From river to delta: down-dip changes in facies, architecture, and key stratigraphic surfaces in a low-accommodation setting

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Preface

This doctoral thesis entitled *“From river to delta: down-dip changes in facies, architecture, and key stratigraphic surfaces in a low-accommodation setting”* has been submitted to the Department of Geosciences at the University of Oslo in accordance with the requirements for the degree of Philosophiae Doctor (PhD). The work presented herein was carried out at the University of Oslo (UiO), where the candidate has been enrolled as a PhD research fellow between 31st of August 2015 and December 2019, during which time the candidate has had approximately two months of accumulated leave. The four-year period has 25% allocated to teaching.

The work presented herein was funded by the Ministry of Education and Research (Norway). The *Lower Cretaceous Basin Studies in the Arctic (LoCrA)* and the *Research Centre for Arctic Petroleum Exploration* (ARCEx) provided allocated funding for field campaigns. Financial support for presentations at international conferences was granted by the *Norwegian Petroleum School of Norway* (NFiP), *Industrial Liaison* (IL) and the *Society for Sedimentary Geology* (SEPM). The principal supervisor for this work was Associate Professor Ivar Midtkandal (UiO) with co-supervision from Professor John Holbrook (Texas Christian University – TCU -, USA) and Professor Snorre Olaussen (University Centre in Svalbard, UNIS). The work was primarily undertaken at the University of Oslo. Fieldwork was conducted in Colorado and New Mexico during four field campaigns (November 2015, May-June 2016, May-June 2017, May 2018). The work of one TCU master student is partially incorporated in one of the manuscripts.

This four-year study is structured in two sections. The first section provides the motivation, objectives, geological framework of the first-authored articles, and includes a brief discussion and concluding remarks. The second section constitutes the main body of the thesis and is a compilation of the four first-authored articles (chapter 9). The first manuscript was published in the *Journal of Sedimentary Research* in July 2019, the second in the *New Mexico Geological Society Guidebook*, October 2019, and the third in *The Depositional Record,* February 2020. The fourth manuscript was accepted with revisions by *Basin Research*. The appendices provide details on additional work completed during the PhD study which includes seven first-author abstracts and four co-authored abstracts submitted to international conferences and two co-authored publications.

Anna van Yperen
Oslo, December 2019
Updated February 2020

Abstract

The depositional history of low-accommodation fluvio-deltaic strata is commonly challenging to decipher due to their amalgamated, thin, and often top-truncated architecture. The adequate documentation and interpretation of changes in facies distribution, depositional geometries and key stratigraphic surfaces are important in order to understand the interaction between sediment supply and changes in base level, and the resulting stratal geometries. Analyses of full-transect depositional profiles are essential to establish robust stratigraphic frameworks.

A full river-to-delta transect is offered by the Cenomanian Mesa Rica Sandstone, which formed under low-accommodation conditions. The ~400 km transect is exhumed along a NNW-SSE oriented depositional dip-parallel profile from southeast Colorado to central-east New Mexico and represents deposition in the Tucumcari Basin, a sub-basin within the continental-scale low-gradient Western Interior Basin. The two sandstone units of the Mesa Rica Sandstone reflect two regressive phases. The first phase resulted in amalgamated sheet-like sandstone deposits throughout the study area, whereas discontinuous channel-belt deposits dominate the second phase.

High-resolution studies were conducted at two key localities along this profile: the fluvial-to-marine transition zone situated at the rim of the Tucumcari Basin, and the fully deltaic development in the centre of the basin. A regional study combined new data with previously published data, collectively forming an extensive dataset with numerous photopanels, drone survey data, and 125 logged sections throughout a ~40,000 km^2 study area. Methods include mapping and analysis of down-dip changes in facies distributions, fluvial architecture, and spatial extent of key stratigraphic surfaces at both local- and regional-scale.

The studied transect is divided into three geographical zones, based on the dominant facies associations and changes in depositional style that distinguish them as proximal, transitional and distal. In the proximal zone, vertically stacked channel belts form amalgamated buffer-valley fills changing down-depositional dip into a >80 km-wide single-story channel sheet. Detailed documentation of changes in stacking patterns, hierarchy of channel-form bounding surfaces and the interpretation of their scouring processes at different scales, is largely provided by previous work. A low-accommodation setting combined with high sediment supply and recurring avulsion is illustrated by the amalgamated and sand-prone character of the sandstone sheet. In the coeval fluvial-marine transition zone, river-dominated delta-front deposits replace fluvial deposits in basinward direction. The laterally extensive sheet forming delta-front deposits allowed for subdivision of individual mouth bars into four different mouth-bar components (or sub-environments); mouth-bar axis, off-axis, fringe to distal fringe, in which the occurrence of upper flow regime bedforms and average bed thickness decreases towards the fringe, whilst the record of interflood beds and bioturbation index progressively increases. The succession reflects deposition at the basin margin with vertical limitations on aggradation and incision. Such low-

-accommodation proximal deltaic setting enhances reworking processes at bed scale which lowers the preservation potential of fine-grained facies of interflood beds. This causes underestimation of the true influence of subordinate coastal processes, with important implications for prediction of facies changes and sediment distribution in similar settings. In the basin centre, coalesced mouth bars consistently overlain by sand-filled amalgamated distributary channels form sheet-like geometries. These geometries resulted from the combined effect of high sandy sediment supply and low accommodation. The latter acted as an accelerator for the interrelated processes of frequent avulsion of distributaries and recurring mouth-bar depositional cycles at short time scales. After deposition, minor wave-reworking facilitated lateral sand redistribution and favored bioturbation. It demonstrates that sheet-like delta front sandstone geometries from low-accommodation systems can be formed without the dominance of wave redistribution processes.

Finally, establishment of a long distance (~400 km) sequence stratigraphic framework unravels down-dip changes in depositional geometries, facies distribution, fluvial architecture and the extent of key stratigraphic surfaces. Maximum regressive surfaces and the Regional Composite Scour (RCS) can be mapped for >300 km in the study area. Surfaces that occur at a sub-regional scale are basal distributary composite scours, composite surfaces bounding incised valleys, and basal surfaces below dispersed trunk channels incising into deltaic deposits. The down-dip equivalent of the sequence boundary/RCS consists of several dispersed surfaces in the marine part of the depositional system, which challenges the idea of a single, equivalent correlatable surface. Regional composite scours (RCSs) may be generated in the fluvial realm throughout the T-R cycle, highlighting that erosion and deposition occurs contemporaneously; not only when considering the complete depositional system, but at local scale as well. This contradicts many stratigraphic models that interpret low-accommodation settings to dominantly promote bypass, especially during forced regressions.

This compilation of studies highlights a sand-rich end-member example of deltaic deposition in a low-accommodation setting. The work shows that the low-accommodation setting plays a crucial role in the formation of sheet-like geometries and laterally extensive surfaces, products that are classically assigned to wave-dominance and allogenic processes, respectively. The dispersive RCS offers an alternative approach for extension of the sequence boundary/RCS into the marine realm. In general, the studies emphasize that low-accommodation settings favour accelerated avulsion frequencies, lowered preservation potential, and formation of laterally extensive stratigraphic surfaces and sheet-like sandstone bodies.

Acknowledgements

The last few years have been an amazing cocktail of experiences and emotions; from fear of my first conference presentation to ultimate joy. From working night and day to enjoying fresh snow and deserted forests on weekdays, indulging in Norwegian *friluftsliv*. From boiling heat, aggressive cacti and rattlesnakes in the vast cowboy states of the USA during fieldwork, to the pristine landscapes of Svalbard, with its fjords full of belugas, amazingly exposed outcrops and cancelled fieldtrips because of polar bears. I would like to thank the following people that made a difference to this PhD journey.

Ivar Midtkandal, from the very start you encouraged me to be independent and showed faith in my capabilities and knowledge. I experienced this as overwhelming at times, but it made me grow as a scientist. You knew what I needed. Thank you for encouraging me to be decisive and bold, thank you for your patience, enthusiasm, knowledge and guidance. *Takk for turen!* John Holbrook - father of the Mesa Rica Sandstone -, your talent for recognizing the uniqueness of research, your expertise, and your valuable comments inspired me to improve my research in many ways. You summarized my PhD/life challenge in one of your emails: 'the perfect is the enemy of the good'. Without your hospitality, help with logistics, sense of humor, and thorough knowledge about any topic, my PhD journey would have been completely different. I think you should get a bull skull for your PhD students as well☺. Miquel Poyatos-Moré, your unwavering enthusiasm, your commitment and scientific talent are boundless. Your co-authorships truly made a difference. Less might be more, but Moré is certainly less; without your chainsaw my manuscripts would definitely have been longer. I hope we will be able to explore more rocks together in the future, with or without mountain lions. Snorre Olaussen, thank you for your help and support if needed. Wolfram Kürschner and Mufak Naoraz, thank you for giving me access to the laboratory and assisting me with processing and analysing palynology samples. The help and support from the administrative and IT staff at the department were essential, and I would like to give special thanks to the support of Anne Catherine and Annik during the final months of my PhD.

Fieldwork in the Quay and Harding counties of New Mexico (USA) showed me that the western legacy is still lasting. Thank you, Tom Mackechnie and your family and friends, Kristen, Richard, and Sally Trigg and your family, Stanley, Bill Humpfry, and everyone else who welcomed me on their properties. Your kindness, storytelling and hospitality made meeting *y'all* was not just part of the fieldwork; it has been a life experience. The logistic help from Gretchen Gurtler and Axel Hungerbuehler from the Mesalands Dinosaur Museum and Natural Sciences Laboratory in Tucumcari were irreplaceable. Thank you Heddi, Cody Myers and Blake Warwick for your field assistance. Your stories, guitar playing, sense of humor and your attitude to life had a big (positive!) influence on the fieldwork.

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Edwin, I lost count of all the meals you cooked for me, while I was working on my thesis. You always encouraged me to keep an eye on the PhD deliverables. I couldn’t have done this without you, and I am thrilled to take the journey of life together. Let’s take some dirt roads!

List of articles

Article I – Published in *Journal of Sedimentary Research*

Van Yperen, A.E.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1], Midtkandal, I.[1] (2019) Coalesced delta-front sheet-like sandstone bodies from highly avulsive distributary channels: the low-accommodation Mesa Rica Sandstone (Dakota Group, New Mexico, U.S.A.). Journal of Sedimentary Research, 89, 654–678. https://doi.org/10.2110/jsr.2019.27

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Article II – Published in *New Mexico Geological Society Guidebook, 70th Fall Field Conference*

Van Yperen, A.E.[1], Line, L.H.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1], Midtkandal, I.[1] (2019) Revised Stratigraphic Relationships of the Dakota Group in the Tucumcari Basin, San Miguel County, New Mexico, USA, in: Ramos, F., Zimmerer, M.J., Zeigler, K., Ulmer-Scholle, D. (Eds.), Geology of the Raton-Clayton Area. New Mexico Geological Society Guidebook, 70th Field Conference pp. 89–100

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Article III – Published in *The Depositional Record*

Van Yperen, A.E.[1], Poyatos-Moré, M.[1], Holbrook, J.M.[2], Midtkandal, I.[1] (2020) Internal mouth-bar variability and preservation of subordinate coastal processes in low-accommodation proximal deltaic settings (Cretaceous Dakota Group, New Mexico, USA). doi:10.1002/dep2.100

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Article IV – Accepted by *Basin Research*

Van Yperen, A.E.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1], Myers, C.[3], Midtkandal, I.[1] Sequence stratigraphy, backwater influences and depositional architecture in low-accommodation, fluvio-deltaic settings (Cretaceous Mesa Rica Sandstone, Dakota Group, USA)

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1. Introduction

1.1 Motivation

Full transect outcrop studies focusing on the internal complexity of low-gradient fluvio-deltaic systems are scarce. Consequently, their expression in the sedimentary record is still poorly understood. However, these systems are potentially good reservoirs for both hydrocarbon and groundwater exploration, and CO2 sequestration because of their tendency to create laterally extensive, amalgamated sandstone bodies. Studies targeting such systems can be important for academia, and industry as they improve our understanding of the interplay between numerous factors that control the eventual sediment distribution. The dataset in this doctoral thesis covers a ~400-km-long depositional profile that consist of fluvial and time-equivalent deltaic deposits. This provides a unique opportunity to conduct both regional-scale and higher resolution studies of selected areas. It also allows predictions to be made about distribution of isolated channel fills or laterally extensive sheets of amalgamated sandy channel-fill elements and shallow-marine delta front sandstones.

Between 500 to 600 million people live on or near delta plains, which are increasingly exposed to flood hazards arising from climate extremes and relative sea-level rise (e.g. Giosan et al., 2014; Higgins, 2016). The inception of most modern deltas worldwide began ~8.5–6.5 kyr ago, when the rate of global sea-level rise significantly decelerated (Stanley and Warne, 1994) after ~12 kyr with global sea-level rise related to the deglaciation after the last glacial sea-level lowstand (Peltier and Fairbanks, 2006). This deceleration led to a tipping point in which the balance between sediment supply, erosion, and eustatic sea-level rise shifted to favour coastal progradation (Stanley and Warne, 1994). After thousands years of progradation, many major river deltas are currently sinking relative to local sea level due to a combination of reduced sedimentation, absolute sea-level rise and subsidence processes related to, amongst others, natural compaction, tectonic subsidence, and extraction of groundwater and hydrocarbons (e.g. Higgins, 2016). The shift from modern delta resilience to collapse will likely occur in the next 50 years when sea level rise reaches between 5 and 10 mm per year (Turner et al., 2017).

Research on modern deltas, including extensive monitoring of discharge, sedimentation and erosion, and accurate elevation models, provide essential data for impact assessments of relative sea-level rise. Therefore, studies on modern deltas are crucial and the learnings cannot be replaced by studying only ancient deltaic systems. However, ancient deltaic systems can provide helpful insights as well. Their applicability is best summarized and simplified by the saying ‘the past is the key to the future’. The documentation of landward- and basinward shifts in facies belts related to changes in relative sea-level can improve our understanding of the impact of small sea-level variations on coastline migration and eventual sediment distribution. This can help assess potential impacts of relative sea-level rise on low-gradient delta plains.

1.2 Aims and objectives

This doctoral thesis aims to improve our general understanding of fluvio-deltaic systems deposited in low-accommodation settings. Therefore, a long distance (~400 km) sequence stratigraphic framework has been developed that highlights down-dip changes in depositional geometries, facies distribution and fluvial architecture in a low-accommodation fluvio-deltaic depositional system (**Article IV**). This was achieved by studying the fluvial-to-marine transitional zone (**Article II, III)** and the fully deltaic (**Article I)** development of such a depositional system in detail. Subsequently, the results and insights were synthesized with an extensive dataset previously published on the fluvial realm of the same system, which facilitated an additional study on regional-scale correlation and depositional architecture (Fig. 1; **Article IV**).

The objective of **Article I** was to examine the fully deltaic development of the Mesa Rica Sandstone in the centre of the Tucumcari Basin. The study aimed to develop a depositional model in order to explain the striking sandy nature of the coalesced mouth-bar deposits of the river-dominated Mesa Rica Sandstone delta.

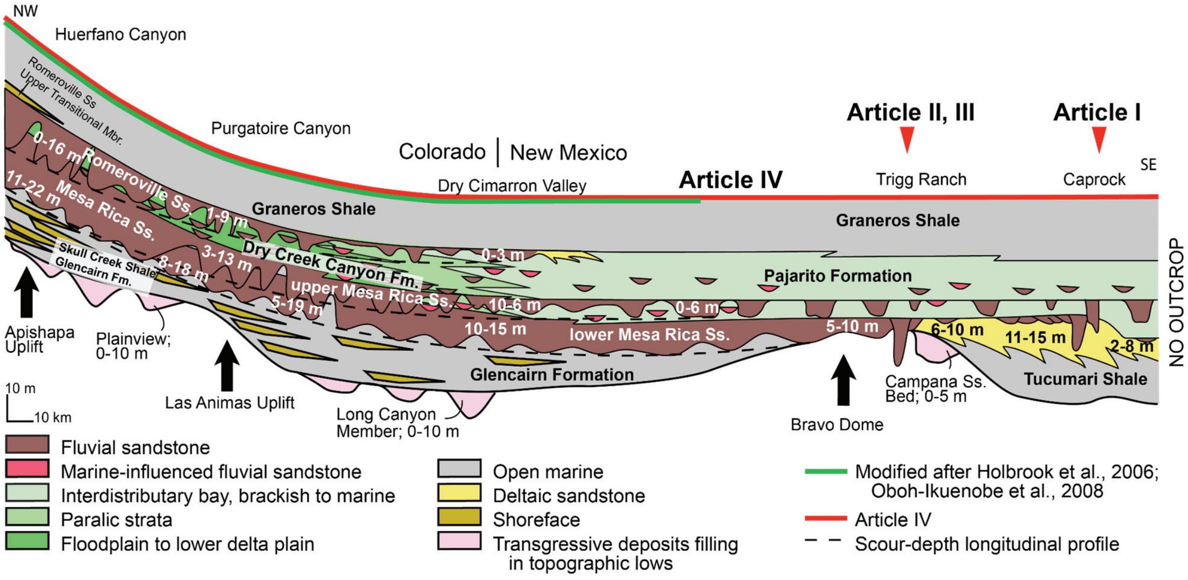

***Figure 1** – Study areas in this PhD thesis, projected onto a longitudinal cross section from southeastern Colorado down depositional dip to east-central New Mexico. The section includes Dakota Group strata and illustrates thickness trends and facies associations. The original slope of longitudinal profiles cannot be measured directly and is shown schematically with ~2.5x vertical exaggeration (based on calculated slopes in Article IV). Thickness trends of the Tucumcari Shale and Glencairn Formation are based on field observations and published isopachs (Holbrook et al., 2006). Locations (e.g. Dry Cimarron Valley, Trigg Ranch) shown in Figure 2.*

Early studies (e.g. Holbrook et al., 1987; Holbrook and Wright Dunbar, 1992) established stratigraphic relationships of Jurassic to Lower Cretaceous strata at the northwestern rim of the Tucumcari Basin. Recent insights into regional stratigraphy identified an additional transgressive surface within the Dakota Group[1] (Scott et al., 2004). This provided improved understanding of the large-scale transgressive-regressive cycles in the Dakota Group. The most recent stratigraphic framework was applied for **Article II,** in which stratigraphic relationships of the Dakota Group at the rim of the Tucumcari Basin were revised.

The third objective was to study the impact of low-accommodation on the preservation potential of interflood and flood beds and to distinguish internal mouth-bar variability in shallow-marine settings. To do so, the area with the least accommodation along the study profile was selected – the rim of the Tucumcari Basin – where onset of deltaic deposition took place (**Article III**).

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[1] The Dakota Group is further subdivided into the Mesa Rica Sandstone, Pajarito Formation and Romeroville Sandstone in southeastern Colorado, Oklahoma and northwestern New Mexico. See 'Chapter 2. Geological Context' for more information.

2. Geological context

2.1 Basinal setting

During the late Mesozoic, the Farallon Plate subducted beneath the North American Plate during the Cordilleran orogeny causing back-arc compression (DeCelles, 2004). Eastward thrusting and folding of the associated Sevier fold-and-thrust belt resulted in crustal shortening and static tectonic subsidence from the Late Jurassic to Early Tertiary time, and formed the Western Interior Foreland Basin (WIFB) (Pang and Nummedal, 1995; Liu and Nummedal, 2004). During the Cretaceous, North America was progressively flooded by the Tethyan and Boreal seas from the south and north, respectively, forming the Western Interior Seaway (Kauffman and Caldwell, 1993; Blakey, 2014). The location of the study area relates to the gently inclined ramp on the tectonically stable passive eastern margin of the WIFB (Kauffman and Caldwell, 1993). The Dakota Group is among the eastward prograding sedimentary systems of the US Western Interior that were sourced from the Sevier fold-and-thrust belt (Fig. 2A) (e.g. MacKenzie and Poole, 1962; Pecha et al., 2018, **Article II**). The Dakota Group also received minor sediment volumes from other smaller topographic highs (Kisucky, 1987; Holbrook and Wright Dunbar, 1992) that were reactivated during the Early Cretaceous (e.g. Holbrook and White, 1998). The Tucumcari Basin forms the depocenter for the delta of the fluvio-deltaic Mesa Rica Sandstone (Fig. 2A), which is the oldest formation within the Dakota Group in Colorado and New Mexico (e.g. Holbrook and Wright Dunbar, 1992). The Tucumcari Basin formed during the Late Carboniferous and Early Permian as a tectonic element of the Ancestral Rocky Mountains (Broadhead, 2004). At times of Dakota Group deposition, the study area was located at ~35° N latitude, with a prevailing warm and humid climate (Chumakov et al., 1995).

2.2 Stratigraphy and sequence stratigraphic framework

An overall NNW to SSE-oriented depositional profile characterizes the Cenomanian Dakota Group (Scott et al., 2018) in southeastern Colorado and northeastern New Mexico. The group is underlain by the open marine Albian Glencairn Formation in Colorado and equivalent Tucumcari Shale in northeast New Mexico, and overlain by the Cenomanian Graneros Shale (e.g. Holbrook et al., 2006). These marine intervals represent the transgressive phase of third-order sequence stratigraphic cycles (Oboh-Ikuenobe et al., 2008). The Dakota Group is further subdivided into the Mesa Rica, Pajarito (Dry Creek Canyon member in south-central Colorado and northeastern New Mexico), and Romeroville formations (Fig. 2B). These represent phases of predominantly fluvial and paralic deposition. In the Tucumcari Basin, the open Tucumcari Shale separates the underlying fluvial Jurassic Morrison Formation from the overlying fluvio-deltaic Cretaceous Mesa Rica Sandstone (Fig. 2B) (e.g. Holbrook and Wright Dunbar 1992; Scott et al., 2004; **Article I-IV**). The Tucumcari Shale is locally underlain by estuarine deposits of the informally defined Cretaceous Campana Sandstone Bed (hereafter referred to as “Campana”) (Holbrook et al., 1987; Holbrook and Wright

Dunbar, 1992; **Article II-III**). This represents the sandy infill of local topographic lows, as the Late Jurassic landscape was progressively inundated during relative sea-level rise (Holbrook et al., 1987).

Regional sequence boundary SB3.1 (Fig. 2B) forms the base of the Mesa Rica and relates to a late Albian – early Cenomanian forced-regression, which caused widespread erosion in southeast Colorado and northeast New Mexico (Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Scott and Holbrook, 2001; Scott et al., 2004; Oboh-Ikuenobe et al., 2008). In east-central New Mexico, the Mesa Rica can be subdivided into lower, middle, and upper units (Scott et al., 2004; **Article II**). The lower Mesa Rica shows a down-dip transition from fluvial to deltaic deposits at the northwestern rim of the Tucumcari Basin, recording the most proximal shallow-marine deposits within the system (Holbrook and Wright Dunbar, 1992; **Article II, III**). Regional sequence boundary SB3.2 forms the base of the upper Mesa Rica and relates to another forced regression after a transgressive event that caused deposition of the paralic middle Mesa Rica (Oboh-Ikuenobe et al., 2008). These two fourth-order transgressive-regressive (T-R) cycles are interpreted to record higher-frequency relative sea-level fluctuations in the Western Interior Seaway within the overall third-order Mesa Rica composite cycle (e.g. Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Scott et al., 2004; Oboh-Ikuenobe et al., 2008). The lower and upper Mesa Rica merge into a single sandstone up-dip (Fig. 2B), where no distinctions between the SB3.1 and SB3.2 are recognizable (Holbrook, 2001).The lower and upper Mesa Rica envelope the middle Mesa Rica, which consists of paralic strata and represents a brief transgressive event during which facies belts shifted ~250 km landwards (Scott et al., 2004; Oboh-Ikuenobe et al., 2008; **Article IV**). The down-dip extent of sequence boundaries received minimal attention; the SB3.1 lower Mesa Rica basal surface is not directly mapped but suggested to extend down dip below the deltaic deposits of the Mesa Rica (Holbrook and Wright Dunbar, 1992). Fluvial deposits of the upper Mesa Rica extent into central-east New Mexico (**Article I, II**), updating previous interpretations in which the upper Mesa Rica was thought to transition from fluvial to marine in the south of the Oklahoma Panhandle (Holbrook et al., 2006; **Article II**).

The Pajarito Formation overlies the Mesa Rica and consists of lower delta plain to interdistributary bay deposits (e.g. Holbrook and Wright Dunbar 1992; Scott et al., 2004; **Article I–IV**) and records flooding from the south by brackish to marine shallow waters (TS3.2; Fig. 2B) during which an ephemeral link between the Boreal and Thethyan seas was established (Oboh-Ikuenobe et al., 2008). Regional sequence boundary SB4 forms the base for the fluvial Romeroville Formation which terminates in northernmost New Mexico (Holbrook et al., 2006). Here and in east-central New Mexico, the Pajarito Formation interfingers with the comformable open marine Graneros Shale above, which represents the beginning of a prolonged full connection of the Boreal and Tehtyan seas in the Western Interior Basin (e.g. Blakey, 2014). These depositional cycles correlate to depositional cycles defined in the Texas Gulf Coast (Scott et al., 2000; 2004) and to the Chihuahua Trough in south New Mexico (Scott et al., 2001) based on biostratigraphic data. The Dakota Group correlates to the base of Muddy Sandstone in Wyoming and Shell Creek Formation in Montana. The Muddy Sandstone and Shell Creek Formations are overlain by the Mowry Shale, of which the top correlates with the base of the Graneros Shale in Colorado (Scott et al., 2018).

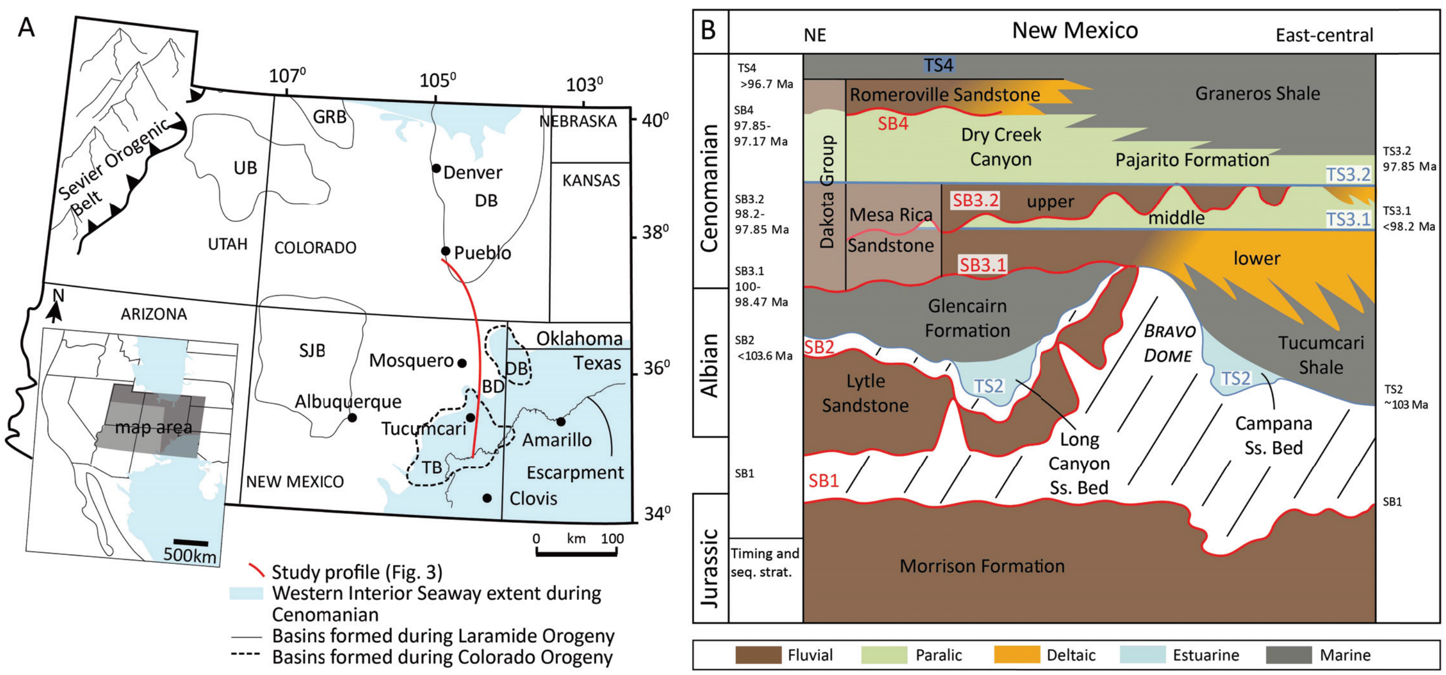


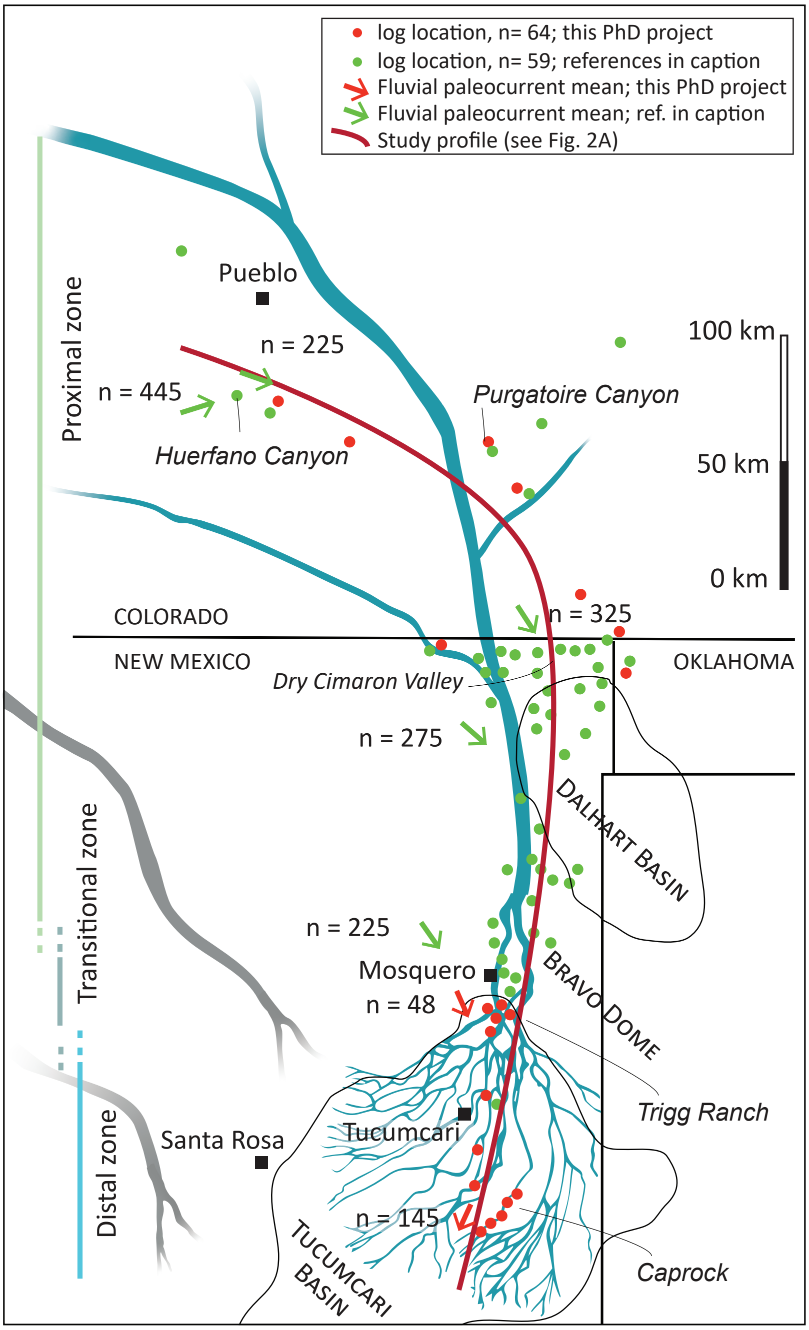
***Figure 2** (modified after Article IV) - **A)** Regional paleogeography of the Western Interior during the Early – Late Cretaceous (Albian-Cenomanian) showing the approximate extent of the Western Interior Seaway (light blue, from Blakey, 2014) and main basins formed during Laramide and Colorado orogenies (modified after Article I) . GRB = Green River Basin; UB= Uinta Basin; DB (Colorado) = Denver Basin; SJB = San Juan Basin, TB = Tucumcari Basin; DB (New Mexico) = Dalhart Basin; BD = Bravo Dome; WIS = Western Interior Seaway; **B)** Chronostratigraphy of the Jurassic to Cenomanian successions in Northeastern and East-central New Mexico. References used for compilation; Waage, (1955); Holbrook et al. (2006); Oboh-Ikuenobe et al. (2008); Article I, II. Albian-Cenomanian boundary from Scott et al. (2018). SB = Sequence boundary, TS = Transgressive Surface.*

3. Data and methods

This PhD project studies the fluvio-deltaic Mesa Rica Sandstone within Dakota Group strata with a main focus on the fluvial-marine transition zone to deltaic deposition in the centre of the Tucumcari Basin. Data collection for this study occurred during four field campaigns, of which one targeted the proximal fluvial part of the Mesa Rica depositional system and the others the fluvial-marine-transition zone to downstream reaches. 64 sections (Fig. 3) were measured using contemporaneous field techniques to document lithology, texture, sedimentary structures, and bioturbation assemblage and intensity. The latter was recorded using the 1–6 bioturbation index (BI) scheme of Taylor and Goldring (1993). A total of ~1785 m was logged across the Jurassic Morrison to Cretaceous Dakota Group stratigraphic interval. Selective samples and X-ray diffraction (XRD) optical microscopy results were used for a preliminary petrographic investigation. Backwater length and paleoslopes were calculated following methods in Holbrook and Wanas (2014) and Trampush et al. (2014). A separate field campaign was conducted by the Texas Christian University in order to select representative trunk channel fills with additional UAV imagery, and to collect grain size samples.

Standard facies and architectural analysis of sedimentary data permits the interpretation of depositional environments. Unmanned Aerial Vehicle (UAV) imagery (shot with a DJI Phantom 4 Pro ®)**,** photomontages, and field sketches are used to map sedimentary body geometries, lateral distributions, architectural elements and extension of key stratigraphic surfaces. Microsoft’s Image Composite Editor was used to produce high-resolution photomosaics. Merging all this data provide the basis for the construction of depositional-dip and strike-oriented panels and the establishment of a regional sequence stratigraphic framework.

