). The units are differentiated by an abundance of river-generated features (e.g., current-generated structures, graded bedding, syneresis cracks, soft-sediment deformation features, and claystone drapes of inferred fluid mud origin), and are interpreted to represent the progradation of a river-dominated, storm-influenced delta (FA1).

FA1 successions are predominantly capped by carbonaceous mudstones, siltstones, sandstones, and coals (Facies 12). These units are lithologically variable, contain anomalously high concentrations of terrigenous material, and are interpreted to represent delta plain/coastal plain deposits (FA6). Fluvial channel deposits (FA3) are also identified on petrophysical logs and in cored intervals. In core, FA3 intervals are erosively based and dominated by cross-bedded (Facies 5) and current-ripple laminated sandstone (Facies 7). The successions are largely contained within thick intervals of FA6, located stratigraphically above FA1 deposits (e.g., wells 00/12-13-43-6W5 and 00/7-34-42-6W5). However, in southern regions of cross-section CC’ (e.g., wells 02/16-16-41-6W5 and 00/16-24-39-5W5), FA3 units incise into previously deposited FA1
intervals. Thick intervals of delta/coastal plain (FA6) and fluvial channel (FA3) accumulations dominate the upper portions of the cross section.
Figure 6.9. Cross-section DD’ is a strike-oriented transect, which intersects Allomember D of the basal Belly River Formation. The correlation is approximately 70 km in length and represents the most proximal correlation of facies associations within the study area. The correlation illustrates the dominance of FA1 successions within Allomember D. Fluvial channel (FA3) and delta/coastal plain (FA6) deposits dominate stratigraphic positions above the deltaic units.
6.4.2. Cross-Section EE’

Cross-section EE’ (Fig. 6.10) is oriented roughly parallel to the inferred paleoshoreline of allomembers D and E. The cross-section is approximately 77 km long, and strikes northwest to southeast across the Minnehik-Buck Lake, Wilson Creek, and Gilby fields. Data from ten petrophysical well logs and seven cored intervals are used in the correlations, which intersect the deposits of allomembers D and E.

Five cored intervals intersect the upper cycles of Allomember D (D3-D4) across the line of section EE’ (Fig. 6.10). In core, these successions are dominated by sand-rich, terminal distributary channel/mouth-bar complexes (Facies 3c). In central regions of the study area, the same units fine upward into interstratified sandstones and siltstones (Facies 9), interpreted to represent the autogenic abandonment of the mouth-bar complex. Both facies 3c and 9 are common elements of FA1, and are considered to be consistent with deposition in a river-dominated, storm-influenced delta (FA1). FA1 successions in central regions are capped by mud-rich, shell-bearing units (Facies 10), which are interpreted to have accumulated within restricted environments on the lower delta plain (FA5).

The base of Allomember E on section EE’ is delineated by MjFS2/WRS2. This surface appears erosive in cored intervals, truncating FA5 deposits (associated with Allomember D) in central regions (e.g., well 00/14-7-43-4W5) and FA1 successions in adjacent areas (well 00/2-32-43-4W5). Cycles E1 and E2 are present within Allomember E along the line of section. Five cores penetrate the lobes, and each succession reflects distal to proximal delta-front deposits. More specifically, the intervals are dominated by apparently structureless (massive) to planar parallel laminated and cryptically bioturbated to bioturbated sandstone (e.g., well 6-31-42-4W5). These units are characteristic elements of FA2, and are interpreted to indicate deposition within the proximal reaches of a storm-dominated, mixed river- and wave-influenced delta. Allomember E is commonly capped by a centimetre- to decimetre-thick coal layer (e.g., well 6-31-42-4W5) that is sharply overlain by interdistributary bay deposits (Facies 11). These intervals are laterally continuous across the majority of the cross-section, and are postulated to typify accumulation within a lower delta plain setting (FA5). FA5 layers pass upwards into thick intervals of alluvial deposits, corresponding to FA3 and FA6.
Figure 6.10. Cross-section EE’ represents a strike-oriented transect, which intersects allomembers D and E of the basal Belly River Formation. The correlation is approximately 77 km in length and shows the exclusivity of FA1 successions within Allomember D, and FA2 successions within Allomember E. Marine-influenced, lower delta plain accumulations (FA5) cap each allomember. Fluvial channel (FA3) and delta/coastal plain (FA6) deposits dominate overlying positions of the correlation.
6.5. STRATIGRAPHIC DISCUSSION AND DEPOSITIONAL INTERPRETATION

