ABSTRACT: Although delta-building processes and the resultant facies and facies associations have been studied for over a century, there remains a lack of well-documented facies architectural studies of ancient deltas. In this study, architectural-element analysis is applied to determine the basic building blocks of a Cretaceous delta at the top of the upper Turonian Wall Creek Member exposed along the western flanks of the Powder River Basin, Wyoming. We document the bed-scale basic building blocks of this ancient delta, and show them in the context of their facies and stratigraphic variability, and their hierarchical spatial arrangement within a single deltaic parasequence. We also test the idea that external sand-body shape may not reflect the internal facies complexity, as has recently been suggested in studies of several modern deltas, including the Burdekin in Australia, the Brazos in the Gulf of Mexico, and the Baram–Trusan in Borneo.

Five orders of bounding surfaces separate six facies architectural elements in the prodelta and delta front deposits. These elements are prodelta fines (PF), frontal splay (FS), channel (CH), storm sheet (SS), tidally modulated deposit (TM), and bar accretion (BA). Seasonal to decadal river floods are thought to represent the main building phases of the delta, producing channels, bars, and frontal splay elements. During intervening periods, the delta was reworked by waves, storms, and tides, producing tidally modulated and storm sheet elements. Due to the complex interactions of river effluents with waves, storms and tides, the delta is interpreted as mixed-influenced. Regional sandstone isolith, facies, and paleocurrent maps help to reconstruct the paleogeography and show how the various architectural elements varied across the delta front. The channels, bars, frontal spays, and tidally modulated elements are found only near the distributary mouth, whereas the storm sheets occur extensively away from the distributary mouth.

The plan-view morphology of the studied delta shows a smooth-fronted, arcuate to cuspatate shape, which should indicate wave dominance. In contrast, our analysis of the internal facies architecture shows that the delta was constructed rapidly during major river floods with significant tidal reworking. Additional outcrop mapping shows that storm-wave-reworked sands are attached to the flanks of the system. Previously published delta models predict incorrectly that the tidal reworking of a river-flood dominated system should result in a more bird-foot shape versus the lobate geometry that is actually mapped. Our analysis of internal facies versus external shape matches similar observations on several modern deltas and suggests that external shape is a poor indicator of internal facies complexity.

INTRODUCTION

Plan-View Morphology vs. Internal Facies Architecture of Deltas

The still popular tripartite classification of deltas into wave-, tide-, and river-dominated end members (Galloway 1975) was based largely on knowledge about the present-day fluvial, wave, and tidal regime as well as the variable plan-view shape of the deltas as observed from air photos or coastline maps (Coleman and Wright 1975). Although the process-based tripartite classification of deltas (Galloway 1975) has been extended to include change of relative sea level (Dalrymple et al. 1992) and variability of grain size (Orton and Reading 1993), only very limited information about facies variability was available, primarily from scattered cores or surface distribution of the modern sediments, in developing these models. As a consequence, there remain almost no studies of modern delta systems that show how internal facies vary laterally (Hori et al. 2002; Ta et al. 2005) and none that document the bed-scale facies architecture (Gani and Bhattacharya 2005a). Although there have been numerous seismic examples from Quaternary systems that show bed-scale architecture, these generally lack core data, and facies and lithologic variability are thus difficult to address (e.g., Suter and Berryhill 1985; Sydow and Roberts 1994; Hart and Long 1996; Hiscott 2003; Roberts and Sydow 2003; Anderson and Fillon 2004; Sidi et al. 2004; Cattaneo et al 2003; Correggiari et al 2005). In addition, most other subsurface and outcrop studies emphasize the more regional-scale sequence stratigraphy, as opposed to the internal facies architecture (e.g., Bhattacharya and Walker 1991; Plint 2000; Bhattacharya and Willis 2001; Willis and Gabel 2001; Porebski and Steel 2003; Pink-Björklund and Steel 2005). Examples of lacustrine deltas studied with ground penetrating
The present study is the first of its kind to propose an architectural-element model for open-marine deltaic deposits in an outcrop. Architectural elements are the 3D building blocks of a depositional system. These architectural elements commonly represent a, or part of, a morphological element. In modern depositional environments important sandy morphological elements include channels, bars, large bedwaves, and spays. These morphological elements migrate and/or grow to produce architectural elements in the rock record. The 3D shape of a morphological element could be significantly different than that of a corresponding architectural element, and depends on how a morphological element evolves, deposits, and is modified through time. For example, migrating hummocky bedwaves may produce a storm sheet sand. In some cases morphological elements may be preserved in the rock record. Although architectural elements can vary in type from one system (e.g., delta) to another (e.g., fluvial), or even within the same system in time and space, there should be a finite number of architectural-element types in any given depositional system. How far a given deposit should be broken down in terms of facies architectural elements involves a balance of how thoroughly but meaningfully the architecture of a deposit can be described. Building blocks (architectural elements) bind with each other in 3D space via bounding surfaces. Permutation and combination (both linear and non-linear) of building-blocks can give rise to an entire depositional system.

Elucidation of architectural elements in shallow marine and deltaic systems is important for several reasons, first, architectural elements link to specific morphometric features, such as bedwaves, mouth bars, and channels, which typically scale to a specific aspect of flow conditions and are thus potentially useful in hydrodynamic analysis (e.g., Bhattacharya and Tye 2004; Willis 2005). This may be critical in developing more quantitative measures of the controlling parameters in predicting delta morphology and growth, which historically emphasizes in a qualitative way the degree of fluvial versus wave and tidal influence, among other factors. Second, surface-bounded geobodies, and specifically architectural elements, are the building blocks routinely used in reservoir and aquifer characterization and fluid-flow modeling (Reynolds 1999; Tye 2004). Thirdly, surface-bounded, bed-scale architecture provides a fundamentally different view of how subsurface facies should be correlated, as is described in detail by Gani and Bhattacharya (2005a), versus the layer-cake correlations that are typically presented in evaluation of many modern delta systems. The architectural-element approach has been enormously useful in the analysis of fluvial and deepwater deposits (Posamentier and Walker 2006) but remains nascent with respect to application to shallow marine and deltaic systems, and we believe that this stems from a lack of well studied examples and models.