Figure 3 *(Next page: modified after Article IV) - Map of study area with locations of previous (green) and newly (orange) collected data, n indicates the total number of logs per dataset. This differs from the number of logs displayed, as scale does not allow for all details. Green datasets includes logs published in Oboh-Ikuenobe et al. (2008) and Scott et al. (2004) and measured sections and ‘locations where facies were identified and described but not measured’ in Holbrook and Wright Dunbar (1992), Holbrook (1996, 2001) and Holbrook et al. (2006). Paleocurrents displayed in green are from Holbrook et al. (2006). Main structural elements are indicated (from Suleiman and Keller, 1985; Broadhead, 2004). Schematic representation of the river pathway is based on previous work (e.g. Holbrook 1992, 1996, 2001; Article I, IV) and reflects the depositional system (lower Mesa Rica) during regressive phase. The indicated zones (proximal, transitional, distal) are based on Article IV. The river patterns in grey are outside the scope of this study.*


● log location, n= 64; this PhD project
● log location, n= 59; references in caption
Fluvial paleocurrent mean; this PhD project
Fluvial paleocurrent mean; ref. in caption
Study profile (see Fig. 2A)
Proximal zone
Transitional zone
Distal zone
Pueblo
n = 225
n = 445
Huerfano Canyon
Purgatoire Canyon
100 km
50 km
0 km
COLORADO
NEW MEXICO
OKLAHOMA
n = 325
Dry Cimaron Valley
n = 275
DALHART BASIN
n = 225
Mosquero
n = 48
BRAVO DOME
Trigg Ranch
Santa Rosa
Tucumcari
n = 145
TUCUMCARI BASIN
Caprock

4. Article summaries, authorship and contribution

This chapter provides a summary of the first-authored Articles. The use of references is kept to a minimum in order to improve readability. Full reference lists can be found in the respective articles in chapter 9.

4.1 Article I: Coalesced delta-front sheet-like sandstone bodies from highly avulsive distributary channels: the low-accommodation Mesa Rica Sandstone (Dakota Group, New Mexico, U.S.A.)

Principle author	Anna E. van Yperen
Co-authors	John M. Holbrook, Miquel Poyatos-Moré, Ivar Midtkandal
Data collection	Van Yperen, Holbrook, Poyatos-Moré, Midtkandal
Data processing and interpretation	Van Yperen, Poyatos-Moré, Midtkandal
Text	Van Yperen, Holbrook, Poyatos-Moré,
Figures	Van Yperen
Concept	Van Yperen, Holbrook
Editing	Van Yperen, Holbrook, Poyatos-Moré, Midtkandal
Approximate contribution	Van Yperen: 70%, Holbrook 10%, Poyatos-Moré 10%, Midtkandal 10%
Status of the manuscript	Published in *Journal of Sedimentary Research*, July 2019, v.89, 654 – 678. https://doi.org/10.2110/jsr.2019.27

The striking sandy nature of coalesced mouth-bar deposits of the river-dominated Mesa Rica Sandstone delta contradicts the general concept of river-dominated deltaic sandstone deposits being interbedded with mudstone resulting from deposition during periods of low discharge. In addition, delta-front sheet geometries are classically assigned to wave-dominated deltas. This article proposes a model to form sheet-like delta front sandstone geometries without the dominance of wave redistribution processes, in which the low-accommodation setting plays a crucial role. The article also emphasizes laterally extensive erosional composite surfaces that have an autogenic origin and should not be mistaken for regional sequence-bounding scours.

The model is based on results from a methodical sedimentological analysis of the fluvio-deltaic Cenomanian Mesa Rica Sandstone, which is exhumed along a NNW-SSE depositional-dip oriented profile from Colorado to east-central New Mexico. The deltaic part of this depositional system was deposited in the Tucumcari Basin. This manuscript targets the fully deltaic development of the Mesa Rica depositional system in the centre of the basin. In the Tucumcari Basin, the Tucumcari Shale embodies the prodelta to open marine facies association and underlies the Mesa Rica Sandstone, which in turn is overlain by the Pajarito Formation. A >20-km-long escarpment, subparallel to the main delta progradation direction, allows for a detailed analysis of facies distribution, depositional architecture, and the spatial extent of stratigraphic surfaces to be conducted. Thirty-one sections were measured.

Eight facies associations were recognized and reveal an arrangement of laterally variable shallowing-upward facies successions with three depositional cycles preserved. Regional key stratal surfaces, incised-valley fills and the presence of lagoonal deposits at a sub-regional scale are recognized based on vertical and lateral relationships between facies associations and architectural geometries (Fig. 4). Delta front strata occur in two subsets that represent deposition near the active distributary river mouth with high fresh-water induced stresses or unstressed depositional conditions and a minimization of water turbidity. Two types of erosional composite surface are distinguished in the study area; i) *the Basal Distributary Composite Scour* (BDCS) bounds sheets of amalgamated distributary-channel deposits, and ii) the *Regional Composite Scour* (RCS) bounds multistory infill of incised valleys (Fig. 4C). The BDCS resembles a sharp, within-trend, facies-bounding surface that separates distributive fluvial strata and underlying proximal deltaic strata along a laterally extensive scour (Fig. 5). This surface is confined to discrete down-stepped shoreline wedges, and is thus not a regional sequence-bounding scour. The surface contrasts with the regional composite scours (RCSs) that underlie incised valleys, record shoreface incision during forced regression, extend beyond single down-stepped wedges, and are part of the regional sequence boundary.

Mesa Rica deltaic deposition was initially dominated by river influence, followed shortly after by minor wave reworking. Wave-reworking is inferred from high bioturbation indices, given that wave agitation optimizes infauna living conditions. The common configuration into tabular geometries of these deposits is interpret to result from lateral sand redistribution. The low-accommodation setting combined with high supply of sandy sediment accelerate mouth-bar depositional cycles. Bedload accumulation at a river mouth can exceed the redistribution capacity of longshore transport and causes local loss of wave energy by dampening the wave impact. This leads to increased sediment concentration in the river mouth, which eventually increases deposition in the channel and leads to bifurcation. Additionally, mouth-bar progradation stops when the water depth over the river mouth bar is equal to or less than 40% of the inlet depth. The river flow diverts around the bar, and a new bifurcation is formed. The low-accommodation setting accelerates this mechanism as well because less sediment is needed to reach the critical bar thickness for bifurcation.

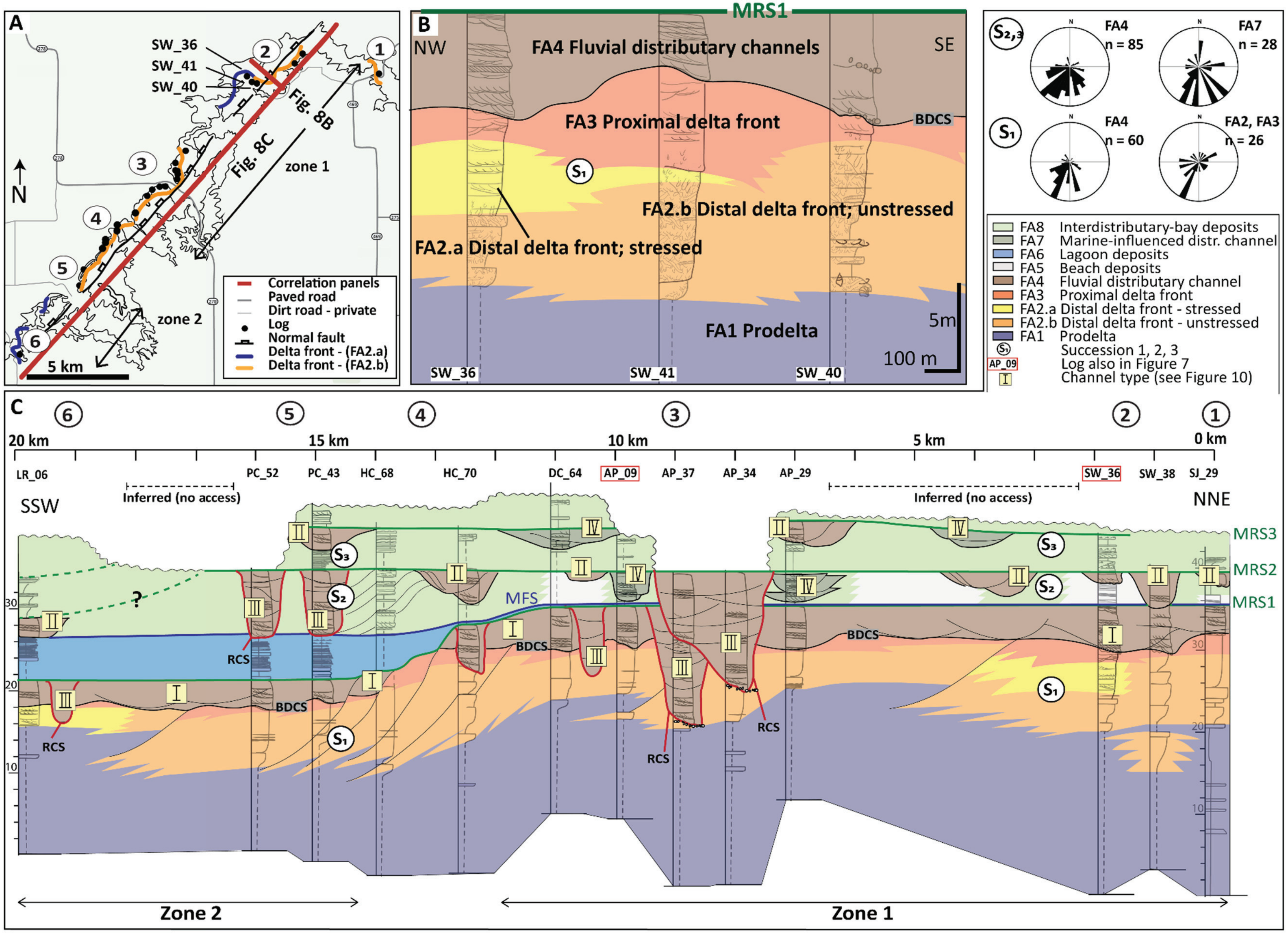
This article has implications beyond the Mesa Rica Sandstone, contributing an improved understanding of deltaic deposition and resulting geometries, as well as key stratigraphic surfaces in low-accommodation basins:

1) The low-accommodation setting acts as an amplifier for the interrelated processes of frequent avulsion of distributaries and recurring mouth-bar development cycles at short time scales accelerates mouth bar depositional cycles. This results in Mesa Rica deltaic sandstone body

geometries that are similar to those described for classic wave-dominated environments. This can be particularly relevant for subsurface studies, because it cautions against interpretations of amalgamated wave-dominated shoreline systems based solely on sandstone geometries, without taking into account the possible limited preservation potential and postdepositional modification of primary deltaic characteristics.

2) The *basal distributary composite scours* are laterally extensive and formed by the autogenic process of distributary-channel avulsion and deposition on a delta plain with limited accommodation. This demonstrates that such laterally extensive erosional surfaces can have an origin that is disconnected from regional sequence-bounding surfaces. This is an important distinction for the interpretation and correlation of key stratigraphic surfaces in low-accommodation settings.

Figure 4 *(Next page: from Article I) -* ***A)*** *Map of study area with distribution of stressed (FA2.a) and unstressed (FA2.b) delta front depositional conditions;* ***B)*** *Strike oriented correlation panel of succession S1 showing intraparasequence variation of stressed delta front environments (FA2.a) vs unstressed delta front environments (FA2.b);* ***C)*** *Correlation panel from NNE (paleolandward) to SSW (paleoseaward) with ~1 km spacing between available log data. Indication of interpreted facies associations and key stratigraphic surfaces. Note the thickness changes between Zone 1 and Zone 2 and the rare absence of fluvial distributary channel deposits (FA4) in the S1 succession. The stratigraphic levels with continuous (S1) and laterally discontinuous (S2) distributary channel deposits (FA4) are used as a datum. Where transgressive deposits are not preserved, the MRS coincides with the MFS. Southward inclined clinoform geometries are observed in location 3, but are otherwise inferred from delta front thickness changes or downstepping. MRS = Maximum Regressive Surface, MFS = Maximum Flooding Surface, RCS = Regional Composite Scour, BDCS = Basal Distributary Composite Scour.*


A
N
SW_36
SW_41
SW_40
1
2
3
4
5
6
Fig. 8B
Fig. 8C
zone 1
zone 2
5 km
Correlation panels
Paved road
Dirt road - private
Log
Normal fault
Delta front - (FA2.a)
Delta front - (FA2.b)
B
MRS1
NW
SE
FA4 Fluvial distributary channels
FA3 Proximal delta front
BDCS
S1
FA2.b Distal delta front; unstressed
FA2.a Distal delta front; stressed
FA1 Prodelta
5m
100 m
SW_36
SW_41
SW_40
S2,3
FA4 n = 85
FA7 n = 28
S1
FA4 n = 60
FA2, FA3 n = 26
FA8 Interdistributary-bay deposits
FA7 Marine-influenced distr. channel
FA6 Lagoon deposits
FA5 Beach deposits
FA4 Fluvial distributary channel
FA3 Proximal delta front
FA2.a Distal delta front - stressed
FA2.b Distal delta front - unstressed
FA1 Prodelta
Succession 1, 2, 3
AP_09 Log also in Figure 7
I Channel type (see Figure 10)
C
20 km
15 km
10 km
5 km
0 km
LR_06
PC_52
PC_43
HC_68
HC_70
DC_64
AP_09
AP_37
AP_34
AP_29
SW_36
SW_38
SJ_29
Inferred (no access)
SSW
NNE
MRS3
MRS2
MRS1
MFS
BDCS
RCS
S1
S2
S3
I
II
III
IV
?
10
20
30
40
Zone 2
Zone 1

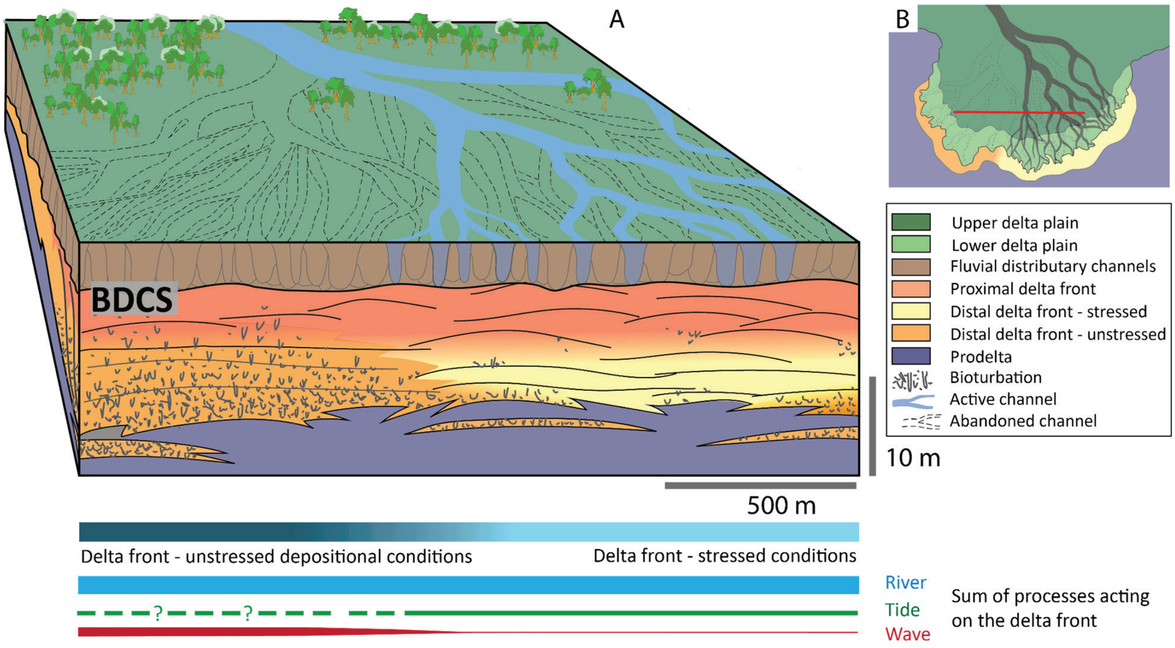


Figure 5 *(from Article I) -* ***A)*** *Conceptual model for coalesced delta front sheet sandstone development from highly avulsive distributary channels. See B for profile location. Laterally amalgamated sand-filled distributary channels overlie delta front deposits, which are characterized by their consistent sandy nature. The straightened low-gradient channels cause frictional processes to increase, hence inducing channel-fill deposition and subsequent bifurcation and/or avulsion. Additionally, the low accommodation acts as an amplifier for the interrelated processes of highly avulsive distributaries and reoccurring mouth bar development cycles at short time scales. Shortly after deposition, minor wave-reworking facilitated lateral sand redistribution and favored faunal living conditions resulting in highly bioturbated sandstone beds. The sum of processes active on the delta front varies as a result of the competition between fluvial, tidal and wave processes during deposition;* ***B)*** *Approximate profile location. BDCS = Basal distributary composite scour.*

4.2 Article II: Revised stratigraphic relationships of the Dakota Group in the Tucumcari Basin, San Miguel County, New Mexico, USA

Principle author	Anna E. van Yperen
Co-authors	Lina H. Line, John M. Holbrook, Miquel Poyatos-Moré, Ivar Midtkandal
Data collection	Van Yperen, Line
Data processing and interpretation	Van Yperen, Line
Text	Van Yperen, Line
Figures	Van Yperen, Line
Concept	Van Yperen, Holbrook
Editing	Van Yperen, Line, Holbrook, Poyatos-Moré, Midtkandal
Approximate contribution	Van Yperen: 80%, Line: 15%, Holbrook, Poyatos-Moré, Midtkandal: 5%
Status of the manuscript	Published in *Geology of the Raton-Clayton Area. New Mexico Geological Society Guidebook*, *70th Fall Field Conference,* October 2019, pp. 89–100

This article documents revised stratigraphic relationships of the Dakota Group at the rim of the Tucumcari Basin, New Mexico, USA. Early studies established stratigraphic relationships of Jurassic to Lower Cretaceous strata (e.g. Holbrook et al., 1987; Holbrook and Wright Dunbar, 1992), but more recent work in the region identified an additional transgressive surface within the Dakota Group (Scott et al., 2004). This provided improved understanding of the large-scale transgressive-regressive cycles within the Dakota Group and gave reason to revisit the area in order to apply the most recent stratigraphic framework. Additionally, the article documents petrographic results which suggest potential recycling of underlying Jurassic strata and reveal extreme mineralogical maturity.

A depositional-dip oriented correlation panel was established based on new and previously published data (Fig. 6). The new data set consists of six sedimentary logs and aerial imagery, which allowed for the identification and interpretation of facies associations, sedimentary body geometry and the extent of key surfaces. These were then matched with log data and facies descriptions from previous work. The resulting correlation panel shows that preservation of surfaces varies significantly throughout the study area (Fig. 6). This cautions against (sequence) stratigraphic interpretations based only on few data points.

The Dakota Group is characterized by two main sandstone packages; a continuous sandstone sheet (S1) consisting predominantly of delta-front deposits, and a discontinuous sheet (S2) consisting of fluvial strata. These have been interpreted as the lower and upper Mesa Rica Sandstone, respectively.

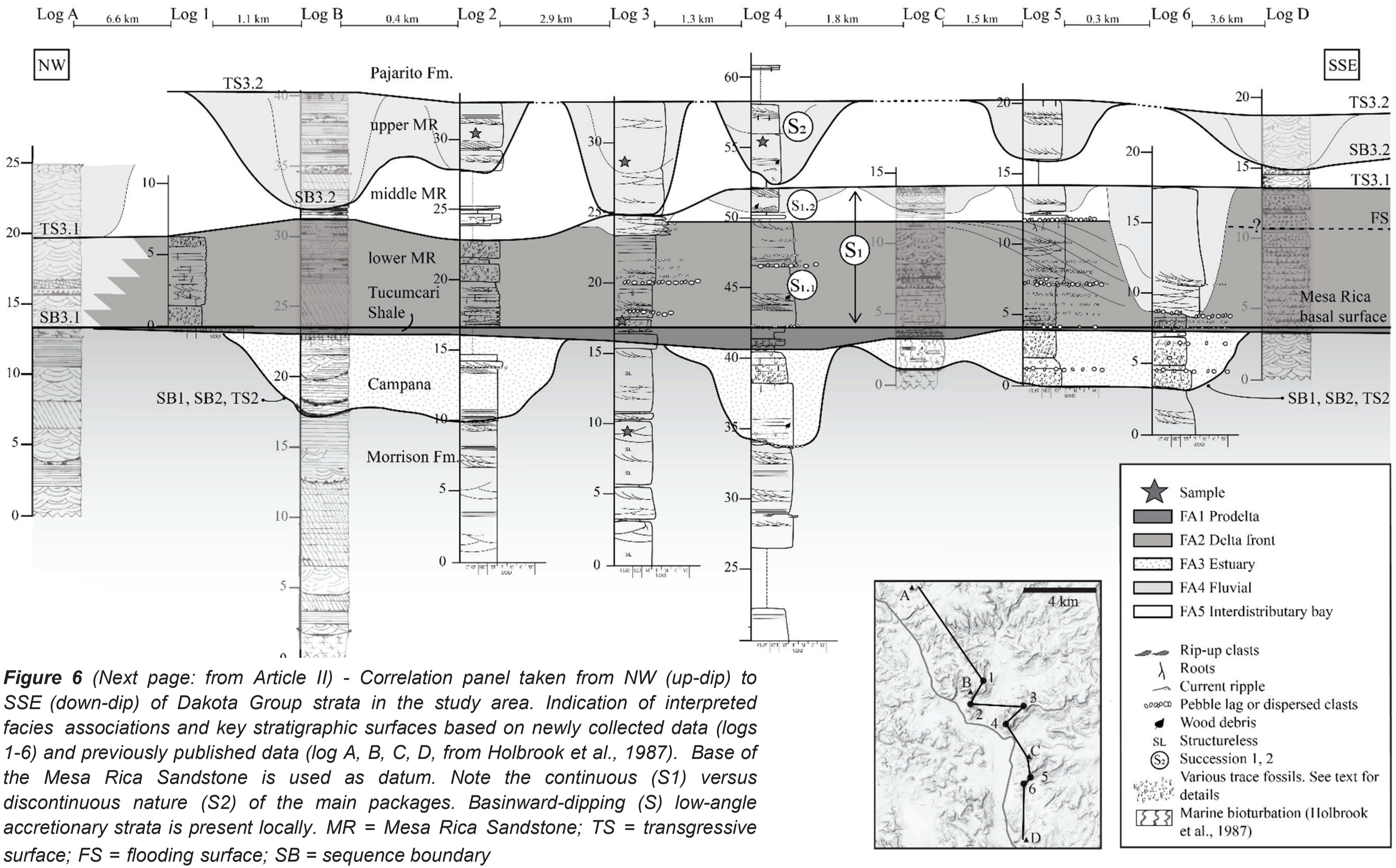


Figure 6 *(Next page: from Article II) - Correlation panel taken from NW (up-dip) to SSE (down-dip) of Dakota Group strata in the study area. Indication of interpreted facies associations and key stratigraphic surfaces based on newly collected data (logs 1-6) and previously published data (log A, B, C, D, from Holbrook et al., 1987). Base of the Mesa Rica Sandstone is used as datum. Note the continuous (S1) versus discontinuous nature (S2) of the main packages. Basinward-dipping (S) low-angle accretionary strata is present locally. MR = Mesa Rica Sandstone; TS = transgressive surface; FS = flooding surface; SB = sequence boundary*

The new understanding of the local stratigraphy results in the identification of the middle and upper Mesa Rica Sandstone in the study area, and a 4–6 m thicker total Mesa Rica Sandstone than shown in previous models. In previous interpretations, the Mesa Rica Sandstone was not subdivided and locally interpreted as the Pajarito Formation (Fig. 7).

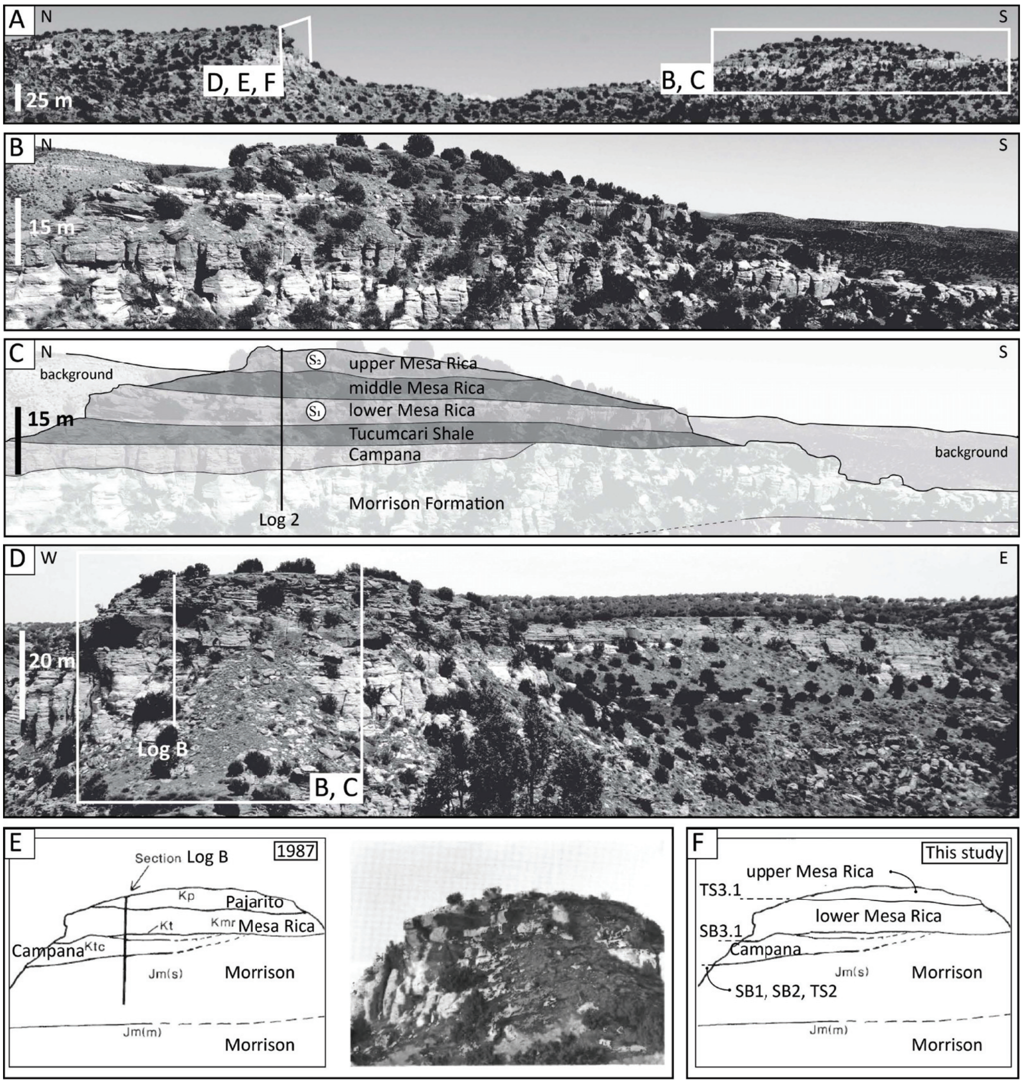


***Figure 7** (modified from Article II) Pictures and line drawings illustrating the revised interpretation of Cretaceous stratigraphy - **A)** Photopanel providing overview and location of pictures B and D; **B)** Photopanel showing Jurassic and Lower Cretaceous strata; **C)** Interpretation of picture B. Note the vertical arrangement of the lower, middle, and upper Mesa Rica Sandstone; **D)** Photopanel showing Jurassic and Lower Cretaceous strata; **E)** Interpretation of picture A, modified from Holbrook et al. (1987). The depicted section corresponds to log B in this study; **F)** Photopanels showing the revised interpretation of Cretaceous stratigraphy. The Mesa Rica Sandstone is subdivided into lower and upper. TS = transgressive surface; SB = sequence boundary. Sequence stratigraphic surfaces correspond to the regional stratigraphic framework (Scott et al., 2004; Oboh-Ikuenobe et al., 2008).*

4.3 Article III: Internal mouth-bar variability and preservation of subordinate coastal processes in low-accommodation proximal deltaic settings (Cretaceous Dakota Group, New Mexico, USA)

Principle author	Anna E. van Yperen
Co-authors	Miquel Poyatos-Moré, John M. Holbrook, Ivar Midtkandal
Data collection	Van Yperen
Data processing and interpretation	Van Yperen
Text	Van Yperen, Poyatos-Moré
Figures	Van Yperen
Concept	Van Yperen, Poyatos-Moré
Editing	Van Yperen, Poyatos-Moré, Holbrook, Midtkandal
Approximate contribution	Van Yperen: 80%, Poyatos-Moré: 10%, Holbrook, Midtkandal: 10%
Status of the manuscript	Published in *The Depositional Record*, January 2020, doi:10.1002/dep2.100

This article targets the sand-prone deltaic package of the Mesa Rica Sandstone at the rim of the Tucumcari Basin, New Mexico. The tabular sandstone beds reveal along-strike differences in sedimentary structures, bed thicknesses, occurrence of interflood beds and bioturbation indexes. In deep-water sedimentology it is common to differentiate submarine-fan lobe deposits internally and distinguish lobe axis, off-axis, fringe and distal fringe sub-environments but a similar subdivision in ancient mouth-bar deposits is uncommon. This article demonstrates the possibility to distinguish such subenvironments within individual shallow-marine mouth bars and discusses the preservation potential of finer-grained interflood beds (i.e. facies deposited during times of low energy between river flood periods) in a low-accommodation setting.

The study focuses on the proximal deltaic expression of the lower Mesa Rica Sandstone depositional system, with 22 sedimentary logs spatially correlated within a ~25-km^2 study area. The log data, UAV (unmanned aerial vehicle) imagery**,** photomontages, and field sketches form the basis of a fence correlation diagram that correlates constructed depositional-dip (~6.5 km) and strike-oriented (~4 km) panels. Analysis of facies distributions, depositional architecture and spatial extent of stratigraphic surfaces reveals a 6–10-m-thick, sharp-based and sand-prone deltaic package, comprising several laterally-extensive (>1.4 km width) mouth bars.

Four different mouth-bar components are recognized, which form a continuum of deposits that are interpreted as different expressions of deposition close to a river outlet. These sub-environments are referred to as ‘axis’, ‘off-axis’, ‘fringe’ and ‘distal fringe’, and represent along-strike changes of processes and resulting deposits within a single mouth bar. They reveal a predictable trend in sedimentary characteristics when moving away from the aixs to the outer parts of the mouth bar (Fig. 8). From mouth-bar axis to fringe, the occurrence of upper flow regime bedforms and average bed thickness decreases, whilst the record of interflood beds and bioturbation index progressively increases (Fig. 8).

In the study area, the record of interflood beds is subordinate to the record of river flood beds. We reason that the low-accommodation setting enforces a negative feedback on the preservation potential of interflood deposits in two ways. First, the low accommodation increases reworking-processes at bed scale and lowers significantly the preservation potential in the axial and off-axis components. The recording of interflood deposits is thus restricted to the mouth-bar fringe and distal fringe components (Fig. 8) because these zones can experience temporary interruptions of the otherwise high-energy depositional setting. Second, the low-accommodation setting increases the potential for fringe-reworking because of accelerated mouth-bar depositional cycles (Fig. 9). This in turn lowers the preservation potential of interflood deposits, as these are predominantly recorded in the fringe and distal fringe mouth-bar components. Because subordinate coastal processes are predominantly recorded in interflood beds, their low preservation potential may mask the true combination of sedimentary processes that were active at time of deposition.

This article has implications beyond the Mesa Rica Sandstone in the following ways:

- Comparison with previously published studies on delta front depositional environments suggests that subdivision of mouth bars and mouth-bar complexes into different components is applicable in other studies, regardless of depositional setting of the studied deltaic succession and/or dominant coastal processes. This improves comparisons between systems and helps predicting facies changes and sand distribution.
- Care should be taken when evaluating the duration and relative dominance of process regime (i.e., river, tides, waves) in low-accommodation deltaic settings (Fig. 9D). The rather low preservation potential of interflood beds might cause underestimation of the true influence of subordinate coastal processes, with important implications towards prediction of facies changes and sediment distribution in similar settings.

