RE-EVALUATING THE PALEOGEOGRAPHY OF THE RIVER-DOMINATED AND WAVE-INFLUENCED FERRON NOTOM DELTA, SOUTHERN CENTRAL UTAH: AN INTEGRATION OF DETAILED FACIES-ARCHITECTURE AND PALEOCURRENT ANALYSIS

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ABSTRACT: This study re-evaluates the paleogeography of a river-dominated and wave-influenced deltaic system in a single parasequence (6a) of the Cretaceous Ferron Sandstone, south-central Utah, which was previously interpreted as a typical asymmetric delta. The conceptual asymmetric-delta model of Bhattacharya and Giosan (2003) has been widely applied to interpret ancient deltaic systems. However, reconstructed paleogeographies relying on this conceptual model are commonly not scaled to the architectural elements, which could possibly lead to inaccurate interpretations, especially when data are relatively sparse. The extensively exposed Ferron Sandstone outcrops provide an opportunity to demonstrate how detailed facies-architecture work can be integrated with regional facies relationships to elucidate a properly scaled paleogeography.

Seven facies associations (FA) are identified in parasequence 6a and are arranged into two distinctively different successions. The river-dominated succession consists of prodelta, distal delta-front, proximal delta-front, and terminal-distributary-channel FA, while the wave- and storm-dominated succession comprises offshore-shelf, lower-shoreface, and upper-shoreface FA. The river-dominated succession is muddier and less bioturbated than the wave- and storm-dominated succession. Facies-architecture analysis shows that the river-dominated proximal delta-front facies consists of mouth-bar and terminal distributary-channel elements that are not seen in the wave- and storm-dominated facies. The scales of mouth bars and terminal distributary channels suggest that they are rather small features compared with the river-dominated delta lobe, which is incompatible with the simple bar-elongation asymmetric-delta model presented by Li et al. (2011). Instead, parasequence 6a is interpreted to be a valley-fed, river-dominated symmetric delta protected from waves by an updrift barrier system, which is analogous to the modern Mongky river delta on the west coast of Madagascar. The progressive change in orientation of west-directed mouth bars, to north-directed and east-directed lobes around the periphery of the river-dominated delta, indicates a highly radial Lafourche-type delta. Moving away from the protection of the barrier system, there is a gradual change from highly river-dominated facies to increasingly wave- and storm-influenced facies toward the southeast. Due to the entrenched nature of the feeder river associated with an incised-valley system, the parasequence 6a delta was bifurcation-dominated rather than avulsion-dominated. This study shows that it is critical to integrate detailed facies-architecture analysis in order to reconstruct properly scaled paleogeographies and hypothesizes that stable bifurcation-dominated deltas should be more common than avulsion-dominated deltas in a lowstand delta system due to the entrenched nature of the feeding trunk river, which inhibits avulsion.

INTRODUCTION

The concept of “skewness” or asymmetry was firstly introduced by Wright and Coleman (1973) to quantitatively describe the nature of lateral variation in delta morphology caused by a pronounced dominant littoral drift. The degree of “skewness” was defined as the ratio of sediment volume on the right side of the delta central axis to the volume on the left side. By studying the wave-dominated São Francisco shoreline system on the Brazilian coast, Dominguez (1996) drew attention to the previously reported “groyne” effect (Zenkovitch 1967; Komar 1973) caused by river discharge in trapping sediments transported by wave-driven longshore drift in the updrift side of the river mouth.

Bhattacharya and Giosan (2003) proposed a conceptual asymmetric-delta model based on re-evaluation of the geomorphology of a number of modern mixed river- and wave-influenced deltas (e.g., Danube delta). Asymmetric deltas develop favorably when waves approach the shoreline from an oblique direction, which produces strong and sustained longshore currents (Giosan et al. 2005; Ashton and Giosan 2011). A key component of the Bhattacharya and Giosan (2003) model is that the downdrift margin forms by the elongation of a single mouth bar that grows to develop a
paired barrier-island and back-barrier lagoonal bay. As the delta progrades, the lagoonal bay fills with a river-dominated and/or tidally influenced bayhead delta. Formation of the initial mouth bar typically occurs during exceptional river floods. MacEachern et al. (2005) further suggested that study of spatial variations in ichnological characteristics of deltaic deposits could be very effective in identifying asymmetric deltas, where open marine and stressed brackish-water ichnological suites are expected to develop in the updrift and downdrift sides of asymmetric deltas, respectively.

Many asymmetric deltas have subsequently been interpreted from the rock record through integrated sedimentological and ichnological analysis of outcrops and cores (Table 1). Most of these studies have documented wave-dominated shoreface succeions and river-dominated delta-front facies, containing normal Skolithos and Craziana ichnofacies and their impoverished equivalents, respectively (Hansen and MacEachern 2007; Charvin et al. 2010; Hampson et al. 2011; Li et al. 2011; Buatois et al. 2012; Forzoni et al. 2015; Ainsworth et al. 2016). However, rigorous testing of the Bhattacharya and Giosan (2003) conceptual model with well-documented examples is still largely lacking. Firstly, many of the existing studies are based on documentation of lateral changes from river-dominated to wave-dominated facies, which, although necessary, may not be sufficient evidence for the interpretation of asymmetric deltas. Secondly, there are no convincing examples that show unequivocal evidence for wave-reworked downdrift-deflected barrier bars (Table 1). It is noteworthy to point out that the downdrift flanks of many of asymmetric delta examples are deflected river-dominated delta lobes rather than individual barrier bars (Hampson and Howell 2005; Fielding 2010; Charvin et al. 2010; Hampson et al. 2011; Ainsworth et al. 2016). We have found only one study that explicitly interpreted deflected barrier bars on the downdrift side of the delta, which is within parasequence 6a of the Ferron Notom Delta, Utah studied by Li et al. (2011). A number of other studies have postulated barrier bars as a shelter from wave damage for the development of river-dominated delta or bayhead deltas (Charvin et al. 2010; Hampson et al. 2011; Ainsworth et al. 2015), but documentation and description of the facies architecture in these barrier bar elements are lacking.

Even though oblique wave-generated longshore drift has been widely interpreted to be the primary driving mechanism for the development of asymmetric or deflected deltas (Table 1), other mechanisms of forming asymmetric deltas have been recognized from both modern and ancient deltaic systems. Fielding et al. (2005) interpreted that Coriolis effects played a significant role in the northward plume deflection and development of asymmetry of the Burdekin delta in northeastern Australia. This analog was later used as a modern analog in interpreting the asymmetry of the Ferron Notom Delta in the Cretaceous Western Interior Seaway, Utah, on the southern flanks of the Henry Mountains (Fielding 2010), immediately south of the area considered in this paper. In examining the flux and fate of the Yangtze River sediments, Liu et al. (2007) concluded that coastal currents are critical in the preferential development of prodelta mud wedges in the downdrift side of the river mouth, which was later extended to many other large Asian-river deltaic systems (Liu et al. 2009). Ayranci and Dashgird (2016) recognized that strong tidal currents are responsible for the net sediment transport below storm-wave base producing prodelta asymmetry in the Fraser River delta system (Ayranci et al. 2014) and also pointed out that the same delta could possibly exhibit wave-induced asymmetry in shallow water (e.g., delta-front environment) and tidal-current-induced asymmetry in deep water (e.g., prodelta environment). A comprehensive list of controlling processes has been summarized in a recent review of 27 Holocene deltas by Korus and Fielding (2015), who proposed a quantitative way to define asymmetric deltas by comparing the downcurrent vs. upcurrent sediment volume and area and also depicted that delta planform asymmetry often varies between different sub-environments (e.g., delta plain, delta front, prodelta) even in the same deltaic system and is not always consistent with internal sedimentary characteristics (e.g., sand:mud ratio).