**Objectives of This Study**

The objectives of this paper are to identify the basic architectural elements (building blocks) and bounding-surface hierarchies in an ancient delta; to examine the relationship between external geometry and internal facies composition by reconstructing the paleogeography of this delta; and to compare it with modern deltas to understand the process variability. The availability of subsurface data adjacent to the outcrops as well as multidirectional cliff exposures led us to focus on the Wall Creek Member of the Frontier Formation (Late Cretaceous) in central Wyoming (Figs. 1, 2). A companion study (Lee et al. 2007, this issue) used 2D and 3D ground penetrating radar to investigate the 3D geometry of the bar and channel elements described in greater sedimentological detail in this paper.

**REGIONAL GEOLOGY**

The Cretaceous Western Interior Seaway (WIS) stretched roughly north–south across central North America, and developed as part of an eastward migrating and asymmetric retroarc foreland basin lying between the present study is the first of its kind to propose an architectural-element model for open-marine deltaic deposits in an outcrop.

Recent facies-oriented studies of several modern deltas have challenged the long-held assumption that external shape predicts internal facies. The modern Brazos and Burdekin deltas, for example, show smooth-fronted plan-view shapes, traditionally classified as wave-dominated end members, but recent detailed internal facies analyses of these deltas (Rodriguez et al. 2000; Fielding et al. 2005) suggest a dominance of river processes. On the other hand, the modern Baram and Trusan delta in NW Borneo shows wave-dominated and river-dominated shoreline geometry, respectively, but both are characterized by tide-dominated internal facies distribution (Lambiase et al. 2003). Clearly what is needed are more studies of systems that allow integration of internal bed-scale facies architecture with plan-view morphology.

Outcrops of deltaic deposits in the Wall Creek Member of Wyoming provide such an opportunity. The outcrops are exposed on the well-drilled flanks of the adjacent Powder River Basin. The arid climate affords superb cliff exposures through these systems, allowing detailed mapping of facies architecture and lateral facies variability. In addition, adjacent well logs allow us to constrain the 3D geometry of the sediment body and then to compare internal facies variability with external morphology in much greater detail than can be achieved by looking at body and then to compare internal facies variability with external morphology. The availability of subsurface data adjacent to the outcrops facilitate studies of deltaic deposits in outcrops are few. Willis et al. 1999; Mellerle et al. 2002; Anderson et al. 2004; Johnson and Graham 2004; Olariu et al. 2005; Pink-Björklund and Steel 2005). Deltaic depositional systems show greater facies architectural complexity and process variability than fluvial and marine depositional systems, because deltas mark the crucial link between the latter two depositional systems. The present study is the first of its kind to propose an architectural-element model for open-marine deltaic deposits in an outcrop.

The Cretaceous Western Interior Seaway (WIS) stretched roughly north–south across central North America, and developed as part of an eastward migrating and asymmetric retroarc foreland basin lying between...
Fig. 1.—A) Cretaceous paleogeography of the Western Interior Seaway during the middle Turonian. During this time the Wall Creek Member was deposited in a foreland basin sourced from the Sevier belt in the west (modified from Bhattacharya and Willis 2001, and others). B) Location map showing the positions of outcrop and subsurface data, and the Wall Creek outcrop belt at the western margin of the Powder River Basin, Wyoming. The present study focuses at Raptor Ridge. C) Raptor Ridge site, showing the studied cliff sections and well locations behind the cliffs. Note the position of Figures 2B, 5A, B, C, D, and 6.
the Cordilleran volcanic arc to the west and the hinterland to the east (Fig. 1A; Lawton 1994). A pronounced and widespread Cenomanian–Turonian transgression led to the joining of an epeiric seaway with the Tethyan Sea towards the south (Leckie et al. 1998). The event was followed by the deposition of a clastic wedge (the Wall Creek Member; Fig. 2A) of Late Turonian age (Cobban 1990; Gardner 1995a, 1995b) in a ramp setting in Wyoming. The Wall Creek Member was sourced from an uplift in the west linked to thrusting associated with the Sevier Orogeny (Fig. 1A), and later itself was deformed into a gently tilted series of anticlines during the Maestrichtian–Tertiary Laramide Orogeny.