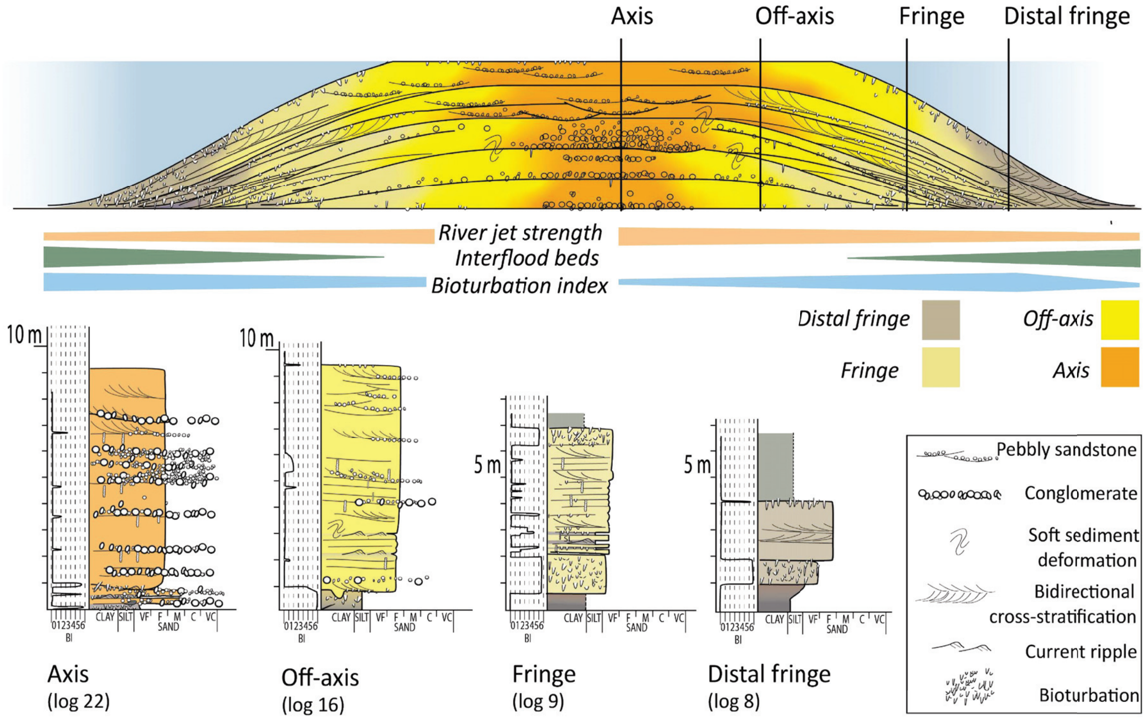
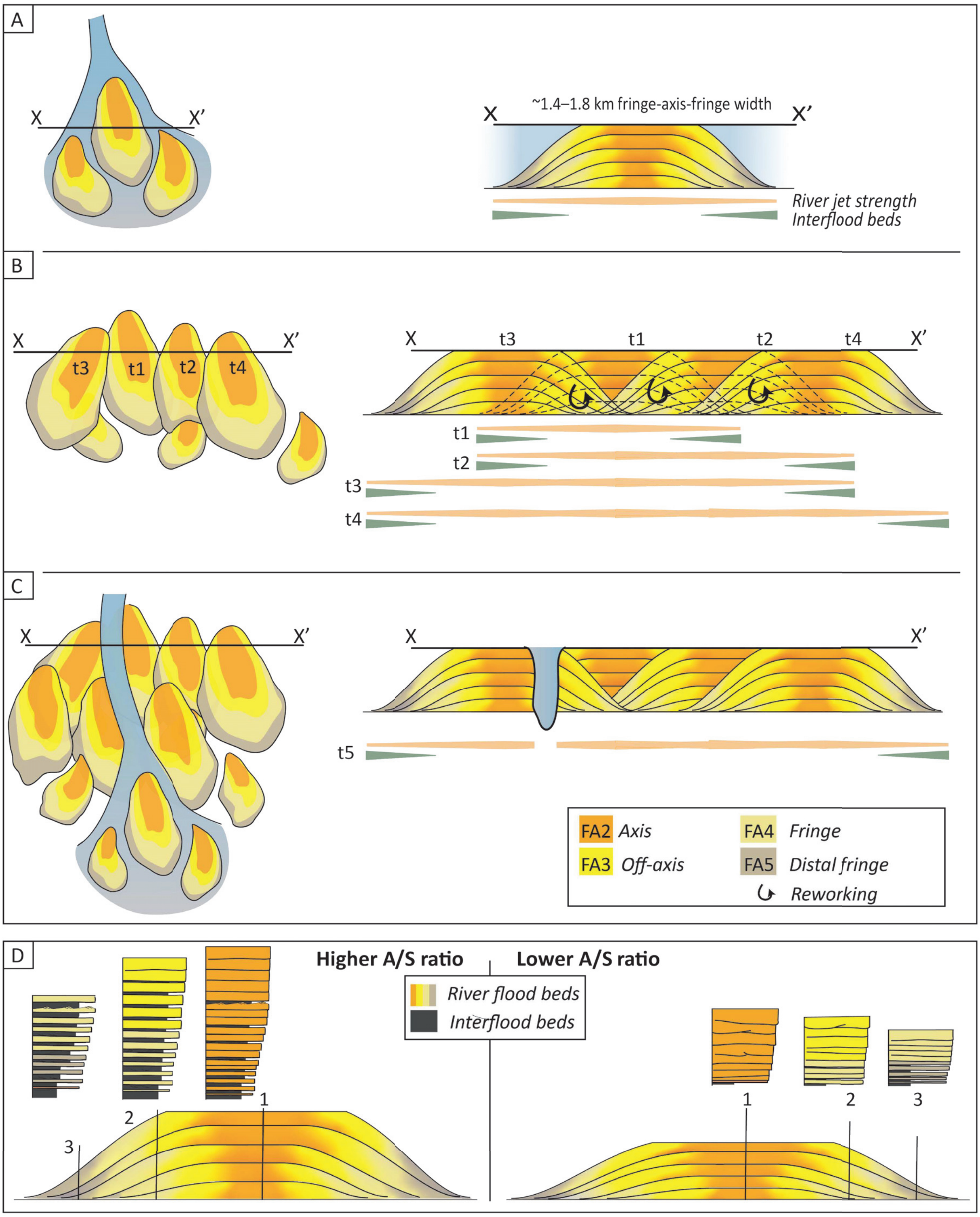


Figure 8 *(modified from Article III) – Schematic representation of a strike-oriented cross-section through an individual mouth bar, indicating the distinguished components. Displayed logs are taken from originally measured logs to enhance differences between components. Mouth-bar axis to distal fringe trends reveal changes in flow regime, bed thickness, occurrence of interflood beds, bioturbation index, and tide-influence. Note that not all fringe components show tide-influence. An increase in tide-influence (imaged by bidirectional cross-stratification, right limb of the mouth bar) is accompanied with a decreasing bioturbation index.*

Figure 9 *(Next page: modified from Article III) – From individual mouth bar to mouth-bar complex;* ***(A)*** *A single mouth bar shows decreasing river jet strength and increase in recording of interflood beds from axis to distal fringe;* ***(B)*** *Multiple mouth bars occupy all available accommodation. Every stage (t1-t4) shows the cumulative preservation of river jet deposits and interflood beds. Successive deposition of mouth bars causes reworking of fringes, subsequently erodin the previously deposited interflood beds and thererby the potential recording of subordinate coastal processes;* ***(C)*** *Eventually, a primary distributary channel erodes through the mouth-bar complex and will initiate new mouth-bar deposition beyond the stranded mouth-bar complex;* ***(D)*** *Facies stacking patterns of river flood and interflood beds. River flood beds are thicker and more amalgamated towards the top and the axial part of the mouth bar. A progressive decrease of preserved interbedding shows a similar trend. The occurrence of interflood beds is lower in the scenario with a lower A/S ratio.*


A
X
X′
X
~1.4–1.8 km fringe-axis-fringe width
X′
River jet strength
Interflood beds
B
X
X′
t3
t1
t2
t4
X
t3
t1
t2
t4
X′
t1
t2
t3
t4
C
X
X′
X
X′
t5
FA2 Axis
FA3 Off-axis
FA4 Fringe
FA5 Distal fringe
Reworking
D
Higher A/S ratio
Lower A/S ratio
River flood beds
Interflood beds
1
2
3
1
2
3

4.4 Article IV: Sequence stratigraphy, backwater limits and depositional architecture in low-accommodation fluvio-deltaic settings (Cretaceous Mesa Rica Sandstone, Dakota Group, USA)

Principle author:	Anna E. van Yperen
Co-authors	John M. Holbrook, Miquel Poyatos-Moré, Cody Myers, Ivar Midtkandal
Data collection	Van Yperen, Myers,
Data processing and interpretation	Van Yperen, Myers (data processing)
Text	Van Yperen,
Figures	Van Yperen
Concept	Van Yperen, Holbrook, Poyatos-Moré, Midtkandal
Editing	Van Yperen, Holbrook, Poyatos-Moré, Midtkandal
Approximate contribution	Van Yperen: 75%, Holbrook, Poyatos-Moré, Myers, Midtkandal: 25%
Status of the manuscript	Accepted with moderate to major revisions in *Basin Research*, February 2020. Revisions partly incorporated.

This Article combines newly measured stratigraphic sections, data and results from Article I, II, and III, and previously published work (Holbrook and Wright Dunbar, 1992; Holbrook, 2001; Scott et al., 2004; Holbrook et al., 2006; Oboh-Ikuenobe et al., 2008). This provides an extensive dataset with numerous photopanels, drone survey data, and 125 logged sections throughout a ~40,000 km^2 study area. Summaries of facies associations, architectural elements and the extension of key stratigraphic surfaces form the basis of a large regional-scale (~400 km) and depositional-dip parallel correlation panel (Fig. 10). The panel is used as the main tool to describe and discuss down-dip changes in facies distribution, depositional architecture and the sequence stratigraphic interpretation. Additionally, grain-size samples from 4 representative trunk channels were collected and used for backwater length calculations. The studied transect is divided into three geographical zones, based on the dominant facies associations and depositional style that distinguish them as proximal, transitional, and distal (Fig. 10B). The proximal zone consist predominantly of fluvial deposits (e.g. Holbrook, 1996, 2001). The transitional zone captures the change from fluvial to deltaic deposits (Holbrook et al., 1987; Holbrook & Wright Dunbar, 1992; **Article II, Article III**). In the distal zone, the lower Mesa Rica represents fully deltaic development (e.g. **Article I**).

Eight facies associations were recognized and six different types of channel deposits were distinguished based on sandstone-body dimensions and vertical and lateral spatial arrangments: buffer multivalley-sheet (channel type I), single story-sheet of trunk channels (channel type II), isolated fluvial distributary channels and channel belts (channel type III), incised valley (channel type IV), fluvial distributary-channel sheet (channel type V), and marine-influenced distributary channels and channel belts (channel type VI). Down-dip changes in facies and thickness distribution, fluvial architecture and spatial extent of key stratigraphic surfaces (Fig. 10B, 11) are consistent with a general accommodation decrease towards the basin rim, and subsequent expansion into deeper waters. In the transitional zone, the lateral change from dominantly fluvial to deltaic deposits reflects an important change in boundary conditions for the lower Mesa Rica depositional system. The location of this facies change is close to the rim of the Tucumcari Basin. Low-accommodation conditions limit the preservation of deltaic sediments deposited at the rim of the basin. Younger prograding fluvial channels are forced to use the same accommodation. Consequently, these channels must have completely eroded the underlying deposits that recorded the gradual vertical facies transition from shallow-marine to fluvial settings, now preserved as a rather abrupt transition.

Maximum Regressive Surfaces (MRS') are regionally traceable throughout the study area (Fig. 10, 11). An erosional composite scour forms the basal surface of fluvial deposits in the proximal zone (Fig. 10) and represents a Regional Composite Scour (RCS). The erosional composite surfaces bounding the incised valleys in the transitional and distal zones, are all interpreted as local expressions of this RCS (Fig. 10C). Backwater length estimates are ~117 km and ~180 km based on i) calculations using the grain-size samples representative for the coarsest material transported as bedload within trunk rivers, and ii) inferred from changes in fluvial architectural style observed in the studied outcrop profile, respectively. The difference is less than a factor 2, which is within the error range intrinsic to slope calculations (Holbrook and Wanas, 2014).

We infer active filling of channels rather than passive backfilling from the sand-prone nature and predominantly fully fluvial infill of single story-sheet of trunk channels (channel type II), incised valleys (channel type IV), and amalgamated distributary channels (channel type V) in the lower Mesa Rica. This suggests continuous reshaping and active deposition at the delta plain and in incised valleys. Additionally, it suggests that erosion and deposition occurred contemporaneously at local scale along the depositional profile, which implies that there is no complete bypass at any given time at any point in the system. This depositional model therefore depicts each part of the RCS is time-equivalent to the clinoform surface underlying each genetically-related clinothem. Consequently, the fluvial RCS disperses into several surfaces in the shallow-marine part of the depositional system. Similarly, segments of the composite scour bounding an incised valley formed contemporaneously with deposition in the valley, trunk channel deposition in the proximal zone, and clinothem deposition in the distal zone. The down-dip equivalent of the sequence boundary / RCS therefore consists of several dispersive elements rather than one single, correlatable surface.

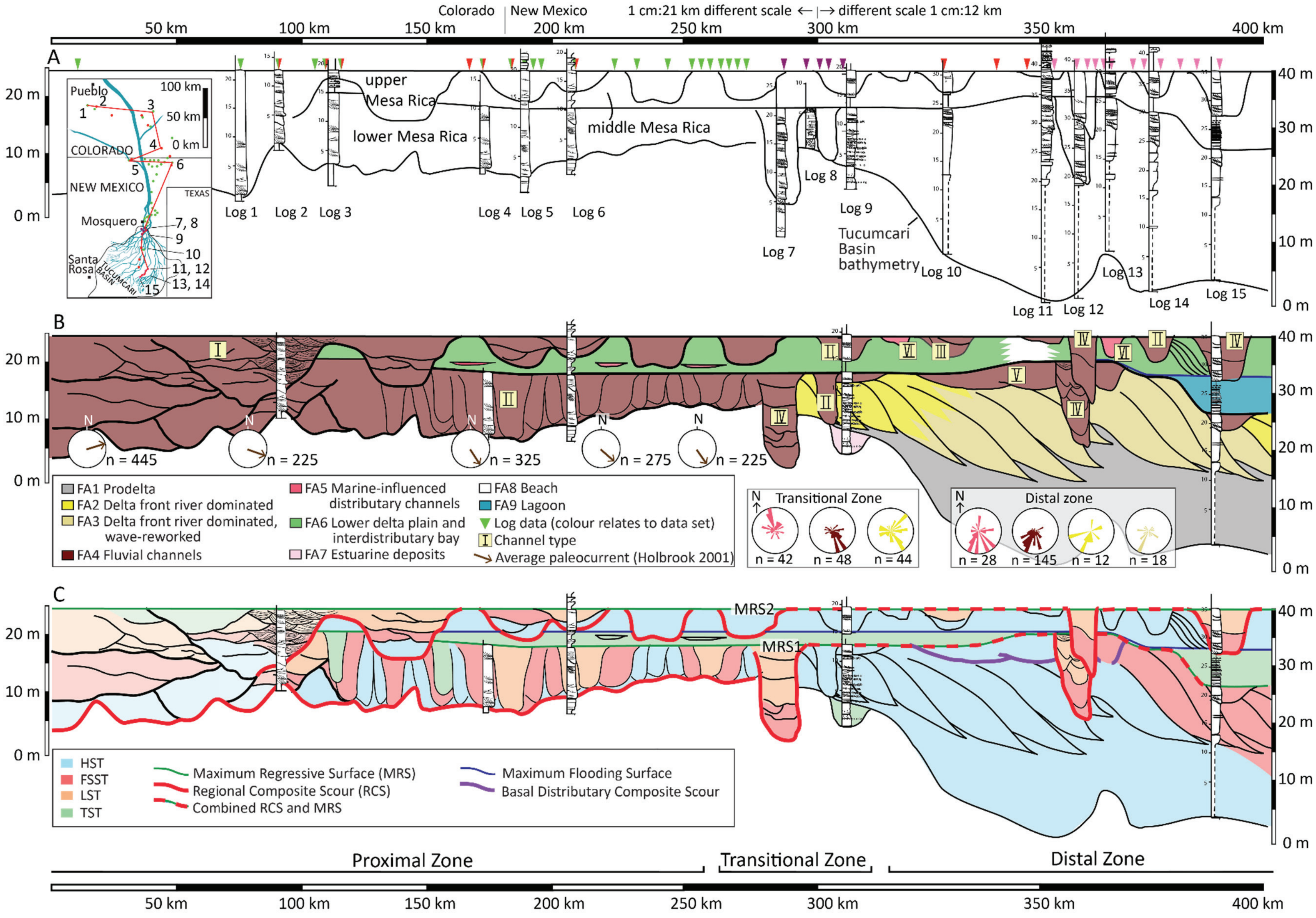
The 'dispersive RCS'-model is based on field observations that suggest that the RCS was generated in the fluvial realm throughout the transgressive – regressive (T-R) cycle. This supports the increasing numbers of studies that highlight the composite and diachronous nature of key sequence stratigraphic surfaces (e.g. Strong and Paola, 2008; Martin et al., 2009; Holbrook and Bhattacharya, 2012; Madof et al., 2016). It also offers an alternative approach to the often heavily debated extent of the traditional sequence boundary into correlative marine strata (e.g. Bhattacharya 2011).

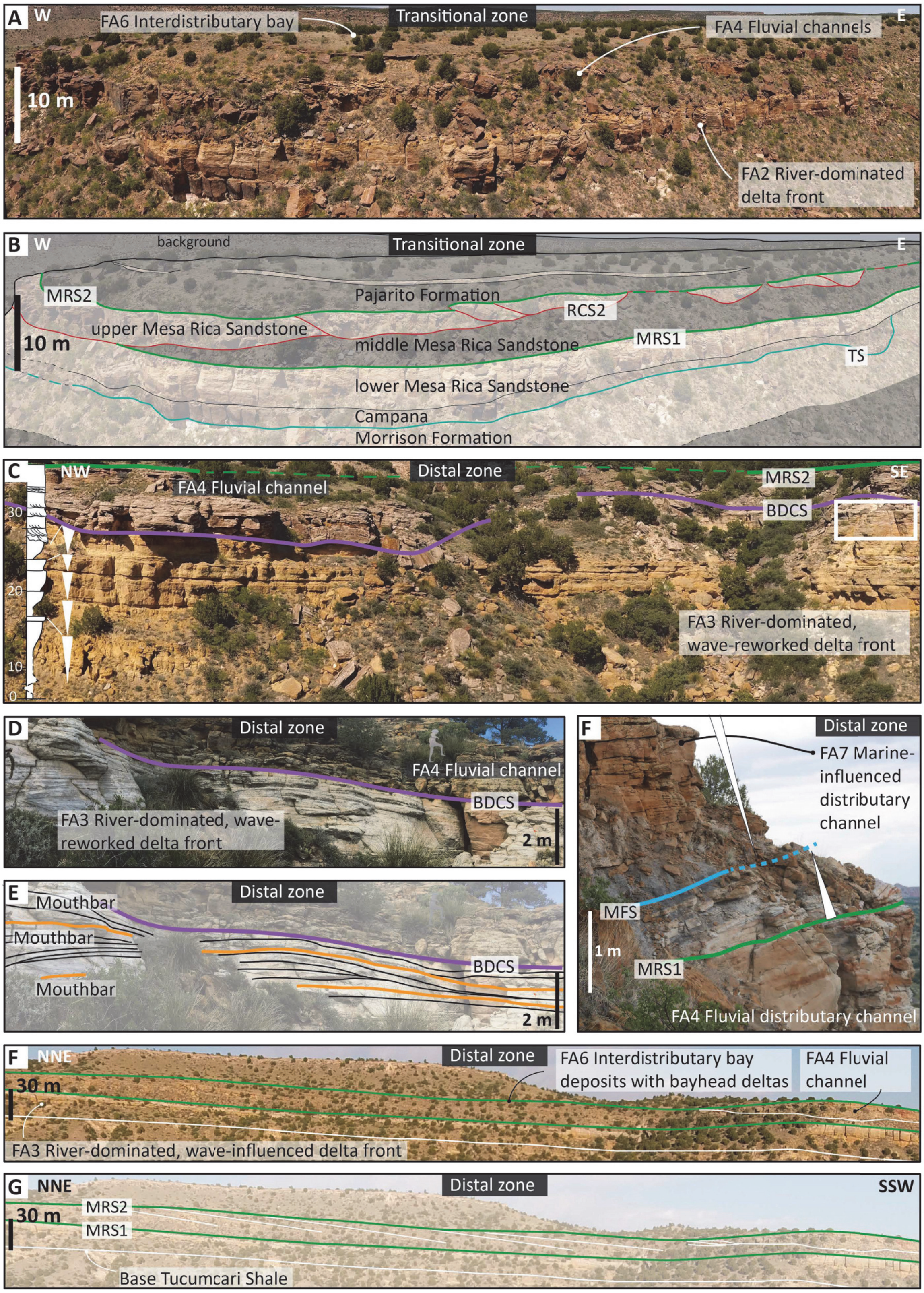
This has implications beyond the Mesa Rica Sandstone in the following ways:

- It highlights that erosion and deposition occur contemporaneously along the depositional profile, not only when considering the complete depositional system, but at local scale as well.
- The aforementiond contradicts many stratigraphic models that interpret low-accommodation settings to dominantly promote bypass, especially during forced regressions. Source-to-sink analyses need to take this into account in order to adequately account for timing and volume of sediment storage in the system throughout a complete relative sea-level cycle.
- The down-dip equivalent of sequence boundaries/RCSs consists of several dispersed surfaces in the marine part of the depositional system, which challenges the idea of a single, equivalent correlatable surface. Application of the dispersive RCS can minimize discussions and misunderstandings related to the correlation between subaerial unconformities in the continental and the extension into marine realm.

Figure 10 *(Next page: modified from Article IV) Regional-scale (~400 km), depositional dip-parallel correlation panel of the Mesa Rica fluvio-deltaic system throughout southeast Colorado to central-east New Mexico –* ***A)*** *Simplified cross section with a selection of log data and main stratigraphic surfaces defining the lower, middle and upper Mesa Rica;* ***B)*** *Lithostratigraphic cross section showing the downdip changes in facies distribution with a display of 6 key logs. Rose diagrams display paleocurrent data grouped according to facies associations;* ***C)*** *Large-scale sequence stratigraphic interpretation for the Mesa Rica depositional system, showing the interpretation of key stratigraphic surfaces and system tracts. Display of 6 key logs. Note the cannibalization of the oldest fluvial-marine transition zone by younger trunk channels. Trunk channel sediment was deposited throughout the sea-level cycle (i.e. HST, FSST, LST, TST) and not only during the LST, as predicted in classic models. Deltaic and distributary channel deposits were formed during HST, FST and LST.*

Figure 11 *(Page modified from Article IV) Overview of key stratigraphic surfaces as present in the transitional and distal zones –* ***A)*** *Photograph showing the Cretaceous stratigraphy in the transitional zone;* ***B)*** *Interpretation of A. Note that the RCS excludes interfluve. Note the limited thickness of the delta front deposits (FA2) compared to the deltaic succession of the lower Mesa Rica in the distal zone (Figure 10C, G, H);* ***C)*** *Stacked coarsening-upward sequences in a river-dominated wave-reworked facies association (FA3), overlain by fluvial distributary channel deposits (FA4). Note the configuration into tabular geometries. White rectangle shows representative stratigraphic level for photograph D;* ***D)*** *Outcrop photograph of fluvial distributary channels (FA4) in erosional contact with delta-front sands (FA3);* ***E)*** *Interpretation of D, with stacked mouth bars based on the presence of lensoid-bar geometries;* ***F)*** *Example of key stratigraphic surfaces in the distal zone separating coarsening- and fining-upward packages;* ***G)*** *Outcrop photograph showing the differences in A/S ratio between the first progradational succession (lower Mesa Rica) consisting of amalgamated sheet-forming delta-front sands (FA3) and the following progradational succession (upper Mesa Rica). The latter consists of interdistributary bay deposits (FA6) with basinward-dipping heterolithic clinothems;* ***(H)*** *interpreted as small bayhead deltas. MRS, maximum regressive surface; RCS, Regional composite scour; BDCS, basal distributary composite scour; Triangles indicate grainsize trend. A, B, D, E, F modified from Article I.*

Colorado | New Mexico
1 cm:21 km different scale ←|→ different scale 1 cm:12 km
50 km
100 km
150 km
200 km
250 km
300 km
350 km
400 km
A
Pueblo
1
2
3
4
5
6
100 km
50 km
0 km
COLORADO
NEW MEXICO
TEXAS
Mosquero
7, 8
9
10
11, 12
13, 14
15
Santa Rosa
TUCUMCARI BASIN
upper Mesa Rica
lower Mesa Rica
middle Mesa Rica
Log 1
Log 2
Log 3
Log 4
Log 5
Log 6
Log 7
Log 8
Log 9
Tucumcari Basin bathymetry
Log 10
Log 11
Log 12
Log 13
Log 14
Log 15
0 m
10 m
20 m
30 m
40 m
B
I
II
III
IV
V
VI
N
n = 445
n = 225
n = 325
n = 275
n = 225
FA1 Prodelta
FA2 Delta front river dominated
FA3 Delta front river dominated, wave-reworked
FA4 Fluvial channels
FA5 Marine-influenced distributary channels
FA6 Lower delta plain and interdistributary bay
FA7 Estuarine deposits
FA8 Beach
FA9 Lagoon
Log data (colour relates to data set)
Channel type
Average paleocurrent (Holbrook 2001)
Transitional Zone
n = 42
n = 48
n = 44
Distal zone
n = 28
n = 145
n = 12
n = 18
C
MRS2
MRS1
HST
FSST
LST
TST
Maximum Regressive Surface (MRS)
Regional Composite Scour (RCS)
Combined RCS and MRS
Maximum Flooding Surface
Basal Distributary Composite Scour
Proximal Zone
Transitional Zone
Distal Zone


A
W
FA6 Interdistributary bay
Transitional zone
FA4 Fluvial channels
E
10 m
FA2 River-dominated delta front
B
W
background
Transitional zone
E
MRS2
Pajarito Formation
RCS2
upper Mesa Rica Sandstone
10 m
middle Mesa Rica Sandstone
MRS1
TS
lower Mesa Rica Sandstone
Campana
Morrison Formation
C
NW
Distal zone
MRS2
SE
FA4 Fluvial channel
BDCS
30
20
10
0
FA3 River-dominated, wave-reworked delta front
D
Distal zone
FA4 Fluvial channel
BDCS
FA3 River-dominated, wave-reworked delta front
2 m
F
Distal zone
FA7 Marine-influenced distributary channel
MFS
1 m
MRS1
FA4 Fluvial distributary channel
E
Distal zone
Mouthbar
Mouthbar
Mouthbar
BDCS
2 m
F
NNE
Distal zone
FA6 Interdistributary bay deposits with bayhead deltas
FA4 Fluvial channel
30 m
FA3 River-dominated, wave-influenced delta front
G
NNE
Distal zone
SSW
MRS2
30 m
MRS1
Base Tucumcari Shale

5. Discussion

Low-accommodation settings tend to form vertically amalgamated sections as compared to high-accommodation settings. Key event beds and / or stratigraphic surfaces that hold valuable information about basin fill history can become cannibalized by subsequent events (Olariu and Bhattacharya, 2006; Ainsworth et al., 2017). It is the ratio between accommodation to sediment supply (A/S) that dictates the sandiness of the resulting depositional geometries. The Mesa Rica Sandstone forms sheet sandstone bodies with a consistent sandy nature throughout the study area and is therefore interpreted as a sand-rich end member within the low-accommodation spectrum. The low A/S of the depositional system highlights issues related to their forcing mechanisms, preservation potential of finer-grained facies, distribution and changes herein of facies and architectural elements, and key stratigraphic surfaces.

5.1 Distribution of time and sediment, and resulting stratigraphic surfaces

The deltaic sands of the Mesa Rica form sheets of coalesced mouth bars overlain by sand-filled distributary channels in the centre of the basin (**Article I**). The hypothesized mechanism is the acceleration of mouth-bar depositional cycles and the increased avulsion frequency of distributary channels, in which both high sandy sediment supply and low accommodation have interrelated roles (**Article I**; Fig. 12A). Such low A/S settings promotes lateral rather than vertical stacking patterns (Ainsworth et al., 2017). Consequently, elapsed time within such a succession is represented by preserved sediment in three dimensions with a strong lateral aspect, rather than by only vertical accumulation (Miall, 2015). This highlights that it is crucial to address depositional systems in 3D when we aim to understand its complete development (e.g. Miall, 2015; Madof et al., 2016; Amorosi et al., 2019). Taking the deltaic lower Mesa Rica as an example, the shifting locus of mouth-bar deposition will first cause all available lateral accommodation to be filled by compensational stacking. If sediment supply continues to outpace accommodation, channel erosion through the delta lobe will initiate new mouth-bar deposition basinwards, causing the delta to prograde. This implies that the sediment record elapsed time first laterally and then progradationally, and the limited accommodation will suppress vertical stacking (Fig. 12B). The lower Mesa Rica spans approximately 0.5–1 myrs but high-frequency depositional cycles such as documented elsewhere in the Western Interior Seaway (e.g. Lin et al., 2019) are not expected to be detectable, because of the strong lateral component, high sand content in sediment distribution and the significant amount of time included/secluded in the bounding surfaces (e.g. Amorosi et al., 2017).

The predominantly lateral distribution of sediment – and consequently – recorded time, has implications for the formation and interpretation of stratigraphic surfaces. The *basal distributary composite scours* (**Article I, IV)** are laterally extensive and formed by the autogenic process of distributary-channel avulsion and deposition on a delta plain. Due to the limited accommodation, the distributary channels amalgamate and erode laterally, rather than vertically (Fig. 12B). Consequently, their erosional bounding surfaces form laterally extensive diachronous and composite erosional surfaces, rather than isolated scours. This demonstrates that such laterally extensive erosional surfaces can have an origin that is disconnected from regional sequence-bounding surfaces. This is an important distinction for the interpretation of key stratigraphic surfaces. One such key stratigraphic surface is the Regional Composite Scour (RCS), which is defined as a Subaerial Unconformity (SU) not including the interfluve (Holbrook and Bhattacharya, 2012). The conformable portion and extension of the SU into the marine realm has become a controversial topic (e.g. Figure 23 in Catuneanu et al., 2009). The *correlative conformity* has been defined in varying ways and placed at stratigraphic surfaces that mark the base (e.g. Posamentier et al., 1988) or top (e.g. Hunt and Tucker, 1992) of forced regressive deposits. Embry (1995) called the *correlative conformity* 'a theoretical time surface with no lithological expression' and proposed to use the maximum regressive surface as the conformable portion of a sequence boundary. Based on the studied profile in this PhD project, we propose an alternative and data-driven approach. In the lower Mesa Rica, reshaping and active deposition at the delta plain and in incised valleys are inferred from the sand-prone nature and predominantly fully fluvial infill of single story trunk-channels, amalgamated distributary channels, and incised valleys. This suggests that erosion and deposition occurred practically contemporaneously. Not only when considering the complete depositional system, but at local scale as well. This in turn implies that there is no complete bypass at any given time in the system. Consequently, the RCS was created in the proximal zone throughout the complete relative sea-level cycle, due to ongoing contemporaneous river erosion. Creation of this erosional basal surface occured virtually contemporaneously to deposition within the channel. The sediment that was not incorporated into the updip fluvial deposits bypassed this surface and fed the deltaic clinothem. Thus, part of the RCS is time-equivalent to the clinoform surface underlying each genetically-related clinothem; the down-dip equivalent of the sequence boundary/RCS consists of several dispersive elements rather than one single, correlatable surface (**Article IV**) (Fig. 12D). It is important to note that the sharp base of the deltaic sandstone bodies (predominantly close to the rim of the basin, **Article III**) should not be mistakenly interpreted as the result of forced regression or as lowstand deposits overlying sequence boundaries (Fielding et al., 2005). Such sharp bases relate to low-accommodation rather than a drop in sea level (Overeem et al., 2003; Fielding et al., 2005).

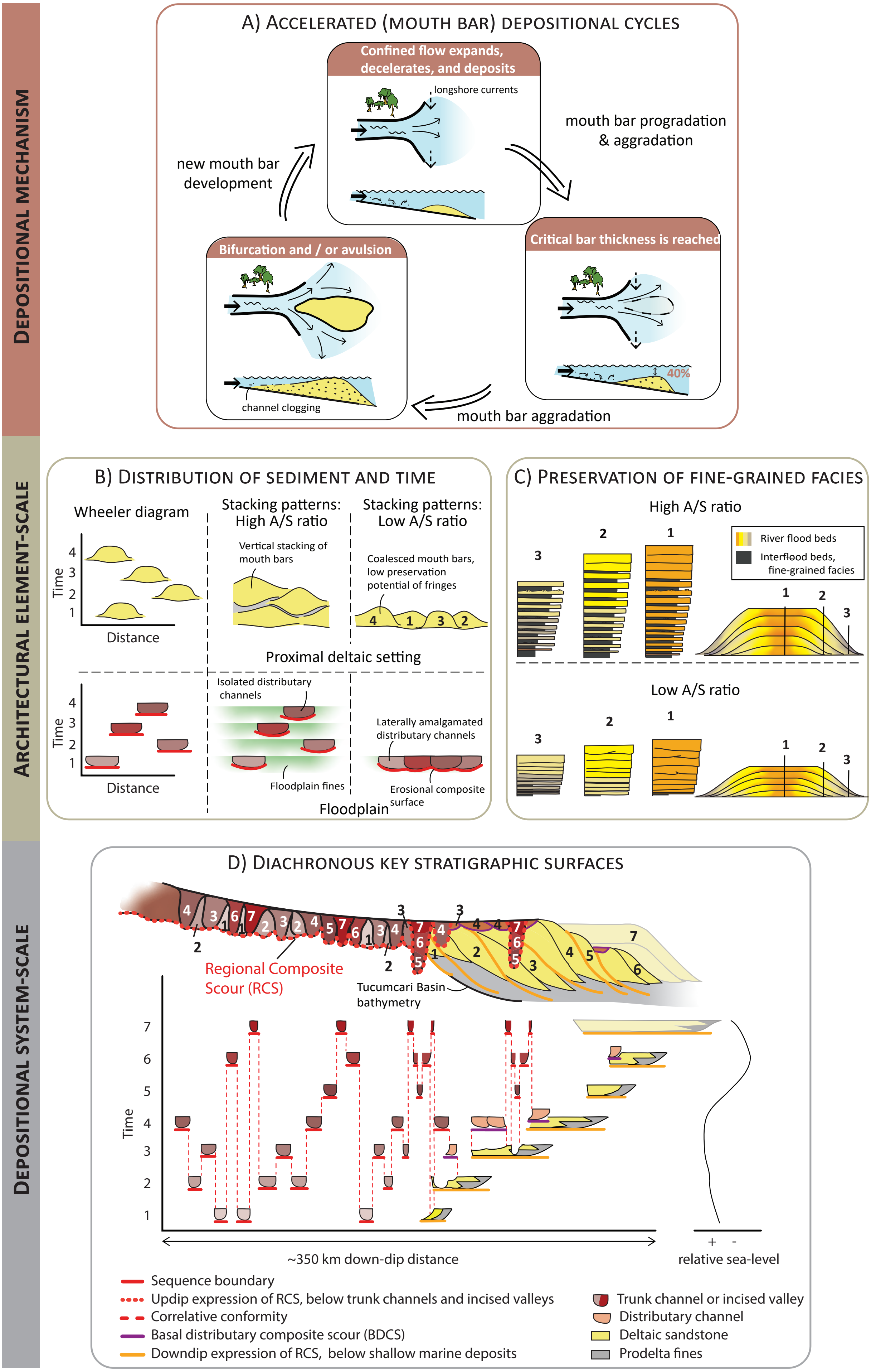
Sediment distribution as influenced by a low A/S setting also impacts preservation potential. In such a setting, older deposits have the lowest preservation potential, as younger prograding fluvial channels erode and rework them as they are forced to use the same accommodation. At the margin of the Tucumcari Basin, where the accommodation is the least and the lower Mesa Rica is thinnest, fine-grained facies (interflood beds) and mouth-bar fringe deposits have a lowered preservation potential (Fig. 12C). Because the amount of time contained in interflood beds is significantly longer than in flood beds (e.g. Miall, 2015), the limited preservation potential of interflood beds lowers the recording of time as well. As interflood beds are better recorders of time and background processes than river flood event beds, care should be taken when evaluating the duration and relative dominance of the active process regime (i.e., river, tides, waves) in low-accommodation deltaic settings. The rather low preservation potential of these beds might cause underestimation of the true influence of subordinate coastal processes, with important implications towards prediction of facies changes and sediment distribution in other similar settings.