Within the study area, the basal Belly River Formation is subdivided into 3 allostratigraphic units (allomembers D, E, and G), based on the occurrence of transgressive, marine, bounding discontinuities (MjFSs/WRSs). Each allomember is interpreted to consist of multiple autogenic lobes that combine to form progradational stacking arrangements, consistent with long-term normal regression (cf. Catuneanu et al., 2011).

Allomember D is bounded below by a regionally extensive major marine flooding surface (MjFS1/WRS1) that shifts distal facies over the more proximal facies associated with the underlying Allomember C. This surface is not penetrated by any cored intervals and, therefore, the contact's character cannot be established with confidence. Allomember D comprises 5 coarsening- and shallowing-upward FA1 successions (D1-D5), interpreted to record the progradation of a river-dominated, storm-influenced delta lobe. Each deltaic cycle is punctuated by a temporary and minor transgressive event (MnFS), postulated to have developed as a result of autogenic processes (e.g., channel avulsion and/or delta lobe switching). Sandstone units within each cycle correlate across the section, thinning and dipping basinwards (east to northeast), to form a progradational stacking pattern. In central regions, local FA1 successions (e.g., cycle D4; Figs. 6.6, 6.8 and 6.10) pass upward into restricted bay or lagoonal deposits that are interpreted to have accumulated within marine-influenced lower delta plain environments (FA5). Autogenic processes, associated with channel migration in a river-dominated delta, are interpreted to have caused the gradual abandonment of terminal distributary channel/mouth-bar complexes. Continued abandonment resulted in the formation of low-energy, restricted environments (restricted bays and/or lagoons) within the paralic setting. In proximal (western) locales, FA1 successions pass upwards into alluvial deposits (FA6), are consistent with the continued progradation of the Allomember D shoreline. Fluvial channel deposits (FA3) are common, predominantly situated within overlying delta/coastal plain accumulations (FA6), but locally incise into the delta front deposits of FA1. Rare distributary channels (FA4) are also incised into FA5 layers associated with cycle D3 (e.g., well 00/8-2-43-5W5; Fig. 6.8). Based on correlations,
these channels are inferred to have supplied sediment to one of the subsequent Allomember D lobes (e.g., D4 or D5).

MjFS2/WRS2 marks the initiation of Allomember E. The surface is regionally extensive across the thesis area and continues into the study area of Power and Walker (1996), totaling an along-strike distance of approximately 126 km. Given this lateral extent, the surface is interpreted to represent an allogenically induced transgression, which forced the shoreline landwards (west to southwest). Cored intervals that intersect distal expressions of MjFS2/WRS2 show prodelta deposits of Allomember E overlying terminal distributary channel/mouth-bar deposits associated with Allomember D. In more proximal locales, the surface appears erosional and proximal delta front deposits sharply overlie and truncate the underlying Allomember D deposits.

Allomember E comprises 3 coarsening- and shallowing-upward FA2 successions (E1-E3), interpreted to record the progradation of a storm-dominated, mixed river- and wave-influenced delta lobe. Like Allomember D, each deltaic cycle is separated by a MnFS and the sandstone units collectively are arranged in a progradational stacking pattern. This stacking pattern is consistent with the resumed and progressive basinward (east) movement of the Allomember E shoreline. A thin coal layer caps the E2 and E3 cycles across the majority of the study area (e.g., Fig. 6.10). The coals are sharply overlain by interdistributary bay deposits, interpreted to have accumulated within a marine-influenced, lower delta-plain setting (FA5).