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**Fig. 2.**—A) Cretaceous stratigraphy of the Powder River Basin, Wyoming (modified from Willis et al. 1999). B) Outcrop type section of the Wall Creek Member at Raptor Ridge site, where Sandstone 7 was not deposited. For location of the sections see Figure 1C. This study deals with Sandstone 6. C) Lithologic and ichnologic symbols used in logs.
A series of gullies dissect the Wall Creek outcrop belt and allow detailed study of Sandstone 6. The strata are gently tilted southeast with a 6° structural dip. The base of the Cody Shale (a maximum flooding surface) was used as a datum (Fig. 2D) to map the sand bodies within the Wall Creek Member using well logs and cores (Sadeque et al. in press). A series of bentonite horizons both below and above the Wall Creek Member and a conglomerate lag in the Emigrant Gap Member stand out as regionally traceable distinct well-log signatures (Sadeque et al. in press). In this study, gamma and resistivity logs of 28 of these exploratory wells (Fig. 1B) were used to calculate the thickness of sandstones in Sandstone 6. Although none of these wells has cores, the boundaries between mudstones and sandstones were picked in the well logs at a precision of < 1 m. Along the outcrop belt, a total of 28 outcrop logs were measured to document grain-size variations, sedimentary structures, ichnology, and paleocurrents. The ichnofacies approach (e.g., Pemberton 1992; Pemberton et al. 2001) is taken in grouping and interpreting identified ichnotaxa. The bioturbation index (BI) of Taylor and Goldring (1993) is used to semiquantitatively measure the degree of bioturbation in the sediments (BI 0 = 0% bioturbation, BI 1 = 1% to 4% bioturbation, BI 2 = 5% to 30% bioturbation, BI 3 = 31% to 60% bioturbation, BI 4 = 61% to 90% bioturbation, BI 5 = 91% to 99% bioturbation, and BI 6 = 100% bioturbation). A portable scintillometer was used to collect gamma ray profiles along each of the measured sections.

The concept of facies architecture and architectural-element analysis of Jackson (1975), Brookfield (1977), Allen (1983), and Miall (1985, 1996) was followed in this study. However, whether an established scheme of bounding-surface hierarchies and architectural elements (e.g., Miall 1985, 1996) should be used in every facies architectural analysis is debatable (e.g., Bridge 1993; Fielding 1993). Miall (1996) defined “architectural elements” as “units enclosed by bounding surfaces of third- to fifth-order rank.” However, in this study we used the term “architectural element” in a more general sense defined as a single stratum or a package of strata that can be regarded as the smallest but meaningful unit (i.e., building blocks) enclosed by distinct, through-going surfaces of a depositional system. Moreover, an independent scheme of ordering and numbering of bounding surfaces was applied in this study. The principles of superposition and crosscutting relationships were used to trace bounding surfaces. Bounding surfaces were ranked starting with the lowest (zero) order and systematically moving up to the highest order, following the general rule that no surfaces truncate against surfaces of lower rank. It is the key to produce a “complete” bedding diagram in order to identify basic building blocks confidently. For example, while tracing beds it was made sure that every bed was traced completely until it onlaps or downlaps on and/or truncates against another bed.

In the study area, one particular ridge, here named “Raptor Ridge” (Fig. 1B) exposes the most complex bedding geometry and the most diverse facies variability of Sandstone 6. At Raptor Ridge, high-resolution (centimeter-scale) cliff maps (bedding, facies, and shale maps; Willis et al. 1999) for both depositional dip-oriented and strike-oriented cliff faces (Fig. 1C) were generated on photomosaic overlays in front of the outcrop. Ten well cores were taken behind these cliffs (Fig. 1C) to link with related studies of the ichnology (Gani et al. in press), ground-penetrating radar, and flow-inhibiting calcite concretions (Lee et al. in press). To reconstruct the paleogeography of Sandstone 6, paleocurrent and facies changes were documented along the Wall Creek outcrop belt for about 20 km around Raptor Ridge. Every measurement was plotted on a map with the aid of a hand-held GPS receiver (5 m accuracy). The morphological elements of the Burdekin Delta, thought to be a close modern analog, were studied using ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images (with 15 m
resolution) that were digitally processed using standard remote-sensing techniques (Jensen 1996).

**SEDIMENTOLOGY**

**Sandstone Isolith Map**

Using subsurface well logs and outcrop measured sections, a sandstone isolith map of Sandstone 6 at Raptor Ridge was generated (Fig. 3). The thickness data were contoured both manually and independently using an automated contouring algorithm. In both cases, the overall shape is similar. Figure 3 shows a representative map combining the two. Paleocurrent data, measured from dune-scale cross-stratification, of this study and using dipmeter data from Sadeque et al. (in press), indicate a northeast–southwest trend of the paleo-shoreline. In Figure 3, the sand body shows a lobate geometry with a slight shore-parallel elongation (Fig. 3), indicating a possible deltaic origin (e.g., Coleman and Wright 1975; Bhattacharya and Walker 1992). The lithofacies, ichnology, and bedding geometry of Sandstone 6, presented later, strongly support this deltaic interpretation. The sand body, henceforth referred to as the Raptor Delta, shows two distinct bulges indicating two possible sediment input points.

**Facies and Facies Architecture**

Six depositional facies were recognized in Sandstone 6 (Table 1; Fig. 4). These facies correspond closely to six basic architectural elements (Table 1; Fig. 5) identified in the Raptor Delta. Cliff mapping at Raptor Ridge shows consistently seaward-inclined bedding in the depositional dip sections (Fig. 5A, C), and parallel to subparallel bedding in the strike sections (Fig. 5B, D). The bedding planes in prodelta mudstones show a structural dip towards the southeast, whereas major bedding planes (interpreted as clinoforms) in delta-front sandstones have dips of up to 10° in the same direction. Therefore, the depositional dip of the clinoforms is approximately 10° – 6° = 4°.

Five orders of bounding surfaces have been established (Fig. 5). Zero-order surfaces include dune and hummocky cross-set boundaries, and accretion stratification within channels. Second-order surfaces bound sets of first-order surfaces (except accretion stratification), and sets of parallel lamination. Third-order surfaces bound channels and sets of second-order surfaces. Most of the second-order surfaces downlap and/or onlap on to third-order surfaces. The fourth-order surface at the top is a marine ravinement surface that truncates lower-order surfaces and eroded delta-plain deposits. This is a regionally traceable surface (extending > 20 km) strewn with granules and pebbles consisting of chert, sharks’ teeth, shell fragments, mudstone rip-ups, and sandstone. Six basic architectural elements (building blocks) have been identified with the help of high-resolution cliff mapping (Fig. 5).