5.2 Allogenic and autogenic controlling factors

Sedimentary characteristics and depositional architecture of the studied profile provide insights in both their allogenic and/or autogenic controlling factors, although their relative contribution is often difficult to distinguish. Allogenic control on the Mesa Rica depositional system is inferred from changes in depositional style related to the position with respect to the basin rim, and evidence for relative sea-level fall. The fall in relative sea level is in turn inferred from downstepping delta front geometries in the distal zone (**Article I**), key stratigraphic surfaces extending over regional distances (> 300 km) which cannot be explained only by autogenic behavior (**Article I),** and multistory sandstone bodies that formed allogenically. The allogenic interpretation of multistory sandstone bodies is based on the regional occurrence of these valleys, the multistory and multi-lateral infill, the estimated channel tops below the surrounding topographic surface, and the coeval downstepping delta front geometries (**Article I, IV)**. Additionally, flume modelling results show improbable autogenic formation of multistory sandstone bodies with more than two channel depths (Strong & Paola, 2008). Backwater effects are considered autogenic dynamics of sedimentary systems (e.g. Trower et al., 2018; Ganti et al., 2019). Backwater effects occur in the zone affected by static water beyond the shoreline. In this backwater zone, rivers behave fundamentally different than farther upstream (e.g. Lamb et al., 2012). The documentation and interpretation of flood-induced scours up to 3x bankfull depth within the backwater zone (Lamb et al., 2012; Fernandes et al., 2016; Trower et al., 2018; Ganti et al., 2019) poses potential challenges to differentiate flood-induced multi-story channels from allogenically formed incised valleys fills. In order to unambiguously distinguish allogenic signals from backwater-induced scours, allogenic scour depths must exceed bankfull flow depth (>3x) and occur over a distance longer than the backwater length (Ganti et al., 2014; Trower et al., 2018; Ganti et al., 2019). Scouring of the incised valleys in the study area happened at less than 3x below bankfull depth, and the knickpoint of these valleys is close to the backwater length. Nevertheless, their origin is interpreted as allogenic (**Article I, IV).** These results do not match the criteria offered by other authors to unambiguously assign an allogenic origin to the incised valleys. This emphasizes the reservation that decoupling autogenic and allogenic controls on erosional surfaces may be especially problematic, particularly in low-gradient river systems (Ganti et al., 2019).

Around the rim of the Tucumcari Basin, the succession is thinner **(Article III)** compared to both the upstream fluvial (e.g. Holbrook, 2001; Holbrook et al., 2006), and downstream fully deltaic time-equivalent strata (**Article I**). This reduced thickness is interpreted to reflect deposition close to base level and to the equilibrium point of the graded stream profile (e.g. Mackin, 1948; Holbrook et al., 2006). Such a position also limits aggradation and incision, which in turn reflects a low-accommodation setting, with either a constant relative sea-level or a sea level that is subjected to slow and minor fluctuations. This allogenically induced low-accommdoation setting promotes the acceleration of an autogenic process; it accelerates mouth-bar depositional cycles, i.e. deposition, extension, avulsion, and abandonment, *sensu* Olariu and Bhattacharya (2006), and all available space in front of the river mouth becomes occupied at a higher rate (e.g. Olariu and Bhattacharya 2006; **Article I**). This is one of the examples that illustrates the interplay between allogenic and autogenic controlling factors.

Figure 12 *(Next page) Summary of concepts distilled from the thesis -* ***A)*** *A high frequency avulsion pattern is the major driving mechanism behind the development of coalesced mouth bars and lobes resulting in laterally extensive sheet sandstones (Article I). A low-accommodation setting combined with high sediment supply accelerates avulsion frequency at the river mouth. High discharge dampens wave impact and its redistribution capacity, and a low gradient causes enhanced bed friction. As a result, sediment load exceeds the carrying capacity. Deposition in front of the river mouth will lead to channel clogging, which promotes bifurcation / avulsion. In addition, the river flow will start to divert around the mouth bar when the water depth over the river mouth corresponds to 40% of inlet depth. Because of the low-accommodation setting, less sediment is needed to reach the critical thickness for bifurcation;* ***B)*** *Simplified Wheeler diagrams illustrate the differences in stacking patterns and nature of erosional surfaces, as a result of different distribution of time and sediment in high and low A/S settings. The wheeler diagrams only illustrate time-relationships of channel and mouth-bar sandstone bodies and neglect the differences in deposition of fine-grained facies (e.g. floodplain fines) and preservation potential between high and low A/S settings;* ***C)*** *The occurrence of fine-grained facies (i.e. interflood beds) is lower in the scenario with a lower A/S. River flood beds are thicker and more amalgamated towards the top and the axial part of the mouth bar. A progressive decrease of preserved interbedding shows a similar trend. Based on Article III;* ***D)*** *Simplified depositional profile and Wheeler diagram showing the diachronous nature of key stratigraphic surfaces. Discrete parts of the highly diachronous erosional composite surface below the fluvial deposits are time-equivalent to individual regressive marine surfaces. Each segment of the Regional Composite Scour (RCS) is contemporaneous to the clinoform surface underlying the genetically-related clinothem. The regional composite scour is generated in the fluvial realm throughout the T-R cycle. Therefore there is no single correlatable surface in the marine realm. Faded deltaic wedges t7 are not documented in this study. Based on complete study profile (Article IV). See text and Articles I, III and IV for further discussion.*


Depositional mechanism
Architectural element-scale
Depositional system-scale
A) Accelerated (mouth bar) depositional cycles
Confined flow expands, decelerates, and deposits
longshore currents
mouth bar progradation & aggradation
Critical bar thickness is reached
40%
mouth bar aggradation
Bifurcation and / or avulsion
channel clogging
new mouth bar development
B) Distribution of sediment and time
Wheeler diagram
Time
4
3
2
1
Distance
Stacking patterns: High A/S ratio
Vertical stacking of mouth bars
Stacking patterns: Low A/S ratio
Coalesced mouth bars, low preservation potential of fringes
4 1 3 2
Proximal deltaic setting
Isolated distributary channels
Floodplain fines
Laterally amalgamated distributary channels
Erosional composite surface
Floodplain
C) Preservation of fine-grained facies
High A/S ratio
3
2
1
River flood beds
Interflood beds, fine-grained facies
1 2 3
Low A/S ratio
D) Diachronous key stratigraphic surfaces
4 3 6 7 1 1 2 3 2 4 5 7 6 1 3 4 7 6 5 4 3 3 4 4 7 6 5 1 2 3 4 5 7 6
2
Regional Composite Scour (RCS)
2
Tucumcari Basin bathymetry
Time
7
6
5
4
3
2
1
~350 km down-dip distance
+ -
relative sea-level
Sequence boundary
Updip expression of RCS, below trunk channels and incised valleys
Correlative conformity
Basal distributary composite scour (BDCS)
Downdip expression of RCS, below shallow marine deposits
Trunk channel or incised valley
Distributary channel
Deltaic sandstone
Prodelta fines

6. Applications and conclusions

The strength and the added value of this collection of studies lies in the availability of a ~400 km depositional profile that covers both the fluvial and time-equivalent deltaic deposits of a system that prograded into an epicontinental and low-gradient basin. Combining the insights gained from newly collected extensive data sets at key localities in the deltaic realm with previously published panels targeting the fluvial realm, provides an analysis that elevates the understanding of low-accommodating settings and forcing factors on sediment distribution. The lower Mesa Rica Sandstone depositional system provides an end-member when considering A/S ratios, with deposition of amalgamated sand-prone sandstone bodies throughout the ~400 km studied profile.

The work compiled in this thesis can be distilled into six main conclusions:

- In low A/S-ratio settings, amalgamated sheet sandstones may form in river-dominated deltas despite not having the wave-dominance as classically assigned to sheet forming deltas (**Article I**). The low-accommodation setting acts as an amplifier for the interrelated processes of frequent avulsion of distributaries and recurring mouth-bar development cycles at short time scales accelerating mouth-bar depositional cycles. This results in the formation of sheet-like delta front sandstone geometries without the dominance of wave redistribution processes. The formation of sheet sandstones in such a setting cautions interpretations of amalgamated shoreline systems based solely on apparent sandstone geometries. This insight can also be applied when predicting shallow-marine sediment distribution based on delta plain characteristics.
- Facies changes and sand distribution reveal predictable patterns both at mouth-bar scale (**Article III)** and dip-oriented at regional scale (**Article IV**). Subdivision of mouth bar, mouth-bar complexes, and delta lobe deposits into their elemental components can reduce complexity of models deriving from a myriad of facies subdivisions, and guide prediction of facies changes and sand distribution.
- In low-accommodation settings, interflood beds are restricted to fringe and distal fringe mouth-bar components. The preservation potential of fringes themselves is also lowered because of increased fringe-reworking during accelerated mouth-bar depositional cycles and compensational stacking. Because interflood beds are better records of time and background processes than river flood event beds, care should be taken when evaluating the duration and relative dominance of the process regime (i.e., river, tides, waves) in low-accommodation deltaic settings. The rather low preservation potential of these beds might cause underestimation of the true influence of subordinate coastal processes, with important implications towards prediction of facies changes and sediment distribution in other similar settings (**Article III**).
- The *basal distributary composite scours* are laterally extensive and formed by the autogenic process of distributary-channel avulsion and deposition on a delta plain with limited accommodation. This demonstrates that such laterally extensive erosional surfaces can have an origin that is disconnected from regional sequence-bounding surfaces.

- The Regional Composite Scour (RCS) can be mapped for >300 km. RCS' may be generated in the fluvial realm throughout the T-R cycle, highlighting that erosion and deposition occur virtually contemporaneously at local scale along the depositional profile (**Article IV**). This contradicts many stratigraphic models that interpret low-accommodation settings to dominantly promote bypass, especially during forced regressions. The down-dip equivalent of sequence boundaries/RCS' consists of several dispersed surfaces in the marine part of the depositional system, which challenges the idea of a single, equivalent and correlatable surface. Application of the dispersive RCS can minimize discussions and misunderstandings related to the correlation between subaerial unconformities in the continental and the extension into the marine realm.
- Fluvial sandstone bodies of the upper Mesa Rica extend into east-central New Mexico, in contrast to previous work which state the upper Mesa Rica transitions from fluvial to marine south of the Oklahoma Panhandle (Holbrook et al., 2006) (**Article II**).

7. Further work

Modern deltas and numerical modelling

Studies on ancient deltas will inevitably deal only with what is preserved, not with what once was (e.g. Miall, 2015). Modern delta studies are therefore essential for the understanding of building mechanisms of deltas, the development of channel networks, and the distribution of architectural elements. In modern delta deposits, few studies describe and discuss the development of individual mouth bars (Van Heerden and Roberts, 1988; Allen and Mercier, 1994; Wellner et al., 2005; Fan et al., 2006; Esposito et al., 2013). However, publications of high resolution core-data based strike- and dip sections through individual mouth bars are scarce and knowledge gaps are still significant at this scale. Additional studies on individual mouth bars would give valuable insights in mouth bar stratigraphy and strike- and dip-oriented variations in sediment distribution. As the mouth bar is the building block for delta systems such studies are expected to hold valuable insights.

The results of this collection of studies show that repetitive cycles of mouth bar deposition and avulsion are expected to remove (at least part of) these beds and that potential loss of preservation of subordinate process indicators needs to be considered. Modern delta studies based on aerial photographs combined with shallow cores should provide estimates for preservation potential at bed scale, mouth-bar scale and mouth-bar complex scale. However, modern deltas have formed over a short geological time frame (Stanley and Warne, 1994), which limits their value as analogues for longer-time-scale (>10 kyr) preservation potential in the sedimentary rock record. Results of modern delta studies can be used as input parameters for numerical modelling studies. Currently, numerical modelling studies focus primarily on the mechanics of river mouth bar formation, the accompanying hydrodynamics and resulting morphodynamics (e.g. Bryant et al., 1995; Edmonds and Slingerland, 2007; Leonardi et al., 2013; Fagherazzi et al., 2015) but mention little on the internal stratigraphy, time aspects, or preservation. Some modelling studies do discuss internal stratigraphy but they tend to focus on the complete delta rather than individual mouth bars (e.g. Storms et al., 2007; van der Vegt et al., 2016). Numerical modelling studies can improve our understanding of the effect of time and preservation and the consequences for resulting internal facies distribution as addressed in this study. They can also improve our insights into the effects of low-accommodation on coalescence and reworking of mouth bar deposits.

Regional scale source-to-sink studies and scaling relationships

Source-to-sink studies examine the supply and fate of sediment, from its erosion in catchment areas, coupled with transport, to its deposition in the oceans. Conventional models often regard the fluvial part of a depositional system only as temporal sediment storage. Our study supports the growing insights that erosion and deposition within the fluvial realm occurs throughout the T-R cycle. This cautions against many stratigraphic models in which low-accommodation settings are interpreted to promote (complete) bypass, especially during forced regression which results in extensive lowstand wedges (e.g. Posamentier et al., 1988; Emery and Myers, 2009). This raises the question to what extent climate-variability signals are buffered or transferred down river systems to where they are preserved in sediments beyond the river mouth. Future source-to-stink studies can help to further test and constrain this. This seems a huge task, but incremental steps can be made by studying tresholds for deposition and/or erosion in different segments along source-to-sink-profiles and how they relate? What controls these forcing mechanisms and what is their timing with respect to one another?

Previous work documents scaling relationships between channel size, slope, and backwater length (e.g. Blum et al., 2013). In addition, grain size is a critical parameter to constrain slope estimates. The backwater length scales with the length over which the scoured channel base is at or below sea level. Within that backwater length, channel bed profiles scour - on average – approximately one channel depth below the surface, but deeper scours up to 3x bankfull depth are locally possible. In other words, one backwater length relates to one channel depth of scour. A channel scour can only be deeper, if it is updip of the backwater zone. One could reason that a scour as deep as two channel depths (such as for the buffer valleys in this study), can only occur more than two backwater lengths up dip from the paleoshoreline. In the studied profile, incised valleys occur over a distance of ~1-2 backwater lengths from the maximum regressive shoreline. All these scaling relationships suggest that when grainsize, channel size, and position within the depositional system are known, one could be able to predict distances to significant changes in architectural style. This potential should be tested and further explored by extensive literature studies and studying satellite images.

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9. Articles

9.1 Article I – Coalesced delta-front sheet-like sandstone bodies from highly avulsive distributary channels: the low-accommodation Mesa Rica Sandstone (Dakota Group, New Mexico, U.S.A.)

Van Yperen, A.E.[1], Holbrook, J.M.[2], Poyatos-Moré, M. [1], Midtkandal, I[1]. (2019) Coalesced delta-front sheet-like sandstone bodies from highly avulsive distributary channels: the low-accommodation Mesa Rica Sandstone (Dakota Group, New Mexico, U.S.A.). *Journal of Sedimentary Research, 89,* 654–678. https://doi.org/https://doi.org/10.2110/jsr.2019.27

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9.2 Article II – Revised Stratigraphic Relationships of the Dakota Group in the Tucumcari Basin, San Miguel County, New Mexico, USA

Van Yperen, A.E.[1], Line, L.H.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1], Midtkandal, I.[1] (2019) Revised Stratigraphic Relationships of the Dakota Group in the Tucumcari Basin, San Miguel County, New Mexico, USA, in: Ramos, F., Zimmerer, M.J., Zeigler, K., Ulmer-Scholle, D. (Eds.), Geology of the Raton-Clayton Area. *New Mexico Geological Society Guidebook, 70th Field Conference* 89–100

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9.3 Article III – Internal mouth-bar variability and preservation of subordinate coastal processes in low-accommodation proximal deltaic settings (Cretaceous Dakota Group, New Mexico, USA)

Van Yperen, A.E.[1], Poyatos-Moré, M.[1], Holbrook, J.M.[2], Midtkandal, I.[1] (2020) Internal mouth-bar variability and preservation of subordinate coastal processes in low-accommodation proximal deltaic settings (Cretaceous Dakota Group, New Mexico, USA). *The Depositional Record, early online view.* https://doi.org/10.1002/dep2.100

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Internal mouth-bar variability and preservation of subordinate coastal processes in low-accommodation proximal deltaic settings (Cretaceous Dakota Group, New Mexico, USA)

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Abstract

Mouth bars are the fundamental architectural elements of proximal deltaic successions. Understanding their internal architecture and complex interaction with coastal processes (fluvial, tide and wave-dominated) is paramount to the interpretation of ancient deltaic successions. This is particularly challenging in low-accommodation systems, because they are commonly characterized by thin, condensed and top-truncated sections. This study analyses the exhumed Cenomanian Mesa Rica Sandstone (Dakota Group, Western Interior Seaway, USA), a fluvio-deltaic system covering a *ca* 450 km depositional dip-parallel profile. The study targets the proximal deltaic expression of the system, using 22 sedimentary logs (total of 390 m) spatially correlated within a *ca* 25 km^2 study area at the rim of the Tucumcari Basin. Analysis of facies distributions, depositional architecture and spatial extent of stratigraphic surfaces reveals a 6–10 m thick, sharp-based and sand-prone deltaic package, comprising several laterally extensive (>1.4 km width) mouth bars. Composite erosional surfaces infilled with multi-storey fluvial and marine-influenced channel deposits (12–20 m thick, 100–250 m wide) scour locally into the deltaic package. Based on differences in sedimentary structures, bed thicknesses, occurrence of interflood beds and bioturbation indexes, four different sub-environments within single mouth bars were distinguished. These range from mouth-bar axis, off-axis, fringe to distal-fringe deposits, which reflect waning depositional energy with increasing distance from the distributary channel mouth. The interpreted mouth-bar components also show internal variability in dominant process regime, with overall river dominance but local preservation of tide influence in the fringe and distal fringe components. Mouth-bar deposits amalgamate to form an extensive sand-rich sheet body throughout the study area, in which interflood mudstone to very-fine grained sandstone beds are nearly absent. These features reflect successive coalescence of mouth bars in a low accommodation/supply (A/S) setting. These conditions promoted recurrent channel avulsion/bifurcation and thus the potential reworking of previously deposited mouth-bar

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fringe and distal-fringe sediments, where time and background processes are better recorded. Results of this study evidence internal process-regime variability within mouth-bar components. They also caution against the possible loss of preservation of subordinate coastal processes (e.g. tidal indicators), and consequent underestimation of the true mixed influence in low-accommodation deltaic settings.

KEYWORDS

Coastal processes, Dakota Group, delta, interflood beds, low accommodation, mouth bar, preservation

1 | INTRODUCTION

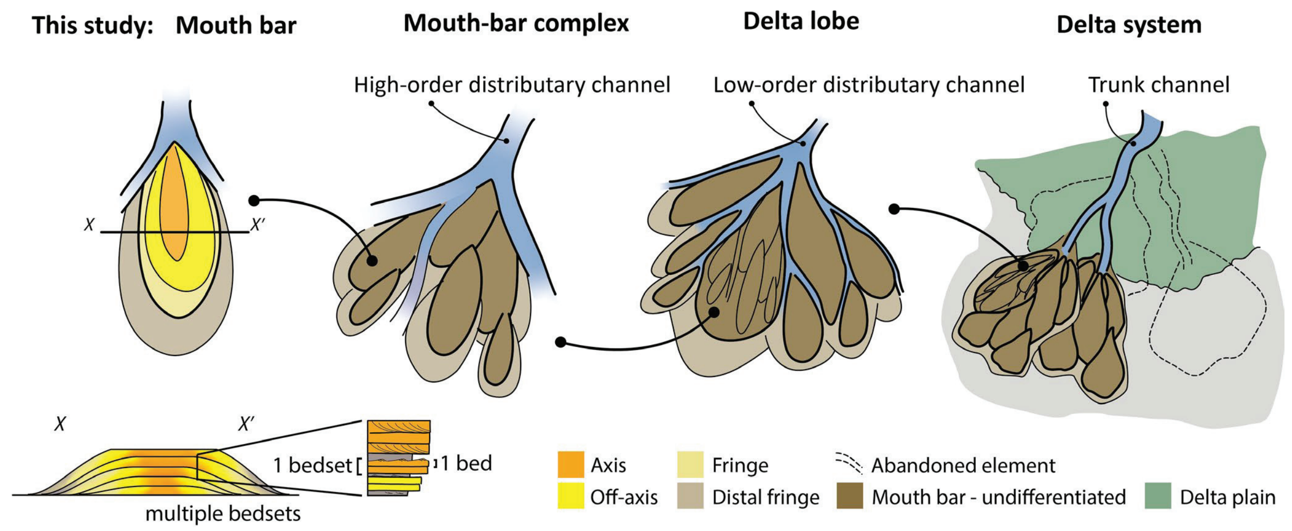
Mouth bars are fundamental architectural elements of proximal deltaic successions. They form at the river mouth, where flows confined within a distributary channel expand and decelerate as they enter a standing body of water (Bates, 1953; Wright, 2019; Elliott, 1986). The plan-view, cross-sectional geometry and scale of mouth bars is controlled by the relative dominance of coastal processes, influencing their shape and typical aspect ratio (length/width) (Wright, 2019; Postma, 1990; Bhattacharya, 2006; Gani and Bhattacharya, 2007). Additionally, increased bedload and/or shallower receiving water depths result in broad mouth-bar deposits, as enhanced effects of bed friction accelerate spatial expansion and deceleration of the river jet (Wright, 2019). Mouth-bar depositional cycles consist of deposition, extension, avulsion and abandonment (Olariu and Bhattacharya, 2006). Numerical modelling suggests that individual mouth bars prograde until the water depth over the bar is equal to or less than 40% of the inlet depth, after which aggradation becomes dominant and river flow is diverted around the bar (Edmonds and Slingerland, 2007). This forces bifurcation and/or avulsion, which leads to the initiation of new mouth-bar deposition (Olariu and Bhattacharya, 2006; Edmonds and Slingerland, 2007; Bhattacharya, 2010). High sediment supply and/or low-accommodation settings accelerate these mouth-bar depositional cycles, as less sediment is needed to reach the critical bar thickness for flow bifurcation (Van Yperen *et al.*, 2019a).

Mouth bars consist of one or multiple bedsets, in turn composed by a succession of beds that reflect flood and interflood variations in flow conditions and sediment input (Figure 1) (Dalrymple *et al.*, 2015; Gugliotta *et al.*, 2016a). Finer-grained facies (i.e. 'interflood beds') deposit during times of low energy between river flood periods, whereas 'river flood beds' tend to be thicker and consist of coarser-grained facies deposited during times of high river discharge. These are amalgamated towards the top and dominant in proximal mouth bars, whereas interflood beds occur predominantly at mouth-bar fringes (Dalrymple *et al.*, 2015; Gugliotta *et al.*, 2016a). If a depositional system or zone experiences only weak tidal energy, tidal indicators have highest preservation potential in the interflood beds (Gugliotta *et al.*, 2016b; Kurcinka *et al.*, 2018). These also tend to represent more time than river flood deposits (Miall, 2015).

Mouth-bar beds represent individual clinothems, and stack into bedsets (clinothem sets) forming basinward-accreting bar-front sand bodies (Figure 1) (Gani and Bhattacharya, 2007) emanating from a relatively fixed distributary channel mouth (Wellner *et al.*, 2005). Individual mouth bars coalesce and stack compensationally to form mouth-bar complexes (Figure 1) (Wellner *et al.*, 2005; Enge *et al.*, 2010). Mouth-bar complexes are related to the same progradation pulse (Ainsworth *et al.*, 2016) and their distributary channel network is genetically linked (Wellner *et al.*, 2005). Delta lobes consist of mouth-bar complexes related to the same primary distributary feeder channel (Ainsworth *et al.*, 2016). At both mouth-bar complex and delta lobe scale, individual mouth bars typically become smaller and finer grained as the distributary channel network progrades (Wellner *et al.*, 2005). The amalgamation of mouth bars into mouth-bar complexes and delta lobes is the building mechanism for deltas, and avulsion and/or bifurcation are the driving forces for their progradational and lateral development (Edmonds and Slingerland, 2007).

A growing number of studies document the variability within delta front deposits (Fielding *et al.*, 2005; Olariu and Bhattacharya, 2006; Gani and Bhattacharya, 2007; Enge *et al.*, 2010; Ainsworth *et al.*, 2016; Fidolini and Ghinassi, 2016; Jerrett *et al.,* 2016). However, internal differentiation of ancient individual mouth bars is uncommon (Enge *et al.*, 2010; Fidolini and Ghinassi, 2016; Jerrett *et al.*, 2016), whereas it is common to distinguish axis, off-axis, fringe and distal fringe sub-environments in deep-water fan lobe deposits (Hodgson, 2009; Prélat *et al.*, 2009; Hofstra *et al.*, 2016; Spychala *et al.*, 2017). Detailed work on modern deltas shows predictable grain size and bedform trends within individual mouth-bar deposits (Wellner *et al.*, 2005), with facies associations showing an overall waning in flow energy away from the central axis.

This study analyses the proximal deltaic expression of the exhumed Cenomanian Mesa Rica Sandstone (Dakota Group, Western Interior Seaway, USA), with the aim to: (a) describe and analyse the spatial distribution of sedimentary



(Stream) mouth bar	Mouth-bar complex / Bar assemblages	Delta lobe	Enge *et al*., 2010
Mouth bar	Mouth-bar complex	Delta lobe	Kurcinka *et al*., 2018 Jerrett *et al*., 2018
Jet deposit	Jet-deposit complex / Sub-lobe	Delta lobe	Wellner *et al*., 2005
Mouth-bar element set	Mouth-bar element complex	Element complex set	Ainsworth *et al*., 2016

FIGURE 1 Coalescence of individual mouth bars forms mouth-bar complexes and delta lobes, which together form the building blocks of a delta system. Mouth-bar complexes are related to the same pulse of progradation and their shallow distributary channel network are genetically linked. Delta lobes consist of mouth-bar complexes related to the same primary distributary feeder channel. Note that the occurrence/preservation of fringe deposits is limited in proximal areas at all scales. Terminology used in previous works and cited in the text is listed

facies and stratigraphic architecture; (b) distinguish and discuss different processes and deposits from internal mouth-bar components; and (c) discuss the role of low-accommodation conditions in resulting deltaic geometries and preservation potential of interflood deposits.

2 | GEOLOGICAL SETTING AND STRATIGRAPHIC FRAMEWORK

The Mesa Rica Sandstone (hereafter referred to as 'Mesa Rica') was deposited during the Cenomanian (*ca* 98 to 99 Ma, Scott *et al*., 2018) and is the oldest formation within the Dakota Group in Colorado and New Mexico (Holbrook and Wright Dunbar, 1992; Scott *et al*., 2004). The Dakota Group is among the eastward prograding sedimentary systems of the US Western Interior that were sourced from the Sevier fold-and-thrust belt (MacKenzie and Poole, 1962; Pecha *et al*., 2018). The latter formed during the Cordilleran orogeny, due to subduction of the Farallon plate beneath the west coast of North America causing back-arc compression in the Late Jurassic (DeCelles, 2004). The Dakota Group also received minor sediment volumes from other smaller topographic highs (Kisucky, 1987; Holbrook and Wright Dunbar, 1992). The study area is located at the north-western rim of the Tucumcari Basin (Figure 2A), which formed during the late Carboniferous and early Permian as a tectonic element of the Ancestral Rocky Mountains (Broadhead, 2004).

An overall NW to SSE-directed depositional profile characterises the Dakota Group in south-east Colorado and north-east New Mexico. The Dakota Group is further subdivided into the Mesa Rica, Pajarito (Dry Creek Canyon member in south-central Colorado and north-eastern New Mexico) and Romeroville formations. These represent phases of predominantly fluvial, paralic and fluvial deposition, respectively (Figure 2B). Regional sequence boundary SB3.1 (Figure 2B) forms the base of the Mesa Rica and relates to a Late Albian–Early Cenomanian forced-regression, which caused widespread erosion in south-east Colorado and north-east New Mexico (Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Holbrook, 2001; Scott *et al*., 2004; Oboh-Ikuenobe *et al*., 2008). In east-central New Mexico, only the Mesa Rica and Pajarito formations are preserved, and the former can be in turn subdivided into the lower, middle and upper Mesa Rica (Figure 2B,C) (Scott *et al*., 2004; Holbrook *et al*., 2006; Van Yperen *et al*., 2019b). These subdivisions relate to depositional transgression–regression (T–R) cycles and

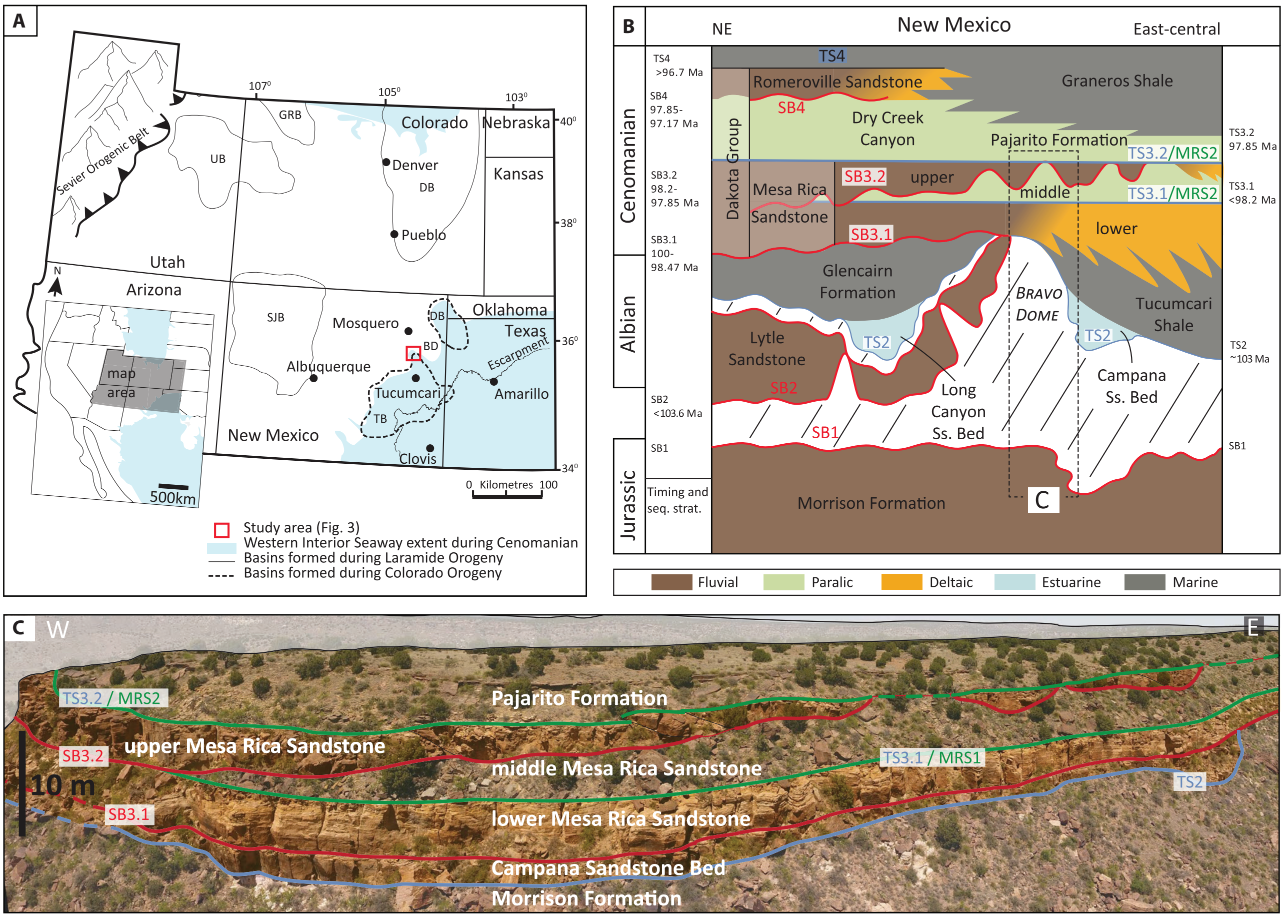


FIGURE 2 (A) Regional map of the Western Interior during the Early–Late Cretaceous (Albian–Cenomanian) showing the approximate extent of the Western Interior Seaway extent (light blue, Blakey, 2014) and main basins that formed during the Laramide Orogeny and Colorado Orogeny (modified after Van Yperen *et al.*, 2019a). The study area is situated at the rim of the Tucumcari Basin (red square). GRB = Green River Basin; UB = Uinta Basin; DB (Colorado) = Denver Basin; SJB = San Juan Basin, TB = Tucumcari Basin; DB (New Mexico) = Dalhart Basin; BD = Bravo Dome. (B) Chronostratigraphic chart for the Jurassic to Cenomanian successions in north-eastern (NE) and east-central New Mexico. References used for compilation; Waage, 1955; Holbrook *et al.,* 2006; Oboh-Ikuenobe *et al.*, 2008; Van Yperen *et al.*, 2019a, b). Albian-Cenomanian boundary from Scott *et al.*, (2018). (C) Photograph showing the stratigraphy in the study area (modified after Van Yperen *et al.,* 2019b). Maximum Regressive Surfaces (MRS1, MRS2) are used as a datum for correlation (see Figure 9). Abbreviations: MRS, Maximum Regressive Surface; SB, sequence boundary, TS = transgressive surface

record higher frequency relative sea-level fluctuations in the Western Interior Seaway (Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Scott *et al.*, 2004; Oboh-Ikuenobe *et al.*, 2008). In the Tucumcari Basin, the open marine Albian–Cenomanian Tucumcari Shale separates the underlying fluvial Jurassic Morrison Formation from the overlying deltaic, Cretaceous Mesa Rica (Figure 2B) (Holbrook and Wright Dunbar, 1992; Scott *et al.*, 2004; Van Yperen *et al.*, 2019a). The Tucumcari Shale is locally underlain by transgressive deposits of the informally defined Cretaceous Campana Sandstone Bed (hereafter referred to as 'Campana') (Figure 2B,C) (Holbrook *et al.*, 1987; Holbrook and Wright Dunbar, 1992). This represents the sandy infill of local topographic lows, as the Late Jurassic landscape was progressively inundated during relative sea-level rise (Holbrook *et al.*, 1987).

