HIERARCHICAL FRAMEWORK AND CYCLICITY IN A FLUVIAL-LACUSTRINE BASIN-FILL SUCCESSION, MIDDLE WASATCH FORMATION, UINTA BASIN, UTAH

by
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Geology).

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ABSTRACT

A three-level hierarchical framework for describing meso- to macro-scale architecture of fluvial systems was developed and tested utilizing exceptionally well exposed, three-dimensional outcrops of the Eocene middle Wasatch Formation. From smallest to largest, this hierarchical framework consists of storys, elements and archetypes. Each hierarchal level is composed of different types or combinations of components from the lower hierarchical level, which accounts for the variability in sedimentation styles recognized in fluvial systems. Three distinct associations between channel-belt elements and their adjacent splays are documented: 1) splays that are spatially isolated from channel-belt elements (unassociated splays); 2) splays that are laterally adjacent and physically connected to a channel-belt element (associated coeval splays); and 3) splays that underlie the channel-belt element (associated non-coeval splays). Deconstructing the sequential evolution of archetypes yielded two distinct upward stacking patterns that differentiate braided and meandering archetypes.

Four hierarchical-orders of cyclicity are documented in the middle Wasatch Formation: 1) archetype cycle; 2) small-scale cycle; 3) intermediate-scale cycle; and 4) large-scale cycle. Each increase in hierarchical level is associated with an increase in size, time-span of existence, cross-cutting relationships, correlation length, and lateral shift in the axis of deposition of stratigraphically adjacent cycles. Archetype though intermediate-scale cycles document scale-dependent compensational stacking resulting in lateral changes in upward patterns across axis-to-margin profiles through the fluvial system. This pattern represents an end-member in fluvial stratigraphy with the other being driven by allogenic controls which display persistent upward patterns in the stratigraphy across axis-to-margin profiles through the fluvial system.

A 77-mile transect up the Green River in Desolation Canyon documents a semi-Waltherian progression interpreted to reflect systematic basinward and landward shifts in a fluvial-lacustrine depositional system. This fluvial-lacustrine system encompasses the Tertiary Flagstaff, lower Wasatch, middle Wasatch, lower Wasatch, Lower Green River and Middle Green River Formations. These basinward and landward shifts contain upward stratigraphic patterns from fluvial, deltaic, lacustrine, and open lacustrine depositional environments. Regionally extensive, compound paleosols bounding the middle Wasatch Formation interrupt this Waltherian progression.
# TABLE OF CONTENTS

ABSTRACT ..................................................................................................................................................... iii  
LIST OF FIGURES .......................................................................................................................................... vii  
LIST OF TABLES ............................................................................................................................................. ix  
ACKNOWLEDGEMENTS ................................................................................................................................. x  

CHAPTER 1. INTRODUCTION TO DISSERTATION ..................................................................................... 1  
  1.1. Introduction ........................................................................................................................ 1  
  1.2. Organization and Content ................................................................................................... 1  
      1.2.1. Chapter 2 ............................................................................................................... 1  
      1.2.2. Chapter 3 ............................................................................................................... 2  
      1.2.3. Chapter 4 ............................................................................................................... 2  
  1.3. References .......................................................................................................................... 3  

CHAPTER 2. A HIERARCHICAL APPROACH FOR EVALUATING FLUVIAL SYSTEMS: ARCHITECTURAL  
ANALYSIS AND SEQUENTIAL EVOLUTION OF THE HIGH NET-SAND CONTENT MIDDLE  
WASATCH FORMATION, UINTA BASIN, UTAH ................................................................... 6  
  2.1. Abstract ............................................................................................................................... 6  
  2.2. Introduction & Purpose ...................................................................................................... 7  
  2.3. Geologic Setting and Field Area .......................................................................................... 9  
  2.4. Data and Methodology ..................................................................................................... 10  
  2.5. Lithofacies ......................................................................................................................... 11  
  2.6. Integrated, Hierarchical Framework for Fluvial Strata ..................................................... 11  
      2.6.1. Story ..................................................................................................................... 11  
      2.6.2. Element ................................................................................................................ 17  
      2.6.3. Archetype ............................................................................................................. 19  
  2.7. Discussion ......................................................................................................................... 22  
  2.8. Application ........................................................................................................................ 23  
  2.9. Conclusion ......................................................................................................................... 24  
  2.10. Acknowledgements .......................................................................................................... 25  
  2.11. References ....................................................................................................................... 25
CHAPTER 3. HIERARCHICAL NATURE OF CYLCITY IN A FLUVIAL SYSTEM: SPATIAL AND TEMPORAL VARIATIONS IN AUTOGENICALLY CONTROLLED COMPENSATIONAL STACKING AND INTERBASINAL SCALE-BREAKS RESULTING FROM CLIMATIC FORCES IN THE MIDDLE WASATCH FORMATION, UINTA BASIN, UTAH ................................................................. 48

3.1. Abstract ......................................................................................................................... 48
3.2. Introduction & Purpose ................................................................................................. 49
3.3. Geologic Setting and Study Area ................................................................................. 51
3.4. Data & Methodology .................................................................................................... 53
3.5. Hierarchical Framework for Fluvial Strata ................................................................. 53
3.6. Cyclicity in Fluvial Strata of the Middle Wasatch Formation ....................................... 54
   3.6.1. Archetype Cycle ..................................................................................................... 54
   3.6.2. Small-Scale Cycle.................................................................................................. 56
   3.6.3. Intermediate-Scale Cycle ...................................................................................... 56
   3.6.4. Large-Scale Cycle ............................................................................................... 58
3.7. Discussion ..................................................................................................................... 59
   3.7.1. Hierarchical Nature of Compensationally Formed Cycles ................................ 60
   3.7.2. Depositional Fairways within Large-Scale Cycles ............................................ 60
   3.7.3. End-member Depositional Trends ..................................................................... 61
3.8. Conclusions .................................................................................................................. 61
3.9. Acknowledgments ........................................................................................................ 62
3.10. References .................................................................................................................. 62

CHAPTER 4. THE STRATIGRAPHIC NATURE OF A FLUVIAL-LAUCUSTRINE BASIN-FILL SUCCESSION, DESOLATION CANYON, SOUTHERN MARGIN OF THE UINTA BASIN, UTAH: IMPLICATIONS FOR WALther’S LAW AND THE PETROLEUM INDUSTRY ................................................................. 85

4.1. Abstract ......................................................................................................................... 85
4.2. Introduction .................................................................................................................. 86
4.3. Physiographic and Geologic Setting .......................................................................... 86
4.4. Data and Methodology ............................................................................................... 88
4.5. Basin-Fill Succession ................................................................................................... 89
   4.5.1. Lacustrine to Fluvial (Flagstaff Limestone) ......................................................... 89
   4.5.2. Low Net-Sand Content Fluvial (lower Wasatch Formation) ............................ 90
   4.5.3. High Net-Sand Content Fluvial (middle Wasatch Formation) ....................... 91
4.5.4. Moderate Net-Sand Content Fluvial-Deltaic-Lacustrine (upper Wasatch Formation) ................................................................. 92
4.5.5. Lacustrine (Uteland Butte member of Lower Green River Formation) ............. 93
4.5.6. Deltaic-Lacustrine (Lower Green River Formation) ........................................ 94
4.5.7. Fluvial-Deltaic (Renegade Tongue of the Lower Green River Formation) ......... 94
4.5.8. Fluvial-Deltaic-Lacustrine (Middle Green River Formation) ............................ 95
4.5.9. Mahogany Oil Shale Zone – Boundary of Middle and Upper Green River Formation ........................................................................................................ 96

4.6. Discussion ........................................................................................................................................................................... 97
4.7. Applications ........................................................................................................................................................................ 98
4.8. Acknowledgments .............................................................................................................................................................. 98
4.9. References ........................................................................................................................................................................... 98

CHAPTER 5. CONCLUSIONS TO DISSERTATION ............................................................................................................. 115

5.1. Summary Conclusions and Contributions ........................................................................................................................ 115
5.2. Chapter 2 Conclusions and Contributions ..................................................................................................................... 115
5.3. Chapter 3 Conclusions and Contributions ..................................................................................................................... 115
5.4. Chapter 4 Conclusions and Contributions ..................................................................................................................... 116
5.5. References ........................................................................................................................................................................... 116

APPENDIX A Measured Sections - SUPPLEMENTAL ELECTRONIC MATERIAL ......................................................... 117
APPENDIX B Uninterpreted Photos and Lidar - SUPPLEMENTAL ELECTRONIC MATERIAL ........................................... 119
APPENDIX C Quantitative Data - SUPPLEMENTAL ELECTRONIC MATERIAL .......................................................... 120
APPENDIX D Permissions and Publication Policies - SUPPLEMENTAL ELECTRONIC MATERIAL .......... 121
LIST OF FIGURES

Figure 1.1. Location of study area and chronostratigraphic chart ............................................................. 4
Figure 1.2 Seven hierarchical scales documented for middle Wasatch Formation ...................................... 5
Figure 2.1. Location of study area and chronostratigraphic chart ................................................................. 30
Figure 2.2. Topographic map of Three Canyon study area ........................................................................... 31
Figure 2.3. Photographic examples of the lithofacies ................................................................................ 32
Figure 2.4. Hierarchical framework ............................................................................................................... 33
Figure 2.5. Uninterpreted and interpreted photo panel of the southeast Rincon wall ...................................... 34
Figure 2.6. Zoom-in of interpreted photo panel of the southeast Rincon wall ............................................... 35
Figure 2.7. Uninterpreted and interpreted photo panel of the east wall of the outcrop ............................ 36
Figure 2.8. Lithofacies and story type proportions ...................................................................................... 37
Figure 2.9. Width-to-thickness plot of storys, channel-belt elements, and archetypes .............................. 38
Figure 2.10. Modern examples of framework architecture ........................................................................... 39
Figure 2.11. Schematic diagram of associated coeval splays ................................................................. 40
Figure 2.12. Schematic diagram of associated non-coeval splays .............................................................. 41
Figure 2.13. Diagrammatic examples of archetypes ................................................................................... 42
Figure 2.14. Paleogeographic reconstruction of a braided-archetype cycle ................................................ 43
Figure 2.15. Paleogeographic reconstruction of a meandering archetype cycle ........................................... 44
Figure 3.1. Strike profiles of allogenically and autogenically controlled cycles ...................................... 68
Figure 3.2. Location of study area and chronostratigraphic chart ................................................................. 69
Figure 3.3 Photographs of lower, middle and upper members of the Wasatch Formation ......................... 70
Figure 3.4 Topographic map of detailed study area ..................................................................................... 71
Figure 3.5. Hierarchical framework ........................................................................................................... 72
Figure 3.6. Cyclicity model......................................................................................................................... 73
Figure 3.7. Diagrammatic examples of archetype cycles. ........................................................................... 74
Figure 3.8. Paleogeographic reconstruction of archetype cycles. ............................................................... 75
Figure 3.9. Width and thickness measurements cycles. .............................................................................. 76
Figure 3.10. Small-scale cycles at Three Canyon......................................................................................... 77
Figure 3.11. Intermediate-scale cycles at Three Canyon. .......................................................................... 78
Figure 3.12. Intermediate-scale cycles at Chandler Canyon. ..................................................................... 79
Figure 3.13. Location axes of deposition intermediate-scale cycles. ........................................................... 80
Figure 3.14. Modern example of axis-to-margin deposition.......................................................................... 81
Figure 3.15. Location and examples of depositional fairways. .................................................................... 82
Figure 3.16. Diagrammatic example of end-member controlled cycles. ...................................................... 83
Figure 4.1. Location of study area and chronostratigraphic chart............................................................ 101
Figure 4.2. Photographs of lower, middle and upper members of the Wasatch Formation................... 102
Figure 4.3. Geologic map of Desolation Canyon study area. ................................................................. 103
Figure 4.4. Map and examples of Flagstaff Limestone.............................................................................. 104
Figure 4.5. Map and examples of lower Wasatch Formation................................................................. 105
Figure 4.6. Map and examples of middle Wasatch Formation............................................................. 106
Figure 4.7. Map and examples of upper Wasatch Formation............................................................... 107
Figure 4.8. Map and examples of Uteland Butte. ..................................................................................... 108
Figure 4.9. Map and examples of Lower Green River Formation........................................................... 109
Figure 4.10. Map and examples of Renegade Tongue. .......................................................................... 110
Figure 4.11. Map and examples of Middle Green River Formation...................................................... 111
Figure 4.12. Cross section of Desolation Canyon basin-fill succession ................................................. 112
LIST OF TABLES

Table 2.1. Terminology used in describing fluvial strata. ................................................................. 45
Table 2.2. Lithofacies descriptions. .................................................................................................... 46
Table 2.3. Width-to-thickness measurements of storys, elements and archetypes. ......................... 47
Table 3.1. Width-to-thickness measurements of cycles .................................................................. 84
Table 4.1. Nomenclature for the Green River Formation. ................................................................. 113
Table 4.2. UTM coordinates for key stratigraphic localities. ............................................................ 114
ACKNOWLEDGEMENTS

I thank my advisor David Pyles and committee members Donna Anderson, Ramona Graves, John Humphrey, Jeff May and Keith Turner for their patience, technical support and advice. Additional thanks are given to Donna Anderson for her friendship and moral support during a transitional time related to this dissertation. I am indebted and deeply grateful to David Pyles for his passion, effort and continual motivation in taking my research to a higher level. I also thank Mike Gardner and Mark Sonnenfeld for starting me on this journey.

I am thankful to all those who discussed, reviewed and challenged my research over the years both in the field and in the office. They are Brain Bracken, Jim Borer, Mary Carr, Marieke Duchesne, Jeremiah Moody, Kasi Sendziak, Ryan Sincavage, Mark Sonnenfeld, Morgan Sullivan, Paul Heller, Mark Tomasso, John Webb and Brian Willis. Additional thanks go to the 611 Woody’s pizza crew and the Dead Base-Level Society for many inspiring conversations.

This dissertation would not have been possible without the tireless effort of those who helped in the field. They are Marieke Duchesne, Joe Ross, Joby McClure, Jennifer Shanley, Jeremiah Moody, Roger Murphy Scotty Mosiman, Richard Quist, Curt Kelsey and Down River Equipment. I also thank Scott Goldsmith, Linda Martin, Cathy Van Tassel and Charlie Rourke for help with drafting questions and logistics.

I graciously thank the Chevron Center of Research Excellence at the Colorado School of Mines for their financial support in 2010, Gene Clower of EOG Resources, Inc. for his incredible patience and the Enhanced Oil Recovery Institute of Wyoming for the use of their lidar equipment.

This dissertation is affectionately dedicated to three incredible women: In memory of my grandmother Pearl M. Orr for being the definition of unconditional love, my biggest cheerleader and teaching me that nothing was beyond my grasp; In memory of my very good friend Lenora Powell for her inspiring smile, her thoughtful insight and her incredible friendship; and to Sheilah McClure for her patience, peaceful spirit and unyielding support through the years.
CHAPTER 1.
INTRODUCTION TO DISSERTATION

1.1. Introduction

This dissertation critically examines the Tertiary middle Wasatch Formation in the Uintah basin, Utah at seven very different scales (Figures 1.1 & 1.2). This dissertation capitalizes on the unparalleled, three-dimensionality and regional extensiveness of outcrops of the middle Wasatch Formation to address goals that are significant to the Wasatch Formation in the Uinta basin, Utah (Figure 1.1), and to other modern and ancient fluvial systems. The goals addressed in the first part of this dissertation focus on architecture and cyclicity in fluvial systems, whereas the goals addressed in the last part of this dissertation document the broader stratigraphy of a fluvial-lacustrine system represented by in an up-river transect through the stratigraphy exposed along the modern Green River in Desolation Canyon, Utah (Figure 1.1). The purpose of this research is to provide a better understanding of the stratigraphic manifestation and sequential evolution of fluvial and fluvial-lacustrine systems.

1.2. Organization and Content

This dissertation contains three Chapters that will be submitted for publication in peer-reviewed journals. Each is described in detail below.

1.2.1. Chapter 2

Chapter 2 is titled, “A hierarchical approach for evaluating fluvial systems: architectural analysis and sequential evolution of the high net-sand content middle Wasatch Formation, Uinta basin, Utah.” Chapter 2 develops a hierarchical framework that can be used to describe reservoir and non-reservoir stratigraphy in fluvial systems (Figure 1.2). The framework accounts for sedimentary processes, temporal context, and hierarchy. The framework proposed herein builds upon legendary work in fluvial stratigraphy (e.g., Beerbower, 1964; Campbell, 1967; Jackson, 1975; Allen, 1983; Miall, 1985; Bridge, 1993). This framework is used to: 1) document the sequential evolution of the middle Wasatch Formation fluvial system, and 2) provide a dimensional dataset for the high net-sand content middle Wasatch Formation. The chapter provides three contributions. First, the chapter introduces a unified, hierarchical framework for describing the architecture of fluvial systems. Second, the chapter documents three channel-belt and splay relationships in outcrop that provide context for understating
evolution of fluvial systems. Third, the dimensional characteristics from this system can be used as constraints in other high net-sand content fluvial system where width and thickness are not known.

### 1.2.2. Chapter 3

Chapter 3 is titled, “Hierarchical nature of cyclicity in a fluvial system: spatial and temporal variations in autogenic controlled compensational stacking and interbasinal scale-breaks resulting from climatic forces in the middle Wasatch Formation, Uinta basin, Utah.” Chapter 3 documents a 4-level hierarchy for stratigraphic cycles in the middle Wasatch Formation and describes how stratigraphic characteristics change upward along axis-to-margin profiles. The three smallest scale cycles are interpreted to result from autogenic processes (i.e., compensational stacking), whereas the largest scale cycle is interpreted to result from allogenic cycles (i.e., climate) (Figure 1.2). The chapter provides three contributions. First, the chapter documents axis-to-margin changes in the upward stacking patterns across strike profiles at varying scales. Second, the chapter documents scale-dependent, compensational stacking in fluvial systems. Third, the chapter documents a scale-break in basin-filling trends resulting from the transition of autogenically to allogenically controlled patterns. Critically, these first two contributions provide an end-member model whereby other fluvial systems can be examined.

### 1.2.3. Chapter 4

Chapter 4 is titled, “Stratigraphic attributes of key intervals in a fluvial-lacustrine basin-fill succession, Desolation Canyon, Uinta basin, Utah.” Chapter 4 documents key stratigraphic characteristics of fluvial-lacustrine strata deposited on the southern margin of the Uinta basin along a 77-kilometer (48-mile) transect up the modern Green River in Desolation Canyon (Figure 1.2). In ascending order the transect describes strata from the Flagstaff Limestone, lower Wasatch Formation, middle Wasatch Formation, upper Wasatch Formation, Uteland Butte member of the Lower Green River Formation, Lower Green River Formation, Renegade Tongue of the Lower Green River Formation, Middle Green River Formation and the Mahogany oil shale zone on the boundary between the Middle and Upper Green River Formations. The chapter provides two contributions. First, the chapter provides outcrop examples for key stratigraphic intervals documenting the evolving fluvial-lacustrine system. Critically, a majority of formations described in the chapter are petroleum reservoirs within ~ 20 km (12 mi) of the outcrop belt. Second, the chapter can be used as a field guide for those who venture down Desolation Canyon from Sand Wash to Three Fords Canyon (Figure 1.1A).
1.3. References


Figure 1.1 A) Map documenting the location of the study areas. The Wasatch Formation outcrop belt and major structural features located around the Uinta basin are labeled (modified from Dickinson et al., 1986; and Hintze et al., 2000). Uinta basin outline courtesy of Utah Geological Survey.

B) Chronostratigraphic chart of Upper Cretaceous and Lower Tertiary strata in the Uinta basin (modified from Fouch et al., 1994).
Figure 1.2. The middle Wasatch Formation is documented at seven different hierarchical scales. A) A three-level hierarchical framework for describing meso- and macro-scale architecture is presented in Chapter 2 of this dissertation. B) Four-orders of cyclicity are presented in Chapter 3 of this dissertation. C) A part of the fluvial-lacustrine basin-fill succession in Desolation Canyon in Chapter 4 of this dissertation.
CHAPTER 2.
A HIERARCHICAL APPROACH FOR EVALUATING FLUVIAL SYSTEMS:
ARCHITECTURAL ANALYSIS AND SEQUENTIAL EVOLUTION OF THE
HIGH NET-SAND CONTENT MIDDLE WASATCH FORMATION,
UINTA BASIN, UTAH

A paper to be submitted to the AAPG Bulletin

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2.1. Abstract

Well exposed, three-dimensional fluvial outcrops of the high net-sand content, middle Wasatch Formation in Three Canyon, Uinta basin, Utah were used to create and develop a new methodology for describing the architecture of fluvial systems. The methodology builds on the works of Campbell (1961), Jackson (1975), Allen (1983) and Miall (1985) and addresses sedimentary processes, scale and temporal context for reservoir and non-reservoir bodies. The methodology developed herein is a three-level hierarchical framework that classifies meso- and macro-scale architecture of fluvial systems. This three-level hierarchical framework contains, from smallest to largest: storys, elements and archetypes. Each hierarchical level is composed of different types or combinations of components which account for the variability in sedimentation styles recognized in this fluvial system. Eight story types provide the foundational building blocks of this framework and account for sedimentation in both channel-belt and floodplain-belt elements, including: 1) downstream accreting; 2) lateral accreting; 3) erosional based fine-grained fill; 4) fine-grained fill associated with lateral accretion; 5) levee; 6) splay; 7) crevasse or overbank channels; and 8) floodplain fines. Two types of elements are recognized in the middle Wasatch Formation: 1) channel-belt elements and 2) floodplain-belt elements. An archetype consists of a channel-belt element and its genetically related floodplain-belt element(s). Two distinct upward stacking patterns differentiate braided and meandering archetypes.