**Element PF: Prodelta Fines.**—This element (Fig. 5) consists mainly of laminated sandy mudstones of Facies 1 (Table 1; Fig. 4A, 4J) and, subordinately, interbedded sandstones and mudstones of Facies 2 (Table 1; Fig. 4B).

A diverse *Cruziana* ichnofacies and high BI (Gani et al. in press) of Facies 1 suggest an open marine environment of deposition (e.g., Pemberton et al. 2001). Significant (~ 15%) disseminated sand grains suggest possible frequent river input, but at low enough rates to be homogenized by bioturbation. This is typical of a distal prodelta to offshore environment (e.g., MacEachern et al. 2005).

Interbedded mudstones and sandstones of Facies 2 (Table 1; Fig. 4B) suggest fluctuating flow conditions. Paleocurrent trends of asymmetrical ripples are indicative of river currents carrying sands farther seaward. Rare symmetrical ripples suggest some wave activity. Coal chips indicate a nonmarine source of sediments delivered to the sea via a possible distributary channel. The trace-fossil assemblage, moderate BI (e.g., Gani et al. in press; MacEachern et al. 2005), and the occurrence of Facies 2 just above Facies 1 (Fig. 5J) suggest that Facies 2 was deposited in a proximal prodelta to distal delta-front environment.

Element PF is interpreted to have been deposited in relatively low-energy conditions with repetitive development of suspension-deposited strata with rare starved-rippled strata. Transition into overlying delta-front facies is sharp to gradational with locally developed *Glossifungites* ichnofacies (Fig. 6). Local, laterally sharp facies change into the delta
<table>
<thead>
<tr>
<th>Architectural elements</th>
<th>Element description</th>
<th>Facies 1: laminated sandy mudstones</th>
<th>Lithofacies description</th>
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<tr>
<td>PF: prodelta fines</td>
<td>Bounded by second-order surfaces; areally extensive sheet-type geometry.</td>
<td>Sandy mudstones with &lt; 25% very fine-grained sands; mostly homogenized by bioturbation; partially preserved paper-thin laminations; sporadic marcasite (FeS2) nodules (1–4 mm in diameter).</td>
<td>BI (bioturbation index) 4 to 5; distal to archetypal Cruziana ichnofacies; ichnogenera include Chondrites, Helminthopsis, Physconichnus, Zoophycos, Asterosoma, Teichichnus, Planolites, Terebellina (sensu lato), Thalassinoides, Palaeophycus heberti, Rosselia, and Cylindrichnus, in order of decreasing abundance.</td>
<td>B1 2 to 3; archetypal Cruziana ichnofacies; ichnogenera include Helminthopsis, Palaeophycus tubularis, Planolites, Chondrites, Thalassinoides, Terebellina (sensu lato), Skolithos, and Asterosoma, in order of decreasing abundance.</td>
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| Architectural elements | Element description | Facies 2: interbedded mudstones and very fine-to-fine grained, ripped sandstone beds (1 to 5 cm thick); Ripples are asymmetrical (southeast paleocurrent) with subordinate symmetrical forms; Mud chips and coal chips (2 to 5 mm long) occur locally within sandstone beds. | Interbedded mudstones and very fine-to-fine grained, ripped sandstone beds (1 to 5 cm thick); Ripples are asymmetrical (southeast paleocurrent) with subordinate symmetrical forms; Mud chips and coal chips (2 to 5 mm long) occur locally within sandstone beds. | B1 0 to 2; distal Skolithos ichnofacies; ichnogenera include Ophiomorpha irregularire, Palaeophycus tubularis, Planolites, Chondrites, Helminthopsis, Skolithos, and fugichnia. |

| Architectural elements | Element description | Facies 3: massive to parallel-laminated sandstones | Medium-grained sandstones; erosional channel bases and mostly sharp upper boundaries; Localized zones of concentrated to scattered mud clasts; rare shell clasts and coal clasts; low-angle (≤ 10°), mostly indistinct accretion surfaces with local convolution; average bed thickness 1 m. | B1 0; rarely 1; Skolithos ichnofacies; ichnogenera include Skolithos, Arenicolites, allochthonous Asterosoma, and allochthonous Teredolites. |

| Architectural elements | Element description | Facies 4: channelized sandstones | Fine to medium grained sandstone; bed thickness range from a few centimeters to few decimeters; hummocky cross-stratified sandstone; Locally, wavy to parallel laminations, gutter casts, and symmetrical wave ripples (at bed tops); rare mud and coal clasts. | B1 0-5; mixed Cruziana and Skolithos ichnofacies; ichnogenera include Ophiomorpha irregularire, Palaeophycus tubularis, Skolithos, Planolites, Chondrites, Helminthopsis, Monocraterium, Gyrochorte, fugichnia, and allochthonous Teredolites. |

| Architectural elements | Element description | Facies 5a: trough cross-stratified sandstones | Fine to medium grained trough cross-stratified sandstones with rare ripple cross-laminations and very rare parallel laminations; Set thickness ranges from 5 cm to 100 cm; mostly seaward-directed and occasionally landward-directed paleocurrents; scattered clasts (mostly mudstones, rarely shells and coals). | B1 0-1 (rarely 2-3 on bedding planes); archetypal Skolithos ichnofacies; ichnogenera include mostly Ophiomorpha irregularire, Palaeophycus tubularis, Skolithos, and Asterosoma, and rarely Thalassinoides, Planolites, Cylindrichnus, Monocraterium, Palaeophycus heberti, Berytia, Diplomaraster hibichi, Lockeia, and fugichnia. |