FA5 deposits are laterally extensive and widespread above Allomember E (e.g., Figs. 6.6, 6.8 and 6.10). A possible explanation for the expansive distribution of FA5 is that following the deposition of cycle E3, autogenic processes (e.g., channel avulsion or lobe switching) associated with a subsequent E4 cycle (deposited outside of the study area) generated an interdistributary environment within the study area. Therefore, it’s possible that the FA5 deposits are equivalent to an E4 cycle and represent continued progradation of the Allomember E shoreline. Unfortunately, the regional work completed by Power (1993) and Power and Walker (1996) does not differentiate individual cycles within an individual allomember and, instead, focuses on the overall distribution trends of each depositional cycle as a whole. Hence, without further investigation, the E4 hypothesis cannot be applied with great confidence.
A second possibility is that the coal layer capping Allomember E represents a major transgressive surface (MjFS), similar to the underlying MjFS/WRS. In this scenario, FA5 accumulations may represent interdistributary bay deposits associated with a local Allomember F. Allomember F could not be reliably discerned within the study area of Hansen (2007), and she recommended that the cycle be discarded from the stratigraphy. She likewise noted that the cycle appeared to be poorly expressed throughout Bruce Power’s doctoral thesis area (Power, 1993). In the regional study completed by Power and Walker (1996), however, they delineated an Allomember F directly north of the current study area, within the eastern Pembina and Keystone fields. If their stratigraphy is correct, it’s entirely possible that the FA5 units in this study area are representative of interdistributary areas associated with Allomember F. FA5 units pass upwards into thick upper delta plain/coastal plain (FA6) and fluvial channel deposits (FA3). Rare distributary channels (FA4) are observed in the easternmost regions of the study area (e.g., Fig. 6.6). FA4 successions incise into the FA5 layers above Allomember E (e.g., well 02/14-7-43-2W5) and are approximately 11 m thick. Based on correlations, these channels are interpreted to be associated with the overlying Allomember G.

Allomember G is bounded below by MjFS3/WRS3, marking another major transgressive event interpreted to result from allogenic processes. Similar to the underlying MjFS2/WRS2, the surface is regionally extensive and extends well beyond the thesis area, totaling an along-strike distance of approximately 110 km (cf. Power and Walker, 1996). Allomember G consists of 3 offlapping, coarsening- and shallowing-upward successions (G1-G3) exhibiting stacking patterns comparable to those of the underlying allomembers. This stratal arrangement is interpreted to represent the resumed and progressive basinward (east) movement of the Allomember G shoreline. Separate correlations extend across the northern and southern portions of the Hansen (2007) study area, in order to “tie-in” the Allomember G accumulations. However, because the estimated initial shoreline position of Allomember G runs approximately parallel to the eastern border of the study area, only one core from the current study penetrated these deposits (e.g., well 00/3-15-43-2W5; Figs 6.6 and 6.7). The overwhelming majority of Allomember G accumulations were deposited to the east of R2W4 (refer to Fig. 6.1), within the study area of Hansen (2007). Therefore the
interpretations of cored intervals included within the cross-sections differ to those of Hansen (2007). Successions in southern regions (e.g., Fig. 6.7; wells 00/16-28-43-28W4, 00/16-34-43-28W4, 00/6-30-44-27W4, 00/11-4-45-27W4, and 00/10-11-46-27W4) were interpreted by Hansen (2007) to record the progradation of a mixed wave- and storm-influenced delta lobe. Careful analysis of her core descriptions and photos (cf. Hansen, 2007) reveals that these deposits compare quite favorably to the FA2 successions of Allomember E, lending support to her interpretation. Deposits in northern regions (e.g., Fig. 6.8; wells 00/6-11-45-2W4 and 00/4-14-46-1W4) were interpreted to represent the progradation of a storm-influenced, river-dominated delta lobe, and compare favorably to the FA1 successions of Allomember D. Once again, adding corroboration to her interpretation. Hansen (2007) further concluded that the facies associations of Allomember G varied along depositional strike, consistent with the asymmetric delta model of Bhattacharya and Giosan (2003). Using this paradigm, the southern cycles in Hansen’s (2007) study area record deposition in updrift areas (relative to distributary channels) of a mixed river- and wave-influenced, asymmetric delta complex, whereas the northern cycles represent deposition in downdrift areas. In proximal (western) regions, the deltaic successions of Allomember G pass upwards into delta/coastal plain (FA6) and fluvial channel deposits (FA3). In more distal (eastern) positions, Allomember G is capped by MjFS4/WRS4 and is overlain by Allomember H, once again marking continued deltaic progradation to the east.