In this paper, we review the previous interpretation of parasequence 6a of the Ferron Notom Delta, presented by Li et al. (2011), and present a revised model based on additional facies-architecture studies (e.g., Ahmed et al. 2014) that emphasizes the size and scale of mouth-bar, terminal distributary channel, and wave-reworked-shoreface elements to better test the applicability of the Bhattacharya and Giosan (2003) model, as well as evaluating the applicability of other aspects that indicate symmetry, such as variations in bioturbation in the prodelta facies.

GEOLoGICAL SETTING AND PREVIOUS STUDIES

The Ferron Sandstone Member of the Mancos Shale Formation consists of a series of east- to northeast-prograding clastic wedges passing from nonmarine to shallow marine successions, which were deposited during the middle to late Turonian at the western margin of the Cretaceous Western Interior Seaway, an epicontinental sea that stretched from the Gulf of Mexico to the Arctic Ocean to the north (Hale and Van De Graaff 1964; Hale 1972; Cotter 1975, 1976; Ryer 1981) (Fig. 1). It was developed in response to the continued thrusting of the Sevier orogenic belt to the west and associated subsidence of the Cordilleran Foreland Basin as sediments were shed from the highland to the seaway eastward (Fig. 1A) (Ryer and Lovekin 1986; Gardner 1995; DeCelles and Giles 1996). The Ferron Sandstone is overlain by the Blue Gate Shale and underlain by the Tununk Shale, all of which are members of the Mancos Shale Formation (Lupoto 1916) (Fig. 1A). Three fluvial-deltaic complexes are identified in the Ferron Sandstone, namely the Vernal, Last Chance, and Notom deltas (Hale and Van De Graaff 1964; Hale 1972; Cotter 1975; Hill 1982; Gardner 1995; Garrison and van den Bergh 2004), which advanced into the seaway across an approximately northeast-trending shoreline (Fig. 1B) (Elder and Kirkland 1994). Simulated results indicate that the circulation pattern of the Turonian seaway is characterized by a large-scale counterclockwise gyre (Sageman and Arthur 1994; Slingerland et al. 1996), which had likely driven southward coastal currents on its western margin (Cotter 1976; Thompson et al. 1986). The general climate during the Turonian was inferred to be humid and subtropical, within a general global greenhouse setting (Dean and Arthur 1998; Bhattacharya and Tye 2004; Bhattacharya and MacEachern 2009). Palynological analysis of Ferron floodplain facies and paleosols by Akyuz et al. (2015) suggests an ever-wet, subtropical environment.

Numerous studies have been published on the Last Chance Delta, which crops out in central Utah (see papers in Chidsey et al. 2004 and Ryer 2004 for an overview of earlier studies). Although it is stratigraphically complex, it has been interpreted as a general lobate-shaped river-dominated and wave-influenced delta (Cotter 1975; Ryer 1981; Thompson et al. 1986; Gardner 1995), locally showing distinctive lateral facies variations (Ryer 1993). Despite numerous studies, and perhaps owing to the largely dip-oriented nature of the outcrop belt, only a few detailed paleogeographic reconstructions of individual sand bodies have been presented (e.g., Anderson et al. 2004; Dewey and Morris 2004), but most indicate some mixture of wave and fluvial influence (Ryer and Anderson 2004). Recent geomorphic models have suggested that the KF-1 parasequence of the Ferron Last Chance Delta should be more lobate than some of these previous models show (Burpee et al. 2015).

The southern Notom Delta, which is superbly exposed in the Henry Mountains area, south-central Utah, has been the focus of many recent studies and is also the focus of this study (Fig. 2). The outcrop belt includes both northeast- and southeast-oriented outcrops, affording the ability to evaluate both depositional dip and strike variability. Sub-regional facies and stratigraphy of the Notom Delta have been mapped and correlated in the western, northern, and southern flanks of the Henry Mountains Syncline (HMS) by Fielding (2010, 2015), Zhu et al. (2012),
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and Korus and Fielding (2017), respectively. In these studies, the Notom Delta is documented as an upward-coarsening succession consisting of shallow-marine deltaic and shoreface deposits passing upward into nonmarine facies (Li et al. 2010; Li and Bhattacharya 2013; Famubode and Bhattacharya 2016).

Zhu et al. (2012) established a sub-regional sequence stratigraphic framework in the northern flanks of the HMS and documented 6 sequences, 18 parasequence sets, and 43 parasequences in the Notom Delta (Fig. 3). By dating the bentonites, Zhu et al. (2012) estimated that the Notom Delta was deposited during a period of ~620,000 yr, between 91.25 and 90.63 Ma.

This study focuses on parasequence 6a of parasequence set 6 in sequence 2 (Fig. 3). Parasequence set 6 consists of three parasequences, 6a, 6b, and 6c in a downward order of superposition, which is characterized by a progradational to aggradational stacking pattern (PA) and a positive shoreline trajectory (Fig. 3). The PA pattern is indicated by the increasing sandstone thickness in the three successive parasequences in strike view (Zhu et al. 2012) (Fig. 3). The accommodation succession suggests deposition as a late lowstand systems tract during which a ~20 m relative sea-level rise and ~7 km basinward shoreline translation occurred (Neal and Abreu 2009; Zhu et al. 2012). The landward extension of parasequence set 6 comprises an incised-valley system, which is interpreted to be the feeder for the deltaic facies of parasequence 6a that are investigated herein (Zhu et al. 2012) (Fig. 3A).

A few studies have been published on parasequence 6a. Li et al. (2011) conducted a sub-regional along-strike stratigraphic correlation of parasequence 6a and interpreted the delta to be asymmetric based on the evidence of lateral changes from wave-dominated shoreface with open-marine ichnofacies to river-dominated delta-front facies with stressed and impoverished ichnofacies. Their interpretation was based largely on 36 measured sections with an average spacing of 1 to 2 kilometers apart and did not incorporate any architectural element analysis. There are three problems with this interpretation, especially in the context of the Bhattacharya and Giosan (2003) model: 1) muddy lagoonal and bayfill deposits, which are predicted to be associated with the downdrift side of modern asymmetric deltas were not observed; 2) the transition between the wave-dominated shoreface and river-dominated delta-front facies were not elucidated due to the relatively wide spacing of measured sections across the transition zone (Fig. 4); 3) the evidence for downdrift-deflected mouth bars was not substantiated with facies-architecture studies.

Subsequent to the work by Li et al. (2011), Garza (2010) and Ahmed et al. (2014) conducted more detailed facies-architecture studies on the river-dominated delta-front part of parasequence 6a in Coalmine Wash (Fig. 4). They showed evidence of river flood-dominated mouth-bar complexes that prograded toward the northwest to west in the Coalmine Wash area at a high angle to the overall inferred northeast to east progradation direction (Fig. 4). These west-directed mouth-bar deposits were not identified in the previous regional studies of Li et al. (2011) and Zhu et al. (2012). The Garza (2010) and Ahmed et al. (2014) studies focused primarily on the interpretation of mouth-bar depositional processes. However, their work did result in a revised regional paleogeography (Ahmed et al. their Figure 3) that showed a much more extensive river-dominated lobate delta flanked by wave-dominated shorefaces and lacking downdrift barrier-lagoon pairs. Subsequent work by Li (2012) conducted detailed facies-architecture...
analysis to the east of the area studied by Garza (2010) and Ahmed et al. (2014). This area also comprises mouth bars and terminal distributary channels, confirming the extent of the river-dominated lobe, but also showed that these channels and bars build to the northeast and east, where Li et al. (2011) hypothesized that wave-deflected mouth bars occur.