| Architectural elements | Element description | Facies 5b: bipolar cross-stratified sandstones | Fine-to-medium grained trough cross-stratified sandstones; rare ripple cross-lamination; Set thickness ranges from 5 cm to 50 cm; mostly landward-directed or alternating seaward-directed and landward-directed paleocurrents; mud and shell clasts, mostly along foresets; locally, hair-thin siltstones and paired mudstone drapes along foresets. | Broadly similar to that of Facies 5a. |

| Architectural elements | Element description | Facies 6: HCS | Fine to medium grained sandstone; bed thickness range from a few centimeters to few decimeters; hummocky cross-stratified sandstone; Locally, wavy to parallel laminations, gutter casts, and symmetrical wave ripples (at bed tops); rare mud and coal clasts. | B1 0-5; mixed Cruziana and Skolithos ichnofacies; ichnogenera include Ophiomorpha irregularire, Palaeophycus tubularis, Skolithos, Planolites, Chondrites, Helminthopsis, Monocraterium, Gyrochorte, fugichnia, and allochthonous Teredolites. |
front is indicative of occasional high sediment supply and/or decrease in local accommodation.

It may not be easy to separate deposits of “fluid muds” (event deposition) from background suspension muds, especially if fluid-mud deposits are thin enough to be obliterated by trace makers, which is suspected to be the case for the Raptor Delta. If identifiable, based on suggestions made by earlier workers (e.g., Dalrymple et al. 2003; Gani 2004), these fluid-mud deposits should be treated as a separate architectural element.

Element FS: Frontal Splay.—This element consists of structureless to parallel laminated sandstone beds of Facies 3 (Table 1; Fig. 4C). Sharp to erosional bases, floating clasts, and structureless to parallel lamination within a single bed suggest deposition from waning sediment gravity flows (Collinson and Thompson 1989; Gani 2004, and references therein). Suspension-feeding structures, such as Ophiomorpha and Skolithos, indicate opportunistic colonization of the event beds, followed by the reestablishment of a low-energy, fairweather community generating dwelling or deposit-feeding structures Planolites, Chondrites, and Helminthopsis (e.g., Pemberton et al. 2001; MacEachern et al. 2005).

Unless truncated, elements FS are mostly continuous across the cliff sections, but they thin basinward (Fig. 5). These elements are interpreted to originate from non-channelized sediment gravity flows. These flows could originate from high sediment discharge during river floods, slumps failures at a river mouth, and/or storm resuspension of bottom sediments. In the first two cases, individual elements are probably lobate-shaped (e.g., Galloway and Hobday 1996) indicative of a point source. However, they can also form wedge-shaped aprons if sediment gravity flows originate by spilling over subaqueous levees (e.g., Fig. 5B) of distributary channels, or by storm resuspension. A lack of hummocky cross stratification and wave ripples suggest that storm resuspension is an unlikely mechanism.

Element CH: Channel.—This element consists of channelized sandstones of Facies 4 (Table 1; Fig. 4D, E, F, J). Erosional U-shape depressions and thin lateral wings (Fig. 5B, C) indicate channelized flow, running down the clinoforms towards the southeast (Fig. 5A, C). Low-angle accretion surfaces (Fig. 4E) dip roughly 90° from inferred channel flow directions, suggesting lateral migration. Abundant floating clasts (Fig. 4F) indicate high (probably > 30% by volume; Gani 2004) sediment concentration of the generating flows, and convolute bedding indicates dewatering shortly after deposition (Collinson and Thompson 1989; Gani 2004). In general, beds are devoid of burrows apart from a very few that penetrate into the bed from the top surface. This probably indicates that each channel fill was deposited rapidly from sediment gravity flows.

Internally lateral-accretion stratification of element CH (Fig. 5) are considered first order surfaces, as, unlike fluvial lateral accretion surfaces, they formed rapidly from sediment gravity flows. In strike section, channels show lateral wings (Fig. 5B). Channels show a gradual transition into mouth-bar elements (BA) in a landward direction (Fig. 5A). Locally, they form two-story amalgamated sand bodies reaching 4 m in thickness. Dimensions of rarely preserved channel forms suggest that these channels were probably < 3 m deep and < 15 m wide.

The depositional mechanism of element CH is considered analogous to that of channels on a submarine fan (e.g., Peakall et al. 2000; Abreu et al. 2003), although our examples are much smaller in scale compared to the submarine examples. Channelized sediment gravity flows can develop unit bars within sinusous channels, probably because of the decreased shear stress within inner banks. If these bars migrate, they produce bar-accretion surfaces, presumably similar to those observed in CH (Figs. 4E, 5). The channels described here are probably chute channels, similar to those described in the delta-front region of fan deltas (Prior et al. 1981; Nemec 1990). If these channels are linked upstream to distributary channels, they should be called “terminal distributary” channels (Olariu et al. 2005). The relatively steep slopes (4°) of the delta front indicate that these channels should show low sinuosity (e.g., Hart et al. 1992, their fig. 2). These channels probably originated during high sediment discharge as bottom-hugging undercurrents. Periodic alternation of CH with other elements (Fig. 5A) indicates a probable periodicity in channel occurrence, which could be the annual to decadal (ENSO type; Rodriguez et al. 2000) high water discharge associated with an upstream river flood. Lack of intra-element bedding surfaces indicates that individual CH elements were probably rapidly filled within a few weeks, probably during the short-lived peak discharge of a trunk distributary (e.g., similar to Burdekin River discharge; Amos et al. 2004; Fielding et al. 2005).