6.6. ASSESSMENT OF ALONG-STRIKE VARIATIONS IN FACIES DISTRIBUTIONS

6.6.1. Allomember D

As expressed by the dip- and strike-oriented cross-sections (AA’ through EE’), 13 cored intervals penetrate Allomember D. In particular, the shoreline-parallel correlations of DD’ (Fig. 6.9) and EE’ (Fig. 6.10) provide the most relevant and diagnostic perspective for an assessment of along-strike variations in facies distribution. Within these cross-sections, a total of nine cores intersect Allomember D (D3-D4), establishing well control for approximately 30 km, extending from townships 41 to 44.
Integration of the physical sedimentologic and biogenic characteristics preserved within the Allomember D deposits reveals an exclusivity of FA1 elements, attributed to deposition within a river-dominated, storm-influenced delta. Deposits pass upwards from interstratified clayey siltstones and sandstones into cross-stratified to rippled sandstones, and are differentiated by an abundance of inferred river-generated features, such as current-generated structures, graded bedding, syneresis cracks, soft-sediment deformation features, and drapes of inferred fluid mud origin (see Chapter 3 and 4). Lesser amounts of wave- and storm-generated physical sedimentary structures are also present locally. Bioturbation is sporadically distributed with generally low intensities (typically BI 0-2). Trace fossil suites display low diversities with abundant facies-crossing elements.

Only minimal along-strike variations are noted within the FA1 successions, expressed as isolated, centimetre-thick intervals displaying increases in bioturbation intensity, trace fossil diversity, range of ethological groupings, and overall sizes of ichnogenera. Such occurrences suggest reductions in fluvial influence. These intervals are sporadically distributed within prodelta successions (Facies 1a), and likely record punctuated re-establishment of ambient (non-deltaic) conditions, related to pauses in fluvial influx (cf. Coates and MacEachern, 2007). Intervals showing increased occurrences of features attributed to direct river influence (e.g., current-generated structures, graded bedding, syneresis cracks, soft-sediment deformation features, and clay drapes of inferred fluid mud origin) also vary slightly along-strike. Graded and/or soft-sediment deformed intervals (Facies 2) are only locally present, and the quantity of syneresis cracks and drapes of inferred fluid mud origin commonly vary from adjacent cores. These variations could be related to the proximity of the environment to distributary mouths, or may result from variations in sedimentation rate or heightened levels of fluvial discharge in the deltaic setting. Such variations lead to changes in the persistence and magnitude of river-induced physico-chemical stresses.

The pattern of limited along-strike variation extends into the deposits that overlie FA1. Intervals consistently pass upward into FA3 and FA6 successions in proximal (western) regions (Fig. 6.9), and are truncated by an erosional surface, upon which lies Allomember E, in more distal (eastern) positions (Fig. 6.10). One notable exception is observed within central portions of cross-section EE', where the terminal distributary
channel/mouth-bar complexes (Facies 3c) of FA1 pass upward into an inferred abandonment deposit (Facies 9) and, finally, into a restricted bay or lagoonal interval (Facies 10; FA5). This is interpreted to result from autogenic processes (e.g., channel avulsion and delta lobe switching), which controlled the evolution of the overall complex, but did not lead to a major change in the degree of fluvial dominance of the delta system. Although local along-strike variations exist, each cored interval is interpreted to consist of FA1 elements and, therefore, is consistent with deposition in a river-dominated, storm-influenced delta lobe.