In another study, Li et al. (2015) focused on detailed thin-bed facies analysis of the prodelta and distal delta-front facies of parasequence 6a. This study documented the along-strike changes in sedimentary structures, bioturbation, and wave versus river influence of thin beds and showed that the highest river influence occurred in the western Coalmine Wash area that was also the focus of the studies of the shallower delta-front sandstone facies architecture by Garza (2010) and Ahmed et al. (2014).

The objectives of this paper are: 1) to more clearly elucidate the nature of the transition zone between wave-dominated shoreface and river-dominated delta front through detailed facies-architecture analysis integrating data from previous studies and additional data collected in this study, 2) to re-evaluate the paleogeography of parasequence 6a and provide an updated interpretation of the morphology of the Notom Delta in a larger geological context, as well as providing constraints on the predictions of models proposed by Bhattacharya and Giosan (2003) and Burpee et al. (2015).

**METHODOLOGY AND DATA SET**

This study focuses on the northern part of the Ferron outcrop belt close to Factory Butte northwest of Hanksville, Utah, with a particular emphasis on the transitional zone between river-dominated deltaic and wave- and storm-dominated shoreface facies identified by Li et al. (2010) (Figs. 2, 4).

Data used for this study were collected in the field by measuring detailed sedimentological sections, in which lithology, sedimentary structures, grain size, bed thickness, paleocurrent direction, and trace fossils were recorded. Gigapan™ hardware and software and telephoto zoom lenses were used to capture and compose photomosaics of sub-centimeter resolution, which were in turn used to make detailed bedding diagrams, illustrating internal bed geometry and facies architecture. Paleocurrent data measured from dips of cross-stratification of angle-of-repose and "rib-and-furrow" structures are plotted on rose diagrams using Geoorient™. Some of the paleocurrent data measured by Li et al. (2011), Garza (2010), and Ahmed et al. (2014) are also incorporated into this study. The apparent dip of mouth-bar accretion clinoforms was recorded and plotted on Google Earth™ maps.

In total, the new data in this study included 18 measured sections (ranging from 7 to 20 m), 9 high-resolution photomosaics (Fig. 4), 10 dips of mouth-bar accretion clinoforms, and more than 1800 paleocurrent readings.

**FIG. 2.—Base map of the study area. A) Base map showing Utah and the location of the Ferron Notom Delta outcrop, which is marked with a red rectangle. B) Base map showing the distribution of the Ferron Notom Delta outcrop and the location of this study area, which is marked with a black rectangle. XX' and YY' mark the locations of cross sections shown in Figure 3. Approximate geographic coordinates for X, X', Y, and Y' are listed below for reference. X (38° 14' 30.56" N; 110° 49' 37.56" W), Y (38° 18' 53.36" N; 110° 49' 37.56" W), Y' (38° 30' 18.53" N; 110° 55' 38.73" W), X' (38° 30' 18.53" N; 110° 55' 38.73" W).**
FIG. 3.—Cross sections showing the regional sequence stratigraphy of the Ferron Notom Delta. A) Oblique-depositional-dip sequence stratigraphy of the Notom Delta. B) Oblique-depositional-strike sequence stratigraphy of the Notom Delta. Parasequence 6a in parasequence set 6 of sequence 2, marked with a black rectangle, is the focus of this study. See Figure 2B for the locations of the two cross sections (modified from Zhu et al. 2012).
measurements. Nine detailed bedding diagrams and two correlated measured sections were made.

DEPOSITIONAL FACIES

Parasequence 6a is ~20 m thick and consists of a general coarsening-upward succession (Fig. 5). Seven facies associations (FA) are identified based on their lithology, sedimentary structures, ichnological information, and their vertical and lateral relationships (Table 2). The river-dominated part of parasequence 6a includes prodelta, distal delta-front, proximal delta-front, and terminal-distributary-channel (TDC) deposits. The wave- and storm-dominated part includes offshore-shelf, lower-shoreface, and upper-shoreface deposits. The river-dominated succession is in general muddier, more heterolithic, and far less bioturbated than the wave- and storm-dominated succession. Similar facies associations described below have been partially observed and documented in detail in previous studies in the same parasequence by Li et al. (2011), Ahmed et al. (2014), and Li et al. (2015).

Prodelta (FA1)

Description.—This facies association occurs at the basal part of parasequence 6a (Fig. 5). It consists of planar-laminated mudstone intermediately interbedded with thin layers of wave- and current-ripple laminated very fine-grained sandstone (Fig. 5). Mudstones can also be massive or graded. Normal grading is common with laminated muddy siltstone grading upward into massive mudstone (Fig. 6A, B). Some of the normally graded beds have erosional bases, which cut into the mudstone layer below (Fig. 6B). Inverse grading is not as common as normal grading, but when present, is mostly associated with normal grading above with either an erosional or conformable boundary (Fig. 6A). Dewatering cracks are seen locally (Fig. 6C). The mudstone is not bioturbated to lightly bioturbated, having a bioturbation index (BI) of 0–2 (cf. Taylor and Goldring 1993). Sporadic thin beds show intense but low-diversity bioturbation (BI of 3–4) comprising small Planolites, Teichichnus, Chondrites, and Conichnus burrows (Fig. 6D). Carbonaceous material is abundant.

Interpretation.—The muddy facies are interpreted to be deposited in a river-dominated prodelta environment. The low BI indicates a stressed environment, likely due to fresh-water input and high sedimentation rates (MacEachern et al. 2005). The presence of dewatering cracks also suggests a high sedimentation rate (certainly high initial porosity at the time of deposition) and possible salinity fluctuation close to the river mouth (i.e., these could be syneresis cracks). Massive mudstone is interpreted to be deposited out of suspension in a buoyancy-dominated setting (Nemec 1995). Normally graded beds are interpreted to be turbidite deposits, with laminated siltstone and massive mudstone respectively, representing Tc and Te Bouma Sequences (Bouma 1962). However, when normal grading is associated with inverse grading below, together they are interpreted to be deposited by hyperpycnal turbidity currents related to river floods (Mulder et al. 2001; Mulder et al. 2003). Inverse grading is the product of waxing flow, and normal grading is the result of waning flow. The occasional erosional contact in between indicates a flood event of exceptionally high magnitude when deposition stopped and erosion occurred (Mulder et al. 2001; Mulder et al. 2003; Bhattacharya and MacEachern 2009).

Distal Delta Front (FA2)

Description.—Muddy prodelta facies grade upward to heterolithic interbedded sandstone and muddy siltstone (FA2) (Fig. 5). Siltstone is planar laminated to massive (Fig. 7A) and locally characterized by ball-and-pillow structures and small-scale growth faults (Fig. 7B, C). Sandstones, which are commonly characterized by planar bedding, are locally capped by wave-ripple cross lamination (Fig. 7D, E). Current ripples, which in places are climbing, are also commonly seen in the
sandstone beds (Fig. 7F, G). Individual sandstone beds can be traced laterally for at least a few hundred meters. Carbonaceous material is abundant. Bioturbation is low, with BI ranging from 0 to 2. Common trace fossils include Planolites and Paleophycus. Anconichnus, Arenicolites, and Conichnus are less commonly seen.