Element SS: Storm Sheet.—This element consists of primarily hummocky cross-stratified (HCS) sandstones of Facies 6 (Table 1; Fig. 4I). HCS has been interpreted to be generated by the combined effect of strong oscillatory flows (dominant) and unidirectional currents (subordinate) during storms (e.g., Myrow and Southard 1991). Gutter casts, and mud and coal clasts indicate strong basal scouring. Wave ripples at tops of HCS beds suggest waning storm waves. The wide range of BI is related to the occurrence of this facies distal (BI 3–5) or proximal (BI 0–2) to river source in the direction of both depositional dip and strike. Based on ichnofacies assemblage and other observations, Facies 6 is interpreted to have been deposited in a distal to middle delta front or shoreface environment. Rarely, Facies 6 was found sandwiched within Facies 1.

At Raptor Ridge, element SS is rare and patchy (Figs. 5, 6). However, northeast from Raptor Ridge, SS contains stacked HCS beds and develops as extensive sheets (Fig. 7). Element SS records deposits of seasonal and/or rare storms in the sea.

Element BA: Bar Accretion.—This element consists mostly of unidirectional trough cross-stratified sandstones of Facies 5a (Table 1; Fig. 4G, H, J). The trough cross-stratification suggests deposition due to migration of simple and/or compound (i.e., superposed) dunes of variable sizes. Rare ripple cross-lamination and parallel lamination record local decreases or increases in flow velocity, respectively. Very low BI is interpreted to indicate proximity to a river mouth (e.g., Gani et al. in press; MacEachern et al. 2005). Dominance of the suspension-feeding structures Ophiomorpha and Skolithos indicates strong currents at the sea bed (e.g., MacEachern et al. 2005). Based on these observations, Facies 5a is interpreted to have been deposited in a lower to upper delta-front environment, and is indicative of mostly riverborne sediments and currents during periods of active mouth-bar growth.

In element BA, inasmuch as the set (in the case of simple dunes) or coset (in the case of superposed dunes) boundaries dip at angles of 1° to 10° seaward (Fig. 5A), they are interpreted to represent accreting bar-front surfaces (Fig. 8). These elements are developed extensively in the upper delta-front region closer to distributary mouths. This suggests that BAs are produced mainly by river-fed unidirectional currents and sediments. Minor tidal influence can be inferred from locally observed landward-directed cross-stratification. However, these tidal facies are patchy and not organized enough to be treated as a separate element (see TM below). Individual BA elements are interpreted to be formed by annual to decadal growth of bars.

Element TM: Tidally Modulated Deposit.—This element consists primarily of bipolar dune cross-stratification of Facies 5b (Table 1; Fig. 4H), interpreted to have been deposited from migration of simple and/or compound (i.e., superposed) dunes of variable sizes. Abundant mud clasts indicate strong currents capable of eroding underlying beds. Abundant herringbone cross-bedding and double mud drapes suggest a tidal influence (e.g., Visser 1980; Nio and Yang 1991). Facies 5b is
FIG. 4.—Representative facies photos of Sandstone 6 at Raptor Ridge. A) Facies 1: sandy mudstones with BI 4–5 including trace fossils Phycosiphon (Phy), Helminthopsis (He), Terebellina (Ter), Planolites (Pl), and Zoophycos (Zo). B) Facies 2: heterolithics comprising interbedded mudstones and rippled sandstones. C) Facies 3: massive to parallel-laminated sandstones with erosional bases. Note pencil (14 cm long) for scale. D) Facies 4: channelized sandstones with erosional U-shape depressions. E) Facies 4: channelized sandstones with lateral-accretion surfaces. Note hammer (30 cm long) for scale. F) Facies 4: mudstone clasts in channel sandstone. Note hammer (30 cm long) for scale. G) Facies 5a: Dominantly seaward-directed (to the right) trough cross-stratified sandstones. H) Facies 5b: Landward-directed (to the left) trough cross-stratified sandstones with double mud drapes and mud clasts. I) Facies 6: hummocky cross-stratified sandstones (HCS) overlying facies 1. J) A coarsening-upward succession showing vertical association of facies 1 to 5 prograding towards sea (to right). This is the same location as log LE4 in Figure 5A.
typically associated laterally with seaward-dipping strata of mouth-bar deposits (element BA) and is thus interpreted to represent a high degree of tidal modulation of the associated bar fronts.

Element TM is the product of tidal modulation of bar-front sediments with deposition mostly from tidal currents. Basal erosion suggests periods of elevated tidal energy. Periodic occurrence of TM, particularly in the upper part of the sand body (Fig. 5), probably indicates periodic enhancement of tidal activity during overall delta-front progradation. This periodicity should be greater than neap–spring cycles, and may indicate semiannual tidal maxima (Kvale et al. 1998), although not necessarily every maximum is preserved.

**Strike Variability of the Raptor Delta: Facies and Paleocurrents**

The farthest accessible outcrop of the Raptor Delta (Sandstone 6) towards the southwest was measured in a gully 1 km west of Raptor Ridge. At this site, tidal facies (i.e., Facies 5b and element TM) and channel facies (i.e., Facies 4 and element CH) are conspicuously absent (Fig. 7, log a). Upward-coarsening facies successions show all other facies with a relatively high BI (3–4) in prodelta and lower delta-front deposits, and a low BI (rarely exceeds 1) in middle to upper delta-front deposits. Dominant paleocurrents are towards the south (Fig. 7). Clinoforms are as steep as at Raptor Ridge (4°). In contrast, the entire northeastern flank of the Raptor Delta, from Raptor Ridge northeastward (Fig. 7), shows a predominance of HCS facies (i.e., Facies 6 and element SS) alternating with parallel-laminated facies (Facies 3) (Fig. 7; logs c, d). Again, tidal facies (Facies 5b) and channel facies (Facies 4) are absent. Upward-coarsening facies successions show a relatively high BI from bottom to top (BI 4 at prodelta to lower delta front, and BI 2–3 at upper delta front). Although the mean paleocurrent is towards 158°, a shore-parallel component (northeast–southwest) is prominent (Fig. 7). Clinoforms are less steep (< 2°) than in Raptor Ridge (4°). These lateral variations of facies, paleocurrents, and BI of the Raptor Delta are discussed in the next section.