In deconstructing the evolution of archetypes, three distinct associations between channel-belt elements and their adjacent splays are documented: 1) splays that are isolated from channel-belt elements, termed unassociated splays; 2) splays that are laterally adjacent and physically connected to a
channel-belt element, termed associated coeval splays; and 3) splays that underlie the channel-belt element, termed associated non-coeval splays.

Width and thickness for storys, channel-belt elements and archetypes are documented providing dimensional constraints for reservoir models in analogs high net-sand content fluvial systems. Additionally, this hierarchical methodology provides object based modelers with shape-defined reservoir and non-reservoir geobodies within channel-belt and floodplain-belt elements that realistically correspond to fluvial reservoirs.

2.2. Introduction & Purpose

Fluvial deposits are significant petroleum reservoirs worldwide, but they create major challenges for the geologists and engineers who work them. Challenges include predicting reservoir dimensions, sand connectivity, and spatial and temporal changes in the system. These challenges are compounded by conflicting terminology and methodologies used to describe fluvial strata (Bridge, 1993). Confusion surrounding the methodologies centers on the difficulty in properly accounting for scale and temporal context. This article presents a methodology for describing fluvial systems and discusses its utility in addressing practical geoscience problems.

Two methodologies are widely used to describe fluvial systems: 1) environmental or architectural elements, and 2) hierarchical order of bounding surfaces utilizing cross-cutting relationships. The first approach, environmental or architectural elements, traces to Beerbower (1964), referencing Fisk’s (1944) work on the Mississippi River System, where he introduces the concept of fluvial architecture using the term environmental elements. Allen (1983) coined the term, architectural element, but does not define it. Later, Miall (1985) defined the term architectural element on the basis of grain size, bedform composition, internal structure, and most critically, external geometry. Miall proposes that fluvial deposits are composed of varying proportions of eight architectural elements: channels, lateral accretion deposits, sandy bedforms, gravel bars and bed forms, foreset macroforms, sediment gravity flows deposits, laminated sand sheets and floodplain fines. His work is the foundation for architectural element analysis.

The architectural element approach is objective and allows geologists to use patterns to describe fluvial systems. However, this methodology does not address sedimentary processes, scale and temporal context. For example, the architectural element “channel” has no distinction as to its fill type (e.g., sand, gravel, mud or any combination thereof) or the hydrodynamic processes under which channels fill (e.g., the mode of deposition for sand is tractive whereas for a mud it is suspension). These
distinctions are important because different fill types have different reservoir characteristics. Additionally, lateral-accretion deposits, sandy bedforms and gravelly bedforms are architectural elements, yet lateral accretion deposits can be constructed by sandy and/or gravelly bedforms allowing one element to be composed of another element. Finally, channels, gravel bars and lateral-accretion deposits are constructed over similar time scales whereas sandy bedforms and gravel bed forms such as dunes are constructed over much shorter time scales (Jackson, 1975).

The second approach for describing fluvial systems utilizes cross-cutting relationships of bounding surfaces in which a numerical or hierarchical order is assigned to each surface. Allen (1983) formalized this methodology building on concepts outlined by Brookfield’s (1977) work on eolian strata. Bridge and Diemer (1983), Miall (1985), Robinson and McCabe (1997) and Holbrook (2001) are well-documented applications of this approach.

The hierarchical, surface-based approach, like the architectural-element approach, is objective; however, it does not account for process, temporal context, and sediment or fill style. For example, this methodology makes no distinction between channels of similar hierarchical order with different fill styles such as lateral accreting sand units or downstream accreting gravel units. This is critical because their reservoir characteristics, such as connectivity and continuity, are vastly different. Additionally, this methodology breaks down in laterally persistent beds such as splay deposits, in which stratal terminations are not abundant, because beds do not cross cut one another. As such, every internal surface in a splay deposit is a first-order surface regardless of the process it records or how large the splay deposit is. In contrast, a dune in a channel that migrates on a daily basis inherently contains second order surfaces; therefore, first-order surfaces in splay deposits have a different temporal context than first-order surfaces in sandy bedforms in the same depositional unit. Also, secondary influences on the strata such as bioturbation can mask bounding surfaces thereby rendering this method unsatisfactory.

The works of Campbell (1967) and Jackson (1975) are exceptions to the issues of sedimentary process, scale and temporal context listed above. Campbell (1967) describes lamina, laminaset, bed and bedsets to be genetically related, but differ in areal extent and time span of deposition. Taking these concepts further, Jackson (1975) presents a dynamic model for the origin of geomorphic fluvial forms of differing scales: microform, mesoform and macroform. His model accounts for four hierarchical attributes: bedform size, time span of bedform existence, flow regime, and cross-cutting relationships (superposition) of bedforms (Anderson, 1997 building on the work of Jackson, 1975). However, reservoirs encompass a larger scale of features than are described by Jackson and Campbell. As such, no
framework currently exists that honors scale, temporal context and sedimentary process while integrating larger-scale hierarchical architecture. Utilizing an outcrop of a well exposed fluvial system, this article develops a methodology for describing the architecture of fluvial systems ranging from one hierarchical level larger than the bedset of Campbell (1967), to one hierarchical level lower than the sequence of Van Wagoner et al., (1990) (Table 2.1).

The Wasatch Formation in the Uinta basin of Utah is one of the most regionally extensive, three-dimensional outcrops of a fluvial system in the world. This, combined with sparse vegetation and minimal structural deformation, creates an ideal opportunity to propose, construct, and test a revised methodology for describing the architecture of fluvial systems. This article uses outcrop data from the middle Wasatch Formation to address 3 goals:

1) develop an integrated, hierarchical framework to classify fluvial strata that can be applied to modern and ancient systems and encompasses reservoir and non-reservoir bodies;
2) document the sequential evolution of fluvial strata in the study area in an effort to understand how these stems evolve;
3) document the dimensional characteristics of the high net-to-gross middle Wasatch Formation utilizing the hierarchical framework.

2.3. Geologic Setting and Field Area

The Uinta basin is located in northeastern Utah and northwestern Colorado, (Figure 2.1A), and encompasses an area of 24,000 km$^2$ (9,300 mi$^2$) (Montgomery and Morgan, 1998). The basin is physiographically bounded on the north by the Uinta Mountains, the east by the Douglas Creek Arch, the south by the Uncompahgree Uplift and San Rafael Swell, and the west by the remnants of the Cretaceous Sevier fold and thrust belt (Figure 2.1B) (Johnson, 1985; Dickinson et al., 1986). The Uinta basin is longitudinally asymmetric with a steeply dipping northern margin adjacent to the Uinta Mountain thrust front and a gently dipping southern margin. It is Late Cretaceous to Early Oligocene in age and contains approximately 5,000 meters (~16,000 ft) of Paleogene alluvial, fluvial and lacustrine strata (Fouch et al., 1994).

The Wasatch Formation is a red to tannish-brown, gray, green and purple variegated succession of sandstone, siltstone, and mudstone with lesser amounts of conglomerate and discontinuous carbonate beds (Fouch, 1976). It unconformably overlies the Paleocene Flagstaff or North Horn Formation and is conformably overlain by the Eocene Green River Formation (modified from Fouch, 1976) (Figure 2.1C). The Wasatch Formation is up to 1,500 m (4,921 ft) thick in the center of the basin, up to 1,000 m (3,281
ft) thick in outcrops near the Green River, and thins toward the eastern and western margins of the basin (Figure 2.1B) (Cashion, 1967; and Dickinson, 1986). The Wasatch Formation contains abrupt upward changes in lithofacies, depositional styles and net-sand content. These upward changes form the basis for informally subdividing the Wasatch Formation into three members: 1) lower, 2) middle, and 3) upper. The upward changes in lithofacies, depositional styles and net-sand content are also documented for the coevally deposited Wasatch Formation in the Piceance basin (Lorenz and Naden, 2002; Johnson and Flores, 2003; and Erhardt, 2005).

Three Canyon, the main study area, is located in the central part of the outcrop belt along the southern margin of the Uinta basin at the confluence of Three Canyon and the Green River (Figures 2.1B & 2.2). The study area is 2 km (1.2 mi) by 1.5 km (0.9 mi) with almost all of the middle Wasatch Formation exposed (Figure 2.2). At this location, the middle Wasatch has a net-sand content of >85% and contains amalgamated, multistory channel-fill and splay deposits with floodplain fines. The upper boundary of the middle Wasatch is a regionally extensive red, compound, paleosol that separates the high net-sand content middle Wasatch from the overlying upper Wasatch. At the Three Canyon locality, strata are nearly horizontal and are exceptionally well exposed in three dimensions. Based on regional mapping, this locality contains some of the highest net-sand content exposures of the middle Wasatch Formation in the basin. The Three Canyon field area is currently only accessible by boating down the modern-day Green River.

2.4. Data and Methodology

An integrated dataset was used to address the goals of this study. 100% of the outcrop belt was photographed from a helicopter and from the ground. Differing vantage points on opposing canyon walls were used for ground-based photographs. Photo panels were collated from merged photographs, USGS 7.5-minute quadrangle maps and handheld GPS units were used to geographically reference the locations of stratigraphic columns, strike and dip measurements, sediment transport measurements, lithosome boundaries, lithostratigraphic contacts, internal stratification, and lithofacies. Twenty-four high-resolution (centimeter-scale) stratigraphic columns totaling 1,238 m (3,882 ft) were described recording physical and biogenic sedimentary structures as well as grain size. XYZ and intensity lidar data was collected over 65% of the Three Canyon field area using a ground-based unit with ~ 2-10 cm (0.7 - 4 in) resolution. Additionally, xyz and intensity lidar data was collected over 80% of the Three Canyon field area from a helicopter-based (airborne) unit with ~ 30 cm (12 in) resolution. Field interpreted photo panels, measured sections, GPS data and the lidar data were used map and measure dimensional
aspects of the stratigraphy and correlate stratigraphic units across canyons walls in the field area. Measurements of width and thicknesses were made perpendicular to sediment transport directions. Dimensional data was only collected for stratigraphic units that have upper, lower and both lateral margins exposed.

2.5. Lithofacies

This study utilizes Gressley's (1838) original definition of facies as “those observable physical, chemical and biological properties of rocks that collectively permit objective description and distinctions from other types of rocks” (Cross and Homewood, 1997, p. 1620). Therefore, the term lithofacies is used descriptively, without connotation as to depositional environment or external form. Seventeen lithofacies are identified in this study: ten are sandstone, three are siltstone, and four are mudstone. Photographic examples and descriptive characteristics of each lithofacies are presented in Figure 2.3 and Table 2.2 respectively.

2.6. Integrated, Hierarchical Framework for Fluvial Strata

A three-level hierarchy is proposed herein for describing the architecture of fluvial systems (Figure 2.4). From smallest to largest these are: story, element and archetype. Each hierarchal level is composed of different types or combinations of components which account for the variability in sedimentation styles recognized in this fluvial system. The hierarchical framework proposed herein is constrained by lithofacies, geometry of units, stratal surfaces and cross-cutting relationships documented in the field area. Components of the framework are described below.

2.6.1. Story

Eight features were identified in the study area and form the foundation of the hierarchical units referred to as storys (Figure 2.4). Potter (1967) translated Feofilova’s (1954) definition of the term story as the erosionally based component of a channel body. Later Friend et al. (1983, p. 40) rephrased the definition as “the volume of material within a body which are separated by scour-surfaces,” based on their work on fluvial outcrops in the Ebro basin, Spain. These definitions of storys pertain to channel deposits only. In this study, we extend the term to apply to strata deposited outside the confines of the channel, thereby encompassing the entire fluvial system. We define a story as a meso-scale volume of strata formed from genetically related beds or bedsets produced by the migration, fill or overbank
discharge of a single fluvial channel. The thickness of a story scales to bank-full discharge and flood-stage water depth and is the basic building block to larger stratigraphic units.

The middle Wasatch Formation is constructed of eight types of stories, each reflects the stratigraphic manifestation of a geomorphic feature (Figure 2.4): 1) downstream accreting; 2) lateral accreting; 3) erosional based fine-grained fill; 4) fine-grained fill associated with lateral accretion; 5) levee; 6) splay; 7) crevasse or overbank channels; and 8) floodplain fines. Each story is distinguished on the basis of external geometry, lithofacies, sediment-transport directions in relation to stratal geometry, and stratigraphic associations. These eight stories account for sedimentation both in the channel and floodplain components of fluvial systems (Figure 2.4). A description of each type of story is included below.

2.6.1.1. **Downstream Accreting**

The lower bounding surface of a downstream accreting story is convex upward and erosional (Figure 2.4 and unit D7a in Figures 2.5, 2.6A & 2.6B). The amount of erosion ranges from 0.5 to 15 m (1.6 to 49.2 ft). The upper bounding surface is conformable and slightly undulatory, except where younger channel-fill stories erode into them. Lateral margins are sharp and erosional.

When viewed in strike orientation, the external form is asymmetrical and lens shaped, thickest in the axis and thinning toward its lateral margins (Figure 2.4 & 2.5). When viewed in dip orientation, the external form is an elongate wedge, tapering in the downstream direction (e.g., unit DSc in Figure 2.7).

The most abundant lithofacies in downstream accreting stories is low-angle, cross-laminated sandstone (Figure 2.8A and Facies 4, Figure 2.3), followed by horizontally-laminated and trough cross-laminated sandstone (Figure 2.8A and Facies 5 & 3, Figure 2.3). However, in the distal end of the story, the dominant lithofacies is horizontally-laminated sandstone (Facies 5, Figure 2.3), followed by low-angle, cross-laminated sandstone (Facies 4, Figure 2.3). Downstream accreting stories constitute 50.8% of the Three Canyon field area and have an average width of 242.6 m (795.9 ft), an average thickness of 4.6 m (15.1 ft) and an average aspect (width-to-thickness) ratio of 53:1 (Figures 2.8B & 2.9A and Table 2.3).

These stories are interpreted as downstream-accreting, mid-channel, longitudinally migrating bars similar to those documented in Figure 2.10A. This interpretation is based on the collective observations of sediment-transport directions aligned with foreset migration, external shape and stratigraphic association of lithofacies overlying a channel base. Whereas the predominant accretion direction is
downstream, lateral accretion is also evident. The naming convention emphasizes the predominant accretion direction.

2.6.1.2. Lateral Accreting

The lower bounding surface of a lateral accreting story is erosional. The amount of erosion ranges from 0.5 to 5 m (1.6 to 16.4 ft). The upper bounding surface is conformable and slightly undulatory, except where younger channel-fill stories erode into them (Figure 2.4 and unit LA10a in Figures 2.5 & 2.6B). Lateral margins are sharp and erosional into adjacent strata. When viewed in strike orientation, lateral accreting stories have an external form that is sigmoidal and equivalent to the epsilon, cross-bedding of Allen (1983). They are thickest in the axis and thin toward their lateral margins (Figure 2.4 & e.g., unit LA10a in Figure 2.5). When viewed in dip orientation, the form is an elongate wedge to sigmoidal shape, tapering in the upstream and downstream directions (e.g., unit LA12a in Figure 2.7).

The most abundant lithofacies within lateral accreting stories is trough cross-laminated sandstone (Figure 2.8A and Facies 3, Figure 2.3) followed by low-angle and horizontally-laminated sandstone, (Figure 2.8A and Facies 4 & 5, Figure 2.3). Lateral accreting stories constitute 2.9% of the Three Canyon field area and have an average width of 266 m (872.7 ft), an average thickness of 3.5 m (11.5 ft) and an average aspect ratio of 76:1 (Figures 2.8B & Figure 2.9A and Table 2.3).

These stories are interpreted as laterally accreting, side-attached bars similar to those documented in Figures 2.10A & 2.10B. This interpretation is based on the combined observations of sediment-transport directions perpendicular with foreset migration, external shape and stratigraphic association of lithofacies overlying a channel base. Whereas the predominant migration direction is lateral, downstream accretion is also evident. Again, the naming convention emphasizes the predominant accretion direction.

2.6.1.3. Erosionally Based Fine-Grained Fill

The lower bounding surface of an erosionally based fine-grained fill story is convex upward and discordant with underlying strata (Figure 2.4 and unit FG7a in Figures 2.5 & 2.6A). The amount of erosion ranges from 0.3 to 10 m (1 to 32.8 ft). The upper bounding surface is conformable, except where younger channel-fill stories erode into them. The lateral margins are sharp and erosional. When viewed in strike orientation, the external form is asymmetrical and bowl shaped, thickest in the axis and thinning towards its lateral margins (Figure 2.4 and unit FG7a-2 in Figure 2.5). When viewed in dip
orientation, the external form is an elongate wedge, tapering in the downstream direction (e.g., unit FG4a in Figure 2.7).

The most abundant lithofacies within erosionally based fine-grained fill storys is burrowed sandstone (Figure 2.8A and Facies 10, Figure 2.3), flaggy sandstone (Facies 12, Figure 2.3) and rippled sandstone (Figure 2.8A and Facies 9, Figure 2.3). Erosionally based fine-grained fill storys constitute 1.8% of the Three Canyon field area and have an average width of 97.9 m (321.2 ft), an average thickness of 12.7 m (41.7 ft) and an average aspect ratio of 8:1 (Figures 2.8B & 2.9A and Table 2.3).

These features are interpreted as fine-grained strata that filled accommodation created by channel erosion. We interpret this succession to result from a channel eroding into underlying strata and avulsing prior to the migration and deposition of sand-rich storys, providing accommodation for the deposition of fine-grained fill from the flood-stage, overbank discharge of an active, nearby channel. The interpretation is based on the collective observations of external shape, lithofacies, onlap of internal bedding on to channel margin, and stratigraphic association of lithofacies overlying a channel base.

2.6.1.4. Fine-Grained Fill associated with Lateral Accretion

The lower bounding surface of a fine-grained fill associated with lateral accretion story is conformable along the margin adjacent to a lateral accretion story and erosional on the margin opposite the lateral accretion story (Figure 2.4 and unit FP10a in Figures 2.6A & 2.6B). The amount of lateral erosion ranges from 0.5 to 5 m (1.6 to 16.4 ft). The upper bounding surface is conformable with overlying strata. When viewed in strike orientation, the external form is bowl shape thickest in its axis and thinning towards its lateral margins (Figure 2.4 and unit FP10a in Figure 2.5). When viewed in dip orientation, the external form is an elongate wedge, tapering in the downstream direction.

The most abundant lithofacies within fine-grained fill associated with lateral accreting storys is flaggy sandstone and siltstone (Figure 2.8A and Facies 12, Figure 2.3) followed by burrowed sandstone (Figure 2.8A and Facies 10, Figure 2.3). Fine-grained fill associated with lateral accretion storys constitute 0.3% of the Three Canyon field area and have an average width of 47.5 m (155.8 ft), an average thickness of 3.4 m (11.2 ft) and an average aspect ratio of 14:1 (Figures 2.8B & 2.9A and Table 2.3).

We interpret these features as fine-grained strata, often referred to as a mud plug, adjacent to channel bar forms (Mohrig et al., 2000). Finer grained strata carried by flood-stage, overbank discharge from an active, nearby channel fills the remaining accommodation. The interpretation is based on the
collective observations of external shape, lithofacies, and stratigraphic association of lithofacies with adjacent channel margin and channel bar form.

2.6.1.5. Levee

The lower bounding surface of a levee story is conformable with underlying strata (Figure 2.4 and unit L10a in Figures 2.6A & 2.6B). The upper bounding surface is also conformable and undulatory to concave downward. The lateral margins are sharp, erosional contacts adjacent to channel-fill strata and thin to a feather edge into overbank strata. When viewed in a strike or dip orientation, levee stories have an external form that is asymmetrical and mound or lobe shaped, thickest adjacent to the channel and thinning towards the story margins. In some cases the levee stories are symmetrical (Figure 2.4 and unit L10a in Figures 2.6A & 2.6B).

The most abundant lithofacies within levee stories is burrowed sandstone (Figure 2.8A & Facies 10, Figure 2.3) followed by rippled and flaggy sandstone (Figure 2.8A and Facies 9 & 12, Figure 2.3). Levee stories constitute 0.05% of the Three Canyon field area and have an average width of 23.1 m (75.8 ft), an average thickness of 2.0 m (6.6 ft) and an average aspect ratio of 12:1 (Figures 2.8B & 2.9A and Table 2.3).

Levee stories are interpreted as natural levees adjacent to channel margins similar to those in Figures 2.10A & 2.10B. This interpretation is based on the combined observations of external shape, lithofacies, sediment transport directions perpendicular to the channel margin, and stratigraphic association of lithofacies with adjacent channel margin and floodplain deposits.