Interpretation.—The heterolithic facies is interpreted to have been deposited in a river-dominated distal delta-front environment. The massive siltstone, characterized by ball-and-pillow structures and growth faults, is interpreted to be slump deposits resulting from gravity flows, similar to those described in the Mississippi delta front (Lindsay et al. 1984). Both soft-sediment deformation and climbing ripples indicate a relatively high rate of sedimentation that is likely linked to periodic riverine floods. Even though other triggering mechanisms (e.g., earthquakes, tsunamis, hurricanes) cannot be completely ruled out (Seilacher 1969; Mazumder et al. 2006), soft-sediment deformation structures are interpreted to have probably been caused by rapid sedimentation and overloading due to the fact that they are mostly confined to distal delta-front environments, localized and not continuous and almost always associated with other indicators of high sedimentation rate, such as climbing ripples (Moretti and Sabato 2007; Owen et al. 2011; Olabode 2016). The planar-bedded sandstone is interpreted to be distal-delta-front splays that were deposited during seasonal floods and have also been interpreted as possible hyperpycnal flows (Ahmed et al. 2014; Li et al. 2015). The wave-ripple cross lamination on top of the planar-bedded sandstones indicates wave influence during inter-flood periods. The low bioturbation index and limited variety of trace fossils indicate a stressed environment, likely close to a river mouth (MacEachern et al. 2005; Buatois et al. 2008; MacEachern et al. 2010; Buatois et al. 2012; Dasgupta et al. 2016).

Proximal Delta Front (FA3)

Description.—Facies association 3 consists of a coarsening-upward fine- to medium-grained, lightly bioturbated (BI of 0–2) sandstone succession, including basal (quasi-) planar beds (FA3a), middle-meter-scale low-angle cross beds (FA3b) and upper decimeter-thick cross beds (FA3c). The basal (quasi-) planar beds directly overlie FA2 with a sharp but conformable contact (Fig. 8A). They are commonly ~1 m thick (up to 2 m) and can be traced laterally for over a few hundred meters (Fig. 8A). They are not always truly planar but locally show centimeter-scale undulations, which is the reason for designating them as quasi-planar beds (Fig. 8B). In places, these quasi-planar beds are interbedded with thin (climbing) current-rippled cross-laminated layers (Fig. 8C). Meter-scale low-angle cross-bed sets occur on top of the basal planar beds with either erosional or conformable contacts and are separated from each other by thin-bedded (centimeter-to-decimeter-scale) mudstone layers (Fig. 9A, B). They make lens-shaped sand-bodies that are commonly ~1 m thick and a few tens of meters wide (Fig. 9A, B), which may show an upward-coarsening trend (Fig. 9B). The meter-scale cross beds are locally truncated on their updip margins and subsequently filled with mud plugs, but show tangential bottom sets (Fig. 9A, B, C). The cross-bedded units form mega rib-and-furrow structures in plan view, with foreset ribs reaching up to 30 m wide (average 5 m) (Fig. 9D). Internally, they comprise multiple coupled inversely and normally graded beds (Fig. 9E). These cross-bed sets show a gradual decrease in dimensions (i.e., thickness and width) upward, along with an increase in dip angles of the cross beds. Decimeter-thick cross beds are commonly < 50 cm thick and no more than a few tens of meters wide (Fig. 9F). Low-relief erosional scours are common. Bioturbation is absent to very light (BI of 0–2). Ichnogenera includes Planolites, Palaeophycus, Ophiomorpha, Skolithos, Asterosoma, and Fugichina.

Interpretation.—This facies association is interpreted to have been deposited in a progressively shallowing proximal delta-front environment. The basal (quasi-) planar beds are interpreted to be deposited by unidirectional and undulating combined flows, probably related to storm-driven flood events (Arnott 1993). The alternating ripple-planar-ripple facies successions indicate changes in flow velocity from lower to upper and then back to lower flow regimes. This is interpreted to indicate the waxing and waning of possible hyperpycnal flows induced by seasonal
river floods (Mulder et al. 2003; Bhattacharya and MacEachern 2009; Ahmed et al. 2014), similar to those described in Pennsylvanian Minturn Formation (Lamb et al. 2008; Myrow et al. 2008) and the Panther Tongue Formation (Olariu et al. 2010). Their internal traction-dominated structures indicate that there was enough inertia in the river flow to allow sand to bypass the river mouth. Consequently, we interpret these planar beds to be inertia-dominated bars as proposed by Wright (1977) and explained in detail by Ahmed et al. (2014). The meter-scale low-angle cross beds are deposited as a result of increasing bed friction caused by a gradual decrease of water depth, which is further supported by the decrease in cross-set dimensions up section. The lenticular-shaped upward-coarsening cross-bed sets represent a basic and essential element (i.e., mouth-bar clinofans) in building mouth-bar complexes, which in turn build the delta lobes (Garza 2010 and Ahmed et al. 2014). These cross beds are thus interpreted to be friction-dominated mouth-bar deposits, as proposed by Wright (1977) and discussed in detail in Ahmed et al. (2014).

### Terminal-Distributary-Channel Deposits (FA4)

**Description.**—Channel-form sandstone bodies are characterized by a basal erosional surface and occur in the middle to upper part of the parasequence (Fig. 10). Erosional surfaces usually have relief of less than 5 m (typically 1 to 3 meters) and widths of a few tens of meters to over 100 meters. FA4 often cuts down to FA3 (Fig. 10). The erosional boundaries are not always well defined. It is common to have only one clear erosional edge, while the other side is laterally conformable with adjacent mouth-bar deposits (Fig. 10A, B). Internally they are filled with decimeter-scale cross-bedded fine- to medium-grained sandstones (Fig. 10A, B) and in places with meter-scale inclined beds (Fig. 10C, D). Channel fills may or may not show a fining-upward trend. Locally, the erosional surface is partially filled with mudstones, which are conformable with the adjacent thick inclined beds. There is largely no to rare bioturbation in this facies association.