A net sand isopach map was constructed for Allomember D (Fig. 6.11), illustrating variations in total (net) sand thickness. The net-sand thickness at any location is representative of the cumulative thickness of sand layers from all cycles of Allomember D (D1-D5). A 60 API cut-off, ground-truthed against the core dataset, was used to pick and calibrate sand units from the gamma-ray logs. Sand accumulations predominantly thin to the east-northeast in the study area, and are largely uniform in their distribution in the along-strike direction of the inferred initial paleoshoreline of Allomember D. Net-sand thicknesses range from 0 m to 10 m and, in plan-view, sand bodies display digitate or lobate morphologies. Such geometries suggest minimal reworking by basinal processes (e.g., waves; cf. Reading and Collinson, 1996) within the delta complexes of Allomember D, and support the facies-driven interpretation of Allomember D FA1 successions as more river-dominated. Nevertheless, it is noted that the data upon which the map is built is sparse (2-7 wells per township), and the map reflects cumulative values and does not differentiate the morphology of individual lobes per se. In this sense, the isopach map represents a useful tool, which when used to supplement core-driven interpretations, may provide a further sense of the overall depositional trends for a particular allomember. The net-sand thickness trends also provide a first order assessment of sand distribution and possible distributary fairways.
Figure 6.11. Net sand isopach map of Allomember D deposits. Locations of two strike-oriented cross-sections (DD’ and EE’) are also shown. Note the lobate sand-body geometries. Dots indicate data points.
However, without additional supporting data, the map does not contribute sufficient evidence to support a depositional interpretation.

Based on the integration of data from cored intervals, multiple dip- and strike-oriented cross-sections, net-sand isopach maps, and the general lack of obvious lateral variations in facies character along depositional strike, Allomember D is deemed to be inconsistent with the asymmetric delta model of Bhattacharya and Giosan (2003). Rather, correlations simply indicate that the deltaic deposits of Allomember D are expressed exclusively as FA1 successions, reflecting a river-dominated delta system with minor storm influence.

6.6.2. **Allomember E**

Twelve cored intervals penetrate Allomember E in the various cross-sections (AA’ – EE’) that have been correlated across the study area. Cross-section EE’ (Fig. 6.10) offers the best perspective for an appraisal of along-strike variations in depositional architecture, and encompasses five cores that intersect Allomember E (E1-E2). These cored intervals establish well control for a ~15 km span extending from township 42 to 43. Petrophysical well logs are used to extend facies correlations further along-strike.

Contrary to the observations within Allomember D, detailed analysis of the Allomember E intervals reveals the total domination of FA2 elements, interpreted to represent deposition within a storm-dominated, mixed river- and wave-influenced delta. Deposits are dominated by thick accumulations of apparently structureless to planar-parallel laminated sandstone (Facies 3a) and cryptically bioturbated to bioturbated sandstone (Facies 3b). Successions are delineated by an abundance of wave- and storm-generated primary physical sedimentary structures, with only subordinate amounts of features attributed to river influence. Bioturbation is sporadically distributed and characterized by low to moderate intensities of burrowing (BI 0-5). Trace-fossil suites show low to moderate diversities of ichnogenera.

The thick, sand-rich successions of FA2 exhibit extensive lateral continuity with very little variability along strike. Deposits reflect deposition within a relatively proximal delta-front setting, and Facies 3a is consistently overlain by Facies 3b within each
depositional cycle. Local intervals preserve a basal centimetre-thick layer of sandy mudstone, which marks the initial Allomember E transgression (MjFS2/WRS2). The trend of limited lateral variability persists into the overlying delta plain/coastal plain accumulations, as FA2 successions are repeatedly capped by a thin coal layer that passes-upward into interdistributary bay deposits of FA5, and alluvial complexes attributed to FA3 and FA6. One distinct along-strike trend within Allomember E is that the overall thickness of the depositional package decreases northward. This suggests that the distributary channels feeding sediment to the Allomember E lobes were likely concentrated in the southernmost regions of the study area or south of the study area.

The net-sand isopach map generated for Allomember E (Fig. 6.12) illustrates an increased amount of strike-elongation of the sand bodies in plan-view. Net-sand thicknesses range from 3 m to greater than 18 m, generally thinning to the east and north, and represent the amalgamation of all the Allomember E deposits (cycles E1-E3). The thickest sand accumulations are preserved in southeastern regions of the study area, and display arcuate to cuspatte plan-view geometries. Towards the north, sand-body morphologies trend towards strike-elongation along the margins of the inferred initial Allomember E paleoshoreline. This tendency towards strike-elongation is interpreted to indicate increased reworking by marine processes (e.g., waves; cf. Reading and Collinson, 1996) within the delta complexes of Allomember E, consistent with the facies-driven interpretation of FA2 successions as wave-/storm-dominated delta deposits.