2.6.1.6. Splay

The lower bounding surface of a splay story is locally erosional in its axis and adjacent to the sourcing channel and conformable elsewhere. The amount of erosion ranges from centimeters to 1 m (3.3 ft). The upper bounding surface is conformable and undulatory to planer, except where truncated by younger strata (Figure 2.4 and splays below unit D7a in Figures 2.5, 2.6A & 2.6B). The lateral margins of splays typically thin to a feather edge into adjacent strata. When viewed in strike orientation, the external form is lobe shaped or a thin, tabular shape; however, in some examples splays can also be asymmetric (Figures 2.5 & 2.6B). When viewed in dip orientation, the external form is wedge shape, tapering in the downstream direction (e.g., splays above unit D1a in Figure 2.7).

The most abundant lithofacies within splay stories is borrowed sandstone (Figure 2.8A and Facies 10, Figure 2.3) followed by red burrowed siltstone and silty-mudstone, rippled and horizontally-
laminated sandstone (Figure 2.8A and Facies 14, 5 & 7, Figure 2.3). Splay stories constitute 8.3% of the Three Canyon field area and have an average width of 155.2 m (509.2 ft) and an average thickness of 2.2 m (7.2 ft) with an average aspect ratio of 71:1 (Figures 2.8B & 2.9A and Table 2.3).

Splay stories are interpreted as crevasse splays similar to the one in Figure 2.10B. This interpretation is based on the collective observations of external shape, lithofacies, sediment-transport directions aligned with form migration and divergent to the channel margin, and stratigraphic association of lithofacies with adjacent channel margin and floodplain deposits.

2.6.1.7. Crevasse Channel

The lower bounding surface of the crevasse channel story is unconformable. The amount of erosion ranges from 0.3 to 1.5 m (1 to 4.9 ft). The upper bounding surface is conformable and undulatory (Figure 2.4 and crevasse channel above unit D9a in Figures 2.5, 2.6A & 2.6B). The lateral margins are sharp and erosional with adjacent strata. When viewed in strike orientation, crevasse channel stories have an external form that is symmetrical and bowl shaped; thickest in the axis and thinning toward the margins (Figure 2.4 and crevasse channel above unit D9a in Figure 2.5). When viewed in dip orientation, the external form is wedge shaped, tapering in the downstream direction.

The most abundant lithofacies within crevasse channel stories is burrowed sandstone (Figure 2.8A and Facies 10, Figure 2.3) followed by rippled sandstone and siltstone (Figure 2.8, Facies 9 & 13, Figure 2.3). Crevasse channel stories constitute 0.15% of the Three Canyon field area and have an average width of 17.3 m (56.8 ft), an average thickness of 2.7 m (8.9 ft) and an average aspect ratio of 6:1 (Figures 2.8B & 2.9A and Table 2.3).

These stories are interpreted as crevasse channels similar to the one in Figure 2.10B. This interpretation is based on the collective observations of external shape, lithofacies, sediment-transport directions aligned with form migration, and stratigraphic association of lithofacies overlying a channel base adjacent to splay and floodplain deposits.

2.6.1.8. Floodplain Fines

The lower and upper bounding surfaces of a floodplain-fine story are conformable. The upper surface is typically undulatory to planer; however, they often are truncated by younger strata (e.g., background photo above unit D7a in Figures 2.5 & 2.6B). Lateral margins are not exposed in the study area as the widths of floodplain-fine stories exceed that of the study area. Exceptions are where floodplain-fine stories are erosionally truncated by younger strata. When not truncated, we assume that
floodplain-fine storys thin to a featheredge towards their margins. When viewed from a strike or dip orientation, floodplain-fine storys have an external form that is rectangular to wedge shaped.

The most abundant lithofacies within floodplain-fine storys is red burrowed siltstone and silty-mudstone (Figure 2.8A and Facies 14, Figure 2.3). Floodplain-fine storys constitute 35.7% of the Three Canyon field area, because the width of floodplain-fine storys typically exceed the width of the outcrop dimensional information is not available (Figure 2.8B).

These storys are interpreted as floodplain fines deposited during flood events from suspension fallout and tractive flow (Figure 2.10B). Floodplain-fine storys are not associated with the floodplain fines that compose splay or levees storys. This interpretation is based on lithofacies, external shape and stratigraphic association with channel margins and floodplain components.

**2.6.2. Element**

To address our goal of creating an integrated, hierarchical framework it is necessary to redefine architectural element. Therefore, an element is defined herein as a macro-scale lithosome produced by channel migration and overbank discharge of a single fluvial channel (Figure 2.4). An element is separated from stratigraphically adjacent elements by floodplain fines and/or a paleosols, except when eroded by younger elements. In the latter case, a sand-on-sand contact separates the older and younger amalgamated elements. Floodplain fines and paleosols are typically preserved adjacent to the site of erosion.

An element is composed of one or more storys referred herein as a single-story element and multistory element, respectively. The term multistory was originally defined as “the sand body of one cycle superimposed on one or more earlier sand bodies” (Potter, 1967, p. 338 translation of Feofilova, 1954). More recently, the term multistory was used to describe the vertical stacking of storys and the term multilateral was used to describe the lateral stacking of adjacent storys (Potter, 1967; Gibling, 2006). We use the term multistory whether the storys stack vertically or laterally based upon the terminology of Feofilova (1954), as our observations indicate that, to some extent, most storys stack both vertically and laterally when viewed in three dimensions.

Two types of elements are recognized: 1) channel-belt elements and 2) floodplain-belt elements (Figure 2.4). Each is described below.
2.6.2.1. Channel-Belt Element

A channel-belt element is composed of one or more channel-fill storys: downstream accreting, lateral accreting, erosionally based fine-grained fill and fine-grained fill associated with lateral accretion. Examples of multistory channel-belt elements in the middle Wasatch Formation are shown in Figure 2.4, examples 1 – 8 (e.g., unit D7a in Figure 2.5 and units La10a-FP10a in Figures 2.6A & 2.6B).

The lower bounding surface of channel-belt elements is erosional. The amount of erosion ranges from 0.5 to 15 m (1.6 to 49.2 ft). The upper bounding surface is conformable and undulatory, except where younger channel-belt elements erode into them (Figures 2.4, 2.5 & 2.6B). The lateral margins are sharp due to erosion into adjacent strata. When viewed in strike orientation, the external form of channel-belt elements is asymmetrical and bowl shaped. They are thickest in the axis and thin towards their lateral margins (e.g., units D7a and LA10a-FP10a in Figures 2.5, 2.6A & 2.6B). When viewed in dip orientation, a channel-belt elements external form is an elongated wedge or tabular (e.g., unit D1a in Figure 2.7).

Two types of channel-belt elements are documented within the middle Wasatch Formation: 1) those containing predominantly downstream accreting storys, and 2) those containing predominantly lateral accreting storys. Channel-belt elements containing predominantly downstream accreting storys are the most abundant (Figures 2.5 & 2.7). Channel-belt elements have an average width of 888.2 m (2,914.1 ft) and an average thickness of 13.1 m (43.0 ft) (Figure 2.9B & Table 2.3). The range of widths of the two channel-belt element types broadly overlaps, yet their thickness and aspect ratios are distinctly different (Figure 2.9B and Table 2.3). Average aspect ratios for downstream accreting channel-belt elements is 55:1 and lateral accreting/fine-grained fill associated with lateral accreting channel-belt elements is 162:1.

Channel-belt elements evolve from the migration, fill and/or abandonment of a single fluvial channel. This interpretation is based on the integration of the story(s) that build these features, bounding surfaces, external shape, lithofacies, sediment-transport directions, stratigraphic association, and similar examples from modern systems (Figures 2.10A & 2.10B).

2.6.2.2. Floodplain-Belt Element

A floodplain-belt element is composed of a combination of floodplain-fill storys: levee, splay, crevasse channel, and floodplain fines (Figure 2.4, examples 9 -11). In the study area of the middle Wasatch Formation, the dominant story types of the floodplain-belt element are floodplain fines followed by splay, crevasse channel and levees, respectively.
The lower bounding surface of a floodplain-belt element is conformable in places and erosional in others depending on the floodplain story(s) that make up the element. The amount of erosion associated with splays and crevasse channels of the floodplain-belt element range from 0.3 to 1.5 m (1 to 4.9 ft) (e.g., crevasse channel and splay above unit D9b in Figure 2.6B). The upper bounding surface is conformable and typically undulatory, except where younger channel-belt elements erode into them. The lateral margins typically thin to a feather edge; however, when adjacent to a channel-belt element, they have a sharp erosional contact. When viewed in a strike orientation, floodplain-belt elements are a long wedge, thickest adjacent to its associated channel-belt element and thinning towards its margins (Figure 2.5). When viewed in dip orientation, floodplain-belt element external form is tabular shaped (Figure 2.7).

Floodplain-belt elements are interpreted to be built by floodplain-fill story(s) created from the overbank discharge and migration of a single fluvial channel. This interpretation is based on the collective interpretations of the story(s) from which these features are built, including: external shape, lithofacies, sediment-transport directions, stratigraphic association, and similar examples from modern systems (Figure 2.10A).

2.6.3. Archetype

An archetype is defined as a macro-scale feature consisting of a channel-belt element and its genetically related floodplain-belt element(s) (Figure 2.4). The boundaries between stratigraphically adjacent archetypes record an abrupt shift in the location of axis of deposition interpreted to record avulsion, abandonment or compensation. Leopold and Wolman (1957) identify four fluvial styles based on their plan-view geomorphology: 1) meandering, 2) straight, 3) braided and 4) anastomosing. These plan-view geomorphologies have been refined by several authors, (e.g., Brice et al., 1978; Schumm, 1985), and are the subject of numerous debates (e.g., Bridge, 1993). The fundamental issues with this nomenclature is that channel-style can longitudinally transition from one type of channel to another and that different types of channels can be located adjacent to one another (Leopold and Wolman, 1957). For example, Figure 2.10A is a photo of the Brahmaputra River, Bangladesh documenting a meandering archetype located adjacent to a larger-scale braided archetype. Understanding the associated issues with this style of nomenclature we herein apply the terms braided and meandering to the archetypes we document in the middle Wasatch Formation.
2.6.3.1. Sequential Evolution of Archetypes and Splay Types

An archetype is the stratigraphic manifestation of an evolving landscape. In an effort to document this evolution, archetypes were deconstructed through an analysis of superposition, cross-cutting relationships, stratal terminations and stratigraphic association. From this analysis three important characteristics were documented: 1) associations between splay stories and channel-belt elements; 2) basal characteristics of archetype; and 3) two distinct upward stacking patterns that differentiate braided and meandering archetypes in the study area (Figure 2.4). These upward stacking patterns constitute archetype cycles.

Splays, a byproduct of avulsion, whether partial, full or failed, are inherently and genetically related to the channel that sourced them (Strouthamer, 2001; Slingerland and Smith, 2004). The association between channel avulsion, splays and the evolution of splays is well documented (e.g., Smith et al., 1989; Smith and Perez-Arlucea, 1994; Willis and Behrensmeyer, 1994; Kraus, 1996; Aslan and Blum, 1999; Bristow, et al., 1999; Mohrig et al., 2000; Farrell, 2001; Strouthamer, 2001; Slingerland and Smith, 2004). Herein, we document three distinct associations between channel-belt elements and their adjacent splays in the Wasatch Formation: 1) splays that are spatially isolated from channel-belt elements, herein referred to as unassociated splays; 2) splays that are laterally adjacent and physically connected to a channel-belt element, herein referred to as associated coeval splays; and 3) splays that underlie the channel-belt element, herein referred to as associated non-coeval splays. These associations refer to the physical relationship observed in the stratigraphic record. In the middle Wasatch Formation we only document associated non-coeval splays and unassociated splays.

Unassociated splays are spatially isolated and have no observable association with a channel-belt element. They are physically encased in floodplain fines. Individual beds within the splay story typically thin from one to the next in an upward succession and are commonly separated by paleosols. The upward decrease in splay-bed thickness is interpreted to represent a decrease in avulsion flow duration and/or frequency or magnitude from one flood to the next. Paleosols that separate stratigraphically adjacent splay beds indicate that the avulsion did not occur over one flood stage. Unassociated splays are interpreted to represent a failed avulsion (Strouthamer, 2001). An example of unassociated splays is presented in Figure 2.5, unit S1b.

The second type of splay documented herein is associated coeval splays. They are laterally adjacent and physically connected to the channel-belt element, indicating that the two were coevally deposited. A schematic diagram of associated coeval splays is presented in Figure 2.11, and a modern example in Figure 2.10B. Associated coeval splays are not documented in the middle Wasatch, although they are
exposed in the lower Wasatch Formation, approximately 13 km (8 miles) south of Three Canyon field area (Sendziak et al., 2012).

The third type of splay documented herein is associated non-coeval splays (Figure 2.12). These types of splays physically underlie the associated channel-belt element and in strike orientation are generally wider than the oldest channel story of the channel-belt element (Figure 2.12 and e.g., splays below unit D7a in Figures 2.5 & 2.6A). The thickest and most sand-rich or axial part of these splays is often located in approximately the same place as the axial part of overlying channel-belt element. Furthermore, individual splay beds typically thicken from one to the next in an upward succession and are commonly separated by paleosols. The upward increase in splay bed thickness is interpreted to document an increase in avulsion flow duration and/or frequency and magnitude. Paleosols that separate stratigraphically adjacent splay beds indicate that the avulsion did not occur over one flood stage. Collectively these observation are interpreted to record a splay story heralding a full channel avulsion resulting in a younger, genetically related channel-belt element eroding into the splay story (Figure 2.12C). This channel-splay relationship for associated non-coeval splays is equivalent to the stratigraphically transitional stratigraphy of Jones and Hajek (2007). Associated non-coeval splays occur below the vast majority of channel-belt elements within the study area. The genetic relationship between associated non-coeval splays and the overlying channel-belt element resulted in the base of an archetype being assigned to the oldest genetic related splay bed, base of the splay story.

### 2.6.3.2. Braided Archetype

An upward succession through the axis, thickest part, of a braided archetype, an archetype containing predominantly downstream accreting channel-belt stories (Figures 2.13A & 2.13B), is: 1) splay story composed of splay beds that increase in thickness from one to the next in an upward transect and associated floodplain fines or paleosols (associated non-coeval splays), 2) a channel-belt element multistory containing predominately downstream accreting storys that is in erosional contact with the underlying splay story (e.g., splays below unit D7a in Figures 2.13B, 2.6A & 2.6B), 3) erosionally based fine-grained fill story and, finally, 4) amalgamated floodplain fine storys and paleosols. In some cases, amalgamated floodplain fine storys and paleosols directly overlie the uppermost downstream accreting story with no erosionally based fine-grained fill story (Figures 2.4, 2.13A & 2.13B).

In most examples the channel-belt elements of braided archetypes are amalgamated with stratigraphically adjacent braided archetypes. This clustering is the product of younger archetypes eroding older archetypes resulting in sand-on-sand contact between them in their axial positions (e.g.,
units D7a, D8a, D9b & D9c in Figures 2.6A & 2.13B). In off-axial positions, adjacent channel-belt elements are separated by floodplain-belt elements containing floodplain fines and paleosols (e.g., units D7a, D8a, D9b & D9c in Figures 2.6A & 2.6B).

A paleogeographic reconstruction based on mapping one braided-archetype around and across the 3-D exposures of the study area is presented in Figure 2.14. Dominated by a downstream accreting channel-belt element, the braided archetype is interpreted to be the depositional product of downstream accreting bars, associated channel fill and the channel-belt element’s genetically related floodplain-belt element (e.g., Figure 2.10B).

2.6.3.3. Meandering Archetype

An upward succession through the thickest part of a meandering archetype, an archetype containing predominantly lateral accreting channel-belt storys, contain: 1) splay story composed of splay beds that increase in thickness from one to the next in an upward transect and associated floodplain fines or paleosols (associated non-coeval splays), 2) a multistory lateral accreting channel-belt element that erosionally truncates the underlying splay(s) and, finally, 3) amalgamated floodplain fine storys and paleosols (Figure 2.4, 13A & 13B).

A paleogeographic reconstruction based on mapping one meandering-archetype around and across 3-D exposures the study area is presented in Figure 2.15. Dominated by a lateral accreting channel-belt element, the meandering archetype is interpreted to be the depositional product of a higher sinuosity fluvial system than those formed by braided archetypes (e.g., Figures 2.10A & 2.10B) (Bridge, 1985).

2.6.3.4. Dimensional Comparison and Properties

Thickness and widths of storys, channel-belt elements and archetypes are documented in Figure 2.9C and Table 2.3. Overlap between domains of storys and channel-belt elements are the result of erosionally based fine-grained fill-channel-belt element composed of single story elements. Otherwise, each hierarchical level (storys, elements and archetypes) occupies its own domain in the plot. The average aspect ratio for archetypes is 98:1.

2.7. Discussion

The commonly used methodologies for describing fluvial systems are: 1) architectural elements, and 2) hierarchical order of bounding surfaces. Issues related to scale, temporal context, and sediment or fill style with context to these two methodologies are documented using four issues in the introduction of
this chapter. Below we critically test the hierarchical methodology proposed in this chapter against the four issues.

The first issue with existing methodologies is the lack of distinction in fill type within a channel. The channel-fill components of the proposed methodology utilizes different story types, (e.g., downstream accreting, lateral accreting, erosional based fine-grained fill, and fine-grained fill associated with lateral accretion), to differentiate between different fill styles and grain sizes. A modifier can easily be applied to differentiate gravel versus sand-dominated bar forms (e.g., gravelly, downstream accreting story). Other authors, such as Robinson and McCabe (1997) and Lynds and Hajek, (2006) differentiate sand versus finer-grained fill types in their models. The second issue with existing methodologies is that the architectural element approach allows one element to be composed of other elements (e.g., lateral-accretion deposits can contain sandy bedforms). The methodology proposed herein recognizes only two elements, channel-belt and floodplain-belt. Neither element is contains storys that compose the other element (Figure 2.4). The third issue with existing methodologies is that the architectural element approach does not distinguish between units of differing temporal scale. For example, lateral accretion deposits are deposited over a longer duration than the sandy bedforms they contain, yet both are considered architectural elements. Each hierarchical level, (story, element and archetype), of the framework proposed herein is characterized by a different time-span of deposition, (e.g., stories are deposited over a shorter duration than elements). The fourth issue with existing methodologies is that the surface-based approach is unreliable in units that contain laterally persistent beds where surfaces do not cross-cut one another, such as bedding in splays and in beds where stratal surfaces are obscured such as in bioturbated units. Although the proposed framework utilizes bounding surfaces and cross-cutting relationships, the interpretations do not rely on any sole attribute, but rather the integration of external shape, lithofacies, sediment-transport directions, bounding surfaces, stratigraphic associations, and modern examples. On additional aspect of the proposed methodology that sets it apart from the other commonly used approaches for describing fluvial architecture is its equal emphasis on the floodplain-fill components as the channel-fill components, although Stouthamer, (2001); Hornung and Aigner, (2002); Gouw (2007); Nichols and Fisher, (2007); and Kjemperud et al., (2008) also focus on this important distinction.

2.8. Application

The hierarchical methodology for describing fluvial architecture proposed in this study provides context for outcrop and subsurface studies, tank experiments, and reservoir models focused on fluvial
systems. Researchers working fluvial outcrops can directly apply this methodology while honoring scale, sedimentary process and temporal context. This hierarchical framework with its associated components (e.g., splay storys) in conjunction with environment analysis interpreted from wireline logs (e.g., Schlumberger, 1985; Bridge and Tye, 2000; Tye, 2004; Patterson et al., 2006) provides geologists and engineers working subsurface datasets with a more robust model for their interpretations that critical accounts for reservoir and non-reservoir bodies.

The economic importance in effectively optimizing well placement, reservoir drainage, and secondary and tertiary recovery has increased the importance of accurately modeling sandstone connectivity and continuity, as well as baffles and barriers to fluid flow in reservoirs. This hierarchical methodology provides object based modelers with shape-defined reservoir and non-reservoir geobodies within channel-belt and floodplain-belt elements that realistically correspond to fluvial reservoirs. Additionally, this methodology provides modelers with a means to scale their object based units.

Finally, the middle Wasatch Formation provides a good outcrop analog for high net-to-gross fluvial reservoirs (e.g., Mungaroo Formation, Kern River Formation, Statfjord Formation, and Wasatch Formation). Architectural dimensions obtained from subsurface mapping and reservoir models in high net-to-gross fluvial systems can be constrained by the dimensional characteristics and relative proportions of storys in this channel-dominated, high, net-sand content system.

2.9. Conclusion

This article develops a methodology for describing meso- to macro-scale fluvial architecture that builds upon previous studies. The unparalleled, three-dimensionality of the middle Wasatch Formation in the Three Canyon study area provides the ideal laboratory for observing, describing and documenting lateral and vertical changes in stratigraphy. Because of this unique outcrop perspective we were able to propose and test a hierarchical methodology for describing fluvial architecture that encompasses the entire fluvial system and includes reservoir and non-reservoir components. Effort was made to relate the architectural framework to modern geomorphic features. This link provides a common language for comparing ancient and modern systems.