<table>
<thead>
<tr>
<th>Facies Associations (FA)</th>
<th>Lithology and Sedimentary Structures</th>
<th>Ichnological Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prodelta (FA1)</td>
<td>Mudstone interbedded with thin-beded very fine-grained sandstone. Mudstone is planar-laminated to massive, locally shows normal and rare inverse grading, dewatering cracks. Thin-beded sandstone is wave- and current-ripple cross laminated and are commonly associated with basal centimeter-scale erosional surfaces</td>
<td>Sparse to low bioturbation, with common trace fossils of low diversity, including Planolites, Chondrites, Teichichnus, and Conichunus. Local intermittent layers with moderate, low-diversity bioturbation of reduced size. Abundant organic material (BI 0–2, locally 3–4, stressed)</td>
</tr>
<tr>
<td>Distal delta front (FA2)</td>
<td>Heterolithic, interbedded very fine-grained sandstone and siltstone. Sandstone is planar-laminated or current-ripple cross laminated (locally climbing), with sporadic wave-ripple cross lamination on top of the bed. Siltstone is planar-laminated or massive with soft-sediment deformation in places</td>
<td>No bioturbation to low bioturbation, with common trace fossils including Planolites, Palaeophycus, Anconichunus, Arenicolites, and Conichunus. Top of beds locally shows moderate bioturbation. Abundant organic material in silty layers (BI 0–2, stressed)</td>
</tr>
<tr>
<td>Proximal delta front (FA3)</td>
<td>Coarsening-upward, fine- to medium-grained sandstone with (quasi-) planar bedding, low-angle meter-scale cross bedding and bar forms, decimeter-thick planar cross bedding, and current-ripple cross lamination (locally climbing). Local low-relief erosional scour.</td>
<td>No bioturbation to low bioturbation, with common trace fossils including Planolites, Palaeophycus, Ophiomorpha, Skolithos, Asterosoma, and escape burrows of Fugichnia (BI 0–2, stressed)</td>
</tr>
<tr>
<td>Terminal distributary channel (FA4)</td>
<td>Fine- to medium-grained sandstone with decimeter-thick planar and trough cross bedding, meter-scale erosional surfaces</td>
<td>Largely no to rare bioturbation (BI 0–1)</td>
</tr>
<tr>
<td>Offshore shelf (FA5)</td>
<td>Mudstone and siltstone interbedded with sporadic thin-beded very fine-grained sandstone that is planar-laminated and locally massive or normal graded. Thin sandstone beds are commonly wave-ripple cross laminated or hummocky cross stratified, locally show current-ripple cross lamination</td>
<td>Moderate to high bioturbation with common trace fossils including Planolites, Chondrites, Teichichnus, Palaeophycus, Rhizocorallium, and Helminthopsis (BI 3–4, locally 5–6, unstressed)</td>
</tr>
<tr>
<td>Lower shoreface (FA6)</td>
<td>Very fine-grained amalgamated hummocky cross stratified (locally planar bedded) sandstone interbedded with sporadic thin-beded siltstone. Tops of sandstone beds commonly show wave-ripple cross lamination</td>
<td>No bioturbation to moderate and diverse bioturbation. Bioturbation intensity decreases from bed top downward. Common trace fossils include Skolithos, Ophiomorpha, Palaeophycus, Diplocraterion, Cylindrichnus, Phycisphon, Planolites, Asterosoma, Thalassinoides, and Chondrites (BI 0–4, unstressed)</td>
</tr>
<tr>
<td>Upper shoreface (FA7)</td>
<td>Fine- to medium-grained sandstone characterized by decimeter-thick cross bedding and common wave-ripple cross lamination</td>
<td>Sparse to moderate bioturbation, with common trace fossils including Ophiomorpha, Skolithos, and Palaeophycus (BI 0–4, locally 5–6, unstressed)</td>
</tr>
</tbody>
</table>
Fig. 6—Photos showing the muddy-prodelta facies association (FA1). A) Inverse to normal graded beds. B) Mudstone interbedded with laminated very fine-grained sandstone. The upper part of the section is characterized by a normally graded bed, as marked with the white triangle, where laminated very fine-grained sandstone grades upward to silty mudstone and then to massive mudstone with clear contacts. The base of the very fine-grained sandstone is characterized by a minor erosional surface. C) Laminated silty mudstone with dewatering cracks. D) Laminated silty mudstone interbedded with bioturbated mudstone. De, dewatering cracks; Pl, Planolites; Te, Teichichnus.
Interpretation.—The erosional surfaces are interpreted to be terminal distributary channels (Olariu et al. 2005; Olariu and Bhattacharya 2006). These terminal distributary channels are interpreted to have directly fed the associated and underlying mouth-bar deposits. The sandy fill of the terminal distributary channels is interpreted to have been formed by lateral, downstream, and possibly upstream accretion of mouth bars. The muddy fill of some of the terminal distributary channels is interpreted to be abandoned-channel deposits. The lack of bioturbation is likely due to high energy and high sedimentation rate. The one-sided nature of scours suggests that both erosion and accretion may occur at the margins of terminal distributary channels, as discussed by Olariu and Bhattacharya (2006).

Offshore-Shelf (FA5)

Description.—This facies association occurs at the basal part of parasequence 6a. It primarily consists of moderately to highly bioturbated (BI of 3–4, locally 4–5) mudstone and siltstone with sporadic thin-beded very fine-grained silty sandstone. Mudstone and siltstone can be planar-laminated, wave-ripple cross laminated, or massive. Thin sandstone layers are commonly wave-ripple cross laminated. However, current-ripple cross lamination and normal grading are locally observed. Common trace fossils are Planolites, Chondrites, Teichichnus, Rhizocorallium, and Helminthopsis.

Interpretation.—These muddy deposits are interpreted to be offshore-shelf facies association. Mudstones were likely deposited from suspension fallout from deflected hypopycnal plumes. Thin-beded sandstone is interpreted to have been deposited from sporadic hyperpycnal flows associated with river floods, as indicated by current-ripple cross lamination and normal grading (Mulder et al. 2003; Bhattacharya and MacEachern 2009; Li et al. 2015). The intense and diverse bioturbation, however, indicates an overall unstressed, open marine environment. The trace-fossil assemblage indicates a Cruziana ichnofacies (MacEachern et al. 2010).

Lower Shoreface (FA6)

Description.—The muddy offshore-shelf facies passes upward into an amalgamated very-fine grained hummocky-cross-stratified sandstone interval in the middle part of parasequence 6a (Fig. 11A). These
Fig. 9.—Photos showing the meter-scale low-angle cross beds (FA3b) and decimeter-thick cross beds (FA3c). A) A meter-scale low-angle cross-bed set on top of planar beds. Note that cross-bed set is truncated on top and tangential at the bottom as marked with the dashed yellow line. The contact between them is conformable to the east and erosional to the west. A mud plug is clearly seen at the back of the cross-bed set. B) A meter-thick low-angle cross-bed set accretes and thins toward the SW. C) Bedding diagram made based on Part B. D) A plan view of meter-scale low-angle cross-bed sets (rib-and-furrow structure). E) A photo showing the internal characteristics of the cross-bed set shown in Part B. Cycles of inversely graded bed overlain by normally graded bed are marked with white triangles. F) Decimeter-thick cross beds.
FIG. 10.—Photomosaics and bedding diagrams showing the terminal-distributary-channel deposits (PA4). A) Photomosaic 1. B) Bedding diagram based on photomosaic 1. Clinoforms dip toward the southwest at the lower-left part of the outcrop. A terminal distributary channel is marked with a thick red line, which cuts down into the mouth-bar deposits on the northeast side of the outcrop. The erosional relief is about 3 meters on the northeast side and gradually decreases toward the southwest, where it becomes more or less conformable with the mouth-bar deposits. C) Photomosaic 4. D) Bedding diagram of photomosaic 4. An erosional surface with a relief of about 5 m is marked with a red line, which is interpreted to be a terminal distributary channel. The channel is filled with large-scale inclined cross beds, which are interpreted to be laterally accreting mouth bars. The terminal distributary channel cuts down into the mouth-bar deposits below, which thicken from the southeast toward the northwest. See Figure 4 for the locations of the photomosaics. LA, lateral accretion; TDC, terminal distributary channel.
hummocky-cross-stratified (HCS) beds are a few decimeters thick and commonly wave-ripple cross laminated on top. They are more intensely bioturbated on top than internally, where bioturbation could be very low or absent (BI of 0–4). In places, they are separated from each other by centimeter-thick mudstone layers (Fig. 11A), which are commonly intensely bioturbated. Trace fossils are quite diverse, including Skolithos, Ophiomorpha, Palaeophycus, Diplorcraterian, Cylindrichnus, Phycosiphon, Planolites, Astrosomia, Thalassinosoides, and Chondrites.

**Interpretation.**—This facies association is interpreted to have been deposited in a lower-shoreface environment. The stacked HCS beds were formed by large storm waves, by which sediments delivered offshore by flooding river were suspended and redeposited below fair-weather wave base (Dott and Bourgeois 1982). Wave-ripple cross lamination on top of the HCS beds indicates the waning stage of a storm event. Intense bioturbation on top of the HCS beds and the highly bioturbated interbedded mudstone layers indicate deposition and organism activities during the intermittent quiescent period between storms. Diverse and varying degrees of bioturbation indicate an unstrusted, open marine environment. The trace-fossil assemblage indicates a mix of the Cruziana and Skolithos ichnofacies (MacEachern and Pemberton 1992; Pemberton et al. 1992; MacEachern et al. 2010).