The study area is situated at the north-western rim of the Tucumcari Basin (Figure 2A). Here, the lower Mesa Rica shows a transition from fluvial to the most proximal shallow-marine deposition within the Mesa Rica depositional system (Holbrook and Wright Dunbar, 1992; Van Yperen *et al.*, 2019b). Upstream of the study area, time-equivalent fluvial strata record deposition of a single-storey channel sheet, which is continuous over >80 km width (Holbrook, 1996; Holbrook, 2001). Downstream, coalesced mouth bars consistently overlain by sand-filled amalgamated distributary channels characterize the contemporaneous deltaic deposits within the central Tucumcari Basin (Van Yperen *et al.*, 2019a). The upper Mesa Rica represents a lower delta plain environment with fluvial distributary channel deposits (Scott *et al.*, 2004; Holbrook *et al.*, 2006) and an increased presence of marine-influenced distributary channel deposits towards the centre of the basin

(Van Yperen *et al.*, 2019a). During the Cretaceous, the study area was located at ~35° N latitude, with a prevailing warm and humid climate (Chumakov *et al.*, 1995).

3 | METHODS AND DATA

Because the main objective of this work is the recognition of internal architecture of ancient deltaic sandstone bodies, the field study focused on the lower Mesa Rica. However, the upper Mesa Rica and the stratigraphic relationships with underlying and overlying strata in the study area are also briefly reported in the results below to provide stratigraphic context.

Stratigraphic sections were measured at 1:100 cm scale (18 logs) and 1:200 cm scale (4 sketch logs) within a *ca* 25 km^2 area, at the Trigg Ranch in San Miguel County, east-central New Mexico (Figure 3). Six of these logs have been used in a previous publication (Van Yperen *et al.*, 2019b). However, a more detailed and extensive sedimentological analysis and focus on sedimentological concepts, principles and application thereof, distinguishes this study from the recently published revision of Cretaceous stratigraphy in the same study area (Van Yperen *et al.*, 2019b).

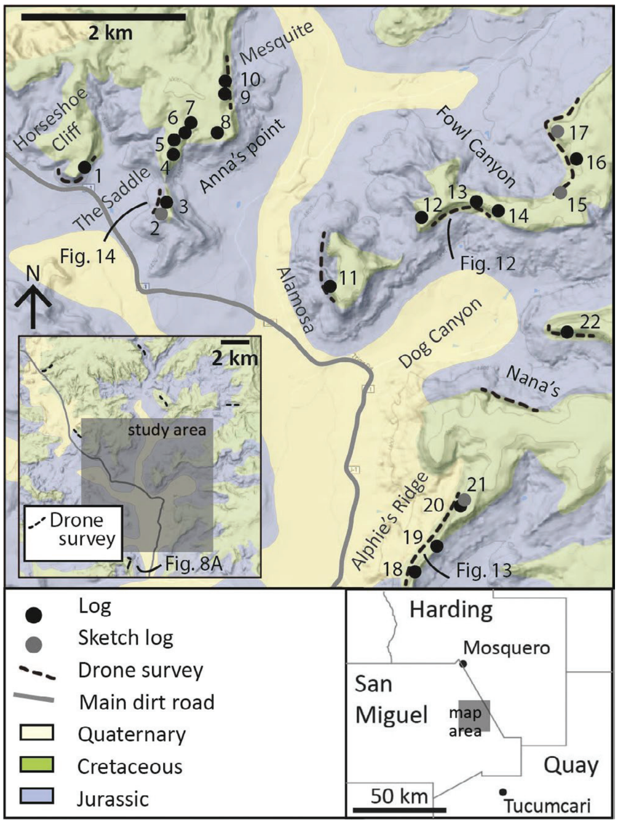


FIGURE 3 Geologic map of the study area around the Trigg Ranch, in San Miguel County, showing the outcrop extent and location of the collected dataset. Drone data was collected outside the main study area as well (see inset). Locations of the photopanoramas in Figures 8A, 13, 14 and 15 are also indicated

Sedimentary facies analysis was based on lithology, texture, sedimentary structures and bioturbation assemblage and intensity. The bioturbation intensity was recorded using the 1–6 bioturbation index (BI) scheme of Taylor and Goldring (1993). Unmanned aerial vehicle (UAV) imagery (shot with a DJI Phantom 4 Pro®), photomontages and field sketches are used to map sedimentary body geometries, lateral distributions, architectural elements and extension of key stratigraphic surfaces. These form the basis for correlation of constructed depositional dip-parallel (*ca* 6.5 km) and along-strike (*ca* 4 km) panels. Palaeocurrent measurements ($N = 260$) were obtained from cross-stratification and cross-lamination ripple foresets.

4 | FACIES ANALYSIS

The studied strata are divided into 13 facies (f1–13) based on observations of lithology, grain size, sedimentary structures, palaeocurrents, bioturbation indices and interpreted depositional processes (Table 1, Figures 4–8). The facies were grouped into nine facies associations (FA1–9) that reflect different environments of deposition, based on the combination of dominant sedimentary processes (facies), bioturbation intensity and lateral and vertical facies relationships.

4.1 | FA1—Prodelta

4.1.1 | Description

Grey, structureless muddy siltstone (f1, Table 1). FA1 thicknesses average 0.3–0.7 m (max. 2 m thick). Bioturbation indices are high (BI 4–5) with *Thalassinoides*, *Phycosiphon*, *Planolites*, *Teichichnus*, *Chondrites* and *Helminthopsis* identified (Figure 6A). Macrofauna was not observed. FA1 is commonly found in sharp contact with overlying delta front deposits (FA2–5).

4.1.2 | Interpretation

Deposition occurred below storm-weather wave base, in a low-energy setting beyond the influence of the river effluent (Wright and Coleman, 2019; Gani *et al.*, 2009). The stratigraphic position of FA1 in the study area makes it equivalent to the open marine Tucumcari Shale, with abundant macrofauna (e.g. *Texigrapheya*, *Peilina levicostata*) within the Tucumcari Basin (Scott, 1974; Holbrook and Wright Dunbar, 1992; Kues, 1997; Oboh-Ikuenobe *et al.*, 2008). In the study area however, a shallower setting is inferred from its thin and silty nature and lack of macrofauna indicative of open marine settings (Holbrook *et al.*, 1987; Kisucky, 1987;

TABLE 1 Summary of facies (f) in the studied interval at the Trigg Ranch study area, east-central New Mexico

	Description	Grain size	Structures	Biogenic structures	Interpretation
f1	Muddy siltstone	Mud—Si	Structureless, grey or grey-brown muddy siltstone. In places fissile. Max 5 m thick. Commonly vegetated	BI 4–6: *Phycosiphon, Thalassinoides, Planolites, Teichichnus, Chondrites, Helminthopsis*. Locally, no bioturbation observed	Suspension fallout, low sedimentation rates in an open marine setting (bioturbated), or brackish setting (non-bioturbated)
f2	Conglomerate	Cgl	Sharp-based, clast-supported, conglomerate, often crudely stratified. No or normal grading. Sub-angular to sub-rounded, poorly to moderately sorted extrabasinal and intrabasinal clasts, average ø 0.5–2 cm (max ø 6 cm). Extrabasinal clasts are predominantly quartz and chert. Fine-grained to medium-grained matrix. Bed thickness 10–30 cm	BI 0–2: *Ophiomorpha*	Predominantly deposition from high-density turbidity currents. When grading and stratification is absent; deposition from debris flows transitional to high-density turbulent flow
f3	Structureless sandstone	VF—F	Erosional, sharp-based, structureless sandstone with normal grading. Bed tops exhibit asymmetrical ripples locally. Bed thickness 5–80 cm	BI 0–5: *Ophiomorpha*, *Skolithos*, *Thalassinoides*, *Conichnus*, *Palaeophycus*, *Rosselia*. High BI-indices on horizontal bedding planes	Lack of structure might be due to intensive surface weathering. Rapid suspension fall out. Waning flow energy when rippled top surface
f4	Parallel-laminated sandstone	VF—F	White and brown sharp-based and sharp-topped, parallel-laminated sandstone. Bed tops exhibit asymmetrical ripples locally. Bed thickness 20–70 cm	BI 0–3: *Skolithos*, *Ophiomorpha*, *Rosselia*	Upper flow conditions
f5	Tabular cross-stratified sandstone	VF—M	Sharp-based and sharp-topped, local lower erosive base, planar and tangential tabular cross-stratified sandstone. Locally, bidirectional. Bed thickness 20–50 cm. In places organized in low-angle accretionary packages. Local wood-remains	BI 0–4: *Ophiomorpha*, *Skolithos*, *Thalassinoides*, *Conichnus*, *Palaeophycus*, *Rosselia*. High BI-indices on horizontal bedding planes	Migrating straight-crested or sinuous dunes with and without flow separation, lower flow regime
f6	Pebbly sandstone	F—F—M	Pebbly sandstone with trough and tangential cross-stratification. Intra- and extrabasinal pebbles, average ø 0.5–1 cm (max diameter 3 cm). In places organized in low-angle accretionary packages	Not observed	High-energy unidirectional traction currents and bed load deposition
f7	Parallel-laminated siltstone	Si—VF	Parallel-laminated siltstone, in places mud-draped. 1–20 cm thick	BI 5–6: undifferentiated Locally, no bioturbation observed	Gentle flow activity with potential tide-influence
f8	Asymmetrical ripple-laminated siltstone to sandstone	VF—F	Unidirectional current ripples in sharp-based sandstone beds. Sparse climbing and/or sigmoidal ripples. Bed thickness 3–40 cm	BI 0–3*: Skolithos*, *Ophiomorpha*, *Macharonichnus*	Migrating straight-crested ripples. Lower flow regime. Climbing ripples indicate high rates of deposition

(Continues)

TABLE 1 (Continued)

	Description	Grain size	Structures	Biogenic structures	Interpretation
f9	Thoroughly bioturbated sandstone	Si—F	Bioturbation obliterates original sedimentary features and bed boundaries. 20 cm–3 m thick	BI 5–6: *Thalassinoides*, *Ophiomorpha*	Bioturbation favourable conditions (optimized oxygen, salinity, temperature)
f10	Trough cross-stratified sandstone	F—M	Single to several sets of trough cross-bedding. Set thickness 15–110 cm	Not observed	Migrating sinuous or linguoid dunes. Lower flow regime
f11	Pebble lag	Cgl	Erosional basal surface with extrabasinal clasts in a finer sandstone matrix. Clast-supported or matrix-supported, subangular to subrounded. Includes mud to silt rip-up clasts and/or wood debris locally	Not observed	High-energy fluvial channel base. When situated at the base of facies structureless or muddy siltstone, potential lag formed by wave-erosion and reworking
f12	Palaeosol	Si—Vf	Purple siltstone with grey rhizoliths and yellow mottling. Yellow-grey siltstone with yellow mottling. Locally, soil development overprints parallel-laminated sandstone	Mottling, rhizoliths	Subaerial exposure, post-deposition weak to moderate pedogenic development
f13	Flaser bedding	VS—F	Ripple- and dune-scale cross-stratified sandstone with single or double mud drapes. Locally, climbing ripples and/ or bidirectional ripples	BI 0–1: unidentified	Current reversals in subtidal zone. Climbing ripples indicate high rates of deposition

Holbrook and White, 1998). The trace fossils indicate brackish to normal marine conditions (MacEachern and Bann, 2008).

4.2 | FA2—Mouth-bar axis

4.2.1 | Description

FA2 consists of two sub-divisions: FA2.a consists of laterally extensive sandstone beds with a tabular nature, and display an alternation of f2 with f3, f4 and/or f5 (Figure 7A, Table 1). Bed boundaries are predominantly sharp. Facies f2 consists of 10–30 cm thick, poorly sorted, clast supported conglomerate beds with common (faint) stratification (Figure 4A). Facies f3 consists predominantly of 30–50 cm thick, fine-grained structureless sandstone beds, and rare planar lamination (f4) and cross-stratification (f5). Conglomerate beds become increasingly amalgamated upwards and grade into better sorted, trough and tangential cross-stratified pebbly sandstone (f6; Figure 4B, Table 1). *Ophiomorpha* trace fossils (BI 0–2) occur predominantly in the upper part of the structureless sandstone beds (Figure 6B). FA2.b consists of 40–60 cm thick cross-stratified (f5) and parallel-laminated (f4) sandstone, with common soft-sediment deformation and an absence of mud. In places, dispersed granules occur in cross-stratified sandstone beds.

FA2 units are 8–10 m thick, revealing *ca* 8° dipping accretionary strata in places, and grade laterally into FA3 (mouth bar—off-axis). FA2 is locally eroded and overlain by FA6 (distributary channel deposits).

4.2.2 | Interpretation

The sediments of FA2 are associated with high-energy deposition close to the river mouth (Wright, 2019; Enge *et al.*, 2010; Fidolini and Ghinassi, 2016). More specifically, FA2.a deposits are interpreted as related to hyperpycnal flow conditions (sensu Mulder *et al.*, 2003; Zavala *et al.*, 2011) because of their position in the sedimentary system, grain size and an alternation of different conforming facies that reflect recurring deposition from different flow types, with dominance of gravity-flow processes (Talling *et al.*, 2012). Deposition from debris flows transitional to high-density, stratified turbulent flows is inferred from the clast supported conglomerate with faintly visible cross-stratification (f2) (Lowe, 1982; Zavala *et al.*, 2011; Talling *et al.*, 2012). Facies f2 alternates with high-density and low-density turbidity currents, as inferred from the structureless (f3) and/or planar laminated or cross-stratified sandstone (f4, f5), respectively. The upward-increasing amalgamation of conglomerate beds throughout FA2 represents an increase in energy and is interpreted as mouth-bar

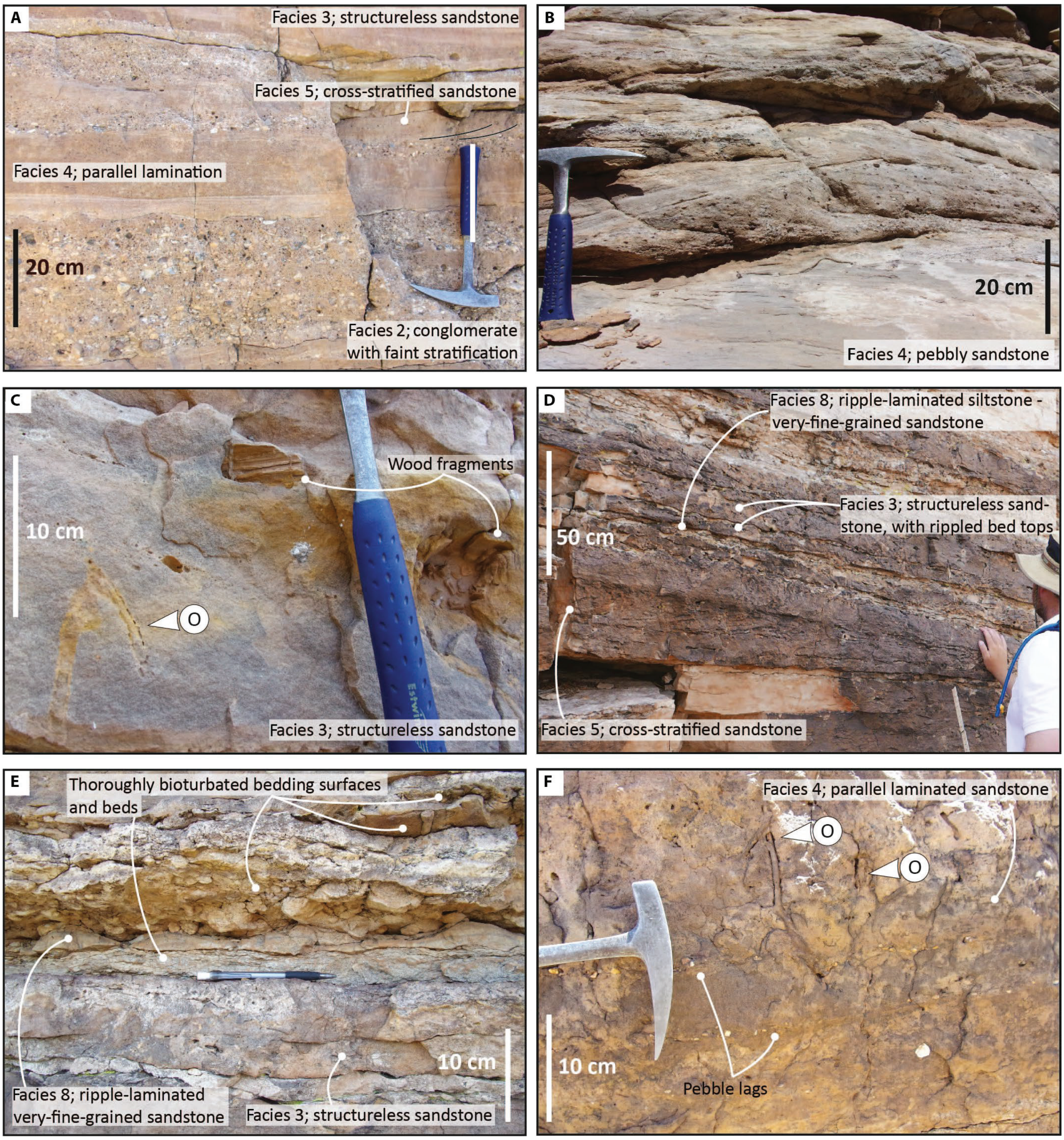


FIGURE 4 Photographs of selected facies (Table 1). (A) Clast supported conglomerate (f2) alternating with structureless sandstone (f3) and/or planar lamination (f4) or cross-stratification (f5). The contact represents an erosive surface related to the reworking of successive bypassing events. This facies assemblage occurs in axial mouth-bar deposits (FA2). (B) Trough cross-stratified pebbly sandstone (f6) in axial mouth-bar deposits (FA2). Common in off-axis deposits (FA3) as well. (C) Structureless sandstone (f3) with wood fragments and low index bioturbation (BI 1) in mouth-bar off-axis deposits (FA3). Common in mouth-bar fringe deposits (FA4) as well. O = *Ophiomorpha*. (D) Thin to thick-bedded (5–40 cm), fine-grained structureless sandstone (f3) and cross-stratified sandstone (f5) in mouth-bar fringe (FA4) deposits. Interbedding with asymmetrical ripple-laminated sandstone (f8). (E) Structureless sandstone (f3) interbedded with asymmetrical ripple-laminated sandstone (f8), with high-index bioturbation on horizontal bedding planes. This is typical for mouth-bar fringe deposits (FA4). (F) Bioturbated parallel laminated sandstone (f4) with scattered pebble lags in mouth-bar fringe deposits (FA4). O = *Ophiomorpha.* 15 cm pencil and 33 cm hammer for scale

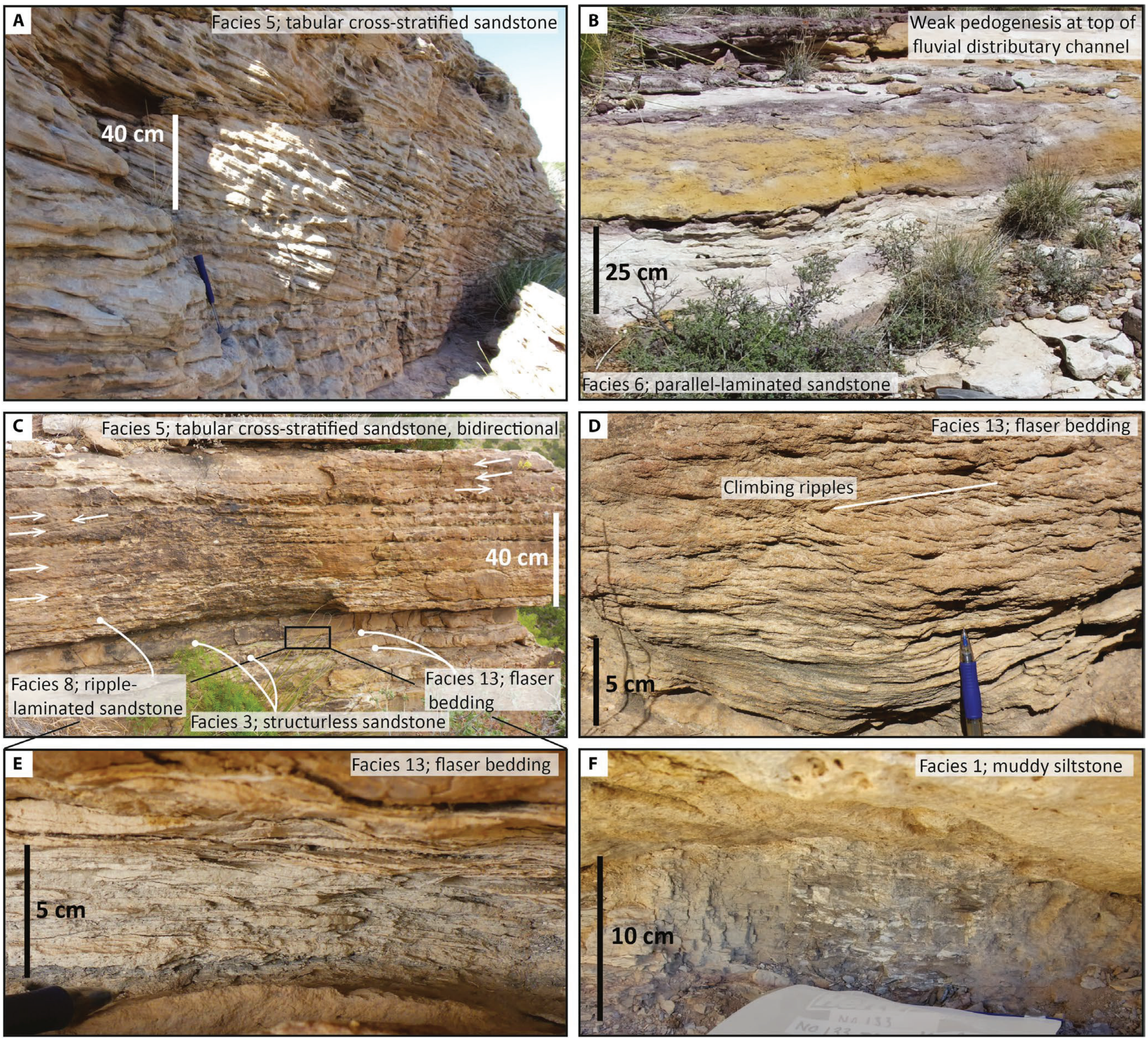


FIGURE 5 Photographs of selected facies (Table 1). (A) Bedsets of tabular cross-stratified sandstone (f5) in fluvial distributary channel-fill deposits (FA6). (B) Weak pedogenesis overprinting parallel-laminated sandstone (f6) at the top of a fluvial distributary channel fill (FA6). (C) Tide-influenced distributary channel-fill deposits (FA7), with bidirectional tabular cross-stratified sandstone (f5) and ripple-laminated sandstone (f8), overlying sand-dominated heterolithic deposits (f3, f13). (D) Flaser bedding (f13) with climbing ripples and upwards-increasing sand content, in tide-influenced distributary channel-fill deposits (FA7). (E) Zoom-in of c, with detail of flaser bedding (f13). (F) Grey-brown muddy siltstone (f1), interpreted as part of interdistributary bay deposits (FA8). Note 15 cm pencil and 33 cm hammer for scale

progradation. Eventually, a decreased depth over the mouth bar causes flow deceleration (Edmonds and Slingerland, 2007), which explains the vertical transition from conglomerate beds into pebbly sandstone that reflect lower energy. Lack of finer-grained facies indicates an absence of interflood beds. The sparse occurrence of *Ophiomorpha* trace fossils supports the interpretation of a marine setting with proximity to the river outlet.

FA2.b lacks any marine indicators. However, the interpretation of mouth-bar deposition close to the river outlet is supported by the gradual lateral facies change into FA3, the local arrangement in dipping accretionary strata, and the lack of erosional channel-shaped surfaces. The soft-sediment deformation is consistent with high sedimentation rates, which matches the interpretation.

FA2.a is dominated by gravitational-flow processes, whereas FA2.b by bedload deposition. Despite their different dominant depositional processes, they both represent a closer position relative to the feeding channel than the deposits assigned to FA3–5. This is based on the complete lack of interflood deposits (FA2.a and FA2.b) and low (FA2.a) to absent (FA2.b) bioturbation.

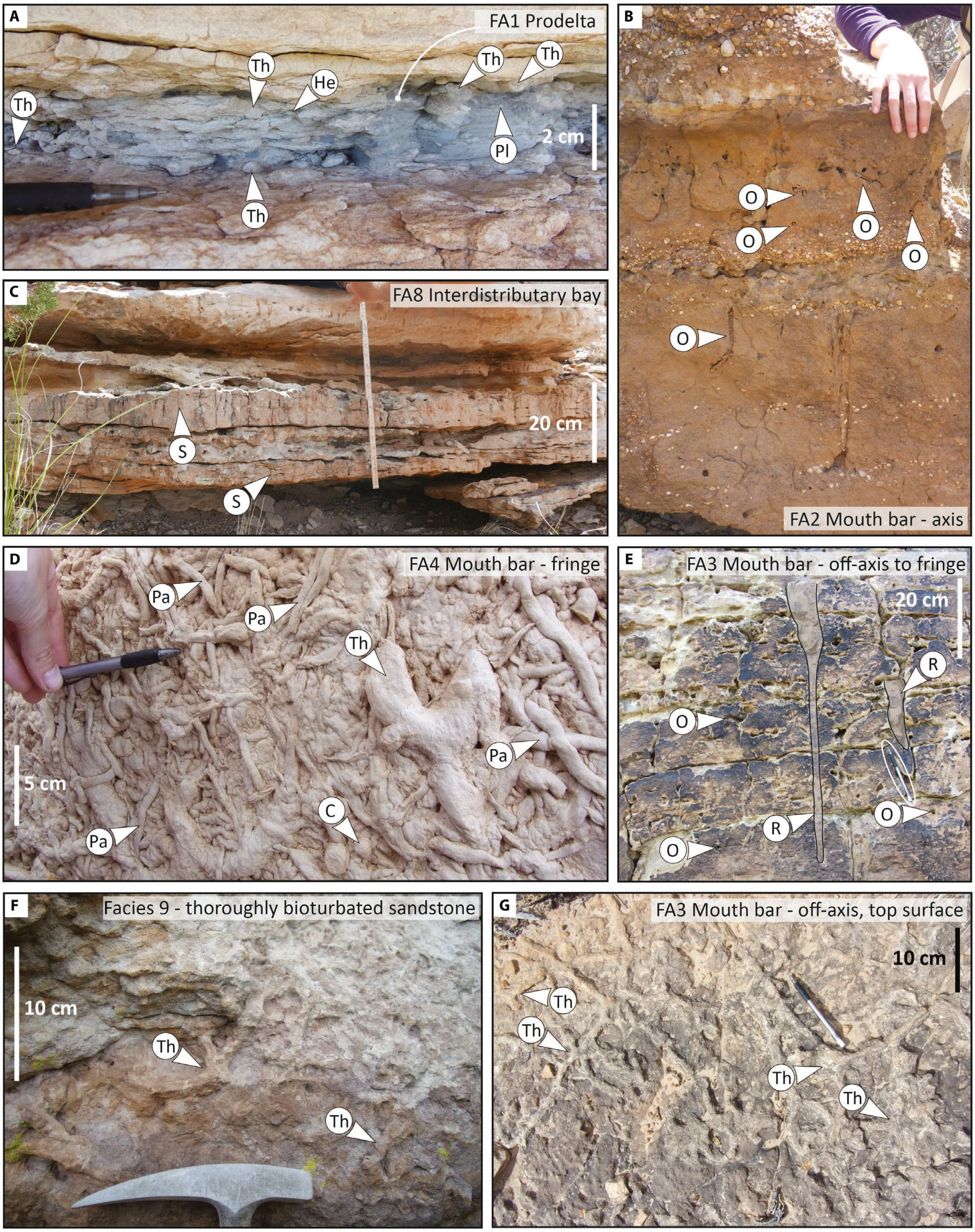

A
FA1 Prodelta
Th
He
Th
Th
Th
Pl
2 cm
Th
B
O
O
O
O
O
FA2 Mouth bar - axis
C
FA8 Interdistributary bay
20 cm
S
S
D
FA4 Mouth bar - fringe
Pa
Pa
Th
5 cm
Pa
C
Pa
E
FA3 Mouth bar - off-axis to fringe
20 cm
R
O
O
R
O
F
Facies 9 - thoroughly bioturbated sandstone
10 cm
Th
Th
G
FA3 Mouth bar - off-axis, top surface
10 cm
Th
Th
Th
Th

FIGURE 6 Photographs of selected ichnotaxa. (A) Muddy siltstone with BI 4–5 in prodelta deposits (FA1). (B) Alternating conglomerate (f2) and structureless sandstone (f3) with non-uniform BI 0–3 in axial mouth-bar deposits (FA2). (C) Structureless sandstone beds with bed tops that exhibit asymmetrical ripples (f3) interbedded with silt to very-fine-grained sandstone (f7). Trace fossils include *Skolithos* and several undefined traces. This facies and trace fossil assemblage occur in interdistributary bay deposits (FA8). (D) High-index (BI 4–5) bioturbation at a basal bedding plane in mouth-bar fringe deposits (FA4). (E) Low-diversity trace fossil suite in mouth-bar off-axis to fringe deposits (FA3, FA4). (F) Thoroughly bioturbated sandstone (BI 5–6) in which traces are only sporadically identifiable. (G) Bioturbated top surface in mouth-bar off-axis deposits (FA3). Th = *Thalassinoides*, He = *Helminthopsis*, Pl = *Planolites*, S = *Skolithos*, O = *Ophiomorpha*, Pa = *Palaeophycus*, C = *Conichnus*, R = *Rosselia*. 15 cm pencil and 33 cm hammer for scale

4.3 | FA3—Mouth-bar off-axis

4.3.1 | Description

FA3 (Figure 7B) consists of very fine to fine-grained, 20–50 cm thick sandstone beds that are structureless (f3, Table 1; Figure 4C) or show parallel lamination and tabular cross-stratification (f4, f5, respectively). Soft-sediment deformation, wood fragments and stringers of extrabasinal clasts (up to 4 cm in diameter) are common. The lower part of FA3 displays rare interbedded siltstone to very fine-grained sandstone (f7). Pebbly cross-stratified sandstone (f6; Figure 4B) dominates the upper part. Sparse and low-diversity bioturbation (BI 0–2, *Ophiomorpha*) characterizes FA3 although rare horizontal bedding planes with BI 4–5 are present. A 20–50 cm thoroughly bioturbated sandstone bed (f9) is commonly found at the base of FA3.

FA3 units are 7–8 m thick with the upper part locally exhibiting low-angle dipping accretionary strata (*ca* 3° dip towards SSW). FA3 grades laterally into FA2 (mouth bar—axis) or FA4

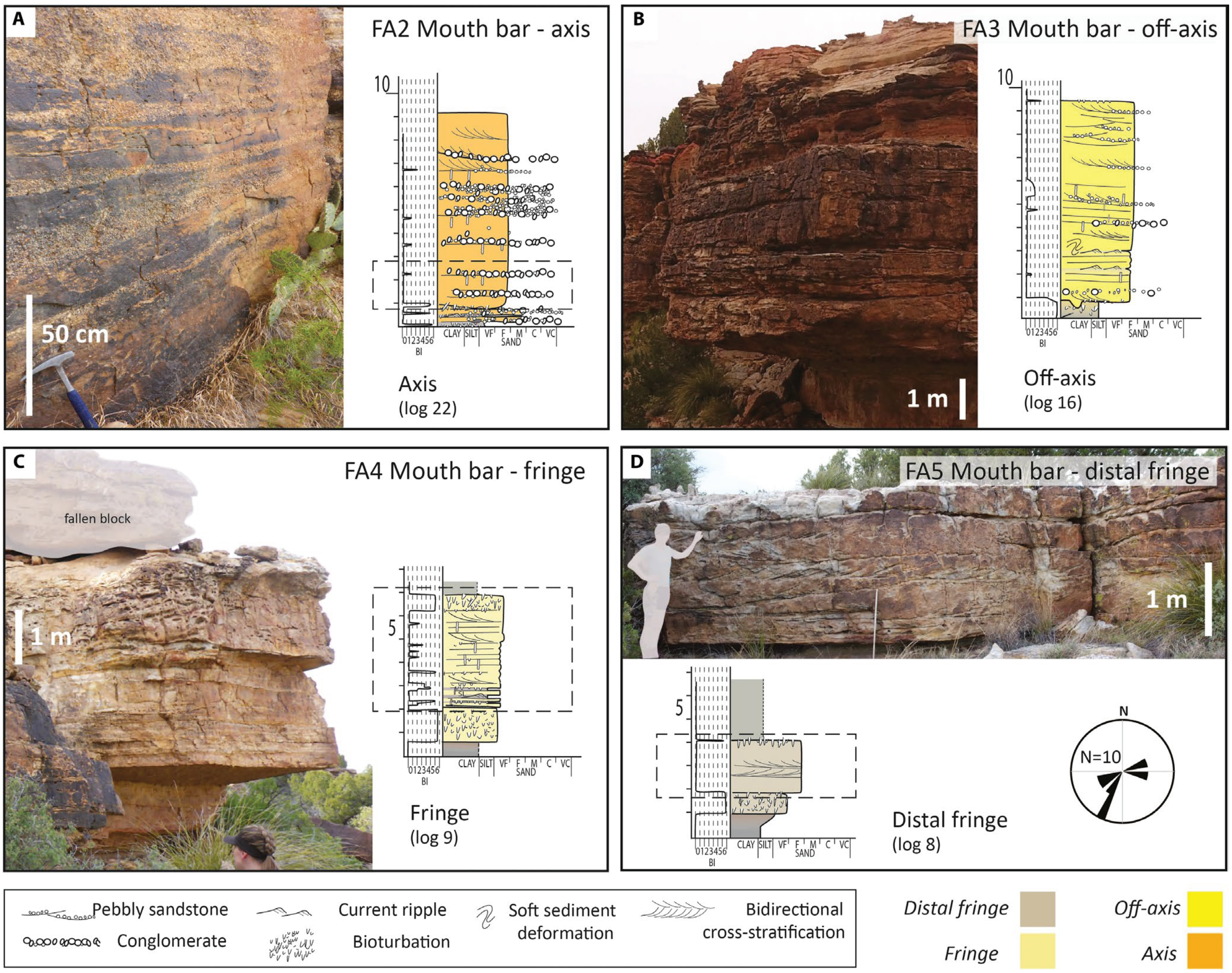


FIGURE 7 Mouth-bar facies associations (FA2–FA5) in the low-accommodation Mesa Rica deltaic system. Selected photographs show representative parts or complete logged sections of the different sub-environments referred to as 'axis' (FA2), 'off-axis' (FA3), 'fringe' (FA4), and 'distal fringe' (FA5). Bidirectional palaeocurrent measurements from distal fringe deposits (D)

FIGURE 8 Photographs of fluvial facies associations that occur in the S1 and S2 successions. (A) Fine-grained abandoned channel fill incising S1 mouth-bar deposits. Location: see Figure 3 inset map. (B) Multi-storey fluvial distributary channel (FA6) bound by composite erosional surface, within the S1. Location: Anna's point (Figure 3). (C) Interpretation and line drawing of B. The multi-storey fluvial body incises into the underlying Jurassic Morrison Formation. (D) Heterolithic deposits interpreted as tide-influenced distributary channel fill (FA7), in S2. Location: Fowl Canyon (Figure 3)

(mouth bar—fringe) and is locally eroded and overlain by FA6 (distributary channel deposits).