The methodology developed herein uses a three-level hierarchy: storys, elements and archetypes. Each hierarchical level is interpreted to reflect discharge and time while accounting for sedimentary process. This methodology allows one to quantitatively analyze and compare the stratigraphic record. Deconstruction of archetypes into their fundamental building blocks using this methodology allows us to document the sequential evolution of part this fluvial system. Finally, three distinct associations
between channel-belt elements and their adjacent splays were observed in the stratigraphic record: 1) unassociated splays; 2) associated coeval splays; and 3) associated non-coeval splays.

2.10. Acknowledgements

This paper has benefitted from the thoughtful review of Donna Anderson and Jeff May. Financial support for the year 2010 was graciously provided by the Chevron Center of Research Excellence at the Colorado School of Mines.

Thanks are also given to the Price, Utah, Bureau of Land Management District office for access to Desolation Canyon, specifically Dennis Willis and Amy Adams for making the process seamless. The authors would also like to thank Mark Tomasso, Ryan Sincavage and The Enhanced Oil Recovery Institute of Wyoming for acquisition and support of the LIDAR data.

In addition, Grace would like to thank Down River Equipment for outfitting a newbie with the best raft ever. Additional thanks go to Roger Murphy, Scotty Mosiman and Richard Quist and the rest of the Moki Mack River Expedition crew for their logistical support during the August 2010 field session. Finally, Grace would like to thank the many field assistants for their tireless effort on the outcrop with special thanks going to Marieke Duchesne and Joe Ross for attempting the daring adventure more than once.

2.11. References


Google Earth, 2012b, 34°32’353.30”N and 100°46’54.08”W, 2012 Texas Orthoimagery program.


National Geographic, 2008, Topo!, map, 1:24,000, 7.5 Minute Series.


National Geographic, 2008, Topo!, map, 1:24,000, 7.5 Minute Series.


Figure 2.1. A) Location of the Uinta basin in NE Utah. B) Map documenting the location of the study area at Three Canyon, Wasatch Formation outcrop belt, and major structural features around the Uinta basin (modified from Dickinson et al., 1986 and Hintze et al., 2000; Uinta basin outline courtesy of Utah Geological Survey). C) Chronostratigraphic chart of Lower Cretaceous and Upper Tertiary strata in the Uinta basin (modified from Fouch et al., 1994).
Figure 2.2. Data used to document the architectural interpretation of the Three Canyon field study area. A) Topographic map of Three Canyon field area showing location of measured sections (blue lines) and sediment-transport directions in the middle Wasatch Formation (National Geographic, 2008). Bold red lines mark the boundary between the middle and upper Wasatch Formation. Bold dashed dark blue line mark the boundary between the lower and middle Wasatch Formation. In the study area the lower Wasatch Formation is covered with Quaternary alluvium (National Geographic, 2008). B) Bare earth model created from airborne lidar (property of EOG Resources, Inc.). C) Angel of slope model calculated from airborne lidar dataset (property of EOG Resources, Inc.).
Figure 2.3. Photographic examples of the 17 lithofacies in the study area of the middle Wasatch Formation. Descriptions and interpretation of the lithofacies are included in Table 2.1.
Figure 2.4. Chart documenting the methodology developed herein for describing the hierarchical architecture of fluvial strata in the middle Wasatch Formation. Time span of deposition, cross-cutting relationships, and superposition increase in an upward transect through the hierarchical levels. Components are not drawn to scale.
Figure 2.5. Uninterpreted and interpreted photo panel of the southeast Rincon wall. Sediment transport is into the photo. The location of the outcrop is documented in the inset map and in Figure 2.2. The alpha-numeric naming convention on the interpreted photo documents: 1) the story type, (see Legend above); 2) the number assigned to the small-scale cycle within the middle Wasatch Formation described in Chapter 3 of this dissertation; and 3) a final alpha character denoting the archetype within the small-scale cycle, (e.g., D3c = downstream-accreting story in the small-scale cycle 3, archetype c).
Figure 2.6. Interpreted photo panel of the upper southwest section of the Rincon wall depicted in Figure 2.5. See Figure 2.5 for explanation of alpha-numeric naming convention.
Figure 2.7. Uninterpreted and interpreted photo panel of the east wall of the outcrop. Sediment transport is approximately right to left. The location of the outcrop is documented in the inset map and in Figure 2.2. See Figure 2.5 for explanation of alpha-numeric naming convention.
Figure 2.8. A) Lithofacies proportions for channel-fill and floodplain-fill storys. Colors correspond to the color insets for lithofacies in Figure. B) Percentage of story types measured in the Three Canyon Study area. Examples of story types are included in Figure 2.4.
Figure 2.9. Width-to-thickness plot of storys (A); channel-belt elements (B); and width-to-thickness plot of storys, elements and archetypes (C). The mean of each dataset is represented by the larger symbol on plots. See Table 2.2 for more detail.
Figure 2.10. Modern examples used as geomorphic guides in the creation of a hierarchical framework architecture presented in Figure 2.4. A) Meandering and braided archetypes, Brahmaputra River, Bangladesh (Google Earth, 2012a). B) Meandering archetype, Prairie Dog Fork of the Red River, Texas (Google Earth, 2012b).
Figure 2.11. Schematic diagram of associated coeval splays in a meandering archetype. Colors correspond to architecture features in Figure 2.4. A) Plan view of associated coeval splays with location of cross section A-A'. B) Cross section view of associated coeval splays. Units are not drawn to scale.
Figure 2.12. Schematic diagram of associated non-coeval splays in a meandering archetype. Colors correspond to architecture features in Figure 2.4. A) Plan view of associated non-coeval splays at time 1. B) Plan view of associated non-coeval splays at time 2 with location of cross section B-B'. C) Cross section view of associated non-coeval splays. Units are not drawn to scale.
Figure 2.13. A) Diagrammatic examples of upward stacking patterns (cycles) displayed by archetypes. Lateral limits are not represented. Upward stacking patterns are also documented in Figure 2.4. B) Interpreted photo panel with archetypes and archetype boundaries labeled. The location of the photo is labeled in Figure 2.6A. See Figure 2.5 for explanation of alpha-numeric naming convention.
Figure 2.14. Paleogeographic reconstruction of braided-archetype D7a documenting undifferentiated downstream-accreting, erosionally based fine-grained fill and floodplain fine storys. The interpretation is constrained by mapping strata on the cliff faces within Three Canyon study area using photo panels, measured sections, ground and airborne lidar. Undifferentiated storys are shown as the thick orange, tan and black lines. The western margin was not exposed in the field area, so it was constrained using the average archetype width from Table 2.3. Refer to Figures 2.5, 2.6 and 2.7 for detailed photo panel interpretation. Red lines mark the boundary between the middle and upper Wasatch Formation. Dashed dark blue line mark the boundary between the lower and middle Wasatch Formation. In the study area the lower Wasatch Formation is covered with Quaternary alluvium.
Figure 2.15. Paleogeographic reconstruction of meandering archetype LA10a documenting undifferentiated lateral accreting, fine-grained fill associated with lateral accretion, levee and floodplain fine stories. The interpretation is constrained by mapping strata on the cliff faces within Three Canyon study area using photo panels, measured sections, ground and airborne lidar. Undifferentiated stories are shown as the thick yellow, tan, white and blue lines. The southwestern and northeastern margins were not exposed in the field area, so it was constrained using the average archetype width from Table 2.3. Refer to Figures 2.5, 2.6 and 2.7 for detailed photo panel interpretation. Red lines mark the boundary between the middle and upper Wasatch Formation. Dashed dark blue line mark the boundary between the lower and middle Wasatch Formation. In the study area the lower Wasatch Formation is covered with Quaternary alluvium.
Table 2.1. Comparison of well cited terminology used in describing fluvial strata and how terminology in this study compares.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>n/a</td>
<td>lamina</td>
<td>microforms</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>lamina</td>
<td>n/a</td>
</tr>
<tr>
<td>n/a</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>laminasets</td>
<td>laminasets</td>
<td></td>
</tr>
<tr>
<td>set</td>
<td>bed</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>bed</td>
<td>bed</td>
<td></td>
</tr>
<tr>
<td>cosets</td>
<td>bedsets</td>
<td>mesoforms</td>
<td>n/a</td>
<td>n/a</td>
<td>1st-order</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>composite set</td>
<td>n/a</td>
<td>first-order</td>
<td>n/a</td>
<td>storey / major surfaces</td>
<td>2nd-order / small architectural element</td>
<td>story</td>
<td></td>
</tr>
<tr>
<td>n/a</td>
<td>n/a</td>
<td>macroforms</td>
<td>second-order / complexes**</td>
<td>n/a</td>
<td>3rd-order / architectural element</td>
<td>element</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>third-order / sheets / architectural element</td>
<td>n/a</td>
<td>4th-order / architectural element</td>
<td>parasequence</td>
<td>archetype</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>5th Order / major sand sheets / channel-fill complexes</td>
<td>parasequence set</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>6th-Order / paleovalleys</td>
<td>sequence</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

** comprise sedimentation units that are genetically related by facies and/or paleocurrent direction
Table 2.2. Descriptive characteristics of the seventeen lithofacies identified in the middle Wasatch Formation. A slash (/) is used in the place of the word “or”. Photographic examples of each lithofacies is documented in Figure 2.3.

<table>
<thead>
<tr>
<th>Facies #</th>
<th>Facies Name</th>
<th>Facies Code</th>
<th>Grain Size</th>
<th>Physical Sedimentary Structures</th>
<th>Bounding Surfaces &amp; Bed Thickness</th>
<th>Interpreted Hydrodynamic Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unorganized Silty, Clay-Clay Sandstone</td>
<td>Sdcc</td>
<td>&gt;1 cm clasts in very fine to medium sandstone matrix</td>
<td>Poor to very poor sorting; clasts range 0.5 cm to 10 cm. Occasional reverse grading. Minor association with pebble clasts.</td>
<td>Erosional basal contact. Gradedal to sharp upper contact. Set thickness 2 to 70 cm.</td>
<td>Cohesive flow and/or bank collapse setting.</td>
</tr>
<tr>
<td>2</td>
<td>Organized Silty, Clay-Clay Sandstone</td>
<td>Stcc</td>
<td>&gt;3 cm clasts in very fine to medium sandstone matrix</td>
<td>Interbedded clast dominated with no clasts. Clast free show alternating grains size. Laminae wavy nonparallel to parallel.</td>
<td>Erosional to turbiditrary basal contact. Gradedal to sharp upper contact. Set thickness 8 to 35 cm.</td>
<td>Upper flow-regime, tractive deposition. Very high energy.</td>
</tr>
<tr>
<td>3</td>
<td>Trough Cross-Laminated Sandstone</td>
<td>Stt</td>
<td>fine to upper-medium sandstone</td>
<td>Occasional clay and pebble clasts on foresets. Reactivation surfaces common.</td>
<td>Erosional to turbiditrary basal contact. Gradedal to sharp upper contact. Set thickness 5 to 15 cm.</td>
<td>Lower flow-regime, tractive deposition. High energy.</td>
</tr>
<tr>
<td>4</td>
<td>Low-Angle Laminated Sandstone</td>
<td>Sla</td>
<td>very fine to medium sandstone</td>
<td>Typically &lt; 5°. Rare clay and pebble clasts on foresets. Occasionally reactivation surfaces.</td>
<td>Undulated to gradational basal contact. Gradedal to sharp upper contact. Set thickness 5 to 100 cm.</td>
<td>Lower flow-regime, tractive deposition.</td>
</tr>
<tr>
<td>5</td>
<td>Horizontal-Laminated Sandstone</td>
<td>Sys</td>
<td>very fine to medium sandstone</td>
<td>Laminae even to wavy parallel. Occasionally wavy discontinuous parallel. Laminae 2 mm to 1 cm in thickness.</td>
<td>Erosional to sharp basal contact. Gradedal to sharp upper contact. Set thickness 5 to 100 cm.</td>
<td>Upper flow-regime, tractive deposition.</td>
</tr>
<tr>
<td>6</td>
<td>Structureless Sandstone</td>
<td>Ssp</td>
<td>very fine to fine sandstone</td>
<td>Non-distinct bedding, overturned and pipe structures.</td>
<td>Gradedal basal contact. Gradedal to sharp upper contact. Set thickness 10 to 100 cm.</td>
<td>Post depositional liquefaction/injection resulting in deformation of sedimentary structures.</td>
</tr>
<tr>
<td>7</td>
<td>Soft-Sediment Deformed Sandstone</td>
<td>Ssd</td>
<td>fine to upper-medium sandstone</td>
<td>Non-distinct bedding. Overturned and pipe structures.</td>
<td>Gradedal basal contact. Gradedal to sharp upper contact. Set thickness 10 to 100 cm.</td>
<td>N/A</td>
</tr>
<tr>
<td>8</td>
<td>Concretion Sandstone</td>
<td>Scn</td>
<td>very fine to fine sandstone</td>
<td>Rare. Found in high-angle accretion bar forms. Concretion parallel laminae. 5 to 15 cm length by 5 to 10 cm wide.</td>
<td>Basal contact covered. Gradedal upper contact. Bed sets couldn't be distinguished.</td>
<td>N/A</td>
</tr>
<tr>
<td>9</td>
<td>Ripple-Laminated Sandstone</td>
<td>Srh</td>
<td>very fine to fine sandstone</td>
<td>Asymmetric to slightly asymmetric unidirectional ripples. Climbing ripples rare.</td>
<td>Gradedal to sharp basalt contact. Gradedal to sharp upper contact. Set thickness 0.3 to 15 cm.</td>
<td>Lower flow-regime, tractive deposition. Lower energy.</td>
</tr>
<tr>
<td>10</td>
<td>Burrowed Sandstone/Siltstone</td>
<td>Sbh</td>
<td>siltstone to fine sandstone</td>
<td>Non-distinct bedding to horizontal or low angle laminations. Often grades laterally into silt or mud. Horizontal and vertical burrows.</td>
<td>Undulatory to sharp basalt contact. Undulatory to sharp upper contact. Set thickness 0.3 to 100 cm.</td>
<td>Post depositional bioturbation resulting in deformation of sedimentary structures.</td>
</tr>
<tr>
<td>11</td>
<td>Burrowed &amp; Rooted Siltstone/Sandstone</td>
<td>Sbr</td>
<td>siltstone to fine sandstone</td>
<td>Non-distinct bedding. Minor asymmetrical ripples laminations. Often wedges laterally into silt- mudstone. Horizontal and vertical burrows.</td>
<td>Erosional to sharp basal contact. Sharp to erosional upper contact. Set thickness 1 to 5 cm.</td>
<td>Post depositional bioturbation and/or disturbance by plant growth resulting in deformed sedimentary structures.</td>
</tr>
<tr>
<td>12</td>
<td>Flaggly Siltstone/Sandstone</td>
<td>Sfh</td>
<td>siltstone to very fine sandy-siltstone</td>
<td>Non-distinct bedding probably rippled even to wavy non-parallel laminae that has been completely burrowed.</td>
<td>Gradedal to sharp basalt contact. Undulatory to sharp upper contact. Set thickness 0.3 to 1 cm.</td>
<td>N/A</td>
</tr>
<tr>
<td>13</td>
<td>Ripple-Laminated Siltstone</td>
<td>Sirh</td>
<td>siltstone to very fine sandy-siltstone</td>
<td>Asymmetrical current ripple laminations. Climbing ripples common. Often grades laterally into mudstone.</td>
<td>Gradedal to sharp basalt contact. Gradedal to sharp upper contact. Set thickness 0.3 to 0.5 cm.</td>
<td>Lower flow-regime, tractive deposition. Lower energy.</td>
</tr>
<tr>
<td>14</td>
<td>Red Burrowed Siltstone to Silty Mudstone</td>
<td>Mrh</td>
<td>very fine sandy-siltstone to silty-mudstone</td>
<td>Horizontally, wavy laminations. Occasional asymmetric ripples. Moderate to heavy vertical and horizontal burrowing.</td>
<td>Gradedal to sharp basalt contact. Erosional to gradational upper contact. Set thickness 0.3 to 3 cm.</td>
<td>Lower flow-regime, tractive deposition. Low energy for silt. Suspension fall-out in waning flows for muds.</td>
</tr>
<tr>
<td>15</td>
<td>Gray Siltstone to Silty Mudstone</td>
<td>Msg</td>
<td>very fine sandy-siltstone to silty-mudstone</td>
<td>Non-distinct bedding, but occasional asymmetric ripples. Minor to moderate burrowing. Roots rare.</td>
<td>Sharp basalt contact. Erosional to gradational upper contact. Set thickness 0.3 to 1 cm.</td>
<td>Lower flow-regime, tractive deposition. Low energy for siltstones. Suspension fall-out in waning flows for mudstones.</td>
</tr>
<tr>
<td>16</td>
<td>Gray Mudstone</td>
<td>Mgh</td>
<td>silty-mudstone to mudstone</td>
<td>Non-distinct bedding, but occasional asymmetric ripples. Minor horizontal and vertical burrowing. Roots rare.</td>
<td>Gradedal to sharp basalt contact. Erosional to gradational upper contact. Set thickness 0.3 to 1 cm.</td>
<td>Suspension fall-out in a waning flow.</td>
</tr>
<tr>
<td>17</td>
<td>Gray-Green Mottled Mudstone</td>
<td>Mgg</td>
<td>silty-mudstone to mudstone</td>
<td>Non-distinct bedding. Minor burrowing and roots.</td>
<td>Gradedal to sharp basalt contact. Erosional to gradational upper contact. Set thickness 0.3 to 1 cm.</td>
<td>Lower flow-regime, tractive deposition. Low energy for siltstones. Suspension fall-out in waning flows for mudstones.</td>
</tr>
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Table 2.3. Average width-to-thickness measurements of storys, channel-belt elements and archetypes.

<table>
<thead>
<tr>
<th>Story</th>
<th>n</th>
<th>width</th>
<th>thickness</th>
<th>aspect ratio</th>
</tr>
</thead>
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<tr>
<td>Downstream Accreting</td>
<td>9</td>
<td>242.6 m (795.9 ft)</td>
<td>4.6 m (15.1 ft)</td>
<td>53:1</td>
</tr>
<tr>
<td>Lateral Accreting</td>
<td>2</td>
<td>266 m (872.7 ft)</td>
<td>3.5 m (11.5 ft)</td>
<td>76:1</td>
</tr>
<tr>
<td>Erosionally Based Fine-Grained Fill</td>
<td>10</td>
<td>97.9 m (321.2 ft)</td>
<td>12.7 m (41.7 ft)</td>
<td>8:1</td>
</tr>
<tr>
<td>Fine-Grained Fill associated with Lateral Accreting</td>
<td>3</td>
<td>47.5 m (155.8 ft)</td>
<td>3.4 m (11.2 ft)</td>
<td>14:1</td>
</tr>
<tr>
<td>Levee</td>
<td>2</td>
<td>23.1 m (75.8 ft)</td>
<td>2.0 m (6.6 ft)</td>
<td>12:1</td>
</tr>
<tr>
<td>Splay</td>
<td>8</td>
<td>155.2 m (509.2 ft)</td>
<td>2.2 m (7.2 ft)</td>
<td>71:1</td>
</tr>
<tr>
<td>Crevasse Chanel</td>
<td>1</td>
<td>17.3 m (56.8 ft)</td>
<td>2.7 m (8.9 ft)</td>
<td>6:1</td>
</tr>
<tr>
<td>Downstream Accreting</td>
<td>9</td>
<td>845.0 m (2,272.3 ft)</td>
<td>15.4 m (50.6 ft)</td>
<td>55:1</td>
</tr>
<tr>
<td>Lateral Accreting</td>
<td>3</td>
<td>1,018.0 m (3,339.9 ft)</td>
<td>6.3 m (20.7 ft)</td>
<td>162:1</td>
</tr>
<tr>
<td>Average</td>
<td>12</td>
<td>888.2 m (2,914.1 ft)</td>
<td>13.1 m (43.0 ft)</td>
<td>68:1</td>
</tr>
<tr>
<td>Archetype</td>
<td>12</td>
<td>1,975.3 m (6,480.6 ft)</td>
<td>20.1 m (65.9 ft)</td>
<td>98:1</td>
</tr>
</tbody>
</table>
CHAPTER 3.
HIERARCHICAL NATURE OF CYCLICITY IN A FLUVIAL SYSTEM:
SPATIAL AND TEMPORAL VARIATIONS IN AUTOGENICALLY CONTROLLED
COMPENSATIONAL STACKING AND INTERBASINAL SCALE-BREAKS RESULTING FROM
CLIMATIC FORCES IN THE MIDDLE WASATCH FORMATION, UINTA BASIN, UTAH

A paper to be submitted to the Journal of Sedimentary Research

Grace L. Ford and David R. Pyles

3.1. Abstract
The exceptional outcrops of the regionally extensive, high net-sand content fluvial system of the middle Wasatch Formation in the Uintah basin, Utah were used to document a hierarchy for stratigraphic cycles in fluvial systems. Stratigraphic cyclicity is redefined as an upward repeating succession of stratigraphic characteristics or stratigraphically equivalent characteristics that occur over a similar time span of deposition and overlain by a surface that records an abrupt shift in deposition interpreted in fluvial systems to result from abandonment and/or avulsion. Using this definition, four hierarchical-orders of cyclicity are documented, from smallest to largest, 1) archetype cycle; 2) small-scale cycle; 3) intermediate-scale cycle; and 4) large-scale cycle. Each increase in hierarchical level is associated with an increase in size, time-span of existence, cross-cutting relationships, spatial shift in the axis of deposition of adjacent cycles, and correlation length. Forty-five archetype cycles are documented, each composed of a channel-belt element and it’s genetically related floodplain-belt element(s). Sixteen small-scale cycles are documented and are composed of two or more archetype cycles that contain similar architecture and facies associations. Five intermediate-scale cycles are documented and are composed of two or more small-scale cycles that contain similar architecture and facies associations. Three large-scale cycles are documented, of which the middle Wasatch Formation is one. Large-scale cycles are composed of two or more intermediate-scale cycles that contain similar architecture and facies association

Upward stratigraphic patterns in archetype, small-scale and intermediate-scale cycles change from their axis to their lateral margins. In contrast, upward stratigraphic patterns in the large-scale cycle are
consistent from its axis to its lateral margins. Archetype, small-scale and intermediate-scale cycles are interpreted to result from autogenic processes (i.e., compensational stacking), whereas the largest scale cycle is interpreted to result from climatically-driven cycles. This study provides an end-member model whereby other fluvial systems can be examined and a scale-break in basin-filling trends resulting from the transition of autogenically to allogenically controlled patterns.