**Upper Shoreface (FA7)**

**Description.**—This facies association occurs above FA6 and consists primarily of nonbioturbated to moderately bioturbated (BI of 0–4) fine- to medium-grained sandstone, which is most commonly tabular or trough cross-bedded, but locally can be planar-bedded or massive. Cross-bed set thickness ranges from 10 to 40 cm. Common trace fossils include Ophiomorpha, Skolithos, and Palaeophycus (Fig. 11B, C, D).

**Interpretation.**—FA7 is interpreted to be upper-shoreface deposits. The tabular and trough cross beds are interpreted to have been produced by longshore currents that run parallel to the shore. Trace fossils indicate a Skolithos ichnofacies developed in a high-energy marine environment (Pemberton et al. 1992; MacEachern et al. 2010).

**Facies-Architecture Analysis**

Figure 12 shows a typical example of an oblique-strike photomosaic in the river-dominated deltaic deposits. Line drawings highlight the lateral and vertical facies changes. From bottom to top, quasi-planar beds (FA3a) pass upward into meter-scale low-angle cross beds (FA3b), which gradually decrease in height and width upward and then change to decimeter-thick cross beds (FA3c). The meter-scale low-angle cross beds downlap toward both the NW and SE, indicating bidirectional downlap of mouth bars in strike view. The offlapping nature and variation in thicknesses of these cross-bed sets likely indicate a compensational stacking pattern. A terminal distributary channel (FA4) is recognized in the middle part of the section, which cuts down into the meter-scale cross beds below with one clear cut bank to the SE and a conformable boundary to the NW. The channel is initially actively filled with meter-scale inclined beds accreting laterally and then abandoned temporarily as indicated by the muddy inclined beds, which are interpreted as abandoned-channel fill. The upper part of the parasequence is dominated by decimeter-thick cross beds (FA3c).

Figure 13 shows an example of an oblique-dip photomosaic in the river-dominated deltaic deposits. The mouth-bar deposits consist of clinothems with fully preserved topset, foreset, and bottomset. These clinothems extend over a hundred meters in the dip direction, and clinothem beds range from a few decimeters to over a meter thick. They are characterized by a thinning and fining trend down dip. From proximal to distal, each clinothem consists of decimeter-thick cross beds (FA3c) in the topset passing into meter-scale low-angle cross beds (FA3b) in the forest, and then into (quasi-) planar beds (FA3a) and heterolithic distal delta-front deposits (FA2). The progradational growth of these clinothems toward the NW is interpreted to be downstream accretion of mouth bars. Abrupt lateral facies changes and onlapping surfaces suggest a compensational stacking pattern of multiple mouth-bar assemblages (Wellner et al. 2005) (Fig. 13).

Mouth bars that accrete upstream are also locally seen at the upper part of parasequence 6a in a dip-oriented photomosaic (Fig. 14), similar to those documented in the modern Atchafalaya (Van Heerden and Roberts 1988; Olariu and Bhattacharya 2006) and Wax Lake delta (Wellner et al. 2005), and the Cretaceous Panther Tongue in Utah (Olariu et al. 2005). In our example, the decimeter-thick cross beds (FA3c) dip toward the east, which is consistent with the paleocurrent direction. In contrast, the clinothems comprising the cross beds dip toward the west, which is opposite to the paleocurrent directions. The mouth-bar deposits are underlain by an erosional surface, which is interpreted to be a terminal-distributary-channel scour.

Additional photomosaics and associated bedding diagrams showing the facies architecture of the river-dominated mouth-bar deposits are included in the Appendix (i.e., P2, P5, P6, and P8, see Supplemental Material). The facies architectures described in these panels are observed exclusively in the river-dominated part of the delta and are incorporated into the detailed paleogeographic maps. The terminal-distributary-channel and mouth-bar elements are not observed in the wave- and storm-dominated deposits.

**Sub-Regional Facies Correlation**

Two sub-regional cross sections were made to show the changes of depositional facies across the study area. Cross section a–a’ has an oblique-dip orientation (Fig. 15A), and cross section b–b’ has an oblique-strike direction (Fig. 15B).

A typical river-dominated deltaic section is interpreted and correlated from S1 to S8 in cross section a–a’, based on the common presence of current-ripple cross lamination, graded bedding, unidirectionally dipping decimeter-scale cross bed bedding, erosional scours, and clinoforms (Fig. 15A). It is in general lightly bioturbated (BI of 0–3) with ichnogenera of limited diversity. It is characterized by a coarsening-upward trend, consisting of muddy prodelta (FA1), heterolithic delta front (FA2), sandy proximal delta front comprising (quasi-) planar beds (FA3a), meter-scale low-angle cross beds (FA3b), and decimeter-scale cross beds (FA3d) from base to top. Terminal-distributary-channel deposits (FA4), at the upper part of the succession, cut into FA3. Sporadic wave-ripple cross lamination and HCS suggest that this was a river-dominated, wave- and storm-influenced system. Storms were likely important in driving rivers into a flood stage and generating hyperpycnal flows. This river-dominated succession changes over a short distance (about a few hundred meters) northeastward into a sandy shoreface system, which is thicker and obviously sandier than the river-dominated succession, as seen in S11 to S14 (Fig. 15A). These sections are characterized by abundant wave-ripple cross lamination, HCS, sporadic current-ripple cross lamination, and a
A regular decrease in cross-set dimensions from the base of the cross section to the top can be seen. In the middle part of the cross section, an erosional surface with a relief of about 2 m is interpreted to be a terminal distributary channel and is marked with a thick red line. The terminal distributary channel is conformable with the mouth bar to the southeast, which are composed of cross sets about 2 m thick and accrete toward the northwest. The terminal distributary channel is represented by a thin red line. Above the abandoned-channel deposit, secondary thin planar beds are seen meeting the top surface. See Figure 4 for the location of the photomosaic.
FIG. 13.—A) Photomosaic 7. B) Bedding diagram made based on photomosaic 7 showing the topset preserved clinoforms and the compensational pattern of mouth-bar assemblages. From Ahmed et al. (2014). See Figure 4 for the location of the photomosaic.
FIG. 14.—A) Photomosaic 9. B) Bedding diagram made based on photomosaic 9 showing upstream-accreting mouth-bar deposits with accretion surfaces (clinoforms) dipping toward the west and internal cross beds dipping toward the east. An underlying terminal distributary channel is marked with a red line. See Figure 4 for the location of the photomosaic.
FIG. 15.—A) Oblique-dip cross section a–a'. Correlation of measured sections shows the transition from river-dominated delta-front facies into wave- and storm-dominated shoreface toward the east. B) Oblique-strike cross section b–b'. Correlation of measured sections shows detailed facies of a shoreface system. See Figure 4 for the location of the cross sections.
more highly bioturbated nature (average BI of 3–4, but up to 5–6). A gradual basinward (east) pinch-out of the sandy lower-shoreface facies (FA6) is illustrated from S13 to S14 (Fig. 15A). S9 and S10 are characterized by a mix of river, wave, and storm influence, as indicated by the interbedding of wave-ripple cross-laminated and HCS beds with current-ripple cross-laminated and unidirectionally dipping decimeter-scale cross beds. There is also a presence of abundant quasi-planar beds. This section is interpreted to represent the transition between river-dominated-delta and wave-dominated-shoreface deposits (Fig. 15A). The interfingering nature of this transitional zone indicates that it was developed as a result of the active interaction of river, wave, and storm processes, and that the river-dominated delta to the SW and the wave- and storm-dominated shoreface to the NE were developed contemporaneously. There is no evidence of significant mudstone at this transition zone, suggesting that mud was not trapped in a bay and likely escaped seaward.

