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 km² 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 deposits.
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, 1977; 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, 1977; 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, 1977). 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 cliniothems, 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 progradation 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 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
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
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.
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 km² 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).

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, 1973; 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;}

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**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.
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 | B14–6: 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 | B10–2: 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 | B10–5: 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 | B10–3: 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 | B10–4: 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 Pebby sandstone                 | F—F—M     | Pebby 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 | B15–6: 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 | B10–3: Skolithos, Ophiomorpha, Macharonichnus | Migrating straight-crested ripples. Lower flow regime. Climbing ripples indicate high rates of deposition |

(Continues)
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 rare planar lamination (f6) sandstone, with common subangular to subrounded, and dispersed granules occur in cross-stratified sandstone beds (Figure 4B, Table 1). Bed boundaries are 10–30 cm thick, poorly sorted and rare planar lamination (f6) and cross-stratification (f5). Conglomerate beds become increasingly amalgamated upwards and grade into better sorted, trough and tangential cross-stratified pebbly sandstone (f6). BI 0–2: Thalassinoides, Ophiomorpha

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 motting. Yellow-grey siltstone with yellow motting. 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 | B10–1: unidentified | Current reversals in subtidal zone. Climbing ripples indicate high rates of deposition |

4.2.2 | Interpretation

The sediments of FA2 are associated with high-energy deposition close to the river mouth (Wright, 1977; Engelse and Mulder et al., 2012). Deposits from debris flows processes and low-density turbidity currents, as inferred from the structureless (f3) and planar laminated (f4), respectively. The upward-increasing amalgamation of conglomerate beds throughout FA2 represents an increase in energy. The upward-increasing amalgamation of conglomerate beds throughout FA2 suggests a change in the energy regime, from low-energy to high-energy deposition sequences. FAC2, as interpreted as related to hyperpycnal flow conditions (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 respect to the high-density and low-density turbidity flows. FAC2.a deposits are interpreted as related to hyperpycnal flow conditions (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.
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.
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 inter-flood 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 inter-flood deposits (FA2.a and FA2.b) and low (FA2.a) to absent (FA2.b) bioturbation.

**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.
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). Pebby 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 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

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)
4.3.2 | Interpretation

The sedimentary features of FA3 also indicate high-energy deposition in a proximal mouth-bar setting (Wright, 1977; 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...
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 synsereis 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., 2015), 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 \((f1; \text{Figure 5F})\). Very fine-grained to fine-grained, sharp-based sandstone beds \((0.1–0.3 \text{ m thick})\) can be traced for 100–200 m and bed tops commonly exhibit asymmetrical ripples \((f8; \text{Figure 6C})\). 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 \((0.3–3 \text{ m})\) that fine upward into very fine-grained sandstone beds \((5–20 \text{ cm})\) with interbedded siltstone in places. This facies association comprises two subsets; FA9.a is characterised by high-index bioturbation \((BI 5–6, \text{Thalassinoides, Ophiomorpha})\) 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 \((f11, \text{Table 1})\). The lags are in places overlain by a thin \((ca 5 \text{ cm})\) siltstone package. FA9.b is characterized by sandstone beds \((30–60 \text{ cm})\) 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 \((max. 1 \text{ km})\) 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) \((\text{Figures 2B and 9})\). 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 2 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 scouras, 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 interpreted 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 lenoid geometries with accompanying onlapping surfaces are observed
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. Préalat et al., 2009).
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)
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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 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
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.*, 2016; 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)
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
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.

**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).
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 basin settings (this study). Studies in shallow lake (Fidolini and Ghinassi, 2016) and foreland basin (Jerrett et al., 2016) settings show along-strike changes from predominately 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-rewiring 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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