3.2. Introduction & Purpose

Wanless and Weller (1932) recognized cyclicity in the stratigraphic record. Cyclicity provides a robust framework for: 1) guiding stratigraphic correlations; 2) analyzing stacking patterns; and 3) creating physical and conceptual models that enhance our predictive capabilities in the exploration and development of petroleum resources. Cyclicity, as it relates to allogenic and/or autogenic processes and their effects on the organization and distribution of channel-belts, floodplain-belts (sensu Ford and Pyles, in prep, Chapter 2 of this dissertation) and the stratigraphic architecture of fluvial systems, has been the focus of numerous studies (e.g., Beerbower, 1964; Bridge and Leeder, 1979; Posamentier and Vail, 1988; Wright and Marriot, 1993; Shanley and McCabe, 1994; Heller and Paola, 1996; Holbrook et al., 1996; Currie, 1997; Ethridge et al., 1998; Legarreta and Ulian, 1998; Kraus and Aslan, 1999; Anderson and Cross, 2001; Catuneanu and Elango, 2001; Holbrook, 2001; Hornung and Aigner, 2002; Kraus, 2002; Cleveland et al., 2007; Hajek et al., 2010, and Leleu et al., 2010). Cyclicity in fluvial systems is interpreted to be the result of variations in allogenic and autogenic controls which change through time and/or scale (Beerbower, 1964; Bridge and Leeder, 1979; Kraus, 2002; Holbrook, 2006; Cleveland et al., 2007; Leleu et al., 2010; and Wang et al., 2011 2011). This paper presents a model for differentiating between allogenic (relative se-level, climatic and tectonic) and autogenically controlled fluvial systems.

Allogenic cyclicity is controlled by external boundary conditions effecting stratigraphic baselevel (sensu Wheeler, 1964) or relative sea-level resulting from the interplay of climate, tectonics, eustacy, and sediment supply (Straub et al., 2009). This interplay is recognized in many studies (e.g., Beerbower, 1964; Bridge and Leeder, 1979; Wright and Marriot, 1993; Shanley and McCabe, 1994; Heller and Paola, 1996; Holbrook, 1996; Currie, 1997; Ethridge et al., 1998; Legarreta and Ulian, 1998; Kraus and Aslan, 1999; Anderson and Cross, 2001; Catuneanu and Elango, 2001; Holbrook, 2001; Hornung and Aigner, 2002; Kraus, 2002; Cleveland et al., 2007; Hajek et al., 2010; and Leleu et al., 2010). The following discussion examines the stratigraphic manifestation of cyclicity in 1-D stacking patterns for strike profiles
across fluvial systems resulting primarily from one allogenic control: 1) eustacy; 2) climatic; and 3) tectonics.

Several authors document examples of cyclicity in fluvial systems that are interpreted to result from changes in eustacy (e.g., Wright and Marriot, 1993; Zaitlin et al., 1994; Holbrook, 1996; Currie, 1997; Zhang et al., 1997; Legarreta and Uliana, 1998; Atchley et al., 2004; Cleveland et al., 2007; and Leleu et al., 2010). The upward succession for a single cycle within fluvial systems primarily controlled by eustacy is: 1) amalgamated fluvial channel deposits; 2) thin, partially isolated channel deposits that are interbedded with fine-grained floodplain strata and tidally influenced heterolithic channel-fill deposits; 3) isolated to multistory fluvial channel deposits interbedded with floodplain strata and coals (Wright and Marriot, 1993; Atchley et al., 2004) (Figure 3.1A). These units are interpreted to record an upward pattern that forms from low-stand, transgression, and highstand of eustatic changes respectively. The pattern can vary from the axis of the system to its margin, but the overall upward pattern is similar.

Three authors document examples of cyclicity in fluvial systems that are interpreted to result from changes in climate (Ashley and Hamilton, 1993; Anderson and Cross, 2001; and Hornung and Aigner, 2002). An upward succession for a single cycle within fluvial systems primarily controlled by climate is represented by channels that increase in thickness upward followed by the systematic decrease in channel thickness (Figure 3.1B). These units are interpreted to record an upward pattern that forms from the expansion and contraction of the depositional system through time as a result of climatic changes (Anderson and Cross, 2001; and Hornung and Aigner, 2002). The pattern can vary from the axis of the system to its margin, but the overall upward pattern is similar.

Four authors document examples of cyclicity in fluvial systems that are interpreted to result from changes in tectonics (Hickson et al., 2005; Roca and Nadon, 2007; Way et al., 1998; and Catuneanu and Elango, 2001). The upward succession for a single cycle within fluvial systems primarily controlled by tectonics is an overall finning-upward succession (Roca and Nadon, 2007; and Hajek et al., 2010) (Figure 3.1C). Coarsening-upward profiles have also been documented (Catuneanu and Elango, 2001). These units are interpreted to record an upward pattern that forms from an increase or decrease in sediment supply, sediment type, and/or gradient that occurs regionally followed by a decrease in these attributes. The pattern can vary from the axis of the system to its margin, but the overall upward pattern is similar.

In contrast to the allogenically controlled patterns discussed above, the 1-D stacking patterns in fluvial systems responding to autogenic controlled avulsions display random, compensational organization that is not persistent for strike profiles across the systems (Figure 3.1E) (Cleveland et al., 2007; and Hajek et al., 2010). Autogenic avulsions are thought to be internal self-organizing processes.
resulting in compensational stacking patterns (Wang et al., 2011). Compensational stacking is the tendency of flow-event deposits to preferentially redirect and fill topographic lows, smoothing out topographic relief and “compensating” for localization of depositional discrete elements that built topography (Straub et al., 2009). The tendency of a depositional system to compensate is interpreted to result from a continuous or episodic reorganization through avulsions of the sediment transport field to minimize potential energy associated with depositionally-elevated gradients (Mutti and Normark, 1987; Stow and Johansson, 2000; Straub et al., 2009; and Straub and Pyles, 2012).

The Wasatch Formation in the Uinta basin, Utah has well-exposed, regionally extensive, three-dimensional outcrops of a fluvial system with minimal post-depositional structural deformation. This setting provides an excellent opportunity to assess stratigraphic cyclicity in fluvial systems. Specifically, this article uses outcrop data from the middle Wasatch Formation to address four goals:

1) document hierarchical orders of cyclicity;
2) document axis-to-margin changes in depositional styles of cycles;
3) test how cyclicity changes with scale;
4) interpret whether cycles result from allogenic or autogenic forces.

3.3. Geologic Setting and Study Area

The Uinta basin in northeastern Utah is a longitudinally asymmetric basin, steeply dipping along its northern margin and gently dipping along the southern margin (Osmond, 1964) (Figure 3.2A). The basin contains over 3,000 meters (9842.5 ft) of Late Cretaceous to Early Eocene age siliciclastic and carbonate sediments (Ryder et al., 1976).

The Paleocene-Eocene Wasatch Formation crops out along the margins of the basin and contains fluvial and lacustrine strata described as a red to tannish-brown, gray, green and purple variegated succession of sandstone, siltstone, and mudstone with lesser amounts of conglomerate and discontinuous carbonate beds (Figure 3.2A) (Fouch, 1976). The Wasatch Formation unconformably overlies the Paleocene Flagstaff or North Horn Formation and is conformably overlain by the Eocene Green River Formation (Figure 3.2B) (modified from Fouch, 1976). The Formation is up to 1,000 m (3,281 ft) thick in outcrops along the modern-day Green River and thins toward the eastern and western margins of the basin (Cashion, 1967; Dickinson et al., 1986) (Figure 3.2A).

The Wasatch Formation contains abrupt upward changes in lithofacies, depositional styles and net-sand content that can be regionally mapped across the outcrop and form the basis for subdividing the Wasatch Formation into three members: 1) lower, 2) middle, and 3) upper (Figures 3.2 & 3.3) (Ford and
The informal units described above correlate to coevally deposited units of the Wasatch Formation in the Piceance basin (Erhardt, 2005; Lorenz and Naden, 2002; and Johnson and Flores, 2003). Two hypotheses are proposed to explain the regionally abrupt upward changes. First, they may reflect tectonic activity related to the Uncompahgree and White River Dome uplifts (Lorenz and Naden, 2002; and Johnson and Flores, 2003) and second, the upward variations may reflect regional climatic changes related to the Paleocene-Eocene Thermal Maximum (PETM) (Remy, 1992; and Erhardt, 2005).

The provenance for Wasatch and Green River Formation sediment varies spatially. The northern part of the basin was sourced from the Uinta Mountains (Ryder et al., 1976; Montgomery and Morgan, 1998). The southern part of the basin was sourced either by: 1) the buried San Luis Uplift in south-central Colorado with contributions from the Monument Uplift, the San Rafael Swell, and remnants of the Cretaceous Sevier fold and thrust belt in Utah (Dickenson et al., 1986; and Ryder et al., 1976) and/or 2) the Cordilleran magmatic arc in the Mojave region of southern California (Davis et al., 2010).

This study uses two field areas of different scales within the middle Wasatch Formation: a regional study and a detailed study. The regional study area is located along the southern margin of the Uinta basin and extends from Whitmore Park in the west to Maverick Canyon in the east and north along the modern day Green River in Desolation Canyon from Three Fords Canyon to 0.8 km (0.5 mi) south of Flat Canyon (Figure 3.2A). The detailed study area is a 2 km (1.2 mi) by 4 km (2.5 mi) area located in the
central part of the outcrop belt at the confluence of Three Canyon and the Green River (Figures 3.2A & 3.4).

3.4. Data & Methodology

Integration of several datasets was used to address the goals of this study. Regional analysis utilized photo panels created from merged photographs, geographically referenced video, USGS 7.5-minute quadrangle maps, UGS 30x60 geological maps and handheld GPS units to map lithosome boundaries and contacts, lithofacies, and correlation lengths. 100% of the Wasatch Formation outcrop strata was photographed from a helicopter and the ground in Desolation Canyon from Three Fords Canyon to 0.8 km (0.5 mi) south of Flat Canyon (Figure 3.2A). Additionally, continuous photographs were taken from a helicopter along the southern outcrop-belt of the Wasatch Formation extending east of the modern Green River to Maverick Canyon (Figure 3.2A). Shot in GPS acquisition mode, high-definition video was acquired from a helicopter with a Sony HDR-XR550V covering the same geographic terrain as the continuous photographs in both Desolation Canyon and east to Maverick Canyon. Photographs of the southern outcrop-belt of the Wasatch Formation west of Desolation Canyon to Whitmore Park were completed on foot and from an all-terrain vehicle. Only the area between Range Creek and the Green River was not mapped due to access restrictions (Figure 3.2A).

Analysis of the middle Wasatch Formation at Three Canyon study area (Figure 3.4) utilized photo panels merged from photographs, XYZ and intensity ground and airborne lidar data, and USGS 7.5-minute quadrangle maps along with handheld GPS units. These tools were used to geographically reference the locations of twenty-four high-resolution (centimeter-scale) stratigraphic columns, strike and dip measurements, sediment transport measurements, lithosome boundaries, lithostratigraphic contacts, internal stratification, and lithofacies. Field interpreted photo panels, video shot from helicopter, measured sections, GPS data and the lidar data were used map and measure dimensional aspects of the cycles and correlate stratigraphic units across canyons walls in the field area. Measurements of width and thicknesses were made perpendicular to sediment transport directions or mathematically adjusted from apparent widths.

3.5. Hierarchical Framework for Fluvial Strata

This study builds upon the three-level hierarchy proposed by Ford and Pyles (in prep, Chapter 2 of this dissertation) for describing the meso- to macro-scale architecture of fluvial systems (Figure 3.5).
This three-level hierarchy includes from smallest to largest (Figure 3.5): stories, elements and archetypes. This framework is equally focused on floodplain strata and strata deposited within channel-belts.

3.6. Cyclicity in Fluvial Strata of the Middle Wasatch Formation

Modifying Duff and Walton’s (1962) original definition of a cycle, we define a “stratigraphic cycle”, (cycle), as an upward repeating succession of stratigraphic characteristics or stratigraphically equivalent characteristics that occur over a similar time span of deposition overlain by a surface that records an abrupt shift in deposition interpreted in fluvial systems to result from abandonment and/or avulsion.

Building on the architectural framework of Ford and Pyles (in prep, Chapter 2 of this dissertation) (Figure 3.5), cyclicity in the middle Wasatch Formation was defined by upward repeating successions of stratigraphic characteristics and the correlation lengths of overbank fines and paleosols in depositional strike and dip profiles across the field area.

Four hierarchical-orders of cyclicity are documented in the study area of the middle Wasatch Formation, from smallest to largest, they are (Figure 3.6): 1) archetype cycle; 2) small-scale cycle; 3) intermediate-scale cycle; and 4) large-scale cycle. Each increase in hierarchical level is associated with an increase in size, time-span of existence, cross-cutting relationships, spatial shift in the axis of deposition of adjacent cycles, and correlation length (Figure 3.6). Components of the model are described below.

3.6.1. Archetype Cycle

An archetype cycle is composed of a channel-belt element and it’s genetically related floodplain-belt element(s) (Figure 3.5 & 3.6A) (Ford and Pyles, in prep, Chapter 2 of this dissertation). The boundaries between stratigraphically adjacent archetypes cycles record an abrupt lateral shift in the location of the axis of deposition which is interpreted to record abandonment and avulsion (i.e., compensation). Forty-five archetype cycles are documented in the Three Canyon study area of the middle Wasatch Formation. Archetype cycles have systematic upward stacking patterns. Two upward stacking patterns are documented (Figure 3.7): 1) braided archetype cycle, and 2) meandering archetype cycles (Ford and Pyles, in prep, Chapter 2 of this dissertation). Each is described below.

The upward succession through the thickest and most sand-rich or axial part of a braided archetype cycle contains (Figure 3.5, 3.6A & 3.7): 1) splay story composed of splay beds that increase in thickness from one to the next in an upward transect and are interbedded with floodplain fines and/or paleosols, 2) a single or multistory downstream accreting channel-belt element that is in erosional contact with the
underlying splay story, 3) erosionally based fine-grained fill story and, 4) floodplain fine story and paleosols. Strata in braided archetype strata laterally thin and become finer grained toward their lateral margins. To the extent that the archetype can be correlated, an upward succession through a margin of a braided-archetype cycle contains associated floodplain-belt components in varying proportions including overbank fines or paleosols with occasional crevasse splay and crevasse channel stories (Figure 3.5, 3.6A & 3.7). A paleogeographic reconstruction based on mapping one braided-archetype cycle around and across the 3-D exposures of the study area is presented in across the Three Canyon study area is presented in Figure 3.8A.

The upward succession through the thickest and most sand-rich or axial part of a meandering-archetype cycle contains (Figure 3.5 & 3.7): 1) splay story composed of splay beds that increase in thickness from one to the next in an upward transect are interbedded with floodplain fines and/or paleosols, 2) a single or multistory lateral accreting channel-belt element that erosionally truncates the underlying splay story and, 3) amalgamated floodplain fine stories and paleosols (Figures 3.5 & 3.7) (Ford and Pyles, in prep, Chapter 2 of this dissertation). Strata laterally thin and become finer grained toward their lateral margins. To the extent that the archetype can be correlated, an upward succession through a margin of a meandering-archetype cycle contains associated floodplain-belt components in varying proportions including overbank fines or paleosols with occasional crevasse splay and crevasse-channel stories (Figure 3.5 & 3.7). A paleogeographic reconstruction based on mapping one meandering-archetype around and across 3-D exposures the study area of a meandering-archetype cycle across the study area is presented in Figure 3.8B.

During the depositional timespan it takes an archetype cycle to evolve, with the exception of lateral migration, the depocenter for that archetype cycles is fixed. Internal cyclicity within an archetype is not recognized, because the boundaries between stories record migration not abandonment or avulsion (sensu bedding structures of Straub et al., 2009).

The range in widths of archetype cycles measured in this study is 1.45 km to 1.6 km (0.9 mi to 1 mi) with an average width of 1.98 km (1.23 mi). The range in thicknesses within the axes of deposition is 9 m to 31 m (30 ft to 102 ft) with and average thickness of 20 m (66 ft) (Table 3.1 & Figure 3.9). Archetype cycles thin toward their margins and can be correlated a maximum distance in a depositional strike direction of 2.25 km (1.4 mi) (Table 3.1A). The average lateral offset between the axes of stratigraphically adjacent archetype cycles is 230 m (739 ft) and interpreted to record the avulsion distance (Table 3.1).
3.6.2. Small-Scale Cycle

Small-scale cycles consist of two or more archetype cycles that contain similar architecture and facies associations. The boundaries between stratigraphically adjacent small-scale cycles record an abrupt lateral shift in the location of the axis of deposition which is interpreted to record abandonment and avulsion (i.e., compensation) (Figure 3.6B). Sixteen small-scale cycles are documented in the Three Canyon study area of the middle Wasatch Formation (Figure 3.10). An upward succession through the thickest and most sand-rich or axial part of a small-scale cycle contains amalgamated archetype cycles expressed as: 1) sand-on-sand contacts between channel-belt elements which represent the axes of adjacent archetype cycles; 2) splay story consisting of upward thickening splay beds interbedded with thin floodplain fines or paleosols separating channel-belt elements of overlying archetype cycles; or 3) thin floodplain fine story or paleosols separating channel-belt elements of overlying archetype cycles (Figure 3.6B & 3.10). The strata of small-scale cycles laterally thin and become finer grained toward their lateral margins. To the extent that the small-scale cycle can be correlated, an upward succession through a margin of a small-scale cycle consists of amalgamated floodplain-belt components of adjacent archetype cycles and including overbank fine stories or paleosols with rare crevasse splay and crevasse channel storys (Figures 3.6B & 3.10).

The range in widths and thickness for small-scale cycles in the study area is 3 km to 6.5 km (1.9 mi to 4 mi) and 18 m to 57 m (59 ft to 187 ft) (Table 3.1 & Figure 3.9), respectively. Small-scale cycles thin toward their margins and can be correlated an average distance in a depositional strike direction of 3.9 km (2.4 mi) (Table 3.1). The average lateral offset between stratigraphically adjacent small-scale cycles is interpreted to record the avulsion distance, is 0.6 km (0.4 mi) (Table 3.1).

3.6.3. Intermediate-Scale Cycle

Intermediate-scale cycles consist of two or more small-scale cycles that contain similar architecture and facies associations, their stratigraphic characteristics change from the axis to its margin. The boundary between stratigraphically adjacent intermediate-scale cycles records an abrupt lateral shift in the location of the axis of deposition which is interpreted to record abandonment and avulsion (i.e., compensation) (Figure 3.6C).

Five intermediate-scale cycles are documented in the detailed study area of the middle Wasatch Formation (Figure 3.11 & 3.12). An upward succession through the thickest and most sand-rich or axial part of an intermediate-scale cycle contains clustered small-scale cycles dominated by braided-
archetype cycles (e.g., intermediate-scale cycle 4, Figure 3.12). Strata in intermediate-scale cycles laterally thin and become finer grained toward their margins. To the extent that intermediate-scale cycle can be correlated, an upward succession through a margin of an intermediate-scale cycle consists of clustered small-scale cycles dominated by meandering-archetype cycles (e.g., cycle 4 of Figure 3.11), or non-clustered, finer grained small-scale cycles (Figure 3.6C).

Axis-to-margin changes in style and size of channel-belt elements are evident in intermediate-scale cycles. For example, in the axis of intermediate cycle 4 at Chandler Canyon contains braided-archetype cycles (e.g., intermediate-scale cycle 4, Figure 3.12). In contrast, coevally deposited strata in the margins of intermediate cycle 4 at Three Canyon contain meandering-archetype cycles (e.g., cycle 4 of Figure 3.11). The average thicknesses of the stories in braided and meandering archetypes were examined to access the difference between these two systems. Thickness of stories is indicative of bankfull channel depth (Allen, 1965; Miall, 1993; and Mohrig et al., 2000). Therefore the thickness of erosionally based fine-grained fill stories are used as proxy for channel depth in the braided-archetype cycles and have an average thickness of 12.7 m (41.7 ft) in the Three Canyon study area (Ford and Pyles, in prep, Chapter 2 of this dissertation). In contrast, fine-grained fill associated with lateral accretion stories, which record channel depth in the meandering-archetype cycles and have an average thickness of 3.5 m (11.2 ft) in the Three Canyon study area (Ford and Pyles, in prep, Chapter 2 of this dissertation). Therefore, braided-archetype channels, which are located in the axis of intermediate-scale cycles, are on average of 4 times deeper (thicker) than coevally deposited meandering-archetype channels, which are located on the margins of intermediate-scale.