A typical wave-dominated shoreface section is interpreted and correlated in cross section b–b’ (Fig. 15B). It is characterized by an upward-coarsening lightly to moderately bioturbated succession, comprising muddy offshore-shelf deposits at the base (FA5), which passes upward into lower-shoreface deposits with amalgamated HCS beds (FA6) overlain by decimeter-scale cross-bedded upper-shoreface sandstones (FA7). A gradual lateral and oblique-basinward transition of depositional facies from upper shoreface to lower shoreface and to offshore-shelf facies can be observed between S18 to S14 (Fig. 15B).

PALEOCURRENT ANALYSIS

In total, more than 1800 paleocurrent measurements were collected and plotted in rose diagrams to assess the plan-view change in bar accretion directions and plume dynamics across the study area (Fig. 16).

Regional River-Flow Direction

The trunk river that fed the deltaic lobes in parasequence set 6a was mapped farther west of the study area and was interpreted as an incised-valley system cutting into older parasequences of lower-shoreface and shelf facies (Fig. 3A) (Zhu et al. 2012). Measured paleocurrent data from these fluvial deposits, as reported by Li et al. (2011), Zhu et al. (2012), and this study, consistently show that the trunk river was flowing toward the northeast as confined by the incised-valley system (N1 and N2) (Fig. 16).

Delta-Progradation Direction

Paleocurrents, which were measured on a sub-regional scale from the rib-and-furrow structures in the river-dominated proximal delta-front deposits exposed in the Skyline Rim area (N3–N6), show a gradual northward change from dominantly east to northeast, which is consistent with the northeastward regional river-flow direction (Fig. 16). Paleocurrents in the Coalmine Wash area, as measured from decimeter-thick cross beds in river-dominated proximal delta-front deposits in this study, Garza (2010), and Ahmed et al. (2014) all indicate a distributary channel
branched to the west and southwest, which is at a high angle to the general northeast direction of the regional delta progradation (N7–12). The progressive change of paleocurrent direction from east to northeast and then to northwest, west, and southwest in the river-dominated delta-front facies (Fig. 16) is interpreted to indicate a radiating flow pattern, which is highly compatible with a river-dominated classical Lafourche-type delta (Bhattacharya 2006, 2010).

**Wave-Approach and Longshore-Drift Directions**

The strike orientations of wave-ripple crests, as reported by Li et al. (2012) and Li et al. (2015), consistently show that waves approached the shoreline from the northeast (N13), which is opposite to the direction of the regional river flow (Fig. 16). Paleocurrent directions as measured from dips of decimeter-thick cross beds within the upper shoreface deposits of parasequence 6a in the northern part of the study area exhibit a bimodal pattern, with a strong component to the northwest and a weak component to the southeast (N14) (Fig. 16).

These cross beds in the upper shoreface facies are interpreted to have been deposited by longshore currents. The bimodal paleocurrent pattern suggests that there was a local stronger net longshore sediment transport toward the northwest, which is quite different from the approximately southward direction of the regional currents within the seaway (Ericksen and Slingerland 1990; Sageman and Arthur 1994; Slingerland et al. 1996). The difference is interpreted to have been caused by the local protuberance of the ancient shoreline, which was oriented NW–SE. The northeast-approaching waves broke on the NW–SE-oriented shoreline at an oblique angle, favoring a slightly stronger longshore transport toward the northwest.

**PALEOGEOGRAPHIC RECONSTRUCTION AND MODERN ANALOGS**

Based on paleocurrent data, clinoform data, detailed depositional facies and facies-architecture analysis, a revised regional paleogeographic map was constructed (Fig. 17B). This map shows a river-dominated delta, which prograded primarily toward the northeast with a significant west prograding delta lobe interpreted to have been fed by a trunk river associated with an incised-valley system. The river-dominated lobe is flanked by wave-dominated shorefaces to the northwest and southeast. This interpretation is different from the asymmetric delta model by Li et al. (2011) (Fig. 17A) but is consistent with the interpretation by Li et al. (2015) based on analysis of the along-strike muddy facies in parasequence 6a (Fig. 17B). Extensive regional-scale paleocurrent analysis indicates a highly radiating pattern typical of a river-dominated delta without obvious southward deflection. A distributary channel apparently branched away from the trunk river toward the northwest and fed a river-dominated delta lobe prograding toward the west to northwest, and is also interpreted in the Coalmine Wash area, based on the observation that mouth-bar deposits prograded in the direction opposite to that of the regional deltaic system (Fig. 17B).

The delta is flanked by a coeval NW–SE-oriented shoreface system to the NW, which refracted the approaching wave from the NE and resulted in

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**Fig. 17.**—Schematic diagrams showing the regional paleogeographic reconstruction of parasequence 6a. **A)** Asymmetrical-delta model proposed by Li et al. (2011). **B)** Symmetrical-delta model proposed in this study, showing a valley-fed delta that prograded toward the northeast, which was protected by a shoreface barrier system to the north. Pie charts showing the relative proportions of river-dominated vs. wave- and storm-dominated facies from Li et al. (2015), based on studies of muddy thin beds in parasequence 6a, indicate a southward decrease in river dominance and increase in wave and storm dominance farther away from the sheltering of the barrier system to the north.
net longshore sediment transport toward the NW. The locally protruding shoreline is interpreted to have protected the delta from severe wave damage and the regional southward longshore drift. However, it does not appear as though this shoreface was important in serving as a barrier, trapping mud, which is assumed to have escaped the bay and subsequently been exported to the offshore shelf and prodelta.

A proposed modern analog to the delta in parasequence 6a is the currently active lobe of the Mongoky River delta, located on the west coast of Madagascar (Fig. 18). The active Mongoky River delta (8 km by 4 km) is characterized by a river-dominated delta lobe with a wave-dominated barrier system updrift of the river mouth, building into the shallow Mozambique Channel (< 10 m). The river-dominated delta lobe has three or four levels of bifurcation from the trunk Mongoky River, which is subject to sporadic high sediment-laden discharges. The interaction between the westward river discharge and the northward regional longshore drift has led to the development of a barrier system updrift of the river mouth (Fig. 18), which acts as a shelter protecting the delta lobe from severe wave reworking and damage. Consequently, the Mongoky River delta is probably river-dominated in nature immediately behind the barrier system and is more wave-influenced farther north, where it lies farther onto the shelf and is thus more open to waves (Fig. 18). Historical images of the Mongoky River delta indicate that the barrier system developed contemporaneously with the river-dominated delta with sediments contributed mostly from updrift exogenous sand and partially from the delta itself. However, the thickness of the Ferron parasequence 6a is ~20 m, which suggests that it was deposited in significantly deeper water than the Mangoky delta.

Fig. 18.—Historical Google Earth images showing the evolution of the Mongoky River delta on the west coast of Madagascar, which is regarded as a good modern analog for the Notom Delta in this study: A) 1990 image showing the emergence of the southern mouth-bar complex and barrier system; B) 1996 image showing the northward migration of the river mouth and the extension of the barrier system; C) present (2017) Mongoky River delta characterized by an established wave-dominated barrier system updrift of the river mouth, which protected the delta from severe wave damage. Directions of longshore drift and wave approach are from Anthony (2015).