Based on the integration of data from cored intervals, multiple dip- and strike-oriented cross-sections, and net sand isopach maps, no lateral variations in facies distribution are apparent, and therefore Allomember E is inconsistent with the asymmetric delta model of Bhattacharya and Giosan (2003). The net sand isopach map (Fig. 6.12) does show an asymmetric distribution of sand parallel to the paleo-shoreline, however, this along-strike pattern is not reflected in core, as the expression and distribution of facies remains constant. Given the supplementary nature of the isopach maps, the overall assessment of asymmetry within Allomember E defaults to the facies expressions observed within subsurface cores and their distributions along the lines of section. Consequently, correlations indicate that the deltaic deposits of Allomember E
Figure 6.12. Net sand isopach map of Allomember E deposits. Location of strike-oriented cross-section BB' is also shown. Note the arcuate to cuspatate, and overall more strike-elongate, sand-body geometries. Dots indicate data points.
are linked exclusively to FA2 successions, and reflect a much more wave-influenced delta system than that expressed by the underlying Allomember D.

6.7. SUMMARY AND DEPOSITIONAL MODELS

Detailed analyses of allomembers D and E confirm that their lateral distributions of architectural elements are not consistent with the asymmetric delta model of Bhattacharya and Giosan (2003). Therefore, it appears that delta asymmetry developed solely within the overlying deposits of Allomember G (cf. Hansen, 2007), despite the fact that the underlying allomembers show generally similar mixed-influence characteristics.

Integration of the data from core, detailed correlations, and net-sand isopach maps allows the comparison of each basal Belly River allomember (i.e., allomembers D and E) with the representative depositional models adapted from the process-based WAVE paradigm (Ainsworth et al., 2011) in Chapter 5. The depositional model for Allomember D (Fig. 6.13a) depicts a river-dominated delta system (modified from the Fwt element complex model; Fig. 5.3). FA1 successions form in fully- to marginal-marine environments, with multiple distributary channels (FA4) feeding sediment to the delta. These channels are locally abandoned due to autogenic processes. Isolated restricted bays/lagoons (FA5) are also established within the lower delta plain, likely in response to similar autogenic events. Fluvial channels (FA3; not shown) and delta/plain/coastal plain deposits represent the most proximal successions within the system.

By contrast, the depositional model for Allomember E (Fig. 6.13b) illustrates a much more wave-/storm-influenced delta system (modified from the Wf element complex model; Fig. 5.6). FA2 successions are initiated within fully- to marginal-marine settings, with interdistributary bays (FA5) developed locally along the lower delta plain. Distributary channels (FA4) are less common as such systems are typified with a single trunk channel and minimal distributaries. Similar to Allomember D, fluvial channels (FA3; not shown) and delta/plain/coastal plain deposits (FA6) represent the most landward accumulations contained within the system.
Figure 6.13. Paleogeographic reconstruction of the depositional setting for allomembers D and E. (A) Illustrates the river-dominated delta system of Allomember D (modified after Ainsworth et al., 2011). (B) Depicts the more wave-influenced delta system of Allomember E (modified after Ainsworth et al., 2011). Figures not drawn to scale.
In closing, this research provides useful insight into the development and evolution of mixed-influence deltaic systems. The total influence of fluvial, wave, and tidal processes within a delta lobe affects the overall distribution of sand. Hence, it has direct implications on the predictive modelling associated with hydrocarbon exploration. An interpretation of a river-dominated delta system (Fwt element complex), such as Allomember D, would result in an assessment that predicted digitate to lobate sand-body morphologies and targeted isolated mouth-bar/terminal distributary channel complexes, delta fronts, and fluvial channels. An interpretation of a wave-/storm-influenced delta system (Wf element complex), such as Allomember E, would result in an assessment that predicted increased strike-elongation of sand-bodies and targeted the laterally continuous delta front deposits. Alternatively, recognition of an asymmetric delta lobe (e.g., Allomember G), which contained river-dominated deposits in downdrift positions (relative to the distributary channel) and wave-dominated deposits in updrift locations, would result in an exploration plan that targeted the thicker, updrift strandplain sandstones rather than the more heterolithic downdrift accumulations. Thus, recognizing the controlling factors in sediment deposition throughout the evolution of a delta system has great implications on the exploration for hydrocarbons. This study helps to advance this understanding by meshing core-based interpretations with stratigraphic correlations, to aid in paleogeographic reconstruction and produce depositional models that enhance the predictability of mixed-influenced delta systems throughout their evolution.
7. Conclusions