**DISCUSSION**

**Delta-Building Processes and Deltaic Architectural Elements (Building Blocks)**

In the Raptor Delta, six types of architectural element were identified in prodelta and delta-front deposits (Figs. 5, 6). Figure 8 shows these deltaic architectural elements in idealized forms both in depositional dip and strike sections. These elements bonded with each other via bounding surfaces (five orders were labeled; Fig. 5) to create the entire delta. Prodelta deposits consist mainly of blanketing sandy mudstones (element PF) at the base of the overall parasequence. Storm sheets (SS) and frontal splays (FS), produced by event deposition, may be found locally sandwiched between muddy PF elements (Fig. 6). In a normal progradational succession and at the transition between the delta-front and prodelta regions, intercalation of delta-front and prodelta elements give rise to facies interfingering (cf. Gani and Bhattacharya 2005a; Fig. 8, element PF).

Delta-front deposits show an alternation of elements FS, SS, TM (tidally modulated deposit), CH (channel), and BA (bar accretion). Processes related to each of these elements have been described previously in the “Sedimentology” section. Broadly, interaction between river and
Fig. 5.—Outcrop panels (photomosaics with bedding and facies maps) of Sandstone 6 at Raptor Ridge. For location of cliff sections, see Figure 1C. Structural dip measured at paleo-horizon surfaces (one such surface is indicated in prodelta deposits of Fig. 5A) is 6° towards the southeast. Detailed identification of sedimentary features, bedding planes, and facies in several depositional dip and strike sections allowed to establish bounding-surface hierarchies and architectural elements (marked on bedding diagrams of Fig. 5A, B) of the Raptor Delta. Note individual bar boundaries in the depositional strike section of Figure 5D. See text for discussion. (Parts 5C and D are in color in the digital version of this article.)
basinal (tide and wave) processes develops these building blocks that fill the accommodation. Both FS and SS represent event deposits that generally smooth out delta-front topography. For example, Kostic et al. (2002) showed that sediment gravity flows can reduce the angle of delta-front clinoforms by 20%.

A conspicuous and geologically significant building block found in delta front-deposits of the Raptor Delta is the element CH (Figs. 5, 8), interpreted as chute or terminal channels. Terminal distributary channels (i.e., subaqueous distributary channels) have been recognized only recently in ancient delta-front deposits (Olariu and Bhattacharya 2006). The present study demonstrates that distributary channels in deltas do not necessarily stop at the delta plain; rather, they can continue subaqueously down the delta-front region as terminal channels or chute channels. Elements CH of the Raptor Delta were rapidly filled with sediment-gravity-flow deposits. Because slump scars, slide and slump deposits, and synsedimentary faults are largely absent, the origin of these channelized sediment gravity flows is likely to be extreme river floods, like those seen in the modern Burdekin River (Alexander et al. 1999; Amos et al. 2004), where much of the annual water and sediment discharge to the delta is delivered in less than five days, and which produces coarse-grained, sharp-based, 1–3 m thick sand beds (cf. Fielding et al. 2005).

Elements BA and TM consist mainly of packages of bedwave deposits originating from river and tidal currents at the delta front. BA corresponds to incremental growth of individual mouth bars. In the Raptor Delta, mouth bars are characteristically identified by the bidirectional downlap of bedding surfaces in strike section (Fig. 5D). The minimum width of a single bar is c. 50 m. The size of the mouth bar developed at the end of a distributary channel should be proportional to the width of the channel and to the horizontal spreading angle of the river effluent. Generally, as the distributary channels bifurcate seaward their widths decrease. Therefore, deltas with high orders of distributaries tend to develop small bars. Bars may coalesce together to form bar assemblages, which are recognized in the depositional strike section by onlapping and/or converging strata of a younger bar onto an older bar (Fig. 5D). Element TM indicates periodic reworking of riverborne sediments by strong tidal currents that normally slows down seaward growth of bars. TM can develop both within and outside of a bar. In the Raptor Delta, a discrete facies association of trough cross-stratified sandstones (BM—bedwave migration) was observed that are not part of any previously described elements. Because the nature of bounding surfaces of BM has not been established, BM could not be ranked as an architectural element. BM can develop within the inter-bar region, and on the wave-dominated upper shoreface, away from distributary mouths. The dune-scale cross-stratified sandstones of logs c and d (Fig. 7), developed at the upper part and in the eastern flank of the Raptor Delta, probably represent upper-shoreface deposits of facies association BM.

The most prominent feature of deltaic deposits is seaward-dipping inclined beds known as clinoforms (Rich 1951; Bhattacharya and Walker 1992; Gani and Bhattacharya 2005a; Bhattacharya 2006). In the Raptor Delta, clinoforms are characteristically observed in the cliff sections (Fig. 5). The depositional dip sections show persistent seaward-dipping clinoforms (Fig. 5A, C), whereas the strike sections show parallel to
subparallel clinoforms (Fig. 5B, D). The height (from the top ravinement surface to the prodelta mudstones) of a single clinoform is, on average, 9 m. Using a compaction factor of 80% (normal for sandstones) the pre-compaction height of a clinoform would have been 11 m, which is interpreted to be the minimum water depth into which the delta front of the Raptor Delta prograded.