4.3.2 | Interpretation

The sedimentary features of FA3 also indicate high-energy deposition in a proximal mouth-bar setting (Wright, 2019; Enge *et al.*, 2010; Fidolini and Ghinassi, 2016). This is based on the coarsening-upward nature, the abundance of well-stratified sandstone, the accretionary architecture and abundant soft-sediment deformation. The latter indicates rapid deposition and dewatering by loading, typical for delta front deposition (Bann *et al.*, 2008). The predominantly absent to sparse bioturbation supports the interpretation of high sedimentation rates and proximity to a river outlet (MacEachern and Bann, 2008). The *Ophiomorpha* structures are also typical of high-energy settings as well (Pemberton *et al.*, 2001). The rare occurrence of thoroughly bioturbated horizontal bedding reflects short time-windows with reduced depositional energy (MacEachern and Bann, 2008), consistent with an off-axis environment. This indicates sparse interruptions of the otherwise high-energy depositional setting and is interpreted as recording interflood periods.

4.4 | FA4—Mouth-bar fringe

4.4.1 | Description

A sharp tabular (at outcrop-scale) nature characterises the thin to thick (5–40 cm), very fine to fine-grained sandstone beds of FA4 (Figure 4D). They are structureless (f2, Table 1), but show progressively more planar and tangential cross-stratification (f5) towards the top (Figure 7C), where trough and cross-stratified pebbly sandstone (f6; Figure 4B) is locally present. Sandstone beds are in places interbedded

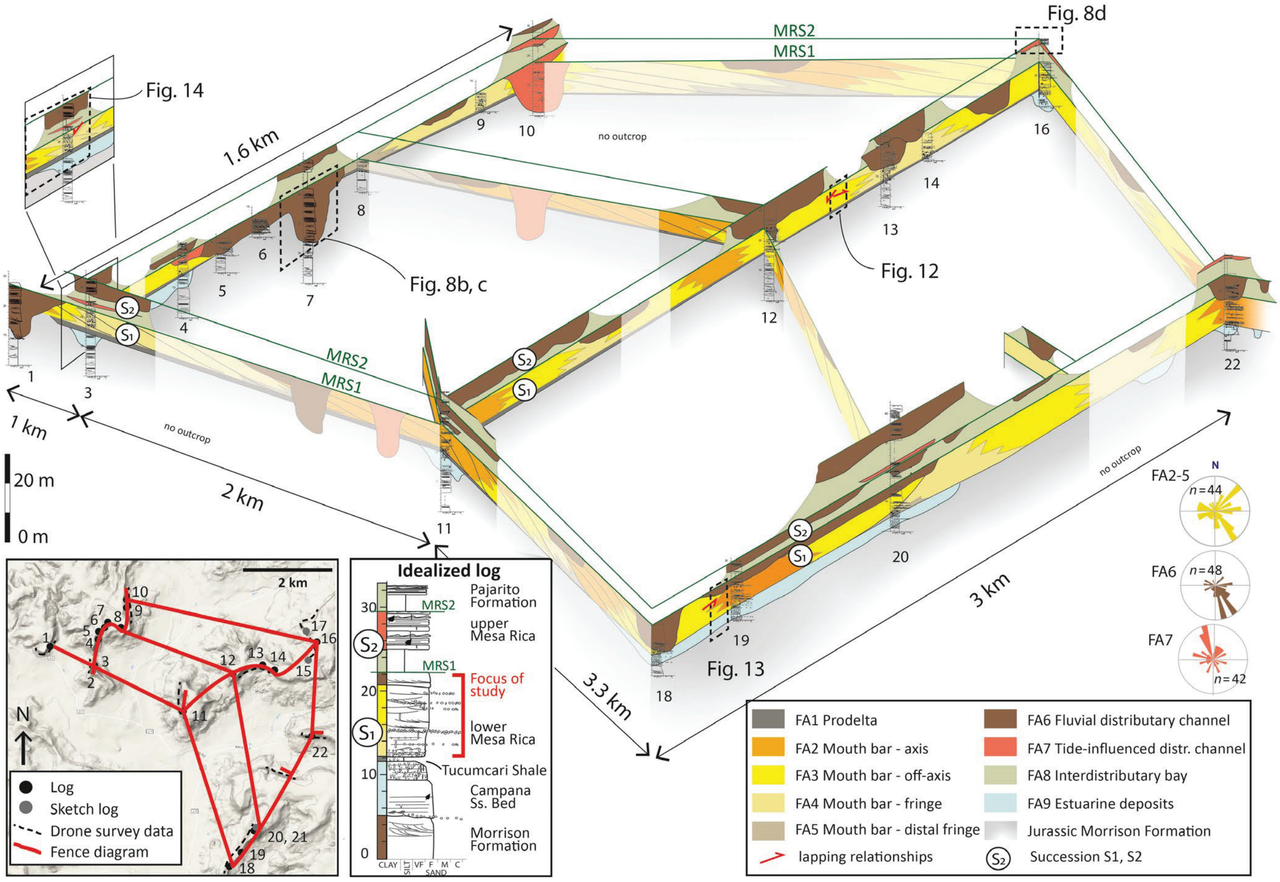


FIGURE 9 Correlation fence diagram illustrating spatial facies distribution offered by physical correlation and interpolation of strike-oriented cross-sections. Map shows the true orientation and distances, whereas the diagram is simplified to maximize clarity. Today's topography is visualized, except for the S1 succession because this is the main focus of the paper. The MRS2 is used as a datum for the fence diagram. Sketch logs are not depicted and rose diagrams display palaeocurrent data from S1 grouped according to facies associations. Abbreviation: MRS, Maximum Regressive Surface

with siltstone to very fine-grained sandstone (f3), with common asymmetrical ripples (f8) (Figure 5E). Mud-drapes are sparse. Stringers of extrabasinal clasts (up to 5 cm diameter) occur locally (Figure 5F). The BI varies (BI 0–5) and is characterised by a non-uniform but upwards-decreasing trend. High-index bioturbation is documented predominantly on horizontal bedding planes (Figure 7D) and/or in parallel-laminated siltstones (f7). Trace fossils observed are *Ophiomorpha*, *Thalassinoides*, *Conichnus*, *Palaeophycus*, *Macaronichnus*, *Teichichnus* and *Rosselia* (Figure 6E). Thoroughly bioturbated sandstone beds (0.3–2 m thick, f9; Figure 6F) occur locally at the base and/ or at the top of FA4.

FA4 units are 6–8 m thick and grade laterally into FA3 (mouth bar—off-axis) or FA5 (mouth bar—distal fringe). Fluvial deposits (FA6) incise into FA4 locally (Figure 8A).

4.4.2 | Interpretation

FA4 represents episodic deposition in a position farther from the river outlet than the previous FA2–3. This is based on the alternation of upper flow regime and lower flow regime bedforms and the non-uniform BI. The interbedded finer-grained facies were deposited during times of lower energy between river floods (i.e. 'interflood beds' cf. Dalrymple *et al.*, 2015; Gugliotta *et al.*, 2016a), with preservation of a minimal tide-influence. The occurrence of intensely bioturbated horizontal bedding planes and/or interflood beds also suggests longer recurrent times with stable conditions in between deposition of individual sandstone beds (Gani *et al.*, 2009). The upward-decreasing BI and local upward-increasing pebble content indicate bar progradation and consequent increasing proximity to the river mouth (MacEachern and Bann, 2008; Bhattacharya, 2010).

4.5 | FA5—Mouth-bar distal fringe

4.5.1 | Description

FA5 consists of thoroughly bioturbated siltstone or sandstone beds (0.4–2 m thick, f7, f9, Table 1) with or without overlying fine-grained sandstone beds with bidirectional cross-stratification (f6). These cross-stratified sandstone beds increase upwards in bed thickness from 10 to 40 cm, and bidirectionality is supported by palaeocurrent measurements (Figure 7D). These sandstone beds display no mud-draping or trace fossils. FA5 units are 3–4 m thick and are adjacent to FA4 (mouth bar—fringe).

4.5.2 | Interpretation

FA5 represents mouth-bar deposition with decreased river influence compared to FA2–4. The bidirectional dune-scale cross-stratification indicates that tidal currents were able to fully reverse the river outflow and suggest a strong tide-influence (cf. Martinius and Gowland, 2011). The bed thickness and lack of mud support a high energy level in which the slack water periods remained in motion. The dune-scale bidirectional cross-stratification potentially reflect an interplay between seasonal changes in ebb or flood-dominance and river discharge variation (Berné *et al.*, 1993). Low index bioturbation (BI 0–2) is common in tide-dominated intervals because such settings typically have salinity fluctuations, increased water turbidity, rapidly shifting substrates and narrow colonization windows associated with daily and monthly changes in tidal periodicity (Gani *et al.*, 2009).

4.6 | FA6—Fluvial distributary channel

4.6.1 | Description

FA6 consists of fine to medium-grained sandstone bodies composed of 10–100 cm thick sandstone beds with parallel lamination, tabular (Figure 5A) and trough cross-stratification (f5, f6, f10, Table 1). Both beds and individual foresets show normal grading and bed thicknesses decrease upwards locally. Erosional flat-upward and concave-upward surfaces bound the single-storey and multi-storey sandstone bodies, and in places they are lined with wood debris, muddy rip-up clasts and/or pebble lag horizons (f11). The single-storey sandstone bodies have average dimensions of *ca* 3/100 m (width/thickness). Multi-storey bodies have erosional bases that form composite surfaces bounding higher order channel-fill elements with rare lateral accretionary packages. The multi-storey bodies are 250–300 m wide and 8–20 m thick, and consist of 2–6 stories (Figure 8B,C). Internally, individual channel-fill elements average 4 m in preserved thickness. Varicoloured mottling overprints the uppermost interval of FA6 units in places (Figure 5B). FA6 is devoid of trace fossils, and only the top surface is commonly bioturbated with *Skolithos* (BI 0–2). Laterally continuous deposits of the Jurassic Morrison Formation also fit with this facies association, but they are outside the focus of this study. FA6 incises into mouth-bar deposits (FA2–5) and is also found isolated within interdistributary-bay deposits (FA8).

4.6.2 | Interpretation

FA6 deposition resulted from the migration of two-dimensional and three-dimensional subaqueous bedforms (dune and ripple-scale), and the formation of parallel laminations in upper flow regime conditions, within subaqueous channels (Flemming, 2000). The absence of bioturbation, marine indicators and mud-drapes suggests deposition by fully-fluvial currents. Preserved fine-grained facies within channel bodies are interpreted as abandoned channel fills, covered by interdistributary fine deposits (FA8). The varicoloured mottling indicates weak pedogenesis on previously deposited channel fills and suggests prolonged subaerial exposure. Holbrook (1996) measured average channel depths of 10–12 m and widths of 90–180 m for equivalent upstream Mesa Rica trunk channels. This implies that the smaller channel dimensions of FA6 (*ca* 3/100 m width/thickness) represent the result of successive downstream bifurcations from the trunk channel. Larger channel dimensions represent trunk-scale or first-order distributaries. Multi-storey channel deposits relate to repeated occupation of a given location and their deep scouring may indicate a link to forced-regression conditions.

4.7 | FA7—Tide-influenced distributary channel

4.7.1 | Description

FA7 consists of sandstone-dominated heterolithic deposits with predominantly very fine to fine-grained sharp-based structureless (f3, Table 1) or tabular cross-stratified sandstone beds (f5) that are 10–40 cm thick (Figure 5C). The cross-stratification is rarely sigmoidal. These sandstone beds alternate with flaser bedding (f13; Figure 5D and E) and/or thin siltstone intervals (1–10 cm thick) (f7, f8). The siltstone intervals are occasionally mud-draped or double mud-draped and have unidirectional and/or bidirectional ripples in places. Wood debris, mud rip-up clasts and syneresis cracks are common. Bioturbation occurs both in sandstone and finer-grained siltstone beds, is non-uniform and low (BI 0–3), and includes *Skolithos*, *Macaronichnus* and *Ophiomorpha*. Erosional concave-upward surfaces bound single-storey (max. 3 m thick, 70 m wide) channel bodies. One multi-storey channel body of 12/75 m (width/thickness) is documented.

FA7 (Figure 8D) occurs embedded in fine-grained interdistributary-bay deposits (FA8) and incising erosively into mouth-bar deposits (FA2–5). Palaeocurrent data (*n* = 42) reveal a mean direction towards the NNW.

4.7.2 | Interpretation

Sediment of FA7 represents the infill of tide-influenced distributary channels. The heterolithic character could result from variations in fluvial discharge (Gugliotta *et al.*, 2016a). However, the occurrence of flaser bedding can be assigned to a tidal origin (Baas *et al.*, 2016), and all channel fills included at least two criteria that may be produced by, although not unique to, tidal processes (e.g. sigmoidal bedding, bidirectional cross-stratification, double mud-draped ripple laminae) (Nio and Yang, 1991). Recurrent tide-influence of river currents is therefore suggested rather than a tide-dominance. The bioturbation reflects a low-diversity expression of the *Skolithos* ichnofacies, which supports the interpretation of tidally affected deposits (Gani *et al.*, 2009). The upstream NNW orientation of the average palaeocurrent direction reflects localised tidal flood-dominance.

4.8 | FA8—Interdistributary bay

4.8.1 | Description

FA8 consists predominantly of grey-brown muddy siltstone (f1; Figure 5F). Very fine-grained to fine-grained, sharp-based sandstone beds (0.1–0.3 m thick) can be traced for 100–200 m and bed tops commonly exhibit asymmetrical ripples (f8; Figure 6C). The sandstone beds are generally structureless (f3), occasionally cross-stratified (f5) and interbedded with rippled siltstone (f8). Syneresis cracks are common, and bioturbation (BI 0–3) includes *Skolithos*, *Arenicolites*, and *Phycodes*. Isolated sandstone bodies of FA6 (fluvial distributary channel) and FA7 (tide-influenced distributary channel) are found in FA8.

4.8.2 | Interpretation

FA8 represents fine-grained lower-delta-plain to interdistributary-bay deposits, based on its close relationship to FA6 and FA7, and absence of coal. The thin-bedded sheet sandstone deposits represent crevasse splays or overbank flow deposits. Trace fossils indicate short-lived marine incursions.

The siltstone holds rare dinoflagellates and abundant spores and pollen (Oboh-Ikuenobe *et al.*, 2008), which supports the interpretation of brackish conditions.

4.9 | FA9—Estuarine deposits

4.9.1 | Description

FA9 consists of fine-grained sandstone beds (0.3–3 m) that fine upward into very fine-grained sandstone beds (5–20 cm) with interbedded siltstone in places. This facies association comprises two subsets; FA9.a is characterised by high-index bioturbation (BI 5–6, *Thalassinoides*, *Ophiomorpha*) that obliterates primary structures and bed boundaries. Extrabasinal clasts (diameter <3 cm) occur dispersed and locally in lag horizons (subangular–subrounded diameter 2–4 cm) together with mud rip-ups (f11, Table 1). The lags are in places overlain by a thin (*ca* 5 cm) siltstone package. FA9.b is characterized by sandstone beds (30–60 cm) that are structureless (f3) or reveal parallel lamination, tabular or trough cross-stratification (f5, f6, f9). Composite surfaces bound higher order scour surfaces and are commonly lined with wood debris and muddy rip-up clasts. Bioturbation is absent in the lower part of FA9.b and shows an upward-increasing trend (BI 0–5) in the upper part. Trace fossils include *Thalassinoides*, *Ophiomorpha*, *Planolites* and *Teichichnus*.

FA9 is limited in lateral extent (max. 1 km) and is found embedded within the underlying fluvial deposits of the Jurassic Morrison Formation; prodelta deposits (FA1) overlie FA9. FA9.a is 2–4 m thick and onlaps the underlying strata, whereas the basal surface of FA9.b is 6–7 m thick and erosional.

4.9.2 | Interpretation

FA9 represents transgressive estuarine deposits, based on localised occurrence, upward-increasing marine influence, and supported by the stratigraphic position below prodelta deposits (FA1) (Holbrook *et al.*, 1987). The high BI of FA9.a is indicative of conditions favouring trace makers, such as wave-agitation (MacEachern and Bann, 2008). FA9.b represents the aggradational fluvial infill of existing topographic lows with a progressively increasing marine influence. The stratigraphic position of FA9 makes it equivalent to the Campana Sandstone Bed (Holbrook *et al.*, 1987).

4.10 | Facies distribution

Estuarine deposits (FA9) unconformably overlie fluvial strata of the Jurassic Morrison Formation and represent the transgressive infill of topographic lows (Holbrook *et al.*, 1987; Van Yperen *et al.*, 2019b) (Figures 2B and 9). The overlying prodelta (FA1) deposits are present throughout the study area, except in the north-west, and separate the Jurassic fluvial strata from Cenomanian

Mesa Rica deposits. The Mesa Rica consist of two sandstone units; Succession 1 (S1) forms a continuous sandstone sheet (6–10 m thick) throughout the study area, whereas Succession 2 (S2) is discontinuous (0–6 m thick) and embedded in interdistributary fines (FA8) (Figure 9). Succession 1 and S2 correlate to the lower and upper Mesa Rica, respectively (Scott *et al.*, 2004; Holbrook *et al.*, 2006) and both successions are capped by a flooding surface with BI 1–5 (*Skolithos*, *Diplocraterion*, *Thalassinoides*) in the study area. These flooding surfaces (Maximum Regressive Surface 1 and 2; Van Yperen *et al.*, 2019b) represent key stratigraphic surfaces and are used as datums for correlation. They correlate to TS3.1 and TS3.2 (cf. Holbrook *et al.*, 2006; Oboh-Ikuenobe *et al.*, 2008).

The sheet-forming S1 (idealized log in Figure 9) contains laterally extensive mouth-bar deposits (FA2–5), except in the north-west corner of the study area, where fluvial strata (FA6) dominate. Previously published work asserted an absence of equivalent shallow marine strata updip of the study area (Holbrook *et al.*, 1987; Holbrook and Wright Dunbar, 1992) and drone data collected outside the main study area (Figure 3) and ground truthing confirms this. Succession 1 is locally incised by composite erosional surfaces containing multi-storey fluvial (FA6) (Figure 8B,C) and marine-influenced (FA7) channel infill (8–20 m thick, 75–300 m wide), and large-scale scours filled with fine-grained material (Figure 8A). While S1 thickens towards the south within the study area, S1 (6–10 m thick) is thin compared to both the upstream fluvial strata (10–15 m, Holbrook *et al.*, 2006) and downstream fully deltaic strata (12–20 m, Van Yperen *et al.*, 2019a), which reflects deposition at the basin margin (Van Yperen *et al.*, 2019b).

Succession 2 consists of isolated, composite fluvial bodies that are amalgamated into multi-lateral single or double stories (Figure 9). They represent mostly fully fluvial channel bodies (FA6), but tide-influenced heterolithic channel bodies occur locally (FA7) (Figure 8D). The isolated nature of FA6 and FA7 suggests a higher accommodation/supply (A/S) ratio (i.e. more accommodation or less sediment supply) than during S1 deposition. Strata overlying S2 belong to the paralic Pajarito Formation (Lucas and Kisucky, 1988; Holbrook and Wright Dunbar, 1992; Holbrook, 1996; Van Yperen *et al.*, 2019b) and are outside the scope of this paper.

Mouth-bar (FA2–5) palaeocurrents reveal a scattered pattern covering 360° variance, explained by the intrinsic compensation and growth in radial patterns during mouth-bar development. Distributary channel deposits (FA6) show a consistent SSE component whereas the tide-influenced distributary channel deposits have a strong NNW component, supporting the interpretation of bidirectionality (Figure 9).

5 | MOUTH-BAR ARCHITECTURE

5.1 | Components

The mouth-bar facies associations (FA2–5) represent deposition of sandstone bodies in a relatively unconfined environment, based on their general lack of deep scours, the laterally extensive individual sandstone beds and the apparent tabular bed geometry. They (FA2–5) form a continuum of deposits that are interpreted as different expressions of deposition close to a river outlet. These sub-environments are referred to as 'axis' (FA2), 'off-axis' (FA3), 'fringe' (FA4) and 'distal fringe' (FA5) (Figure 7), and represent along-strike changes of processes and resulting deposits within a single mouth bar (Figure 10).

Mouth-bar facies associations (FA2–5) reveal a predictable trend in flow regime, bed thickness, occurrence of interflood beds, BI and tide-influence, when moving away from the centre to the outer parts of the sedimentary body (Figure 10). From mouth-bar axis to fringe, the occurrence of upper flow regime bedforms and average bed thickness diminishes. Soft-sediment deformation is most common in axis and off-axis deposits (FA2 and 3). The record of interflood beds and BI progressively increases towards the fringe (FA4; Figure 10). Interflood beds display varying thicknesses (Figure 11) and are expressed only by a bioturbated surface in places (Figure 11A). These thoroughly bioturbated surfaces separate upper flow regime beds and reflect time-windows with reduced depositional energy (MacEachern and Bann, 2008). Therefore, these are intepreted as having formed during interflood periods, although they likely represent less time than the thicker expressions of interflood beds. In addition, some fringe sections (FA4 and 5) show thoroughly bioturbated top surfaces, which may indicate early abandonment of certain mouth-bar components (Figure 11E, F). The lack of trace fossils in axial deposits (FA2) can be ascribed to the proximal deltaic setting, in which increased river discharge and heightened water turbidity make it unfavourable for infaunal colonization (MacEachern and Bann, 2008). Where there are no clear shallow-marine indicators in axial deposits, lateral facies changes into off-axis deposits (FA3) are used to interpret the correct sub-environment. Mouth-bar deposits are sharp-based and a vertical grain-size trend is often absent or in a few cases coarsening-upward. This is similar to the Holocene shallow-water deltaic successions of the Burdekin River, north-eastern Australia (Fielding *et al.*, 2005).

5.2 | Internal geometries and stacking patterns

At bed and bedset scale, in the Mesa Rica, subtle lensoid geometries with accompanying onlapping surfaces are observed

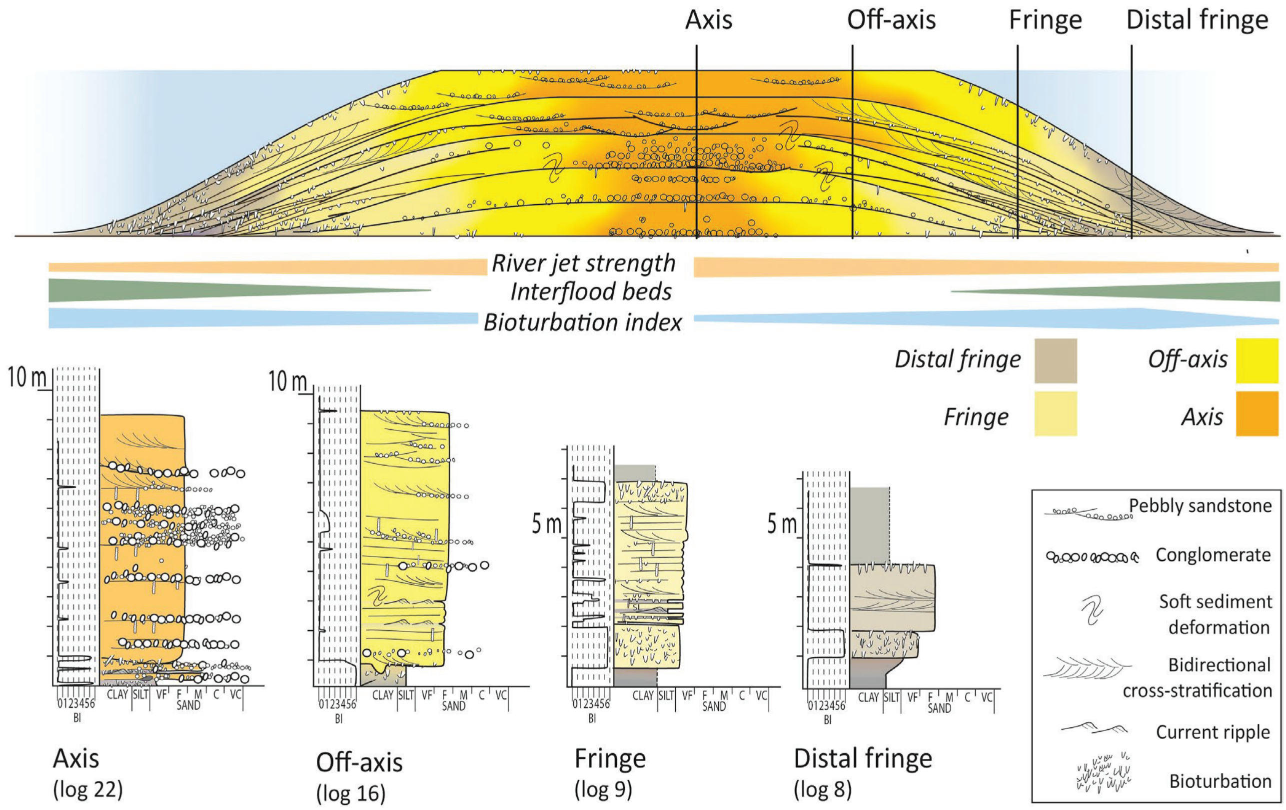


FIGURE 10 Schematic representation of a strike-oriented cross-section through an individual mouth bar, indicating the distinguished components. Displayed logs are taken from originally measured logs to enhance differences between components. Mouth-bar axis to distal fringe trends reveal changes in flow regime, bed thickness, occurrence of interflood beds, bioturbation index and tide-influence. Note that not all fringe components show tide-influence. An increase in tide-influence (imaged by bidirectional cross-stratification, right limb of the mouth bar) is accompanied with a decreasing bioturbation index. See text for further discussion

in strike-oriented outcrops, which are characterized by a tabular nature and laterally extensive individual sandstone beds. Top-truncated terminations of bedding surfaces and discordances of various geometries indicate erosion by successive discharge pulses and bed deposition with varying orientation in a setting with limited accommodation (Figure 12). Low-angle accretionary surfaces occur in oblique-oriented sections of axis and off-axis mouth-bar deposits (FA2 and 3) (Figure 13). These oblique to strike-oriented accretionary surfaces are interpreted to result from mouth-bar compensational stacking and growth in radial growth patterns. Irrespective of their direction, accretionary surfaces are also expected in fringe and distal fringe deposits (FA4 and 5), although axial areas (FA2 and 3) are likely to develop steeper, and more evident foresets (cf. Fidolini and Ghinassi, 2016). The absence of documented accretionary surfaces in fringe sections is ascribed to the low-accommodation setting, which enforces the development of laterally widespread and very low-dipping accretionary surfaces that are difficult to resolve from outcrop data (Anell *et al.*, 2016; Van Yperen *et al.*, 2019a).

At mouth-bar scale, new bars lap onto older ones, creating inter-mouth-bar bounding surfaces (Figure 14). Two different expressions of bounding surfaces are observed: (a) abrupt vertical changes from distal fringe (FA5) to off-axis (FA3) mouth-bar deposits (Figure 9, log 20) accompanied with *ca* 20 to 30 cm of erosional relief indicate a spatial shift of active bar deposition as a result of (compensational) stacking of mouth bars. The erosional contact suggests reworking potential of axial mouth-bar deposits. (b) Coarse silt to very-fine-grained thoroughly bioturbated facies (f7) locally onlap onto mouth bars (Figure 14, log 3), and result from prolonged lowered depositional rates. These onlapping relationships are interpreted to result from avulsion and the development of a new mouth bar adjacent to an older one. The fine-grained deposits are time-equivalent to and represent the distal fringe deposits of the new mouth bar. Contacts between individual mouth bars are not mantled by mud, which suggest either short periods between continuous deposition of successive mouth bars or removal by erosion. Bar deposits are thicker above thinner units of the underlying mouth-bar deposits (e.g. Figure 14). This is indicative of lateral compensational stacking, and maintenance of a topographic low while the successive mouth bar was being deposited (cf. Prélat *et al.*, 2009).

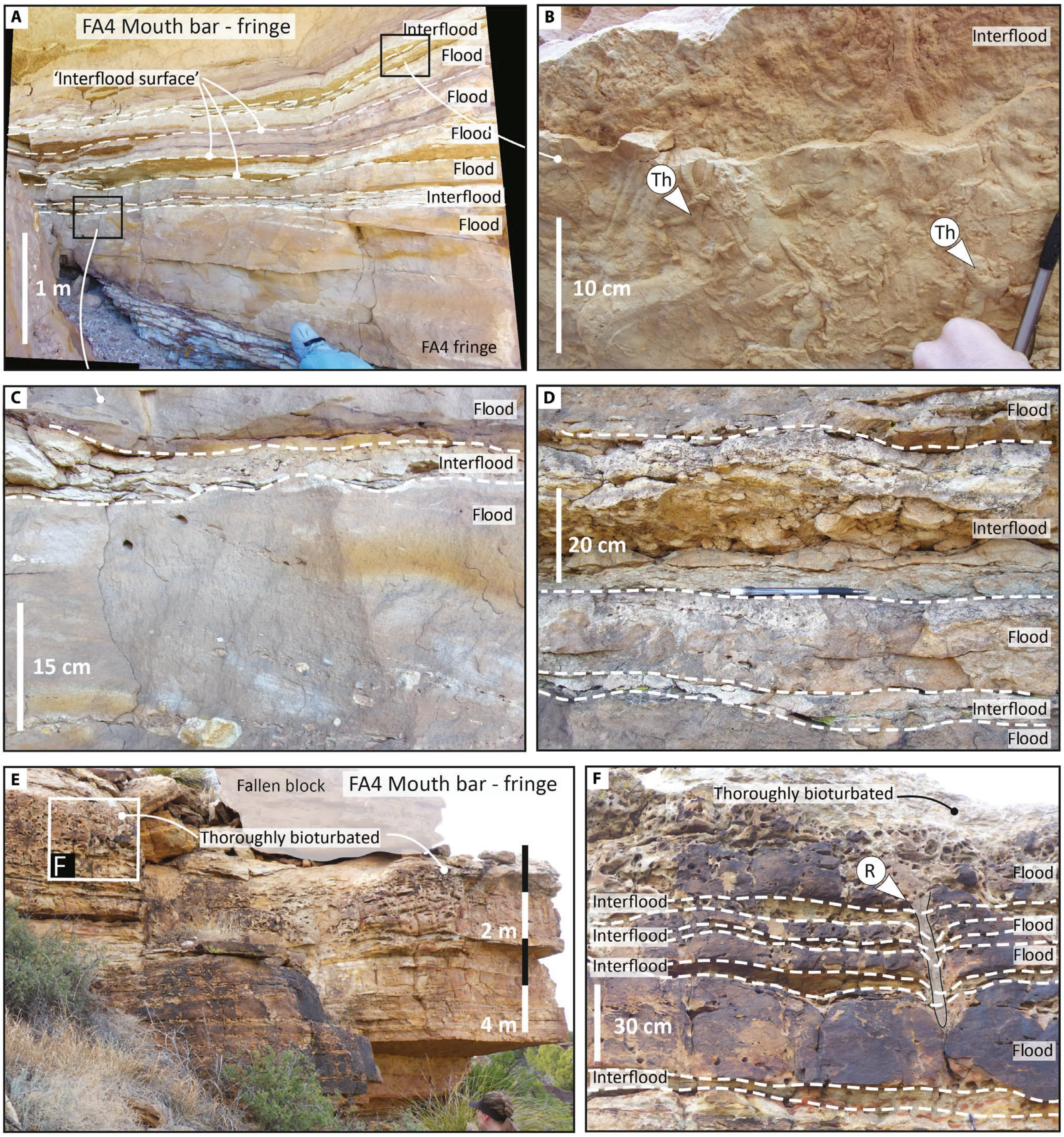


FIGURE 11 River flood and interflood beds in FA4 deposits (mouth-bar fringe). River flood beds have a sharp base, coarser grain size and lower BI (0–3) than interflood deposits. In places, the interflood is represented only by a thoroughly bioturbated surface (A). Bioturbated horizons commonly require several months to form (Gringras *et al.*, 2002) and contrast with upper flow regime beds interpreted as river flood event beds, which can be as short as a few hours (Gugliotta *et al.*, 2016a and references herein). Note that the upper part of the facies association is thoroughly bioturbated in E, F which indicates early abandonment. Th = *Thalassinoides*, R = *Rosselia.* 15 cm pencil for scale

To summarize, the observed geometries result from the progradation and aggradation of mouth bars during deposition and reveal a predictable architectural hierarchy, with basinward dipping strata at bed scale and lapping relationships at bed and mouth-bar scale (Bhattacharya, 2006; Enge *et al.*, 2010; Kurcinka *et al.*, 2018).