1. Based on the integration of physical sedimentological and ichnological characteristics, Cycles D and E of the basal Belly River Formation can be subdivided into 13 depositional facies. Sedimentary facies are further grouped into 6 recurring and mappable facies associations; each representing a distinct depositional setting. Depositional environments are interpreted to record a variety of marginal-marine, paralic, and coastal environments that include: river-dominated, storm-influenced deltas (FA1); storm-dominated, mixed river- and wave-influenced deltas (FA2); fluvial channels (FA3); fluvio-estuarine distributary channels (FA4); marine-influenced, lower delta plains (FA5); and delta/coastal plains (FA6).

2. FA1 and FA2 can be characterized within the WAVE classification scheme, allowing for the semiquantification of subtle differences in fluvial, wave, and tidal processes within each mixed-influence system. Using this process-based approach, FA1 is categorized as a fluvial dominated, wave influenced, tide affected element complex (Fwt), whereas FA2 is designated as a wave dominated, fluvial influenced element complex (Wf).

3. Within the study area, the basal Belly River cycles are subdivided into 3 allostratigraphic units (allomembers D, E, and G) based on the occurrence of laterally extensive, marine-generated bounding discontinuities (MjFSs/WRSs). Each allomember is interpreted to comprise multiple autogenic lobes/cycles, which are terminated by minor transgressive surfaces (MnFSs) and combine to form progradational stacking patterns.

4. Allomember D comprises 5 coarsening- and shallowing-upward FA1 successions (D1-D5); Allomember E comprises 3 coarsening- and shallowing-upward FA2 successions (E1-E3); and Allomember G consists of 3 offlapping, coarsening- and shallowing-upward successions (G1-G3) that are compatible with FA1 deposits in northern regions and FA2 deposits in southern regions. Overall, the allomembers are interpreted to be consistent with deposition during a period of long-term normal regression, and they collectively represent a prograding parasequence set.

5. Based on the integration of data from cored intervals and multiple dip- and strike oriented cross-sections; no lateral variations in facies distribution, consistent with the asymmetric delta model (Bhattacharya and Giosan, 2003), are identified within allomembers D or E. Correlations indicate that the deposits of Allomember D are exclusively linked to FA1 successions, whereas the deposits of Allomember E are exclusively linked to FA2 successions. Therefore, Allomember D is interpreted to represent a river-dominated, storm-influenced delta lobe, and Allomember E is interpreted to reflect a storm-dominated, mixed river- and wave-influenced delta lobe.
6. Net sand isopach maps were constructed for allomembers D and E. Sand-bodies within Allomember D display digitate or lobate plan-view geometries, which suggest minimal reworking by basinal processes (e.g., waves). Sand-units within Allomember E exhibit arcuate to cuspatc geometries with heightened tendencies towards strike-elongation, indicating increased reworking by marine processes (e.g., waves). These observations are consistent with the interpretations garnered from the integrated correlations, as Allomember D geometries reflect a river-dominated deltaic system and Allomember E geometries reflect a more wave-influenced deltaic system.
References


Elliot, T., 1974, Interdistributary bay sequences and their genesis: Sedimentology, v. 21, p. 611-622.


Appendices
Appendix A.

CD-ROM LITHOLOG DATA

The attached CD-ROM contains PDF files of lithologs generated for the 50 cored intervals logged as part of this study. The files may be opened using any PDF program.