DISCUSSION

Initially, Li et al. (2011) interpreted parasequence 6a as asymmetric on the basis of regional stratigraphic correlation and the clear lateral change from shoreface into deltaic facies, an observation with which we broadly concur. They further inferred that the asymmetry reflected formation by the Bhattacharya and Giosan (2003) mechanisms of mouth-bar elongation, despite a lack of obvious lagoonal bay facies or simple barrier islands, as predicted by the model. They suggested that these facies were not preserved as a consequence of deposition during a forced regression with subsequent wave ravinement during transgression. Although their interpretation was made in the absence of detailed facies-architecture analysis, their map (Fig. 17A) shows elongate mouth bars that are about 4 km long and 1 km wide, and associated with a river mouth that is also several kilometers wide.

Subsequently, Garza (2010) and Ahmed et al. (2014) elucidated the nature and number of terminal distributary channels and mouth bars in parasequence 6a. These newer studies, as well as data presented herein, demonstrate that the scale of terminal distributary channels is on the order of 2–3 m deep and 10–100 m wide, versus several kilometers. The mouth bars (i.e., clinothems) are also of a similar scale, with up to about 10 meters of clinoform relief, lengths of a few hundred meters, and widths of about 100 meters. In contrast, the river-dominated facies comprises a distinct delta lobe, consisting of the smaller-scale terminal distributary channels and mouth bars, that extends across an area of about 200 km². The scale of the mouth bars and terminal distributary channels and the scale of the associated delta lobe are incompatible with the simple bar-elongation model, and these observations invalidate the conceptual model presented
by Li et al. (2011). However, we nevertheless still observed a transition from river-dominated facies to wave-dominated facies to the northwest and southeast of the river mouth, indicating that it is a mixed river- and wave-influenced system. However, the river-dominated deltaic system is a rather larger feature than originally mapped by Li et al. (2011).

We also extended the mapping and the paleogeographic understanding of the terminal distributary channels and showed that there is a progressive change in the orientation of west-directed mouth bars, to north-directed and east-directed lobes around the periphery of the regional delta lobe. This is comparable to the highly radial Lafourche delta of the Mississippi, which builds into 10–20 meters of water. This interpretation is also supported by the study of Li et al. (2015), who evaluated the prodeltaic facies in parasequence set 6 and showed a gradual and progressive change from a highly river-dominated delta in the northwest, indicating this was the most protected area to a wave- and storm-dominated shoreface with a gradual increase in bioturbation toward the southeast.

One of the key controls on the stability of the delta associated with parasequence 6a is that it was fed by a river that is incised within a valley. Despite the fact that the river entered into a seaway that is wave- and storm-dominated, the entrenched nature of the river likely induced avulsion and resulted in a much more stable river-dominated delta lobe. We predict that non-incised rivers, such as those associated with highstands, might show a greater level of avulsion with a greater degree of subsequent wave reworking. The dominant style of the long-term evolution of the coast in an entrenched system may be less driven by the accommodation dynamics, but more driven by the bifurcation dynamics of the terminal end of the system. This suggests that the parasequence 6a delta is bifurcation-dominated rather than avulsion-dominated (Jerolmack and Swenson 2007).

We, therefore, hypothesize that avulsion-dominated deltas are inhibited in lowstand systems where rivers are entrenched.

Despite the extensive exposure of these Ferron outcrops, it is clear that in order to correctly elucidate a properly scaled paleogeography, it is critical to integrate detailed facies-architecture work (e.g., detailed facies photomosaic of bar- and bedform-scale features) with regional facies relationships. This, of course, may not always be possible, especially in sparse datasets, but consideration of the broader quantitative source-to-sink relationships can help determine the scaling of architectural elements (Somme et al. 2009; Bhattacharya et al. 2016). One of the lessons that we have learned is that there may be considerable inaccuracy in the paleogeographic maps determined by data that would normally be considered as reasonably tight control with sections that are a kilometer apart. But clearly, this study shows that the regional paleogeography must be reconciled with the actual scale of the terminal distributary channels and mouth bars to apply the bar-elongation model of Bhattacharya and Giosan (2003). This study demonstrates the mismatch between the scale of the river-lobe and the associated mouth-bar and terminal-distributary-channel elements, which are comparatively small in scale. This also supports the models of Edmonds and Slingerland (2007) and Burpee et al. (2015), who showed that Ferron rivers had likely built more lobate-shaped deltaic systems.

Although the paleogeographic interpretation by Li et al. (2011) seemed reasonable at the time, this paper illustrates the danger of qualitative cartoon paleogeographies that rely on conceptual models that are not scaled to the architectural elements and river discharge (e.g., Bhattacharya and Tye 2004). These types of paleogeographic reconstructions are rife in the literature (e.g., Bhattacharya 1994; Ryer 2004), and represent a necessary and valuable evolutionary step in how we interpret the paleogeography of depositional systems. However, accurate paleogeographies will have to increasingly honor scaling relationships that can be derived by integrating a more quantitative source-to-sink approach, especially aided by architectural-element analysis (e.g., Bhattacharya and Tye 2004; Somme et al. 2009; Blum et al. 2013; Bhattacharya et al. 2016).

CONCLUSIONS

Based on lithology, sedimentary structure, ichnological information, and vertical and lateral relationships, seven facies associations, which occur in two distinctively different coarsening-upward successions, are described and interpreted in parasequence 6a. The river-dominated successions consist of muddy prodelta (FA1), heterolithic distal delta-front (FA2), and sandy proximal delta-front (FA3) deposits, which are in places cut by terminal-distributary-channel deposits (FA4). The wave- and storm-dominated successions occur at both flanks of the delta and comprise offshore-shelf (FA5), lower-shoreface (FA6), and upper-shoreface (FA7) deposits. The river-dominated successions are muddier, more heterolithic, and far less bioturbated than the wave- and storm-dominated successions.

Detailed facies-architecture analysis through high-resolution photomosaics and centimeter-scale bedding diagrams reveals that the river-dominated delta consists of mouth-bar (i.e., clinolithem) and terminal-distributary-channel elements that are not observed in the wave-dominated deposits. The scales of mouth bars (up to 10 m high, a few hundred meters long and ~100 m wide) and terminal distributary channels (average 2–3 m deep and 10–100 m wide) and the scale of the associated delta lobe (~200 km²) are incompatible with the simple bar-elongation asymmetric-delta model presented by Li et al. (2011), whose interpretation was based on widely spaced sections in a regional study.

In contrast, in this study parasequence 6a is reinterpreted as an eastward-prograding river-dominated symmetric delta, which is flanked by wave-dominated shoreface. The delta was fed by an incised-valley system to the west and was protected from wave damage by an updrift barrier system, which developed contemporaneously with the delta. The progressive change in the orientation of west-directed mouth bars, to north-directed and east-directed lobes around the periphery of the river-dominated delta indicating a highly radial Lafourche-type delta. The gradual and progressive change from a highly river-dominated delta in the northwest at the most protected area to more wave- and storm-influenced shoreface with a gradual increase in bioturbation toward the southeast also supports this interpretation. The delta in parasequence 6a is analogous to the modern Mongoky River delta on the west coast of Madagascar, which is a river-dominated system due to the protection from wave reworking by an updrift barrier system but is open to more wave influence away from the barrier. The revised interpretation in this study indicates that the parasequence 6a delta, which was fed by a river associated with a lowstand incised-valley system is bifurcation-dominated rather than avulsion-dominated. We predict that avulsion-dominated deltas are likely inhibited and less commonly developed in a lowstand system tract where rivers are entrenched.

This study also demonstrates that there may be considerable inaccuracy in paleogeographic maps constructed based on data that would normally be considered as reasonably tight controls with sections that are a kilometer apart. Integration of detailed facies-architecture analysis with regional facies mapping and correlation is critical to correctly reconstruct a properly scaled paleogeography, avoiding the danger of qualitative cartoon paleogeographies relying on conceptual models.

SUPPLEMENTAL MATERIAL


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