6 | DISCUSSION

6.1 | Mouth-bar dimensions

The distance between different mouth-bar components observed in the field and their extrapolation (see Figure 9)

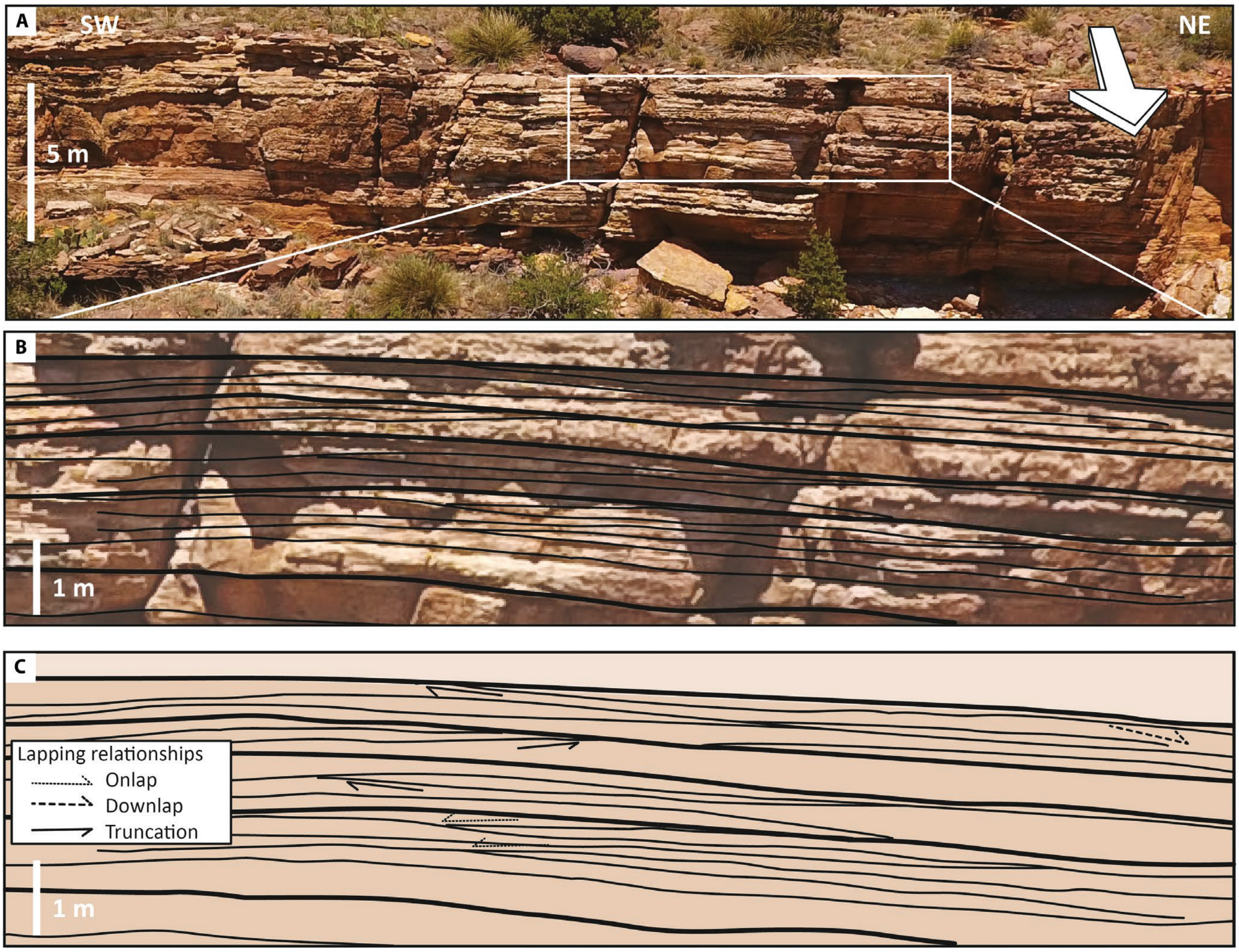


FIGURE 12 (A) Field photograph showing along-strike internal mouth-bar geometries. The white arrow indicates average palaeocurrent direction. Inset box shows location of (B). (B) Zoom in on subtle lensoid geometries. (C) Subtle lensoid geometries show accompanying onlapping, downlapping and truncation relationships

provides an estimate of mouth-bar dimensions, and helps in defining a palaeogeography (Figure 15). In combination with the observed internal geometries and stacking patterns, and previous studies, this is utilized to assess the hierarchy of preserved geometries (Figure 1); what are the largest architectural elements observed within the S1 sheet-forming sandstone, mouth-bar complexes or delta lobes?

The estimation of mouth-bar dimensions is challenged by the fragmented nature of the outcrops and the distribution of data points (Figures 3, 9, and 15). Log correlation reveals spatial relationships between different mouth-bar components, but no complete pinch-out was documented, which limits the assessment of complete mouth-bar width. Assuming a similar overall distance between mouth-bar components gives a minimum mouth-bar width. Facies changes from fringe to off-axis deposits and back to fringe occur in logs 14, 15, 16 and 17 (Fowl Canyon; Figures 9 and 15) and constrain a fringe-axis-fringe mouth-bar width of *ca* 1.4 km. Log 19 and 20 show a transition from axis to off-axis deposits over a distance of *ca* 400 m (Figures 9 and 15). The assumption of a similar distance to the fringe component, gives a distance of *ca* 800 m for one mouth-bar limb from fringe to axis. The resulting fringe-axis-fringe mouth-bar width is *ca* 1.6 km. Axial mouth-bar deposits are documented at log 11 (Alamosa) and off-axis and fringe deposits at logs 12 and 13 (Dog Canyon; Figures 9 and 15). If these belong to one mouth bar only, the resultant size (i.e. *ca* 4.4 km) is significantly larger than the other width estimates of *ca* 1.4 and *ca* 1.6 km. The size constraints of the other mouth bars were used as a guide and the axis-to-fringe distance (*ca* 900 m) between logs 12 and 13 was used to estimate a fringe-axis-fringe minimum width of *ca* 1.8 km, which would then suggest the presence of two mouth bars within log 11 (Alamosa) and logs 12 and 13 (Dog Canyon; Figures 9 and 15). Farther to the northwest, facies change from fringe to axis deposits

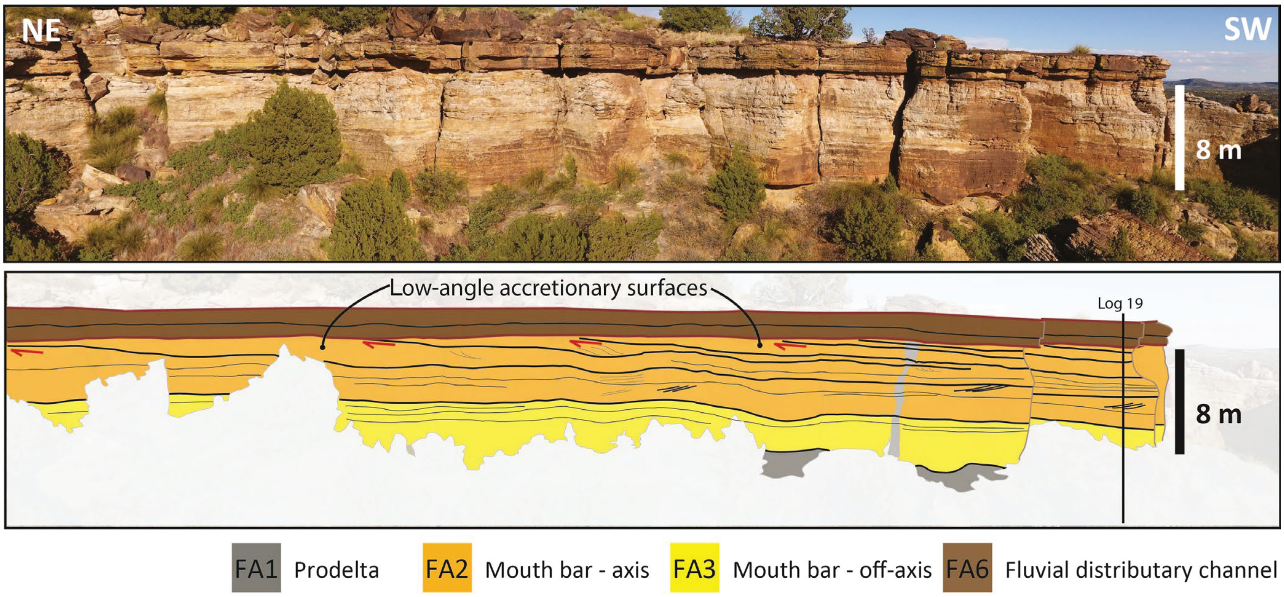


FIGURE 13 Field photograph (and interpretation) of a mouth-bar section, showing low-angle accretionary surfaces (clinoforms) top-truncated by distributary channels. Note the cross-stratification that is locally in an opposite direction to the larger accretionary surfaces (accretion towards SW). Clinoforms could evidence oblique compensational growth of mouth bars as these are complex geobodies that grow in a radial pattern. See Figures 3 and 9 for location. See text for further discussion

in *ca* 300 m between logs 3 and 2 (Figures 9, 14, and 15). This narrow width may indicate that this mouth bar represents a low-relief bar adjacent to the main mouth bar (cf. Fidolini and Ghinassi, 2016). The limited *ca* 5 m thickness would fit this interpretation.

In the studied interval, however, lapping relationships or abrupt vertical changes in facies associations are only rarely observed, suggesting that inter-mouth-bar bounding surfaces are scarce. Therefore, the architectural elements that form the S1 sheet-forming sandstone throughout the study area are interpreted as mouth bars constituting part of a single mouth-bar complex, rather than lateral stacking of several mouth-bar complexes that would in turn constitute a delta lobe (Figure 1). In addition, average dimensions of ancient mouth bars range from 1.1 to 14 km wide with lengths between 2.6 and 9.6 km (Reynolds, 1999). The inferred dimensions of individual mouth bars in the study area (Figure 15) fit well within this, even though they fall in the small part of the spectrum. The S1 sheet-forming deposits thus represent amalgamation of mouth bars into a single mouth-bar complex (Figure 1).

6.2 | Dominant process regime of the lower Mesa Rica

Facies and stratigraphic analysis suggest mouth-bar deposits of the lower Mesa Rica represent river-dominated proximal deltaic deposition in a low-accommodation setting. The river-dominance is inferred from the alternation of upper flow regime and lower flow regime bedforms, the absent, low-diversity or non-uniform varying BI, and near-absence of wave-induced bedforms. Based on the latter, the wave-energy was minimal and/or dampened by river discharge.

Tidal evidence is absent in mouth-bar axis and off-axis deposits (FA2 and 3). In mouth-bar fringe deposits (FA4), evidence for tidal modulation is inferred from finer-grained interflood beds with mud drapes and rare upstream-migrating current ripples (Figures 5 and 11), although the mud drapes are not unique tidal indicators (Nio and Yang, 1991). The interflood beds are thoroughly bioturbated and include fully-marine trace fossils. These reflect interflood periods, in which decreased discharge allows the salinity gradient to re-establish in the off-axis areas between active mouth bars (Dalrymple *et al.*, 2015). This in turn influences the ichnological character of the deposit, resulting in more diverse trace-fossil assemblages (Gingras *et al.*, 2002) and/or higher BI (Gugliotta *et al.*, 2016b; Kurcinka *et al.*, 2018). This evidence for salt-water intrusions holds the potential tidal influence, as the action of tides often extends farther landward than marine, salt-water intrusions (Dalrymple *et al.*, 2015). Full current-reversals represent unambiguous tidal indicators and are documented as bidirectional cross-stratification at Anna's point in mouth-bar distal-fringe deposits (FA5) (Figures 3 and 7D). This opposes the otherwise absence or rare presence of tidal indicators (in FA2–4) and suggests a differential nature and preservation of tidal indicators.

Tide energy is interpreted as variable throughout the study area, in which mouth-bar fringes (FA4 and 5)

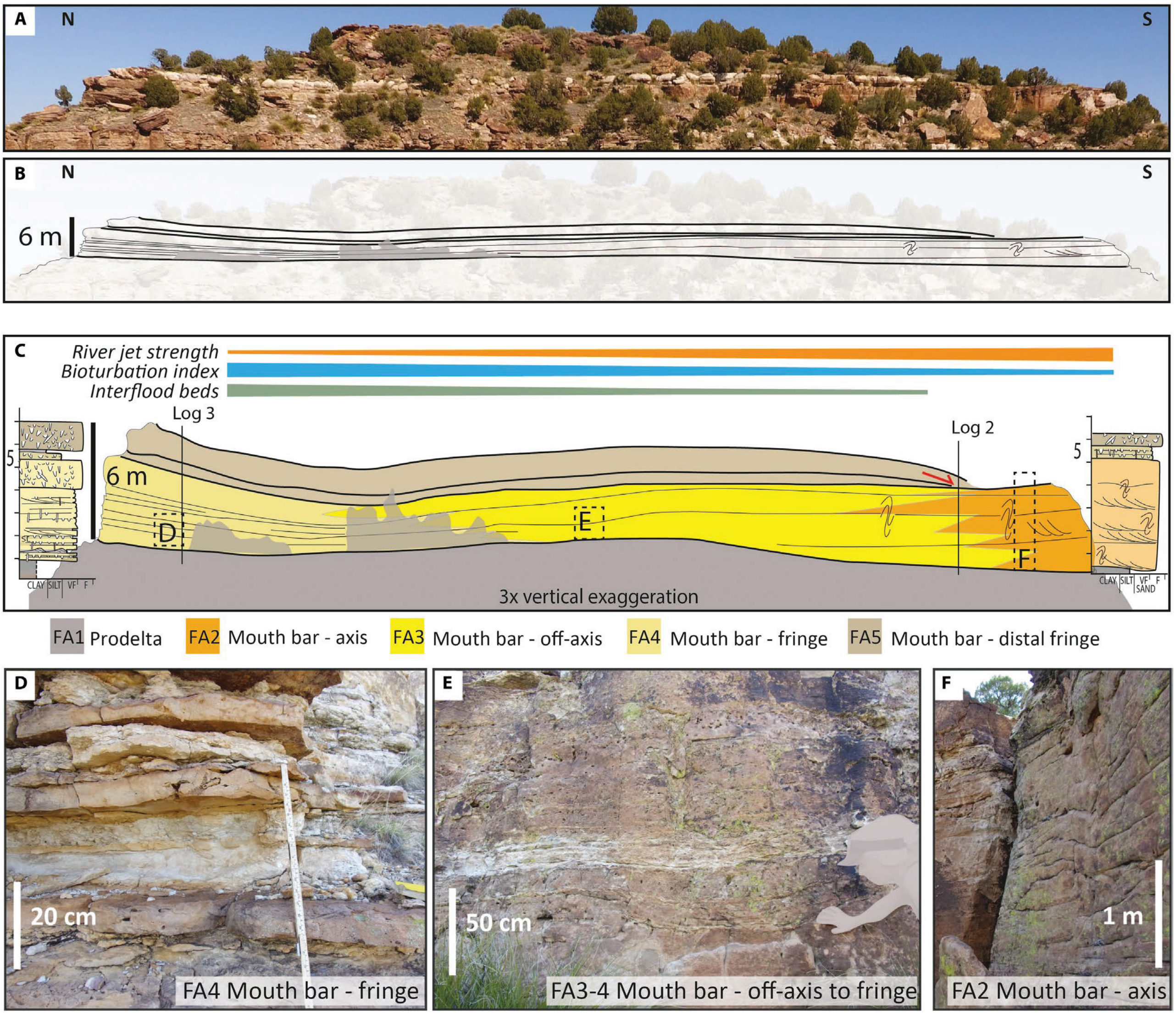


FIGURE 14 (A) Photograph of a strike-oriented section, see Figures 3 and 9 for location. (B) Line drawing and interpretation of (A), showing onlapping relationships between mouth bars. (C) Vertical exaggeration of (B), enhancing onlapping relationships (red arrow). The mouth bar laps onto older fringe strata, creating inter-mouth-bar bounding surfaces. This represents the bounding surface between two individual mouth bars in which the younger mouth bar onlaps the off-axis and fringe sections of the previous. Note that the older mouth bar shows lateral facies transitions from heterolithic fringe (D), to sand-prone off-axis deposits (E), to mouth-bar axis deposits with common soft-sediment deformation and an absence of trace fossils (F)

experienced different tidal impact depending on when and where they formed. For instance, places with weak tidal energy resulted in tidal indicators only present in fine-grained interflood beds, whereas tide-dominated areas favoured formation and preservation of sand-prone, bidirectional cross-stratified sandstone beds. Both are documented in this study and suggest strike-variability in tidal energy. It is argued here that decreased river influence allowed higher tidal energy locally. This indicates that 'background' tidal energy was moderate, but still only recorded (and preserved) in the distal mouth-bar fringes, and when river discharge was low.

6.3 | From mouth bar to delta front—Controlling factors

Sedimentary characteristics and depositional architecture of the studied mouth-bar complex provide insights regarding both allogenic and/or autogenic controlling factors, although their relative contribution is often difficult to distinguish because of their close interaction, particularly at high-resolution mouth-bar and complex scales.

Major allogenic controls on a mouth-bar complex scale are inferred from the following: the succession is thinner compared to both the upstream fluvial (Holbrook,

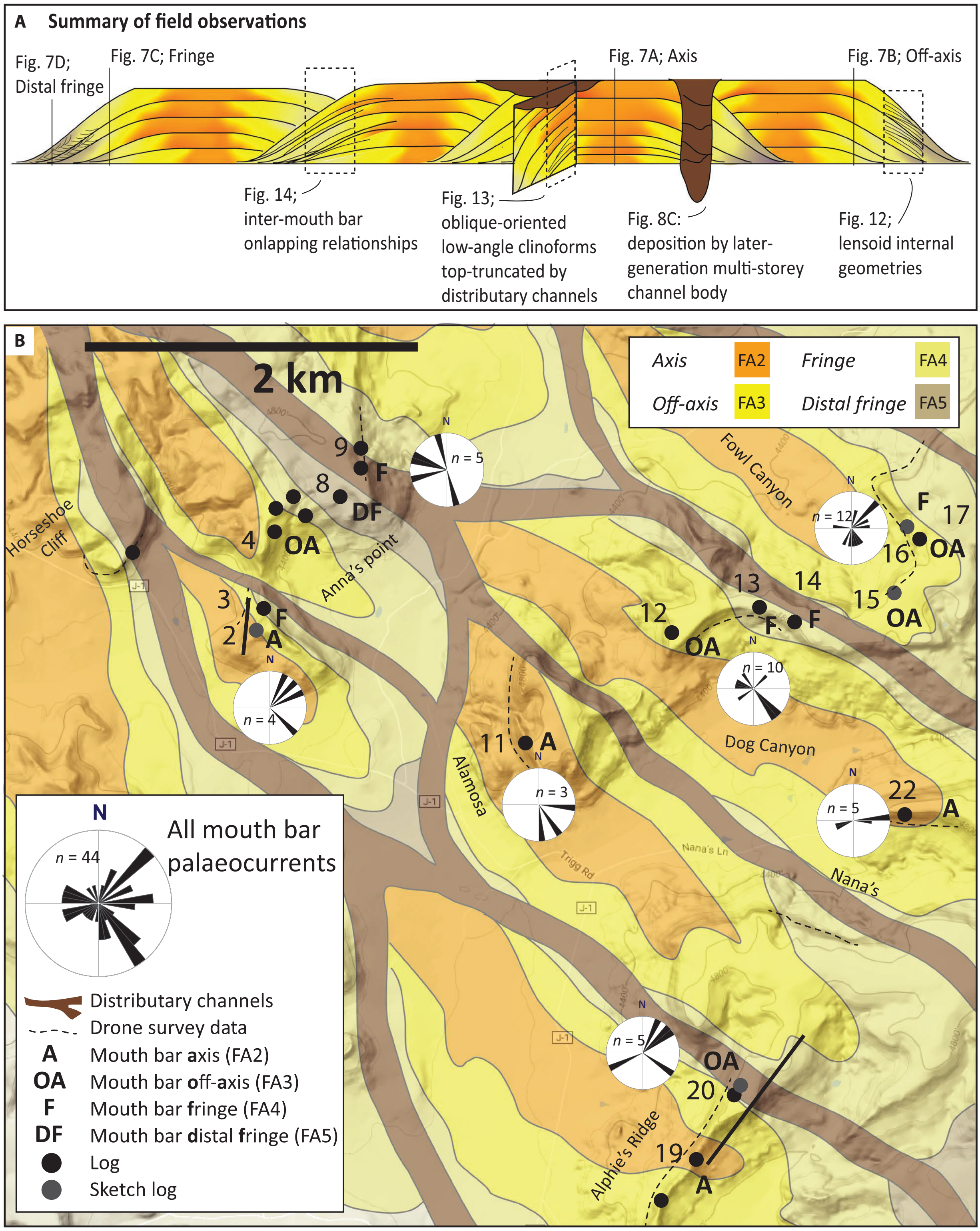


FIGURE 15 (A) Summary of field observations, as a basis for (B). (B) Palaeogeographic reconstruction of the lower Mesa Rica in the study area, based on onlapping relationships, the distribution of mouth-bar components and interpolation between them. Mouth bars range 1.4–1.8 km in width. Where no mouth-bar abbreviation is indicated, strata are eroded by trunk channels. These trunk channels are not visualized in the figure as these reflect a later generation and feed a delta outside and down-dip of the study area. Palaeocurrent readings were collected from mouth-bar deposits. The displayed distributary channels are inferred based on the reconstructed mouth-bar components and based on the bifurcation of river flows around mouth bars when they reach a critical thickness (Edmonds and Slingerland, 2007)

2001; Holbrook *et al.*, 2006), and downstream fully deltaic time-equivalent strata (Van Yperen *et al.*, 2019a). This reduced thickness is coincident with the position of the study area at the rim of the Tucumcari Basin, and is interpreted to reflect deposition close to base level and to the equilibrium point of the graded stream profile (Mackin, 1948; Quirk, 1996; Holbrook *et al.*, 2006). Such a position also limits aggradation and incision, which in turn reflects a low-accommodation setting, with either constant relative sea level or subjected to slow and minor fluctuations. The sharp-based deltaic sandstone bodies of the Mesa Rica fit such low-accommodation shallow-water setting (Overeem *et al.*, 2003; Fielding *et al.*, 2005). The limited accommodation promotes faster occupation of all available space in front of the river mouth and thus acts as an accelerator for autogenic mouth-bar depositional cycles (Olariu and Bhattacharya, 2006; Van Yperen *et al.*, 2019a). Low-accommodation conditions also make lateral sedimentary accretion a prime mechanism for sediment distribution. The laterally shifting locus of mouth-bar deposition means that more elapsed time is represented by preserved sediment in three dimensions than in only vertical accumulation (Miall, 2015). Each mouth bar represents a relatively short period of time but the lateral set (in this case mouth-bar complex, but the same scenario also applies to delta lobes) captures depositional conditions over longer time scales. Successive mouth-bar coalescing in such space-limited conditions caused the sheet-like nature (cf. Olariu and Bhattacharya, 2006; Van Yperen *et al.*, 2019a).

At individual mouth-bar scale, both allogenic and autogenic factors influence the resultant depositional products. Along-strike differences between axial and fringe deposits are assigned to varying sediment distribution patterns inherent to mouth-bar deposition. Autogenic processes also forced deposition between previously deposited mouth bars (i.e. autogenic compensation) (Figures 14 and 15). In addition, an allogenically driven overall high sediment supply is inferred based on the following: (a) river-sourced flow-energy was too high to allow finer-grained particles to settle, based on the absence of mud and silt in mouth-bar axial deposits (FA2), and the rare occurrence of these in mouth-bar fringe deposits (FA4 and 5; Figure 11). (b) In mouth bar axis to off-axis deposits (FA2 and 3), low-index and low-diversity trace fossils assemblages (*Ophiomorpha*) combined with a local absence of trace fossils, suggest a rather continuous sedimentation and recurrent stressed conditions, which prohibits colonization by trace makers. Variations in sediment supply are inferred from the alternation between upper flow regime bedforms and bioturbated surfaces or interflood beds in fringe deposits (FA4 and 5). These variations could be linked to seasonal fluctuations in river discharge, although the overall high sediment supply in the study area can be a result of the 'equable' climate of the mid-Cretaceous (Fluteau *et al.*, 2007). Such a warm, low seasonality climate would imply semi-constant high river discharge conditions and could explain the relative dominance of river flood beds suggesting a rather continuous sedimentation rate with only small variations. However, modelling studies show that there are significant uncertainties in the effect of the sea surface temperature gradient from equator to pole. A reduction in this temperature gradient might cause Hadley cell atmospheric transport reduction which in turn enhances seasonal thermal contrasts (Fluteau *et al.*, 2007; Hasegawa *et al.*, 2012). Therefore, these models cannot be used to unambiguously confirm or falsify the interpretation of seasonality in the studied depositional system.

As a summary, the evidence provided suggest that the sheet-like nature of the lower Mesa Rica, the compensational stacking and sand-dominated nature of the mouth bars reflect the multi-scale interplay of allogenic and autogenic controlling factors.

6.4 | Influence of low accommodation on preservation of subordinate coastal processes

In the Mesa Rica system, subordinate coastal processes are predominantly recorded in interflood beds, which is an important aspect to consider when interpreting competing coastal processes. For example, if a depositional system or zone only experiences weak tidal energy, the tides modulate, rather than reverse, river currents (Martinius and Gowland, 2011; Gugliotta *et al.*, 2016b). In these settings, tidal indicators have the highest preservation potential in the interflood beds (Gugliotta *et al.*, 2016b; Kurcinka *et al.*, 2018).

The low-accommodation setting limits the preservation potential of interflood deposits in two ways, and subsequently masks the true sedimentary processes that were active at time of deposition. First, river floods have the potential to erode interflood beds, despite floods only lasting several days to weeks in medium-sized rivers close to the coast (Dalrymple *et al.*, 2015). The low-accommodation setting increases such reworking-processes at bed scale, and thereby lowers significantly the preservation potential in the axial and off-axis components. The recording of interflood deposits is thus restricted to the mouth-bar fringe and distal-fringe components (FA4 and 5) because these zones can experience longer or more recurrent periods of lower energy conditions. Second, low accommodation lowers the preservation potential of the fringes themselves, which consequently lowers the preservation potential of interflood deposits. Due to limited accommodation, mouth-bar depositional cycles accelerate (Olariu and Bhattacharya, 2006), which increases the reworking potential of older deposits (Van Yperen *et al.*, 2019a). Mouth-bar deposition with short recurrence intervals might prevent lithification of previously deposited mouth-bar sediment. Additionally, reworking of

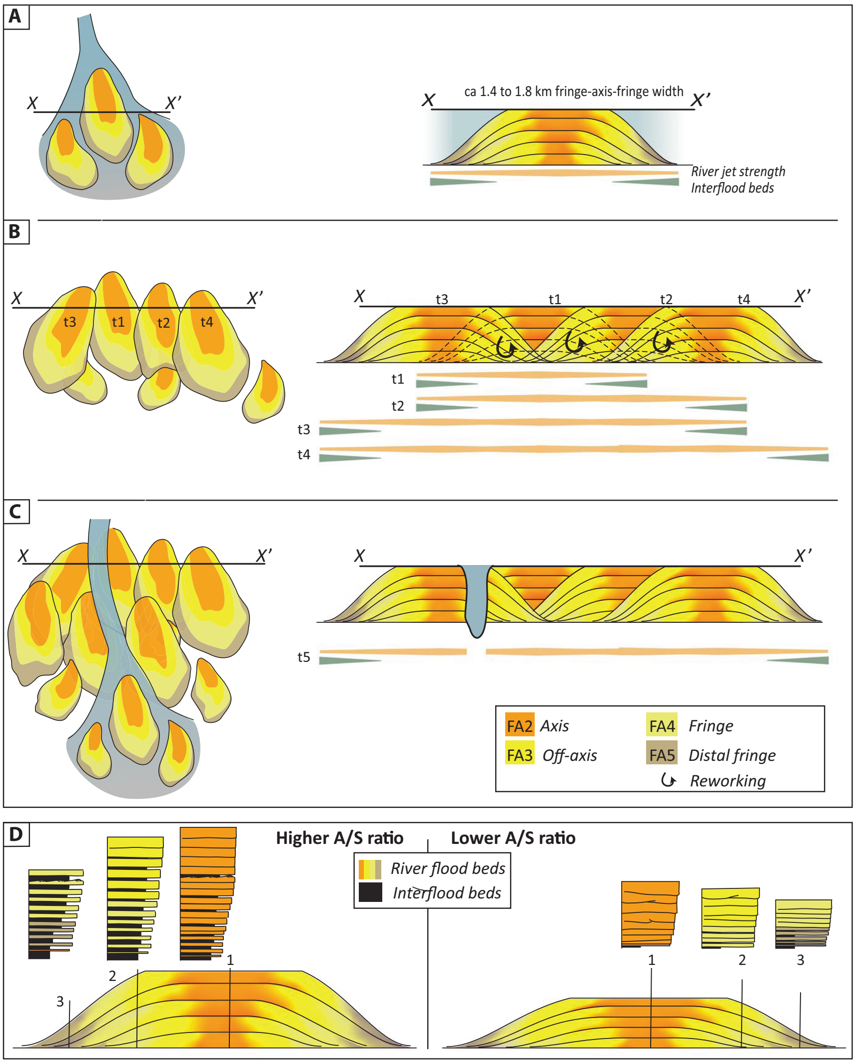


FIGURE 16 From individual mouth bar to mouth-bar complex. (A) A single mouth bar shows decreasing river jet strength and increase in recording of interflood beds from axis to distal fringe. (B) Multiple mouth bars occupy all available accommodation. Every stage (t1–t4) shows the cumulative preservation of river jet deposits and interflood beds. Successive deposition of mouth bars causes reworking of fringes and subsequently erodes the previously deposited interflood beds, there by potentially recording subordinate coastal processes. (C) Eventually, a primary distributary channel erodes through the mouth-bar complex and will initiate new mouth-bar deposition beyond the stranded mouth-bar complex. (D) Facies stacking patterns of river flood and interflood beds. River flood beds are thicker and more amalgamated towards the top and the axial part of the mouth bar. A progressive decrease of preserved interbedding shows a similar trend. The occurrence of interflood beds is lower in the scenario with a lower A/S ratio (modified after Gugliotta *et al.*, 2016a)

fringe deposits is expected because their position will likely coincide with the higher energy zones (i.e. axis, off-axis) of subsequent mouth bars, as these migrate to stack compensationally (Figure 16A, C). This (together with the proximal deltaic setting) also explains the overall sand-prone nature of the fringes, and the small differences in grain size between mouth-bar axis and fringe components. It seems unrealistic to preserve abundant fine-grained fringes in low-accommodation deltaic systems like the Mesa Rica, but a trend in decreasing energy when moving away from the axis is still evident. Compared to high-accommodation settings, offset stacking rather than vertical stacking is the norm in low-accommodation systems (Ainsworth *et al.*, 2016). Additionally, mud/sand ratios and thus the preservation potential of finer-grained facies are demonstrably lower in low-accommodation systems (Figure 16D) (cf. Charvin *et al.*, 2010; Klausen *et al.*, 2017).

Low-accommodation settings are also especially prone to preserve less time. Because the amount of time contained in interflood beds is significantly longer than in flood beds (Miall, 2015), the stratigraphic record of low-accommodation settings will be more fragmentary than in high-accommodation settings, as the first preserve less interflood deposits. Additionally, as interflood beds have low preservation potential at all scales in low-accommodation proximal deltaic settings (Figures 1 and 16), time is best recorded at the outside edges of the delta system.

As a summary, interflood beds are better recorders of time and background processes. However, their rather low preservation potential might cause underestimation of the true duration and influence of subordinate processes, particularly in low-accommodation deltaic settings.

6.5 | Applications to other deltaic studies

This work demonstrates that axis, off-axis, fringe and distal fringe mouth-bar components (FA2–5) can be differentiated in ancient river-dominated deltaic settings. These along-strike changes in flow regime, bed thickness, occurrence of interflood beds, BI and tide-influence are predictable and can be applied to other deltaic studies.

Wave-dominated deltas show potential for differentiation of internal mouth-bar components as well. The wave-dominated deltaic Horseshoe Canyon Formation (SW Alberta, Canada) transitions laterally into fluvial dominance at mouth-bar complex scale (Ainsworth *et al.*, 2016). Internal variability within their individual mouth bars is observed in the strike-oriented correlation panels (fig. 11 in Ainsworth *et al.*, 2016), although this is not described or discussed in detail. In their paper, axial components consist of higher energy facies associations (foreshore or upper shoreface), whereas lower shoreface heterolithics become dominant towards the fringes. This lateral facies change within individual mouth bars follows similar trends as those documented for the river-dominated mouth bars in the present study.

Recognition of internal mouth-bar components is not limited to low-gradient epicontinental basinal settings (this study). Studies in shallow lake (Fidolini and Ghinassi, 2016) and foreland basin (Jerrett *et al.*, 2016) settings show along-strike changes from predominantly high-density currents in axial zones, to alternating low- and high-density deposits in the fringe zones, combined with an increased recording of finer-grained facies. This trend resembles the predicted changes in sedimentary characteristics from mouth-bar axis to fringe documented in this study, and demonstrates the possibility of further subdividing individual mouth bars in different basinal settings, albeit not discussed in the respective papers.

A growing number of studies document variability within delta front deposits (Gani and Bhattacharya, 2007; Enge *et al.*, 2010; Ainsworth *et al.*, 2016; Fidolini and Ghinassi, 2016; Jerrett *et al.*, 2016) but few document internal characteristics of mouth-bar deposits and their lateral relationships (Enge *et al.*, 2010; Fidolini and Ghinassi, 2016; Jerrett *et al.*, 2016). However, the above mentioned examples, complemented with this study, demonstrate that internal hierarchy of mouth bars is evident and observed regardless of dominant coastal processes and/or depositional setting. Subdivision of mouth bar, mouth-bar complexes, and delta lobe deposits into different components can reduce complexity of models deriving from a myriad of facies subdivisions, and guide prediction of facies changes and sand distribution in future studies of proximal deltaic settings.