A 1-D upward transect at Three Canyon records an upward change from predominantly braided-archetype cycles (e.g., intermediate-scale cycles 1-3 in Figure 3.11), to predominantly meandering-archetype cycles (e.g., intermediate-scale cycle 4 in Figure 3.11), then back to predominantly braided-archetype cycles (e.g., intermediate-scale cycles 5 in Figure 3.11). Conventional interpretations of this 1-D upward succession could be climate change, change in gradient due to tectonics, or change in sediment source. However, mapping the intermediate-scale cycles across the field area documents that the upward pattern results from lateral shifts in the axis of intermediate-scale cycles (Figure 3.13). A similar change in depositional style from axis to margin is documented in modern fluvial archetypes (Figure 3.14) (Ford and Pyles, in prep, Chapter 2 of this dissertation). The change in the 1-D upward pattern in combination with the change in stratigraphic characteristics (braided archetype to meandering archetype) from axis to margin and channel size (thickness) from axis to margin documents
that this change in upward pattern results from compensational stacking at the scale of intermediate-scale cycles.

The range in widths and thickness of intermediate-scale cycles in this study is 10 km to 16 km (6.2 mi to 10 mi) and 95 m to 126 m (312 ft to 413 ft) (Table 3.1 & Figure 3.9), respectively. Intermediate-scale cycles thin toward their margins and can be correlated an average distance in a depositional strike direction of 17.3 km (10.7 mi) (Table 3.1A). The average lateral offset between stratigraphically adjacent intermediate-scale cycles is interpreted to record avulsion distance, is 1.9 km (1.2 mi) (Table 3.1).

### 3.6.4. Large-Scale Cycle

Large-scale cycles consist of two or more intermediate-scale cycles that contain similar architecture and facies association. They record regional, system-scale changes in architecture, and lithofacies. The boundary between stratigraphically adjacent large-scale cycles records system-scale shut-down or abandonment and reinitiation (Figure 3.6D). Three large-scale cycles are documented in the regional study area and are synonymous with the lower, middle and upper Wasatch Formation (Figures 3.2A, 3.3 & 3.12). An upward transect through these large-scale cycles documents an upward pattern from a low net-sand content lower Wasatch Formation, a high net-sand content middle Wasatch Formation, and intermediate net-sand content middle Wasatch Formation (Figures 3.3 & 3.12). The boundaries between the lower, middle and upper Wasatch Formation are ~ 5 m (~16 ft) thick compound paleosols that can be correlated across the regional study area. The boundaries between the large-scale cycles of the lower, middle and upper Wasatch Formation are interpreted to record system scale shutdown followed by reinitiation. Large scale cycles are thickest in their axis (Figure 3.3B) and thin towards their margins (Figures 3.3A & 3.3C).

This upward transect documented through large-scale cycles (low net-sand-content, high net-sand-content, and intermediate net-sand-content), could result from a number of reasons. First, large interbasinal-scale avulsion. This is not the case, because the lower, middle and upper Wasatch units can be correlated to other basins (e.g., Piceance basin) (Erhardt, 2005; Lorenz and Naden, 2002; Johnson and Flores, 2003). Second, the progradation of a broad distributary fluvial system resulting in an upward increase in channel size and a decrease in floodplain strata (e.g., Hartley, et al., 2010). This is not the case, because this progradational model has to cross the abrupt interbasinal surface that separates older from younger strata and have distinctively different characteristics. Dip stratigraphy are exposed along the walls of Desolation Canyon (Figure 3.2) and no change in stratral patterns along this ~30.6 km (19 mi) depositional dip profile are evident. Third, large-scale climate change. This is most likely
hypothesis and as has been documented by other authors (e.g., Remy, 1992; Erhardt, 2005; and Plink-Bjorklund et al., 2012). Supporting evidence for a changing climate during middle Wasatch stems from: 1) the regional, abrupt increase in net-sand content of up to 50% documenting and major change in the sediment and mode of transport (i.e., Suspension fallout to tractive deposition), 2) the major increase in the number of fluvial channels and the capacity and competency of those channels; 3) with the major increase in the number of fluvial channels and associated sediment moving through the system during this time one would assume a large amount of water was equally moving though the system. Yet the lacustrine shoreline, which is more than 80 km (50 mi) to the north of the Three Canyon, doesn’t document any appreciable expansion during this time of increased fluvial sediment into the basin. Therefore, it is interpreted that the water entering the basin via middle Wasatch Formation channels was evaporating at extreme rate and/or going into the subsurface. These facts lead us to the interpretation that the boundaries between middle Wasatch Formation records a large-scale increase in rain in the hinterland and monsoonal climatic events that were alternating wet and dry seasons. A monsoonal climate has been documented in the Wasatch of the Uinta basin by Plink-Bjorklund et al., (2012), the Piceance basin by Erhardt (2005), and hot-monsoonal conditions in the Green River basin of Wyoming by Will (2000).

Large-scale cycles measured in the regional study area have widths greater than 150 km (93 mi), and range in thickness from 240 m to 305 m (787 ft to 1,007 ft) (Table 3.1 & Figure 3.9). According to Fouch et al., (1994) the Wasatch Formation in the Uintah basin is between 3 - 4 million years. Using Fouch et al., (1994) number for the Wasatch Formation, we estimate that the three large-scale cycles are each ~ 1 my in duration. Continuing with this logic we estimate the intermediate-scale cycles to represent ~100,000 year, small-scale cycles to represent ~ 30,000 years and archetype cycles to represent ~ 10,000 years (Figure 3.6).

The depositional differences between intermediate-scale and large-scale cycles described herein are interpreted to document what Wang et al., (2011) call a “scale break in basin-filling trends,” representing a transition between autogenic and allogenic stratigraphy.

3.7. Discussion

Three key aspects provide insight into the evolution of cyclicity in the middle Wasatch Formation fluvial system: 1) the hierarchical nature of compensationally formed cycles; 2) deposition fairways; and 3) end-member depositional trends.
3.7.1. **Hierarchical Nature of Compensationally Formed Cycles**

This study documents three-scales of compensational cyclicity in the middle Wasatch Formation: archetype, small-scale, and intermediate-scale. Cycle boundaries at all the hierarchical levels record abrupt lateral shifts in the axes of deposition (Table 3.1), resulting in upward patterns in the stratigraphy that change laterally (Figure 3.6). For example, the 1-D upward transect at Three Canyon (Figure 3.11) compared to the 1-D upward transect at Chandler Canyon (Figure 3.12) are different. In contrast, allogenically controlled cycles have upward patterns in the stratigraphy that are persistent across strike profiles of the systems (Figures 3.1A-C). As such, the compensational driven cycles, (archetype cycles, small-scale cycles and large-scale cycles), are interpreted to result from autogenic (internally driven) processes. Additionally, spatial off-set in between the axes of deposition for stratigraphically adjacent cycles increase across hierarchical levels, supporting our hierarchical designation for compensation (Figure 3.9 and Table 3.1).

Critically, Schlager (2004) documents the shape of clinoforms to be fractal and goes on to use this observation to state that, “Orders of stratigraphic sequences are being used loosely and with widely varying definitions. The orders seem to be subdivisions of convenience rather than an indication of natural structure” (Schlager, 2004, p. 185). However, the off-set in axis of deposition between cycles supports the hierarchical nature to cyclicity. Compensation is therefore scale-dependent.

3.7.2. **Depositional Fairways within Large-Scale Cycles**

Five sustained, depositional fairways are documented from regional mapping of the middle Wasatch Formation large-scale cycle (Figures 3.2A & 3.15). They are relatively narrow, high net-sand content zones of clustered channels that persist upward through the middle Wasatch large-scale cycle. The strata in the fairways laterally transition into low net-sand content strata in the inter-fairway areas. Critically, stratal surface can be correlated from the depositional fairways representing axis of deposition into the inter-fairway, off-axis areas, documenting that the depositional fairways are not erosionally-bounded intervals (i.e., incised-valley fills or deposition canyons). Additionally, the ability to correlate between fairways leads to the interpretation that these high net-sand content, depositional fairways record coevally active fluvial systems and not one fluvial channel that was avulsing between adjacent fairways.

The widths of depositional fairways are ~3.5 km (2.2 mi) wide, which is greater than the maximum lateral offset measured for intermediate-scale cycles resulting in compensational playground for intermediate-scale cycles, small-scale cycles and archetype cycles respectively (Table 3.1).
The locations of three of the five depositional fairways (F1, F2, and F4 of Figure 3.15) of the middle Wasatch large-scale-cycle are coincident with the largest modern canyons in the area (Figure 3.15). This alignment is interpreted to result from up-dip focusing, such as an up-dip valley or canyon and/or underlying structures, which serves to focus river systems through the area. Avulsion by channel reoccupation could be an alternative explanation, but is less satisfying based on the upward persistence of the pattern (Aslan et al., 2005).

3.7.3. End-member Depositional Trends

This study documents cyclicity resulting from end-member controls (autogenic and allogenic) (Figure 3.16). Allogenically driven cycles, which are controlled by eustacy, tectonic, climate and sediment supply document an upward pattern that can vary from the axis-to-margin, but the overall upward pattern is similar (Figure 3.16). Autogenically driven cycles, are controlled by local topography and hydrodynamic processes. These cycles document no consistent upward pattern from the axis of the system to its margin (Figure 3.16). This lack of pattern is interpreted to reflect scale-dependent compensational stacking. Between these two end-member controls (autogenic and allogenic) lies a stratigraphic style that reflects a balance between external drivers of eustacy, tectonic, climate and sediment supply and the internally driven tendency to reorganize the system (Figure 3.16). The resulting stratigraphic signature would be a mixture of the stratigraphic manifestation of the autogenic and allogenic controls (Figure 3.16).

3.8. Conclusions

The unique outcrop exposures of the Wasatch Formation provide an opportunity to document cyclicity at different scales. This article documents four hierarchical orders of cyclicity within the middle Wasatch Formation: archetype, small-scale, intermediate-scale and large-scale. Archetype, small-scale, and intermediate-scale cycles are interpreted to result from autogenic, compensational stacking. Whereas, the large-scale cycles of the Wasatch Formation are interpreted to result of allogenic forces, most likely climate.

This study provides one the first documented outcrop examples of: 1) changes in the depositional style from axis-to-margin positions within a fluvial system documenting an alternative model, compensational stacking, for interpreting upward changes in fluvial styles; 2) scale dependent compensational stacking; and 3) a scale break in basin-filling trends resulting from the shift of autogenic to allogenic controlled stratigraphy between intermediate and large-scale cycles, respectively.
3.9. Acknowledgments

Thanks are given to the Price, Utah Bureau of Land Management District office for access to Desolation Canyon. The authors also thank Mark Tomasso, Ryan Sincavage, The Enhanced Oil Recovery Institute of Wyoming and EOG Resources, Inc. for acquisition and support of the lidar data. We would also like thank Curt Kelsey of Classic Helicopters along with Jeremiah Moody and Brian Willis in the acquisition of helicopter photos and video. Financial support for the year 2010 was graciously provided by Chevron Center of Research Excellence at the Colorado School of Mines.

3.10. References


National Geographic, 2008, Topo!, map, 1:24,000, 7.5 Minute Series.


Figure 3.1 Strike profiles for: A) Eustatically controlled cycles from another fluvial system documenting similar pattern (modified from Atchley et al., 2004); B) Diagrammatic example of climatically controlled cycles documenting similar 1-D patterns from axial to margin positions utilizing concepts from Anderson and Cross (2002), and Hornung and Aigner (2002); C) Tectonically controlled cycles documenting similar 1-D patterns from axial to margin positions (modified from Hajek et al., 2010); E) Autogenically controlled, compensational stacking documenting changes in the upward pattern from axis-to-margin positions in middle Wasatch Formation.
Figure 3.2 A) Map documenting the location of the regional and detailed study areas. The Wasatch Formation outcrop belt and major structural features located around the Uinta basin are labeled (modified from Dickinson et al., 1986; and Hintze et al., 2000). Uinta basin outline courtesy of Utah Geological Survey.

B) Chronostratigraphic chart of Upper Cretaceous and Lower Tertiary strata in the Uinta basin (modified from Fouch et al., 1994).
Figure 3.3 Photographs of the lower, middle and upper members of the Wasatch Formation at Whitmore Park (A); McPerson (B); and Maverick Canyon (C). Yellow lines demarcate the boundaries between the members. Locations of photos are labeled in Figure 3.2A. Pseudo gamma ray documenting sand versus heterolithic mudstone units in the middle Wasatch Formation. The white line in photo (C) separates the foreground features from the background features in the photo.
Figure 3.4. Topographic map of the detailed field area (Three Canyon area) showing the locations of measured sections (blue lines) and sediment-transport directions in the middle Wasatch Formation (National Geographic, 2008). See Figure 3.2 for location. Bold dark blue lines mark the boundary between the lower and middle Wasatch Formation and it is dashed where the lower Wasatch Formation is covered with Quaternary alluvium. Bold dark red lines mark the boundary between the middle and upper Wasatch Formation.
Figure 3.5 Hierarchical framework for classifying fluvial strata in the middle Wasatch Formation. Time span of deposition, cross-cutting relationships, and superposition increase in an upward transect through the hierarchical levels. Components are not drawn to scale. (Reproduced from Ford and Pyles, in prep, Chapter 2 of this dissertation).
Figure 3.6 Four-fold hierarchical model for cyclicity in the middle Wasatch Formation. Size, time span of existence, cross-cutting relationships, and correlation length increase through the hierarchical cycles. Cycle boundaries are dashed where inferred. Components are not drawn to scale.
Figure 3.7  A) Diagrammatic examples of upward stacking patterns within archetype cycles in the detailed field (Three Canyon area). Lateral limits are not represented. Upward stacking patterns are also documented in Figures 3.5 & 3.6A. B) Interpreted photo panel of the southeast Rincon wall. Sediment transport is into the photo. The location of the outcrop is documented in Figure 3.4. C) Zoom-in of interpreted photo panel (3.7B) with archetype cycles boundaries labeled.
Figure 3.8 A) Paleogeographic reconstruction of a braided archetype cycle documenting undifferentiated down-stream accreting, erosionally based fine-grained fill and and floodplain fine storys; B) Paleogeographic reconstruction of the meandering archetype cycle documenting undifferentiated lateral accreting, fine-grained fill associated with lateral accretion levee and floodplain fine storys. The interpretation is constrained by strata on the cliff faces within Three Canyon study area shown as thick yellow, tan, white and blue lines. Dashed dark blue line mark the boundary between the lower and middle Wasatch Formation. In the study area the lower Wasatch Formation is covered with Quaternary alluvium. Red lines mark the boundary between the middle and upper Wasatch Formation. Modified from Ford and Pyles, (in prep, Chapter 2 of this dissertation).
Figure 3.9 Width and thickness measurements of archetype cycles, small-scale cycles, intermediate-scale cycles and large-scale cycles. Average measurement shown as larger symbol with standard deviation as smaller symbols. See Table 3.1 for a detailed list of range, standard deviation and average width and thickness measurements for each cycle.
Figure 3.10 Interpreted photo panel of the southeast Rincon wall documenting boundaries between small-scale cycles. Sediment transport is into the photo. The location of the outcrop is documented in Figure 3.4. The thickest part of the cycle is the axis of deposition.
Figure 3.11 Interpreted photo panel of the southeast Rincon wall documenting boundaries between intermediate-scale cycles. Sediment transport is into the photo. The location of the outcrop is documented in Figure 3.4. The thickest part of the cycle is the axis of deposition.
Figure 3.12 Interpreted photo panel of the southwest wall of Chandler Canyon documenting boundaries between intermediate-scale cycles. The location of the outcrop is documented in Figure 3.4. The thickest part of the cycle is the axis of deposition.
Figure 3.13 Topographic map of the detailed field area (Three Canyon area) documenting the spatial shifts in the locations of axes of deposition for selected intermediate-scale cycles (National Geographic, 2008). Bold dark blue lines mark the boundary between the lower and middle Wasatch Formation; it is dashed where the lower Wasatch Formation is covered with Quaternary alluvium. Bold red lines mark the boundary between the middle and upper Wasatch Formation.
Figure 3.14 Modern example of braided archetype deposition in axial position and meandering archetype in off-axis position along the Brahmaputra River, Bangladesh (Google Earth, 2012). Reproduced from Ford and Pyles (in prep, Chapter 2 of this dissertation).
Figure 3.15. A) Map documenting the locations of sustained, high net-sand content depositional fairways in the middle Wasatch Formation. Outcrop belt and major structural features around the Uinta basin are labeled (modified from Dickinson, 1986, and Hintze et al., 2000). Uinta basin outline courtesy of Utah Geological Survey; Photographs documenting transition from high net-sand content, depositional fairways to low net-sand content areas in the middle member of the Wasatch Formation at Horse Canyon (B); Floy Canyon (C). Yellow lines demarcate the boundaries between the lower, middle and upper members of the Wasatch Formation.
Figure 3.16 Diagrammatic example of end-member controls on cyclicity documenting the upward axis-to-margin stratigraphic patterns that might be result from allogenically controlled cycles, autogenically controlled cycles, and a system responding to allogenic and autogenic controls.
Table 3-1. Width, thickness, and lateral offset measurements for archetype cycles, small scale cycles, intermediate-scale cycles and large-scale cycles.

<table>
<thead>
<tr>
<th>cycle scale</th>
<th>range in width</th>
<th>average width</th>
<th>standard deviation</th>
<th>range in thickness</th>
<th>average thickness</th>
<th>standard deviation</th>
<th>range in lateral offset between units</th>
<th>average lateral offset between units</th>
<th>standard deviation</th>
</tr>
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<tr>
<td>archetype</td>
<td>1.45 - 2.31 km</td>
<td>1.98 km</td>
<td>2.9</td>
<td>9 - 31 m</td>
<td>20.1 m</td>
<td>7.1</td>
<td>13 m - 0.56 km</td>
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<td>0.2</td>
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<tr>
<td></td>
<td>0.9 - 1.4 mi</td>
<td>1.23 mi</td>
<td></td>
<td>29.5 - 102 ft</td>
<td>65.9 ft</td>
<td></td>
<td>42 ft - 0.35 mi</td>
<td>0.14 mi</td>
<td></td>
</tr>
<tr>
<td>small</td>
<td>3 - 6.5 km</td>
<td>4.8 km</td>
<td>1.6</td>
<td>18 - 57 m</td>
<td>27 m</td>
<td>19.5</td>
<td>80 m - 1.4 km</td>
<td>0.6 km</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1.9 - 4.0 mi</td>
<td>3.0 mi</td>
<td></td>
<td>59 - 187 ft</td>
<td>88.6 ft</td>
<td></td>
<td>264 ft - 0.87 mi</td>
<td>0.4 mi</td>
<td></td>
</tr>
<tr>
<td>intermediate</td>
<td>10 - 16 km</td>
<td>13.6 km</td>
<td>2.4</td>
<td>95 - 126 m</td>
<td>89 m</td>
<td>34.6</td>
<td>0.6 - 3.5 km</td>
<td>1.9 km</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>6.2 - 10 mi</td>
<td>8.5 mi</td>
<td></td>
<td>312 - 413 ft</td>
<td>292 ft</td>
<td></td>
<td>0.37 - 1.2 mi</td>
<td>1.2 mi</td>
<td></td>
</tr>
<tr>
<td>large</td>
<td>&gt; 150 km</td>
<td>157.5 km</td>
<td>n/a</td>
<td>240 - 305 m</td>
<td>272.5 m</td>
<td>32.5</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
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<tr>
<td></td>
<td>&gt; 93 mi</td>
<td>98 mi</td>
<td></td>
<td>787 - 1,007 ft</td>
<td>894 ft</td>
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CHAPTER 4.

THE STRATIGRAPHIC NATURE OF A FLUVIAL-LACUSTRINE BASIN-FILL SUCCESSION, DESOLATION CANYON, SOUTHERN MARGIN OF THE UINTA BASIN, UTAH: IMPLICATIONS FOR WALther’S LAW AND THE PETROLEUM INDUSTRY

A paper to be submitted to The Mountain Geologist

Grace L. Ford, David R. Pyles and Marieke Dechesne

4.1. Abstract

A continuous window into the fluvial-lacustrine basin-fill succession is documented along a 77-kilometer (48-mile) transect up the modern Green River from Three Fords to Sand Wash in Desolation Canyon, Utah. In ascending order the transect describes strata from the Flagstaff Limestone, lower Wasatch Formation, middle Wasatch Formation, upper Wasatch Formation, Uteland Butte member of the Lower Green River Formation, Lower Green River Formation, Renegade Tongue of the Lower Green River Formation, Middle Green River Formation and the Mahogany oil shale zone on the boundary between the Middle and Upper Green River Formations. A detailed map, photographs and a description of key stratigraphic characteristics for each of the intervals is presented along with bounding surfaces and stratigraphic changes up and down the river for the interpreted succession. This transect is used to create a cross section through the basin-fill succession. The cross section contrasts with that of Ryder et al., (1976). Three key differences are noted: 1) distinct and abrupt shifts in the system defined herein, contrast with the broadly interfingering relationships proposed by Ryder et al., (1976), 2) herein we document fluvial deposits of the lower and middle Wasatch Formation to be more widespread than previously recognized, and 3) we document that the Uteland Butte member of the Lower Green River Formation contains evidence of being deposited in a lacustrine environment in Desolation Canyon. Two distinct Waltherian progressions are documented for this basin-fill succession. First, the Flagstaff Limestone to lower Wasatch Formation, interpreted as a lacustrine to fluvial transition. This lacustrine to fluvial transition documents basinward progradation of the system and an increase in channel dimensions from the upper Flagstaff Limestone to the lower Wasatch Formation. The second Waltherian progression begins at the upper Wasatch Formation and extends through the Middle Green
River Formation, interpreted as a fluvial-to-deltaic-to-lacustrine deposition. This fluvial-deltaic-lacustrine transition documents several higher-frequency basinward and landward shifts in the depositional system. The interbasinal compound paleosols bounding the middle Wasatch Formation separate these two distinct basin-fill successions.

4.2. Introduction

“The walls are almost without vegetation; a few dwarf bushes are seen here and there clinging to the rocks, and cedars grow from crevices... not like the cedars of a land refreshed by rains, but ugly clumps, like war clubs beset with spines. We are minded to call this Canyon of Desolation,” (p. 191, of Powell, 1895). For adventurers who see the visual beauty, the wilderness, the geological action and the power of these canyons, Desolation Canyon provides a window into the past and a hint of the future (Figure 4.1) (Rampton, 2003). Desolation Canyon tells the history of a basin in which fluvial and lacustrine processes struggled for dominance, each proving at one time or another that it was king of the basin.

The stratigraphy of fluvial-lacustrine systems is inherently variable (Carroll and Bohacs, 1999). Small-scale changes in lake level and sediment supply can translate to large-scale changes in the depositional system. A 77-kilometer (48-mile) transect up the modern Green River, Desolation Canyon, southern margin of the Uinta basin, Utah provides a uniquely continuous window to document the inherent variability of associated fluvial-lacustrine systems in the Wasatch and Green River Formations. This paper documents the upward change in stratigraphy due to systematic shifts in the fluvial-lacustrine depositional system in an upward transect through this basin-fill succession. Results of this study can be used by petroleum geologists as an outcrop analog to reduce uncertainty in the interpretation of subsurface datasets in the Uinta basin and other fluvial-lacustrine basins such as Bohia Bay, Jungarr, Ordos and South Caspian. Furthermore, this paper can be used as a field guide for geologists who brave the Green River between Sand Wash and Three Fords. Please note that Three Fords is not the residence to the primary author of this article.

4.3. Physiographic and Geologic Setting

The Uinta basin is located in northeastern Utah and northwestern Colorado, (Figure 4.1A), and encompasses an area of 24,000 km$^2$ (9,300 mi$^2$) (Montgomery and Morgan, 1998). The Uinta basin is bounded on the north by the Uinta Mountains, the east by the Douglas Creek Arch, the south by the Uncompahgree Uplift and San Raphael Swell, and the west by the remnants of the Cretaceous Sevier
fold and thrust belt (Figure 4.1A; Johnson, 1985; and Dickinson et al., 1986). The basin is longitudinally asymmetric with a steeply dipping northern margin adjacent to the thrust front and a gently dipping southern margin. The Uinta basin sediments are Late Cretaceous to Early Oligocene in age and contain approximately 5,000 meters (~16,000 ft) of alluvial, fluvial and lacustrine strata (Fouch et al., 1994).

Tertiary strata of the Uinta basin examined in this study are: 1) the Flagstaff Limestone, 2) the Wasatch Formation, and 3) the Green River Formation (Figure 4.1B). We utilize the nomenclature of Spieker (1946), “Flagstaff Limestone” instead of the nomenclature proposed by Fouch (1976) and Ryder et al., (1976) of “Flagstaff member of the Green River Formation” because we found the Flagstaff to be a regionally extensive, mappable unit separated from the Green River Formation by several system-scale unconformities. The Flagstaff Limestone is described as a succession of green and gray claystones, brown mudstones and carbonates interpreted as lacustrine deposits. The Wasatch Formation is described as a succession of red to tannish-brown, gray, green and purple variegated sequence of sandstone, siltstone, and mudstone with minor amounts of conglomerate interpreted as fluvial facies along with discontinuous carbonate beds interpreted as lacustrine facies (Fouch, 1976; and Ryder et al., 1976). It is conformably overlain by the Eocene Green River Formation (modified from Fouch, 1976) (Figure 4.1B).

The Wasatch Formation contains abrupt upward changes in lithofacies, depositional styles and net-sand content that can be regionally mapped across the outcrop and form the basis for subdividing the Wasatch Formation into three members: 1) lower, 2) middle, and 3) upper (Figures 4.1A & 4.2) (Ford and Pyles, in prep, Chapter 2 of this dissertation). The lower Wasatch has a net-sand content of <30% and contains isolated sandstone bodies interpreted by the authors as multistory channel-fill deposits with splays and floodplain fines (Sendziak et al., 2012). The upper boundary of the lower Wasatch Formation is a regionally extensive, dark-red interval interpreted as a compound paleosol herein referred to as Rojo Diablo (Figure 4.2). The overlying middle Wasatch has a net-sand content of >85% and contains amalgamated sandstone bodies interpreted by the authors as multistory channel-fill deposits with splay and floodplain fines (Ford and Pyles, in prep, Chapter 2 of this dissertation). The upper boundary of the middle Wasatch is a regionally extensive, dark-red interval interpreted as a compound paleosol herein referred to as Rojo Grande (Figure 4.2). The overlying upper Wasatch has a net-sand content of ~65% and contains sandstone bodies interpreted by the authors as amalgamated, multistory channel-fill and distributary mouth-bars. The sandstone units are interbedded with lacustrine carbonate and mudstone interpreted herein as floodplain strata. The upper boundary of the upper Wasatch Formation is also a regionally extensive, red paleosol dark-red interval interpreted as a
compound paleosol underlying lacustrine carbonates of the Lower Green River Formation. The Green River Formation is described as a gray to white sequence of mudstones, carbonates, oil shale and salt interpreted as lacustrine facies. The Green River Formation also includes red-brown siltstones and very-fine to coarse grained sandstones interpreted as deltaic, distributary mouth bar and distributary channel facies (Fouch, 1976; Ryder et al., 1976; and Remy, 1992). It is unconformably overlain by the Late Eocene Uinta Formation (modified from Fouch, 1976) (Figure 4.1B).

The provenance for Flagstaff, Wasatch, and Green River Formations varies spatially. The detrital sediments in the northern part of the basin are sourced from the Uinta Mountains (Morgan, 2003; Montgomery and Morgan, 1998; and Ryder et al., 1976). The detrital sediments southern part of the basin is sourced either by: 1) the buried San Luis Uplift in south-central Colorado with contribution from the Monument Uplift, the San Raphael Swell, and remnants of the Cretaceous Sevier fold and thrust belt in Utah (Dickenson et al., 1986 and Ryder et al., 1976); or 2) the Cordilleran magmatic arc in the Mojave region of southern California (Davis et al., 2010).

The study area for this article is located in the central part of the outcrop belt along the southern margin of the Uinta basin and covers 77 km (48 mi) transect up the modern Green River in Desolation Canyon, Utah (Figures 4.1A & 4.3). The strata along the river are nearly horizontal to gently dipping (<3°), exceptionally well exposed with little vegetation. A vast majority of the field area is currently only accessible by boating down the modern Green River.

4.4. Data and Methodology

Several datasets were integrated to address the goals of this study. Outcrop strata were photographed from a helicopter, from the ground and from the river. USGS 7.5-minute quadrangle maps and handheld GPS units were used to geographically reference the locations of stratigraphic boundaries, sediment transport measurements, and lithofacies. Interpretations are based facies, facies associates and geometric patterns observed in the outcrop strata. This approach describes an upward transect in a basin fill succession, as such, the observation are documented from south to north up the modern Green River. The stratigraphic characteristic of each type local in this fluvial-lacustrine succession is described, including: 1) general appearance; 2) bounding surface conditions; and 3) stratigraphic expression in an upward succession; 4) depositional interpretation for key interval in Desolation Canyon.
4.5. Basin-Fill Succession

Following the initial work of Cashion (1967), Morgan (2003) provides an introduction to the geology and a historical guide for Desolation Canyon. The purpose of this paper is not to duplicate Morgan’s (2003) work, but to document: 1) the facies; 2) the gradational shifts in facies tracts through time; and 3) changes in vertical profiles (cycles) through the upward transect along the river. The basin-fill succession described below starts in the incipient lake Flagstaff at Three Fords (e.g., river mile 36 in Whitis and Vinson, 2003) and ends at Sand Wash just below the Mahogany oil shale zone marking the boundary between the Middle and Upper Green River Formation (e.g., river mile 12 in Whitis and Vinson, 2003; Figure 4.1, Table 4.1). The documented depositional environments in the upward transect through the Flagstaff, Wasatch, and Green River Formations are: 1) marginal lacustrine to fluvial; 2) low net-sand content fluvial; 3) high net-sand content fluvial; 4) fluvial to deltaic to marginal lacustrine; 5) lacustrine; 6) fluvial to deltaic to lacustrine; 7) fluvial to deltaic; 8) fluvial to deltaic to lacustrine; and 8) open-water lacustrine. Figure 4.3 and Table 4.2 document the location of the key intervals described below.

4.5.1. Lacustrine to Fluvial (Flagstaff Limestone)

The key locality for the Flagstaff member of the Green River Formation in Desolation Canyon is located on the west-side of the river at Three Fords Canyon (Figures 4.3 & 4.4A and Table 4.2). At this locality the Flagstaff Limestone is distinctive due to the striking color contrast between its whitish-gray weathered appearance and the rock of the overlying dark reds to purplish-reds of the lower Wasatch Formation (Figure 4.4B). The lower boundary of the Flagstaff Limestone is abrupt with the Price River Formation below. The upper boundary of the Flagstaff Limestone is abrupt with the lower member of the Wasatch Formation. The upper boundary has been mapped by the authors from Nine Mile Canyon to just east of Floy Canyon (Figure 4.1A). The Flagstaff Limestone is informally subdivided into a lower and upper unit in Desolation Canyon. The lower Flagstaff Limestone contains alternating ooid and white to gray carbonate mudstone beds. These two lithofacies stack in couplets to form rhythmic upward cycles that increasingly thicken upward from one to the next reaching a thickness greater than one meter (> 3 ft) (Figure 4.4C). The upper Flagstaff Limestone contains channel-belt sands and floodplain-belt fines and paleosols (Figure 4.4D). The channel-belts contain ooids that are probably derived from the underlying lower Flagstaff member. The transition between the lower and upper Flagstaff members is gradational.
Based on the lithofacies associations and geometric patterns of the stratigraphic features described above, the Flagstaff Limestone in Desolation Canyon is interpreted to represent a basinward advance in the depositional system that transitions upwardly from cyclic lacustrine deposition (carbonate beds of the lower Flagstaff Limestone) to a floodplain dominated fluvial system (upper Flagstaff Limestone) (Figures 4.4C & 4.4D).

4.5.2. Low Net-Sand Content Fluvial (lower Wasatch Formation)

The key locality for the low net-sand content lower Wasatch Formation in Desolation Canyon is located on the west-side of the Green River across from McPherson Ranch (e.g., river mile 39.5 in Whitis and Vinson, 2003) (Figures 4.3 & 4.5A and Table 4.2). At this locality the lower Wasatch Formation is distinct due to the color abrupt contrast between it and the underlying Flagstaff Limestone, (described above), and the striking contrast in net-sand content between it and the overlying middle Wasatch Formation (Figures 4.5B & 4.2). The lower boundary of the lower member of the Wasatch Formation is abrupt with the Flagstaff Limestone. This boundary has been mapped by the authors from Nine Mile Canyon to just east of Floy Canyon (Figure 4.1A). The upper boundary of the lower Wasatch Formation is the regionally extensive, dark-red compound paleosol (Rojo Diablo) in abrupt contact with amalgamated channel-belt sands of the middle Wasatch Formation (Figures 4.5B & 4.2). This upper boundary has been mapped by the authors from Nine Mile Canyon to Maverick Canyon (Figure 4.1A). The lower Wasatch has a net-sand content of <30% (Sendziak et al., 2012). The lower Wasatch is characterized by two distinct stratigraphic features: 1) interbedded red mudstone and sandstone or siltstone beds that are bioturbated (Figures 4.5C & 4.5D), and 2) large sandstone bodies encased by the interbedded red mudstones and sandstones similar to the previous group (Figures 4.5C & 4.5D). The interbedded red mudstone and sandstone or siltstone beds are interpreted as floodplain-belt deposits containing floodplain fines, splays and crevasses channels (Sendziak et al., 2012) (sensu Ford and Pyles, in prep, Chapter 2 of this dissertation). The large sandstone bodies are interpreted as multistory downstream and lateral accreting channel belt-elements (Sendziak et al., 2012) (sensu Ford and Pyles, in prep, Chapter 2 of this dissertation).

Based on the lithofacies associations and geometric patterns of the stratigraphic features described above, as well as the dominance of preserved floodplain-belt strata and the work of (Sendziak et al., 2012), the lower Wasatch Formation in Desolation Canyon is interpreted as highly aggradational floodplain dominated fluvial system followed by a system-scale shut-down represented by the regionally extensive compound paleosols of Rojo Diablo (Figures 4.5B & 4.2) (Ford and Pyles, in prep, Chapter 3 of...
The lower Wasatch Formation displays no changes in stratigraphic nature (e.g., fluvial) along the ~12 river miles of dip orientated exposure (Figure 4.3).

4.5.3. **High Net-Sand Content Fluvial (middle Wasatch Formation)**

The key locality for the high net-sand content middle Wasatch Formation in Desolation Canyon is located on the west-side of the Green River at Three Fords (e.g., river mile ~50 in Whitis and Vinson, 2003) (Figures 4.3 & 4.6A). The middle Wasatch Formation in Desolation Canyon is distinct due high net-sand content creating castellan-like appearance in contrast to the dark red intervals that bound it (Figures 4.6B & 4.2). The lower boundary of the middle Wasatch Formation is the regionally extensive, dark-red compound paleosol (Rojo Diablo) in abrupt contact with floodplain dominated strata of the lower Wasatch Formation (Figures 4.6B & 4.2). This lower boundary has been mapped by the authors from Nine Mile Canyon to Maverick Canyon (Figure 4.1A). The upper boundary of the middle Wasatch Formation is a regionally extensive, dark-red compound paleosol (Rojo Grande) (Figures 4.6B & 4.2). The upper boundary has also been mapped by the authors from Nine Mile Canyon to Maverick Canyon (Figure 4.1A). The middle Wasatch has a net-sand content of >85% and is characterized by two stratigraphic features: 1) large, amalgamated sandstone bodies separated by interbedded red mudstones, thin sandstone or siltstone beds that are bioturbated (Figures 4.6C & 4.6D), and 2) interbedded and bioturbated red mudstones and sandstones or siltstones (Figures 4.6C & 4.6D). The large amalgamated sandstone bodies are dominated by multistory downstream accreting channel belt-elements with occasional lateral accreting channel belt-elements (Ford and Pyles, in prep, Chapter 2 of this dissertation). The interbedded red mudstone and sandstone or siltstone beds are floodplain-belt deposits containing floodplain fines, splays and crevasses channels (Ford and Pyles, in prep, Chapter 2 of this dissertation).

Based on the lithofacies associations and geometric patterns of the stratigraphic features described above and the dominance of preserved channel-belt strata, the middle Wasatch Formation in Desolation Canyon is interpreted as highly aggradational fluvial system followed by a system-scale shut-down represented by the regionally extensive compound paleosols of Rojo Grande (Figures 4.6B & 4.2) (Ford and Pyles, in prep, Chapter 3 of this dissertation). The middle Wasatch Formation displays no changes in stratigraphic nature (e.g., fluvial) north or south of the key locality along the ~34 river miles of dip orientated exposure (Figure 4.3).
4.5.4. **Moderate Net-Sand Content Fluvial-Deltaic-Lacustrine (upper Wasatch Formation)**

The key locality for the moderate net-sand content upper Wasatch Formation in Desolation Canyon is located on the west-side of the Green River above Flat Canyon (e.g., river mile ~63.2 in Whitis and Vinson, 2003) (Figures 4.3 & 4.7A). At this locality the upper Wasatch Formation in Desolation Canyon is less distinct than the lower and middle Wasatch Formations in their key localities. The lower boundary of the upper Wasatch Formation is a regionally extensive, dark-red compound paleosol (Rojo Grande) (Figures 4.7B & 4.2). The upper boundary has also been mapped by the authors from Nine Mile Canyon to Maverick Canyon (Figure 4.1A). The upper boundary separating the upper Wasatch Formation with the Uteland Butte member of the Lower Green River Formation is abrupt noted by a slight color change and a distinct change increase in the blocky nature of the strata. The noted color change goes from a yellow-red or dark red of the upper Wasatch Formation to grayish-white or yellowish-orange of the Uteland Butte member of the Lower Green River Formation. The upper boundary between the upper Wasatch Formation and the Uteland Butte is distinct based on the contrasting reddish-orange of the upper Wasatch Formation and the whitish-gray of the Uteland Butte. This upper boundary has been mapped by the authors from Nine Mile Canyon to the Green River (Figure 4.1A). The upper Wasatch has a net-sand content of ~65%. It is characterized by several stratigraphic features: 1) large, amalgamated sandstone bodies separated by interbedded red mudstones, thin sandstone or siltstone beds that are bioturbated, (Figures 4.7B & 4.7C), 2) smaller amalgamated sandstone bodies (Figure 4.7D), 3) yellowish-orange carbonate beds interbedded with gray and white carbonate mudstones (Figure 4.7E), and 4) large sandstone bodies displaying large foresets (Figure 4.7F). The large amalgamated sandstone bodies are interpreted as multistory downstream accreting channel belt-elements with occasional lateral accreting channel belt-elements (Figures 4.7B & 4.7C). The interbedded red mudstone and sandstone or siltstone beds are interpreted as floodplain-belt deposits containing floodplain fines, splays and crevasses channels (Figures 4.7B & 4.7C). The smaller amalgamated sandstone bodies are interpreted as distributary channels cutting into shoreface sands or distributary mouth bars (Figure 4.7D). These smaller amalgamated sandstones typically overlie gray mudstones interpreted as lacustrine deposits. The yellowish-orange carbonate beds interbedded with gray and white carbonate mudstones are interpreted to be quite water lacustrine deposits (Figure 4.7E). Finally, the large sandstone bodies displaying large foresets are distributary mount bars (Figure 4.7F).

Based on the lithofacies associations and geometric patterns of the stratigraphic features described above the upper Wasatch Formation in Desolation Canyon is interpreted as highly variable system displaying alternating basinward and landward-stepping cycles that range from fluvial to lacustrine...
deposition with intermediate facies also being deposited between these two end-members. The upper Wasatch Formation is bound at the top by the fully lacustrine facies of the Uteland Butte member of the Lower Green River Formation. The upper Wasatch Formation displays dynamic changes in its stratigraphic nature (e.g., fluvial to deltaic to lacustrine) along the ~ 61 river miles of dip orientated exposure where it goes into the subsurface. From the key locality of the upper Wasatch Formation the unit becomes more fluvial dominated as you go south in Desolation Canyon and more lacustrine as you go north from the key locality (Figure 4.3).

4.5.5. Lacustrine (Uteland Butte member of Lower Green River Formation)

The key locality for Uteland Butte member of the Lower Green River Formation (Uteland Butte) in Desolation Canyon is located on the west-side of the river at Cedar Ridge (e.g., river mile ~65.1 in Whitis and Vinson, 2003) (Figures 4.3 & & 4.8A). At this locality the Uteland Butte is distinctive due its whitish-gray or yellowish-orange blocky appearance compared to the yellow-red or dark red surrounding strata (Figure 4.4B). The lower boundary between the upper Uteland Butte and the Wasatch Formation is distinct based on the contrasting whitish-gray of the Uteland Butte and the reddish-orange of the upper Wasatch Formation. This lower boundary between the Uteland Butte and the upper Wasatch Formation has been mapped by the authors from Nine Mile Canyon to the Green River (Figure 4.1A). The upper boundary between the Uteland Butte and the overlying strata of the lower Green River is fairly abrupt also based on color change from the grays of the Uteland Butte and the yellowish-orange of the Lower Green River Formation. The Uteland Butte in Desolation Canyon contains three distinct features: 1) alternating ooid and whitish-gray to gray carbonate mudstone beds (Figure 4.8B), 2) stacked ooid beds that occasionally include shell fragments (Figure 4.8C), 3) ooid beds capping algal mats (Figure 4.8D). The alternating ooid and whitish-gray to gray carbonate mudstone beds lithofacies stack in couplets to form upward cycles that can be more than one meters thick (> 3 ft) (Figure 4.8B). The ooid beds stack to form more massive blocky units more than two meters thick (> 6 ft) (Figures 4.8B & 4.8D).