7 | CONCLUSIONS

- In the study area, the lower Mesa Rica represents a river-dominated proximal deltaic succession, based on the recognition of dominant river flood beds, rare tidal-indicators, and a near-absence of wave-induced bedforms. In such a proximal setting, river-discharge dominance can locally overprint the marine influence. However, lateral relationships within the deposits are still recognizable, and key for accurate identification of depositional sub-environments and associated dominant processes.
- Mouth-bar deposits of the Mesa Rica Sandstone can be subdivided into four different mouth-bar components (or sub-environments); mouth-bar axis, off-axis, fringe to distal fringe, in which the occurrence of upper flow regime bedforms and average bed thickness decreases towards the fringe, whilst the record of interflood beds and BI progressively increases. Mouth bars range *ca* 1.4 to 1.8 km in width.
- Onlapping relationships between mouth-bar strata and compensational stacking patterns demonstrate the amalgamation of mouth bars into mouth-bar complexes. Coalescence of mouth bars resulted in sheet-like geometries, which together with their sand-rich nature and near-absence of fine-grained interflood deposits reflects deposition in a low A/S setting. Deposition occurred at the rim of the Tucumcari Basin, which caused vertical limitations on aggradation and incision close to the equilibrium point of the graded stream profile.
- Subdivision of mouth bars and mouth-bar complexes into different components is applicable in other studies, regardless of the depositional setting of the studied deltaic succession and/or dominant coastal processes. This improves comparisons between systems and helps predict facies changes and sand distribution.
- The low-accommodation setting lowers the preservation potential of interflood deposits. The recording of these becomes restricted to the fringe and distal fringe mouth-bar components, due to increased reworking-processes and low preservation potential of interflood deposits in the axial and off-axis components. The preservation potential of fringes themselves is also lowered because of accelerated mouth-bar depositional cycles and consequent increase of fringe-reworking during compensational shifting.
- As interflood beds are better recorders of time and background processes, care should be taken when evaluating the duration and relative dominance of process regime (i.e. river, tides, waves) in low-accommodation deltaic settings. The rather low preservation potential of these beds might cause the timing and true influence of subordinate coastal processes to be underestimated, with important implications for prediction of facies changes and sediment distribution in other similar settings.

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CONFLICT OF INTEREST

There are no conflicts of interest in the preparation or publication of this work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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9.4 Article IV – Sequence stratigraphy, backwater limits and depositional architecture in low-accommodation fluvio-deltaic settings (Cretaceous Mesa Rica Sandstone, Dakota Group, USA)

Van Yperen, A.E.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1], Myers, C.[3], Midtkandal, I.[1] Sequence stratigraphy, backwater limits and depositional architecture in low-accommodation fluvio-deltaic settings (Cretaceous Mesa Rica Sandstone, Dakota Group, USA).

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10. Appendices

10.1 Abstracts, first author

10.1.1 Van Yperen et al. (2017), International Meeting of Sedimentologists, Toulouse, France

Van Yperen, A.E.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1], Midtkandal, I.[1] (2017). Facies architecture and stratigraphic development of a thin, low-gradient delta along a sandy coast – the Cretaceous Mesa Rica Sandstone in New Mexico (USA)

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Accepted for oral presentation

Facies architecture and stratigraphic development of a thin, low-gradient delta along a sandy coast – the Cretaceous Mesa Rica Sandstone in New Mexico (USA)

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A rare case of thin, low-gradient delta architecture is documented along Albian-Cenomanian cliff sections in New Mexico, where analysis of facies distribution, depositional architecture and the spatial extent of stratigraphic surfaces reveal a characteristic pattern of laterally varying shallowing-upward facies successions. The dominantly fluvial Mesa Rica Sandstone is characterized by a ~350 km NNW-SSE depositional profile from southeast Colorado to northeast New Mexico where it feeds a 15-20 m thick contemporaneous delta. The upstream fluvial strata record deposition of an extensive sandstone sheet, as documented by others. Its delta terminus has received limited attention besides micropaleontology, palynology and organic geochemistry, which has been applied to reconstruct sea level fluctuation and coastline migration.

Strike-, and dip sections were constructed from observations along a 20km+ escarpment in the Tucumcari Basin, east-central New Mexico, ~60 km down-dip from the first indicators of deltaic development in the hitherto fluvial system. Five facies associations were recognized in the study area, and form the basis for this reconstruction. Moderately bioturbated prodelta mudstones grade into completely bioturbated distal sandstone bars of which the high and uniform bioturbation index suggests slow sedimentation and persistent wave agitation. The presence of thin hyperpycnal deposits in the lower part of the distal bars is evidence for occasional high river-discharge events. The strata grade further into slightly coarser grained indistinctly bedded mouth bar sandstones with a uniform and low bioturbation index. Erosive and channelized cross-stratified channel sandstones (distributary or trunk) with a commonly present pebble-sized lag form the top of the upward shallowing succession. Channel-incision depth varies significantly within the study area, and is ascribed to interplay between sediment supply and base level change. The number of vertically stacked parasequences varies locally, but an inverse relationship between thickness and parasequence count results in a generally constant thickness for the whole succession. Areas with only a few or several stacked parasequences contain thicker or thinner units, respectively. Distal- to mouth bar clinothem geometries are observed in just one locality, typically reaching 120-160 m in down-dip extent. Here, the total interval thickens significantly over a short distance, possibly explained by a local depression in the paleo-basin bathymetry.

The presence of sub-regional flooding surfaces and a laterally varying number of paraseqeuences is interpreted to reflect lobe abandonment followed by local subsidence and possible later re-activation. In turn, this suggests that autogenic lobe switching accounts for flooding surfaces of limited lateral reach, whereas allogenic forcing explains widespread flooding and their associated surfaces. Accurate identification and temporal constraints on flooding events may be applied as a framework to improve facies mapping and consideration for compartmentalization in delta successions. The dimensions of the incising channels are comparable with the upstream trunk channels, indicating a further continuation of the delta in the down-dip direction, beyond outcrop exposure to the SSE. Unraveling the interplay of paleo-bathymetry, dominant processes (fluvial, wave, tidal) and slope gradients for the Mesa Rica Sandstone delta will significantly contribute to the understanding of delta development in low-gradient basins in general.

10.1.2 Van Yperen et al. (2017), British Sedimentological Research Group (BSRG) annual meeting, Newcastle upon Tyne, United Kingdom

Van Yperen, A.E.[1], Midtkandal, I.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1] (2017). Facies architecture and stratigraphic development of a thin, low-gradient delta along a sandy coast – the Cretaceous Mesa Rica Sandstone in New Mexico (USA)

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Facies architecture and stratigraphic development of a thin, low-gradient delta along a sandy coast – the Cretaceous Mesa Rica Sandstone in New Mexico (USA)

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A rare case of thin, low-gradient delta architecture is documented along Albian-Cenomanian sections in New Mexico, where analysis of facies distribution, depositional architecture and the spatial extent of stratigraphic surfaces reveal a characteristic pattern of laterally varying shallowing-upward facies successions. Its upstream equivalent, the dominantly fluvial Mesa Rica Sandstone is characterized by a ~350 km NNW-SSE depositional profile from southeast Colorado to northeast New Mexico. Here, it feeds a 15-20 m thick contemporaneous delta that has received limited attention besides micropaleontology, palynology and organic geochemistry. This study focuses on its facies architecture and the spatial distribution of architectural elements and key stratigraphic surfaces in order to unravel controlling factors, locally and regionally.

Seven facies associations form the basis for constructed cross-sections along a 20km+ escarpment, which has an oblique orientation relative to sedimentary transport direction. The number of vertically stacked parasequences varies locally, but an inverse relationship between thickness and parasequence count results in a generally constant thickness for the whole succession. Within-parasequence variation in dominant processes occurs over less than 2 km. Key stratal surfaces show remarkable similarities with the previously established framework for the updip fluvial part of the system, allowing long-distance correlation.

Sub-regional flooding surfaces and a laterally varying number of paraseqeuences are interpreted to reflect lobe abandonment followed by local subsidence and later re-activation. This suggests that autogenic lobe switching accounts for flooding surfaces of limited lateral reach, whereas allogenic forcing explains widespread flooding and their associated surfaces. Accurate identification and temporal constraints on flooding events may be applied as a framework to improve facies mapping and consideration for compartmentalization in delta successions. Unraveling the interplay of paleo-bathymetry, dominant processes (fluvial, wave, tidal) and slope gradients for the Mesa Rica Sandstone delta will contribute to the understanding of delta development in low-accommodation basins in general.

10.1.3 Van Yperen et al. (2018), Nederlands Aardwetenschappelijk Congres – Dutch Geoscience Conference (NAC), Veldhoven, Netherlands

Van Yperen, A.E.[1], Midtkandal, I.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1] (2018). Allogenic and autogenic controls on low-accommodation deltaic systems: the Cretaceous Mesa Rica Sandstone (New Mexico, USA)

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Allogenic and autogenic controls on low-accommodation deltaic systems: the Cretaceous Mesa Rica Sandstone (New Mexico, USA)

Van Yperen, A.E.[1], Midtkandal, I.[1], Holbrook, J.M.[2], Poyatos-Moré, M.[1]

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Low-gradient deltaic systems in the subsurface are often thin and amalgamated, and therefore fall below seismic resolution; outcrop analogue studies that could help studying the internal complexity of such systems are surprisingly scarce, and consequently their expression in the sedimentary record is still poorly understood. Their geometries tend to be less well developed and surfaces of stratigraphic importance have the potential to become cannibalized by subsequent regressive pulses.

In this study, a rare case of a thin, low-gradient delta architecture is documented along Albian-Cenomanian sections in east-central New Mexico. A detailed analysis of facies distribution, depositional architecture and the spatial extent of stratigraphic surfaces reveals a complex arrangement of laterally variable and shallowing-upward facies successions. Their upstream equivalent units, part of the dominantly fluvial Mesa Rica Sandstone, are characterized by a ~350 km NNW-SSE depositional profile from southeast Colorado to east-central New Mexico. Here, the fluvial feeders build a 15-20 m-thick contemporaneous deltaic system that has received limited attention besides micropaleontology, palynology and organic geochemistry analyses. This study aims to fill the gap in knowledge, focusing on its facies architecture and the spatial distribution of architectural elements and key stratigraphic surfaces, in order to unravel their potential allogenic and autogenic controlling factors, both locally and regionally.

25 studied sections (with a total of 760 m logged) form the basis for constructed cross-sections along a 20km+ escarpment, which has a mostly down-dip orientation (NNE-SSW) relative to the main sediment transport direction within its depocenter. Within-parasequence variation in dominant process regime (mainly fluvial- or wave-dominated) occurs in less than 2 km in a strike-oblique direction. Key stratal surfaces (sequence boundaries, maximum regressive and flooding surfaces) show remarkable similarities with the previously established framework for the updip fluvial part of the system, which allow establishing a relatively confident long-distance correlation and propose for the first time a regional along-dip reconstruction of the Mesa Rica Sandstone.

Sub-regional flooding surfaces (mappable for < 7 km) are interpreted to reflect delta lobe abandonment followed by local subsidence and later re-activation of sediment pathways. This suggests that solely autogenic lobe switching accounts for flooding surfaces of limited lateral reach, reflecting a complex lateral lobe compensation. However, both allogenic and autogenic controls alone can explain the combination of key stratal surfaces (regionally mappable), succession thickness differences and the internal architecture of trunk size composite scours, which are therefore inconclusive on their dominant driving forces.

We argue that the overall low-accommodation setting enforces a “filter” on signals recorded in the upstream part where confinement results in a preferential expression of allogenic factors. This can then be used to understand the recording of these signals in the relatively less confined downstream part of the depositional system. Accurate identification and temporal constraints on flooding events may be applied as a framework to improve facies mapping and consideration for compartmentalization in deltaic successions elsewhere. Unraveling the interplay of paleo-bathymetry, dominant processes (fluvial, wave, tidal), forcing mechanisms and slope gradients for the Mesa Rica Sandstone delta will contribute to the general understanding of deltaic development in low-accommodation settings.

10.1.4 Van Yperen et al. (2018), British Sedimentological Research Group (BSRG) annual meeting, Edinburgh, Scotland

Van Yperen, A.E.[1], Poyatos-Moré, M.[1], Holbrook, J.M.[2], Line, H.L.[1], Midtkandal, I.[1] (2018). The “filtering” effect and internal delta-lobe variability in low-accommodation fluvial-marine transition zones: the Cretaceous Mesa Rica Sandstone (New Mexico, USA)

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The “filtering” effect and internal delta-lobe variability in low-accommodation fluvial-marine transition zones: the Cretaceous Mesa Rica Sandstone (New Mexico, USA)

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The complex interaction between marine and terrestrial processes at the fluvial-marine transition zone is challenging to decipher in low-accommodation systems, characterized by relatively thin, condensed, and often top-truncated sections. This study investigates the exhumed Albian-Cenomanian Mesa Rica Sandstone (Western Interior Seaway, USA), which is exposed along a ~450 km, NNW-SSE oriented depositional profile, from southeast Colorado to central-east New Mexico. The profile covers a complete transect from channel belt deposits upstream to fully deltaic deposits downstream. The study area is located within the fluvial-marine transition zone, approximately ~70 km updip from the most distal deltaic expression that can be studied. 23 sedimentary logs (total of 390 m) are spatially correlated within a ca. 20 km2 study area. Detailed analysis of facies distribution, depositional architecture, and spatial extent of stratigraphic surfaces reveals a lower 7-11 m-thick, sharp-based and sand-prone deltaic succession, occasionally incised by composite erosional surfaces with multi-storey fluvial and marine-influenced sandstone-filled channels (12-20 m-thick, 100-250 m-wide). Internal geometries are characterized by tabular and laterally-extensive deltaic lobes. Based on differences in grain size, sedimentary structures, bed thicknesses and bioturbation, four different delta lobe sub-environments can be distinguished, ranging from lobe axis, off-axis, fringe to distal fringe. They reflect differences in depositional energy but also the presence of intra-lobe variation in dominant process regime, with diminishing river-dominance and potential increase in tide-influence from the lobe axis to fringe. Fringe-sections are characterized by thoroughly bioturbated top surfaces which are interpreted as a result of early abandonment. Architectural elements and interpreted depositional sub-environments suggest an overall river-dominated delta, although with local preservation of tidal signatures. The combined effects of high sediment supply and low-accommodation resulted in a sheet sandstone that is significantly thin compared to both the upstream fluvial- and downstream fully deltaic strata. This supports deposition close to base level with vertical limits on aggradation and incision and thereby prompting lateral reworking of strata into amalgamated deltaic sheets. We caution against the resulting potential ‘filtering’ effect on the preservation and recording of interacting marine and terrestrial processes in low-accommodation fluvial-marine transition zones.

10.1.5 Van Yperen et al. (2019), Winter Conference, Bergen, Norway

Van Yperen, A.E.[1], Poyatos-Moré, M.[1], Holbrook, J.M.[2], Line, H.L.[1], Midtkandal, I.[1] (2019). Internal delta-lobe variability and the "filtering" effect in low-accommodation fluvial-marine transition zones: the Cretaceous Mesa Rica Sandstone (New Mexico, USA)

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Internal delta-lobe variability and the “filtering” effect in low-accommodation fluvial-marine transition zones: the Cretaceous Mesa Rica Sandstone (New Mexico, USA)

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The complex interaction between marine and terrestrial processes at the fluvial-marine transition zone is challenging to decipher in low-accommodation systems, characterized by relatively thin, condensed, and often top-truncated sections. This study investigates the exhumed Albian-Cenomanian Mesa Rica Sandstone (Western Interior Seaway, USA), with 23 sedimentary logs (total of 390 m), spatially correlated within a ca. 20 km^2 study area. Detailed analysis of facies distribution, depositional architecture, and spatial extent of stratigraphic surfaces reveals a lower 7-11 m-thick, sharp-based and sand-prone deltaic succession, occasionally incised by composite erosional surfaces with multi-storey fluvial and marine-influenced sandstone-filled channels (12-20 m-thick, 100-250 m-wide). Internal geometries are characterized by tabular and laterally-extensive deltaic lobes. Based on differences in grain size, sedimentary structures, bed thicknesses and bioturbation, four different delta lobe components or sub-environments can be distinguished, ranging from lobe axis, off-axis, fringe to distal fringe. They reflect differences in depositional energy but also the presence of intra-lobe variation in dominant process regime, with diminishing river-dominance and potential increase in tide-influence from the lobe axis to fringe. Architectural elements and interpreted depositional sub-environments suggest an overall river-dominated delta, although with local preservation of tidal signatures. The combined effects of high sediment supply and low-accommodation resulted in a sand-prone, regionally-extensive unit, which forms the most proximal deltaic expression of a large-scale (ca. 450 km along depositional profile) low-accommodation system. This fluvial-marine transition zone is located ~70 km updip from the most distal deltaic expression that can be studied. Results of this study evidence a common presence of internal variability in dominant processes regime within proximal delta-lobe sub-environments, but cautions against the potential ‘filtering” effect in the preservation and recording of interacting marine and terrestrial processes in low-accommodation fluvial-marine transition zones.

10.1.6 Van Yperen et al. (2019), AAPG ACE, San Antonio, USA

Van Yperen, A.E.[1], Poyatos-Moré, M.[1], Holbrook, J.M.[2], Midtkandal, I.[1] (2019). From river to delta: down-dip changes in amalgamated sheet sandstones along an exhumed transect

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From River to Delta: Down-dip Changes in Amalgamated Sheet Sandstones Along an Exhumed Transect

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Sediment storage within the fluvial segment of a depositional system impacts the volume of sediment reaching the contemporary shoreline zone, and thus decreases significantly the amount of sediment available for developing shallow-marine reservoirs. Exhumed examples of low-accommodation systems with a well preserved, and consistent sandy nature throughout the full transect are rare. In this study, we utilize the ~450 km transect of the Cretaceous Mesa Rica Sandstone, which is exhumed along its NNW-SSE depositional profile, from southeast Colorado to central-east New Mexico. These excellent conditions allowed conducting both seismic-scale and higher resolution studies of key-areas. Analysis of facies distribution and architectural geometries led to the recognition of multiple depositional environments, regional key stratigraphic surfaces, and sub-regional flooding surfaces.

The upstream fluvial strata record deposition of vertically stacked channel belts forming multi-valley sheets, changing downdip into a >80 km-wide single-storey channel sheet. Downstream, the coeval fluvial-marine transition zone represents deposition in a shallow mixed-energy setting. The most distal expression that can be studied is characterized by coalesced mouth bars, consistently overlain by sand-filled amalgamated distributary channels. This sheet-like geometry is interpreted to result from the combined effects of high sediment supply and low-accommodation, and bioturbation as a post-depositional homogenization process. This demonstrates that these sand sheets can be formed without necessary dominance of wave redistribution processes and therefore cautions against the classical interpretation of these geometries as the product of wave-dominated coastlines.

Additionally, this study provides an example of sand-prone shallow-marine reservoir deposition despite significant fluvial sediment storage. The work is important to understand other systems elsewhere, like the Lower Cretaceous on Svalbard. Here, outcropping fluvial sandstones form the upstream equivalent of undrilled but seismically-imaged sediment lobes that form a potential play model in the adjacent Barents Sea Shelf. Studying exhumed systems like the Mesa Rica Sandstone improve our understanding of facies changes and sediment partitioning and distribution along different source to sink segments of low-gradient depositional systems, with important implications on sand prediction and reservoir quality.

10.1.7 Van Yperen et al. (2019), International Association of Sedimentologists, Rome, Italy

Van Yperen, A.E.[1], Poyatos-Moré, M.[1], Holbrook, J.M.[2], Midtkandal, I.[1] (2019). Internal mouth-bar variability and preservation potential of tide-influence in a low-accommodation setting (Dakota Group, USA)

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Internal mouth-bar variability and preservation potential of tide influence in a low-accommodation setting (Dakota Group)

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Determining the relative impact of coastal processes on delta fronts is fundamental to the interpretation of delta development. Deciphering the complex interaction of fluvial-, tide- and wave-energy recorded in ancient deltaic deposits becomes challenging in low-accommodation systems because they are characterized by relatively thin, condensed, and commonly top-truncated sections. In this study, we analyze the exhumed Cenomanian Mesa Rica Sandstone (Dakota Group, Western Interior Seaway, USA), which encompasses a fluvio-deltaic system covering a ~450 km along a depositional dip-parallel profile. The study targets the most proximal deltaic expression of the Mesa Rica system, with 22 sedimentary logs (total of 390 m), spatially correlated within a ~ 25 km2 study area at the rim of the Tucumcari Basin. Analysis of facies distributions, depositional architecture, and spatial extent of stratigraphic surfaces reveals a lower 6–10-m-thick, sharp-based and sand-prone deltaic package. This package comprises laterally-extensive mouth bars that are locally incised by composite erosional surfaces containing multistory fluvial and marine-influenced channel infill (12–20 m thick, 100–250 m wide).

We distinguish four different sub-environments within single mouth-bars, based on differences in grain size, sedimentary structures, bed thicknesses, and bioturbation indices. These range from mouth bar axis, off-axis, fringe to distal fringe deposits, and each reflects differences in hydraulic conditions moving away from the main feeding channel. Architectural elements and interpreted depositional sub-environments also show intra-mouth-bar variability in dominant process regime, with overall river dominance but potential increase and local preservation of tide influence from the mouth-bar axis to distal fringe. Mouth-bar deposits amalgamate to form an extensive sand-rich sheet body throughout the study area, in which interflood siltstone to very-fine grained sandstones are nearly absent. The sheet-like nature and near-absence of fine-grained interflood deposits reflects successive coalescence of mouth bars in a relatively low A/S ratio. These conditions increase channel avulsion/bifurcation and thus the potential reworking of previously deposited mouth-bar-fringe and distal-fringe sediments, where tide influence tends to be better recorded.

Results of this study evidence a common presence of internal variability in dominant process regime within mouth-bar sub-environments. Additionally, it cautions against the possible loss of preservation of tidal indicators, and a consequent underestimation of the true tidal influence in low-accommodation deltaic settings with interacting fluvial-tidal processes.

10.2 Abstracts, co-author

10.2.1 Serck et al. (2017), International Meeting of Sedimentologists, Toulouse, France

Serck, C. [1], Yperen, A.E.[1], Braathen, A.[1], Midtkandal, I.[1], Olaussen, S.[2], Appleyard, T.[2], Osmundsen, P.[3] (2017). Carbonate-to-clastic sediment dynamics in a high-relief supra-detachment basin: continental to marine deposition in the Bandar Jissah Basin, NE Oman

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Accepted for oral presentation

Carbonate-to-clastic sediment dynamics in a high-relief supra-detachment basin: continental to marine deposition in the Bandar Jissah Basin, NE Oman

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A close relation between fault movement and sedimentary stacking is evident from the tectonostratigraphic signature of the mostly Eocene Bandar Jissah Basin, near Muscat in the Sultanate of Oman. The basin evolved above a major extensional detachment linked to extensional collapse following the Late Cretaceous Oman ophiolite emplacement. The basin infill is exposed along excellent, kilometer-scale cliffs, revealing a ~1,5 km thick sedimentary succession in the hanging wall of a major segmented boundary fault locating roll-over folds. The Paleocene (?) to Eocene basin fill records extensional faulting episodes along two hard-linked, large normal faults striking NW and NE, respectively. Initial high input of coarse clastic material is considered a response to basin-bounding fault activity in a continental setting. A coarse conglomerate was deposited near the fault escarpment during the early stage of faulting, and grain size reduction away from the fault reflects increased distality. Conglomerates proximal to the fault represent alluvial fan and braid-plain deposits with scattered patches of preserved soil profiles that are otherwise eroded. Braid-plain deposits dominate with greater distance from the fault, while soil profiles increase in thickness and lateral extent. Sediment maturity and palaeocurrent data suggest a localized sediment source, presumably a canyon cut across the boundary fault. A thin transgressive lag marks the boundary between continental conglomerates and mixed carbonate/siliciclastic sandstones formed in a submarine setting. These mixed deposits are considered to represent an extensional faulting climax, where tectonic subsidence outpaced sedimentary input, thus effectively drowning most of of the basin. Sediment supply caught up with tectonic subsidence during the late stage of this episode, as evident by a shallowing-upward signature in the carbonate/siliciclastic sandstones, culminating with development of carbonate reefs in the uppermost stratigraphic level. Continued base-level fall led to deposition of soils on top of the carbonates. Thereafter, a deepening-upward trend suggest renewed extensional fault activity mainly on the NE-trending, southern fault segment, with a second extensional faulting climax indicated by a 500 m thick grain-stone to marly limestone succession. Limited siliciclastic input in this succession suggests the basin was detached from the sediment source represented by the nearby footwall basement (core complex), and that the aforementioned feeder-canyon was abandoned as a sediment point-source. Instead, debris from shallow marine carbonate production interfingered with small fans sourced from spatially limited footwall catchments. The marine to continental transition in the Bandar Jissah Basin highlights the delicate balance between sedimentary base-level and fault activity along basin bounding faults, which results in significant spatial and vertical facies contrasts.

10.2.2 Midtkandal et al. (2018), AGU, Washington, USA

Midtkandal, I.[1], Holbrook, J.M.[2], Faleide, J.I.[1], Myers, C.[2], Van Yperen, A.E.[1], Shephard, G.E.[1], Nystuen, J.P.[1] (2020). Early Cretaceous Arctic Palaeotopography as Constrained by Barents Sea Sediment Budget

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Accepted for poster presentation

Early Cretaceous Arctic Palaeotopography as Constrained by Barents Sea Sediment Budget

Midtkandal, I.[1], Holbrook, J.M. [2], Faleide, J.I.[1], Myers, C.[2], Van Yperen, A.E.[1], Shephard, G.E.[1], Nystuen, J.P. [1]
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Sedimentary volume estimates in the Barremian Boreal Basin of the Barents Shelf are used to calculate catchment area and improve plate tectonic reconstructions in the present-day Arctic. The Festningen Member of the Barremian Helvetiafjellet Formation developed as a braided river, leaving a widespread braidplain deposit. The river sediments crop out along on southern Spitsbergen, with palaeocurrent data consistently showing flow to SE, and stratal architecture indicating the whole outcrop area is contained within the upstream reaches of the system. The interplay of incipient Amerasia Basin opening, and long-wavelength doming associated with the High Arctic Large Igneous Province (HALIP) is related to the topography and fluvial runoff in the area. Contemporaneous deltaic strata are mapped 300 km SE of Spitsbergen, providing basin scale constraints.

The fulcrum method for analysis of fluvial channel dimensions assumes the balance of sediment and water upstream and downstream from a cross section placed along the river path are equal. The method calculates palaeo-river characteristics from channel infills and bar dimensions coupled with grain size distribution. The model output values broadly a river with a drainage area between about 250,000 km2 (drainage length 2500km) and 600 km2 (drainage length 4000km). A high end modern analogue system is the Missouri River upstream from Sioux City, Iowa which drains 600km2.

This new framework offers the ability to test and refine a circum-Arctic plate tectonic model; resultant palaeogeography is proposed to account for a river catchment area as scaled to the Festningen Member and is further tuned to fit recent spatio-temporal data from neighbouring Arctic basins and highs. The model re-iterates the presence of a massive northern, continental source, Crockerland, as also indicated in studies centred on the Canadian Sverdrup Basin. Consequently, a challenge remains with constraining the timing and kinematics of the Amerasia Basin opening, especially the Canada Basin portion, where a potentially competing sedimentary sink during the Barremian places. Further constraints as to the size and distribution of land-masses in the sediment source area provide a critical step forward in linking regional fluvial, sedimentary, tectonic and deeper geodynamic processes.

10.2.3 Midtkandal et al. (2020), Winter Conference, Bergen, Norway

Midtkandal, I.[1], Holbrook, J.M.[2], Faleide, J.I.[1], Myers, C.[2], Van Yperen, A.E.[1], Shephard, G.E.[1], Nystuen, J.P.[1] (2020). Testing arctic tectonic plate models with Cretaceous sediment source to sink budgets

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Accepted for oral presentation

Testing arctic tectonic plate models with Cretaceous sediment source to sink budgets

Midtkandal, I.[1], Holbrook, J.M. [2], Faleide, J.I. [1], Myers, C. [2], Van Yperen, A.E.[1], Shephard, G.E. [1], Nystuen, J.P. [1]

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A numerical architectural analysis of an outcrop belt is coupled with grain size analysis and zircon data to constrain river dimensions, load, and capacity. This data is used further to quantify sediment volumes that passed through the outcrop belt in order to improve estimates on downstream strata and the catchment area size. This substantiates a refinement of upstream palaeogeography and palaeotectonic plate configurations. The study object is the lower Cretaceous fluvial strata on Spitsbergen and its basinward equivalent in the Barents Sea.

The onshore outcrops are a fluvial braidplain deposit up to 20-m-thick and mappable across southern Spitsbergen, while offshore subcrops, mapped by seismics 300 km further to the SE, are marine shelf platform strata. The river discharge supported up to five contemporaneously active braided channels, each at least 200 m wide. A ~50,000 km^2 drainage area is estimated based on application of the mass balance fulcrum test when a temperate climate model is used.

The results have implications for the palaeotectonic configuration in the since fragmented Cretaceous source area, and is used to promote a revised plate tectonic model for the present-day Arctic during the Barremian. The notion of a landmass of sufficient size to feed large-size rivers across and beyond Spitsbergen, and into the western Barents Sea area is supported.

10.2.4 Holbrook et al. (2020), AAPG ACE, Houston, USA

Holbrook, J.M.[1], Van Yperen, A.E.[2], Bhattacharya, J.[3], Miall, A.[4] (2020). The diachronous sequence

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The diachronous sequence

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Sequence stratigraphy began as a way to conceptualize strata in both time and space, but the concept of the sequence has evolved considerably since. Initial views of the sequence showed major bounding surfaces as time lines, plotted flat in space vs. time Wheeler diagrams with sequence boundaries recording long hiatuses closing down dip. Direct testing of these original concepts with experiments and more precise field dating has resulted in significant modifications in the original slug diagram, showing that sequences are dissected by a series of hiatuses at finer scales than originally presented. Preservation is fractional and on orders as low as 10-6 vertically along any two-dimensional dip or strike section because of spatial irregularity in deposition. When time is considered in three-dimensional space, most of these gaps converge. Similarly, flume observations and field data have shown that fluvial sediment delivery is semi-continuous throughout the sequence cycle. Therefore, the sequence boundary is not a bypass surface, a time line, nor an unconformity. Instead it is a composite surface with continuous deposition at some point in three-dimensional space for its terrestrial duration. This results in the key understanding that discrete parts of this surface are equivalent to single/individual regressive marine surfaces. Particular surfaces commonly mapped in terminal regressive deposits, equivalent to the up-dip sequence boundary, include the basal surface of forced regression, the correlative conformity, scours below extending truck channels, surfaces below distributary channels, and the knickpoint valley surfaces sliced through the highstand and falling stage prisms. Each of these are traceable to and time equivalent with the composite subaerial unconformity/sequence boundary farther up dip. Consequently, the down-dip equivalent of the sequence boundary consists of several dispersive elements rather than one surface. This approach acknowledges the diachronous nature of surfaces and deposits in 3D. It also suggests a resolution to debates about sequence stratigraphic nomenclature and the impossible quest for a single surface correlatable to the sequence boundary in the marine realm. Sequence boundaries in fact may be generated throughout the T-R cycle in the fluvial realm and are correlate to a series of divergent surfaces and intervening deposits down dip.

10.3 Articles, co-author

10.3.1 Braathen et al. (2018), Basin Research, 30(4), 688-707

Braathen, A.[1], Midtkandal, I.[1], Mulrooney, M.[1], Appleyard, T.[2], Haile, B.G.[1], Yperen, A.E.[1] Growth-faults from delta collapse–structural and sedimentological investigation of the Last Chance delta, Ferron Sandstone, Utah.

[1]University of Oslo, Department of Geosciences, P.O. Box 1047 Blindern, 0316 Oslo, Norway
[2]Department of Arctic Geology, UNIS, Longyearbyen, Norway

10.3.2. Serck et al. submitted to Basin Research

Serck, C.[1], Braathen, A.[1], Olaussen, S.[2], Midtkandal, I.[1], Osmundsen, P.[3], Yperen, A.E.[1], Indreværa, K.[4] Carbonate-to-clastic sediment dynamics in a high-relief supra-detachment basin: continental to marine deposition in the Bandar Jissah Basin, NE Oman

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10.4 Teaching and outreach

GEO2120 – Sedimentology

Role: Responsible for practical,

Semesters taught: Autumn 2018

Frequency of meetings: 1 morning

Enrolment & student profile: ~10 undergraduate

GEO4230 – Basin formation and sequence stratigraphy

Role: Responsible for practicals, assisting with report and exam assessments

Semesters taught: Autumn 2015; 2016; 2017

Frequency of meetings: Five to ten 3 hour sessions per semester

Enrolment & student profile: ~10–20, graduate MSc

GEO4011 – Field course in basin analysis

Role: Field work supervision and field report assessment

Semesters taught: 2015; 2016; 2017; 2018

Frequency of meetings: 10 days fieldwork per year

Enrolment & student profile: ~10–12, graduate MSc

GEO4216 – Sedimentology and sequence stratigraphy

Role: Responsible for practicals

Semesters taught: 2018

Frequency of meetings: Nine 3 hour sessions

Enrolment & student profile: ~10, graduate MSc

Supervision of MSc theses

Student: Thea Sveva Faleide, University of Oslo, Norway

Completed: July 2017

Topic: Lower Cretaceous delta system in the Hoop area, SW Barents Sea

Student: Cody Myers, Texas Christian University, Texas, USA

Completed: December 2018

Topic: Sediment budget estimates for the Cretaceous Festningen Member, Spitsbergen

Outreach

November edition, 2019

Article in ‘Hoogtelijn’, magazine of the Dutch Mountaineering Society (NKBV), on the geology of Spitsbergen and how our research on fluvio-deltaic systems can help refining palaeogeography and palaeotectonic plate configurations in the arctic.

February, 2020

‘Time traveling on Spitsbergen; from desert to polar bear in ~400 million years’

Invited speaker on the annual day of the Dutch Mountaineering Society (NKBV)