Based on the lithofacies associations and geometric patterns of the stratigraphic features described above, the Uteland Butte in Desolation Canyon is interpreted as shallow-water lacustrine deposits that record a several changes in baselevel represented by the cyclic sedimentation. The upward succession is interpreted as an overall decrease in baselevel (basinward-stepping system), followed by a turnaround and an increase in baselevel and accommodation (aggrading or landward-stepping system), reflected by the thick stack of ooid beds at the top of the interval (Figures 4.8B). The Uteland Butte displays only lacustrine deposition along the ~ 8 river miles of dip-orientated exposure (Figure 4.3).
4.5.6. **Deltaic-Lacustrine (Lower Green River Formation)**

The key locality for the Lower Green River Formation in Desolation Canyon is located on the west-side of the Green River 2.5 river miles above Jack Creek (e.g., river mile ~72.5 in Whitis and Vinson, 2003) (Figures 4.3 & 4.9A). At this locality the Lower Green River Formation has similar stratigraphic characteristics as the upper Wasatch Formation. The lower boundary between the lower Green River and the underlying strata of the Uteland Butte is fairly abrupt. The lower boundary between the Lower Green River and the underlying strata of the Uteland Butte is fairly abrupt and based on color change from the grays of the Uteland Butte and the yellowish-orange of the Lower Green River Formation. The upper boundary of the Lower Green River Formation is an transitional contact with the Renegade Tongue of the Lower Green River Formation. The Lower Green River Formation is characterized by several distinct stratigraphic features: 1) large, amalgamated sandstone bodies displaying large foresets bound by gray mudstones interbedded (Figure 4.9C), 2) yellowish-orange carbonate beds interbedded with gray carbonate mudstones (Figure 4.9D), and 3) medium-size sandstone bodies that cannibalize underling sandstone beds (Figure 4.9E). The large, amalgamated sandstone bodies displaying large foresets and are interpreted as distributary mount bars. The yellowish-orange carbonate beds interbedded with gray carbonate mudstones are interpreted to represent cyclic sedimentation in quite lacustrine setting. The medium-size sandstone bodies are interpreted as distributary channels cutting into shoreface sands or distributary mouth bars. These amalgamated sandstones typically bounds by gray mudstones interpreted as lacustrine deposits.

Based on the lithofacies associations and geometric patterns of the stratigraphic features described above, the Lower Green River Formation in Desolation Canyon is interpreted as a highly variable deltaic to lacustrine depositional systems resulting from alternating basinward and landward-stepping cycles. The Lower Green River Formation displays dynamic changes in stratigraphic nature (e.g., deltaic to lacustrine) along the ~ 35 river miles of dip orientated exposure where it goes into the subsurface. From the key locality of the Lower Green River Formation the unit becomes more lacustrine as you go south in Desolation Canyon and displays increasingly shallower deltaic features as you go north from the key locality (Figure 4.3).

4.5.7. **Fluvial-Deltaic (Renegade Tongue of the Lower Green River Formation)**

The key locality for the Renegade Tongue of the Lower Green River Formation (Renegade Tongue) in Desolation Canyon is located on the west-side of the Green River above Rock House (e.g., river mile ~83
in Whitis and Vinson, 2003) (Figures 4.3 & 4.10A). At the key locality the Renegade Tongue is less
distinct from lower the Lower Green River Formation, but takes on fairly distinct castellan like
appearance as you go north in places. The lower boundary of the Renegade Tongue is fairly transitional
with the Lower Green River Formation. The upper boundary of the Renegade Tongue is transitional with
the Middle Green River Formation. The Renegade Tongue has a high net-sand content and is
characterized by features that dominate the lower part of the interval and those that dominated the
upper part of the interval. The lower part of the Renegade Tongue contains smaller sandstone bodies
cannibalizing larger lenticular sand bodies below bounded by gray carbonate mudstones (Figure 4.10C).
The upper part of the Renegade Tongue contains large amalgamated sandstone bodies with lateral
accretions separated by red mudstones interbedded with red siltstones or gray carbonate mudstones
(Figure 4.10B & 4.10D). The smaller amalgamated sandstone bodies cannibalizing larger sandstone
bodies of the lower Renegade Tongue are interpreted as distributary channels eroding into shoreface
sands. The interesting aspect about lower Renegade Tongue is in most places the distributary mouth
bars are not preserved or present indicating that baselevel was decreasing at such a rate that the
distributary channels cannibalized their own mouth bars or they weren’t deposited in the locality,
respectively. The large amalgamated sandstone bodies of the upper Renegade Tongue are interpreted
as multistory lateral accreting channel belt-elements with occasional downstream accreting channel
belt-elements interbedded with red paleosol or gray carbonate muds

Based on the lithofacies associations and geometric patterns of the stratigraphic features described
above, the Renegade Tongue in Desolation Canyon is interpreted as a fluvial to marginal lacustrine
deposition in a dynamic interval alternating between basinward and landward-stepping cycles. The
overall upward succession of the Renegade Tongue documents a basinward-stepping system as the
system systematically changes from marginal lacustrine deposition as shoreface and distributary
channel sandstones of the lower Renegade Tongue to the fluvial-dominated upper Renegade Tongue.
The Renegade Tongue displays dynamic changes in stratigraphic nature (e.g., marginal lacustrine to
deltaic to fluvial) along the ~ 35 river miles of dip orientated exposure where it goes into the subsurface.
From the key locality of the Renegade Tongue the unit becomes more lacustrine as you go south in
Desolation Canyon and is fluvial dominated as you go north from the key locality (Figure 4.3).

4.5.8. Fluvial-Deltaic-Lacustrine (Middle Green River Formation)
The key locality for the Middle Green River Formation in Desolation Canyon is located on the west-
side of the Green River above Maverick Canyon and below Little Horse Bottom (e.g., river mile 85 in
Whitis and Vinson, 2003) (Figures 4.3 & 4.11A). This is not the same Maverick Canyon referred to in the regional mapping. The lower boundary of the Middle Green River Formation is transitional with the Renegade Tongue. The upper boundary of the Middle Green River Formation is abrupt with the white beds of the Mahogany oil shale zone. The Middle Green River Formation in Desolation Canyon has two distinct stratigraphic patterns and is informally divided into a lower section and an upper section. At the key locality the Middle Green River Formation is very distinctive in its alternating units of whitish-gray and orangish-brown. The lower section of the Middle Green River Formation is characterized by two distinct stratigraphic features: 1) large sandstone bodies with reworked ooids often displaying large foresets bound by gray carbonate mudstones (Figures 4.11B & 4.11C), 2) yellowish-tan carbonate beds interbedded with gray and white carbonate mudstones (Figure 4.11D). The upper section of the Middle Green River Formation is characterized by whitish-gray, course-fine carbonate couplets (Figure 4.11E). The large sandstone bodies in the lower section of the Middle Green River Formation are interpreted as shoreface deposits and distributary mouth bars. The yellowish-tan carbonate beds interbedded with gray and white carbonate mudstones are interpreted as open lacustrine desisted displaying cyclic sedimentation. The whitish-gray, course-fine carbonate couplets of the upper section of the Middle Green River Formation are interpreted to be lacustrine turbidites with occasional subaqueous channels cutting into them (Figure 4.11E).

Based on the lithofacies associations and geometric patterns of the stratigraphic features described above, the Middle Green River Formation in Desolation Canyon is interpreted alternating deltaic to lacustrine basinward and landward-stepping cycles. The overall upward succession of the Middle Green River Formation documents a landward-stepping system that transitions from deltaic deposition dominated by detrital input to deeper-water lacustrine turbidites. The Middle Green River Formation displays dynamic changes in stratigraphic nature (e.g., deltaic to pro-delta, to lacustrine) along the ~ 15 river miles of dip orientated exposure where it goes into the subsurface. From the key locality of the Renegade Tongue the unit becomes shallower-water deltaic deposition as you go south in Desolation Canyon and is becomes deep-water lacustrine as you go north from the key locality (Figure 4.3).

4.5.9. Mahogany Oil Shale Zone – Boundary of Middle and Upper Green River Formation

The Mahogany oil shale zone is the boundary between the Middle and Upper Green River (Morgan 2003). It is distinct abrupt appearance in Desolation Canyon because of its bleached-white laminated nature (Figure 4.11B). The zone can be tracked along the canyon walls for over 18 river miles beginning at the Sand Wash put-in, river mile 72 (Figure 4.3) (Whitis and Vinson, 2003). The Mahogany oil shale
zone is interpreted to represent organic-rich, open-water lacustrine deposition during the maximum extent of Lake Uinta (Ryder et al., 1976).

4.6. Discussion

The 77-mile transect up the Green River in Desolation Canyon from Three Fords to Sand Wash provides an almost continuous window into the fluvial-lacustrine basin-fill succession (Figure 4.3). This unique perspective documents a basin-fill succession that is diverges from previously described succession. Ryder et al., (1976) cross section from Solders Summit to Green River has been the Rosetta stone for Tertiary stratigraphy for over 30 years (Figures 4.12B & 4.12B). The basin-fill succession described in this study provides an alternate view into this fluvial-lacustrine system (Figure 4.12C). Three key differences are documented: 1) this study documents distinct and abrupt shift in the system defined by our key interval in contrast to the interfingering nature displayed by Ryder et al., (1976) (e.g., lack of distinction in the lower, middle and upper Wasatch Formation), 2) more regionally extensive deposition of the fluvial deposited lower and middle Wasatch Formation, 3) recognition of the lacustrine deposited Uteland Butte in Desolation Canyon. Although, we note several key differences between the basin-fill succession documented by Ryder et al., (1976) and this study, future work is needed to fully understand the implications of these differences to petroleum resources in the basin.

Two distinct Waltherian progressions are documented for the Desolation Canyon study area. First, the lacustrine to fluvial succession of the Flagstaff Limestone to lower Wasatch Formation interpreted to document a basinward advance in the depositional system and an increase in channel dimensions transitioning from the upper Flagstaff Limestone to the lower Wasatch Formation. The second Waltherian progression documents the dynamic evolution of a fluvial-to-deltaic-to-marginal lacustrine-to-open-water lacustrine deposition, displaying multiple higher-frequency basinward and landward shifts in the depositional system. The second Waltherian progression also documents three larger-scale shifts in the depositional system: 1) first, a landward shift, 2) then a basinward advance, and 3) lastly, landward shift. The first landward shift is documented the fluvial upper Wasatch Formation overlying lacustrine Uteland Butte. The basinward advance is documented by the lacustrine Uteland Butte overlying lacustrine by the fluvial dominated Renegade Tongue. The final landward shift is documented by the fluvial dominated Renegade Tongue overlain by to the open-water lacustrine deposits of the Mahogany oil shale zone.
4.7. Applications

The basin-fill succession described in this study provides a direct outcrop analog for petroleum geologists exploiting these same formations in the Uinta basin subsurface. Additionally, this succession can be used as a soft analog for other fluvial-lacustrine systems, facilitating our understanding of stratigraphic manifestation of lateral and upward changes in depositional system. Finally this study can be used as an introductory geological field guide for the Desolation Canyon.

4.8. Acknowledgments

Thanks are given to the Price, Utah Bureau of Land Management District office for access to Desolation Canyon. In addition, Grace would also like to thank Down River Equipment for their help with river equipment. Additional thanks goes to Roger Murphy, Scotty Mosiman and Richard Quist along with the rest of the Moki Mack River Expedition crew for their awesome logistical support during the August 2010 field session. Grace would also like thank the many field assistants for their tireless effort on the outcrop. Financial support for the year 2010 was graciously provided by Chevron Center of Research Excellence at the Colorado School of Mines.

4.9. References


Ford, G. L., and D. R. Pyles, in prep, Chapter 3, of this dissertation, Hierarchical nature of cyclicity in a fluvial system: spatial and temporal variations in Autogenically controlled compensational
stacking and interbasinal scale-breaks resulting from climatic forces in the middle Wasatch Formation, Uinta Basin, Utah.


Figure 4.1 A) Map documenting the location of the study area. The Wasatch Formation outcrop belt and major structural features located around the Uinta basin are labeled (modified from Dickinson et al., 1986; and Hintze et al., 2000). Uinta basin outline courtesy of Utah Geological Survey.

B) Chronostratigraphic chart of Upper Cretaceous and Lower Tertiary strata in the Uinta basin (modified from Fouch et al., 1994).
Figure 4.2 Photograph of the lower, middle and upper members of the Wasatch Formation at McPherson Ranch. Yellow lines demarcate the boundaries between the members. Locations of photo are labeled in Figure 4.1A.
Figure 4.3 Geologic map of Desolation Canyon study area showing the locations of key stratigraphic units and their interpreted depositional environment. Location of map is shown in Figure 4.1. UTM coordinates for the key stratigraphic units are labeled in Table 4.2.
Figure 4.4  A) Map documenting the type locality for Flagstaff Limestone in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the Flagstaff Limestone looking up river south of Three Fords (B); and Three Fords area (C & D). The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.4A and in Table 4.2.
Figure 4.5. A) Map documenting the type locality for lower Wasatch Formation in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the lower Wasatch Formation looking up river south of Three Fords (B); and McPerson Ranch area (C & D) (Sendziak et al., 2012). The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.5A and in Table 4.2.
Figure 4.6. A) Map documenting the type locality for middle Wasatch Formation in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the middle Wasatch Formation at Three Canyon (B); and Chandler Canyon area (C & D). The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.6A and Table 4.2.
Figure 4.7 A) Map documenting the type locality for upper Wasatch Formation in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the upper Wasatch Formation near Fretwater Falls area (B & C); and above Flat Canyon (D, E & F). The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.7A and Table 4.2.
Figure 4.8 A) Map documenting the type locality for Uteland Butte in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the Uteland Butte near Fretwater Falls area (B); and ooids and algal mat below Cedar Ridge (C & D). Locations of photos are labeled in Figure 4.8A. The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.8A and Table 4.2.
Figure 4.9 A) Map documenting the type locality for Lower Green River Formation in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the Lower Green River Formation above Fretwater Falls (B), location is labeled on Figure 4.8 above Jack Creek (C); and above Flat Canyon (D, & E). The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.9A and Table 4.2.
Figure 4.10  A) Map documenting the type locality for Renegade Tongue in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the Renegade Tongue above Jack Creek (B), location is labeled on Figure 4.8; and below Rock House (C); and above Rock House (D). The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.10A and Table 4.2.
Figure 4.11 A) Map documenting the type locality for Upper Green River Formation in Desolation Canyon. See Figure 4.3 for geologic legend. Photographs documenting small-scale and large-scale features of the Upper Green River Formation between Maverick Canyon and Little Horse Bottom (B); below Maverick Canyon (D) and above Gold Hole (C & D). The location of this field area is shown in Figure 4.3B. Locations of photos are labeled in Figure 4.11A and Table 4.2.
Figure 4.12 A) Map documenting the location cross sections (modified from Dickinson et al., 1986; and Hintze et al., 2000). Uinta basin outline courtesy of Utah Geological Survey. B) Commonly cited cross section of Ryder et al., (1976) (modified from Keighley et al., 2002 after Ryder et al., 1976). C) Desolation Canyon cross section documented from this study.
Table 4.1 Generalized nomenclature for the Green River Formation for the south-central to south-west Uinta basin compared to terminology used in this study, modified from Morgan (2003).

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Table 4.2. UTM Coordinates for key localities used in Desolation fluvial-lacustrine study.

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* from Whitis and Vinson (2003)
CHAPTER 5.
CONCLUSIONS TO DISSERTATION

5.1. Summary Conclusions and Contributions

This dissertation contains three outcrop-based studies that collectively document the stratigraphy of the Middle Wasatch Formation and adjacent formations on the southern margin of the Uinta Basin. The key conclusions, contributions and implications of each chapter are described below.

5.2. Chapter 2 Conclusions and Contributions

Chapter 2 develops a unified, hierarchical framework for describing meso- to macro-scale fluvial architecture and while addressing the inadequacies of two commonly used approaches. This framework equally emphasizes reservoir and non-reservoir stratigraphy and provides a common language for comparing modern and ancient systems. The hierarchical framework was used to document three distinct associations between channel-belt elements and adjacent splay elements. These associations are observed in the stratigraphic record: 1) unassociated splay; 2) associated coeval splay; and 3) associated non-coeval splay. Using these associations between channel-belt elements and their adjacent splay, two distinct upward stacking patterns were recognized: braided and meandering archetypes cycles. The final contribution of Chapter 2 is the documented framework provides a means to quantitatively analyze and compare the stratigraphic record. Using this framework dimensional data is presented for the middle Wasatch fluvial system in the Three Canyon study area. These width and thickness measurements can be used as a guide for containing reservoir models in similar systems.

5.3. Chapter 3 Conclusions and Contributions

Chapter 3 uses upward patterns to define four scales of stratigraphic cycles in the fluvial system of the middle Wasatch Formation. The smallest three cycles - archetype, small-scale, and intermediate-scale - result from scale-dependent compensation. These compensationally driven stratigraphic cycles document changes in the upward stratigraphic pattern across strike profiles for the basin. These three smaller cycles stack to build a large-scale cycle (e.g., middle Wasatch Formation). The lateral change in the upward stacking patterns for the three smaller cycles’ contrasts with this large-scale cycle and other fluvial systems where allogenic controls were documented to be the primary driver such as those derived from relative changes in sea level, changes in climate, and tectonics. Each of these allogenically
controlled fluvial systems has relatively persistent upward patterns across strike profiles. A second contribution of Chapter 3 is that it is the first outcrop example documenting changes in depositional style from axial to margin positions within a fluvial system at different stratigraphic scales. Another contribution of Chapter 3 is the documentation in outcrop of the scale break from autogenic to allogenic controlled stratigraphy (Wang et al., 2011).

Additionally this Chapter documents that the middle Wasatch Formation large-scale cycle is comprised of sustained, high net-sand content depositional fairways interpreted to result from up-dip focusing and/or underlying structure. The final contribution of Chapter 3 is the dimensional characteristics of the cycles are presented for the middle Wasatch fluvial system. The widths, thickness and lateral offset measurements can be used as a guide for constraining models in similar systems that don’t have associated dimensional data.

5.4. Chapter 4 Conclusions and Contributions

Chapter 4 documents key stratigraphic examples in a fluvial-lacustrine basin-fill succession. Additionally, this chapter provides two examples of Waltherian progression through a dynamic and highly variable fluvial-lacustrine system. Lastly, if read in reverse this chapter can be used as a geologic field guide from Sand Wash to Three Fords Canyon, Desolation Canyon, Utah.

5.5. References

Appendix A includes all files related to the measured section from the Three Canyon study area.

<table>
<thead>
<tr>
<th>File Name</th>
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<tr>
<td>A_Map_and_Legend.pdf</td>
<td>Map documenting location of measured sections and a legend of colors and symbols used in the drafted sections</td>
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APPENDIX B
Uninterpreted Photos and Lidar - SUPPLEMENTAL ELECTRONIC MATERIAL

Appendix B includes all the uninterpreted photos from the Three Canyon area and selected helicopters photos used in the dissertation. The airborne LIDAR data is the proprietary property of EOG Resources, Inc. and has not been released to the public. The ground-based LIDAR data is the proprietary property of Chevron and has not been released to the public. The author would like to thank EOG Resources, Inc. and Chevron for the use of these datasets.

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<tr>
<td>Walls Around Three Canyon.pdf</td>
<td>Uninterpreted photos of the outside ring at Three Canyon</td>
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APPENDIX C
Quantitative Data - SUPPLEMENTAL ELECTRONIC MATERIAL

Appendix C includes copies of quantitative data used in this dissertation. The lithofacies in Facies_Sand_Attributes.pdf correspond to Lithofacies_Properties.pdf numbers. Lithofacies numbering was redone for dissertation see Figure 2.4 and Table 2.1 to compare.

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<td>Lithofacies_Proporitons.pdf</td>
<td>Spreadsheet data used to calculating proportion of lithofacies</td>
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<td>Sand_Attributes_of_Measured_Sections.pdf</td>
<td>Spreadsheet data exported from GeoGraphix related to digitized measured sections</td>
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<tr>
<td>Width_Thickness_Measurements.pdf</td>
<td>Spreadsheet data used to calculating width and thicknesses of architectural units</td>
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APPENDIX D
Permissions and Publication Policies - SUPPLEMENTAL ELECTRONIC MATERIAL

Appendix D includes copies of letters from co-authors of chapters 2, 3, and 4 granting permission to publish the paper(s) in this dissertation. The publication policies for the journals to which chapters 2, 3 and 4 are being submitted are also included.

David R. Pyles, the co-author of chapters 2, 3 and 4, contributed to each of the chapters through field assistance, discussion of concepts and ideas related to each chapter, review of the manuscripts, as well as providing mentorship. Marieke Dechesne, the co-author of chapter 4, contributed by means of field assistance, discussion of concepts and ideas and input geologic filed mapping into GIS system to create the geologic maps.

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