Knowledge of facies associations, general basinward-dipping clinoform geometry, and the modern geomorphic units of deltaic systems are well known (Bhattacharya 2006). However, the understanding of internal geometrical complexity and variability of a single deltaic sandbody, and the polyphase evolution history (in terms of variability of river, wave, and tidal processes) of a single delta during basinward progradation, are handicapped by the lack of well-documented example of how to identify and interpret unit building blocks of deltaic deposits. In the studies of modern deltas, a major challenge is depicting the internal geometry of deltas by correlating the limited subsurface cores (cf. Gani and Bhattacharya 2005a, and references therein). This study has identified the basic architectural elements of the delta-front and prodelta environment within a mixed river, wave, and tide influenced delta from a detailed outcrop study. The information of the external morphologies (e.g., shape, placement, aspect ratio, preferred orientation) and the internal bedding geometries (e.g., stratal dip and truncation, facies heterogeneity) of these 3D building blocks (Fig. 8) can be used as predictive tool while correlating the subsurface data, as shown in Figure 6. Once the facies are identified from the cores and/or wireline-logs, the knowledge of deltaic architectural elements should guide the subsurface correlation of bedding surfaces.

Dimensional and geometrical data of a sandbody plays a critical role in quantitative reservoir modeling (North 1996; Willis and White 2000; Tye 2004; Miall 2006). This study reveals detailed and useful geometrical and dimensional data of unit building blocks of deltaic reservoirs below the level of channel and mouth-bar sands, particularly for object-based modeling (cf. Tye 2004). Incorporation of the facies architectural model presented in this study in characterizing deltaic reservoirs would result in far more complex but realistic reservoir behavior (e.g., compartmentalization, heterogeneity, sweep efficiency). For example, the oppositely dipping stratal geometry of BA versus TM elements could complicate the sweep efficiency of deltaic reservoirs.

**Paleogeographic Reconstruction**

The shape of the sandstone isolith map of the Raptor Delta (Fig. 3) reflects the general paleogeography of the delta. A slight shore-parallel elongation of this lobate sand body may be interpreted to indicate an overall wave influence (e.g., Coleman and Wright 1975). There are two thicks in this lobate sand body. Outcrops of the northeastern thick (Raptor Ridge), particularly the identification of elements CH and BA, clearly indicate the presence of a major, subaerial distributary channel in this region. Although no outcrop data are available for the southwest thick, it can be logically concluded that this region was also close to a major distributary channel. Therefore, these two thicks may represent two depositional loci of the Raptor Delta. The sand isolith maps of the Holocene Burdekin delta in NE Australia (Fielding et al. 2005) and of the Rhone delta in France (Galloway and Hobday 1996, p. 111) are smooth-fronted like the Cretaceous Raptor Delta. The Rhone Delta is being built by two main distributary channels of the Rhone River, as has been inferred for the Raptor Delta. However, whether the two main distributaries of the Raptor River coexisted, or one is slightly younger than the other (i.e., lobe switching) is not certain. In this study, a significant criterion in paleogeographic reconstruction is the way paleocurrent data are utilized. When entire paleocurrent data
of the region are lumped and plotted together (Fig. 3), they fail to show the local but significant variations of paleocurrents (Fig. 7) that are diagnostic of dominant processes. For example, in the Raptor Delta, the local plots of paleocurrents show that (1) river and tidal processes were dominant around the Raptor Ridge, (2) tidal processes were absent in the southwest of the Raptor Ridge, and (3) wave processes were prominent in the northeast of the Raptor Ridge (Fig. 7).

The regional outcrop section of the Raptor Delta (Fig. 7) shows a predominance of element SS developed as an extensive sheet in the northeast flank (Fig. 7, logs c and d). In this region, comparatively high BI and an increase in the shore-parallel component of paleocurrents suggest that the northeast flank of the Raptor Delta had less river influence, and hence may lie on the updrift side of the distributary mouth, forming an asymmetric wave-influenced delta, as predicted by the model of Bhattacharya and Giosan (2003).

Incorporating the above observations, a true-scale paleogeographic reconstruction of the Raptor Delta (Fig. 9) is made. Figure 9 suggests that the Western Interior Seaway, at least in the studied region, was mainly wave- and storm-dominated, had shore-parallel currents dominantly towards the south and occasionally towards the north, and had very localized tides. All of these observations are consistent with the findings of paleo-oceanographic modeling of the seaway (Ericksen and Slingerland 1990; Slingerland et al. 1996) mentioned earlier. Like other parasequences of the Wall Creek (Fig. 2), an extensive marine ravinement surface was observed at the top of Sandstone 6. A relative rise in sea-level is thought to have produced this transgressive erosion surface, which eroded delta-plain deposits and left the Raptor Delta top-truncated.

**Limitation of Tripartite Classification of Deltas**

As introduced earlier, several recent studies of modern deltas, including the Brazos and Burdekin deltas, have questioned their placement in end-member fields (Galloway 1975) of the tripartite classification of delta (Gani and Bhattacharya 2005b; Bhattacharya 2006). The Brazos delta in the Gulf of Mexico, for example, has long been cited as a classic example of a wave-dominated delta, on the basis of its plan-view morphology, but recent coring studies show that, internally, much of the delta was built during major river-floods, and it is now classified as a river-flood-dominated delta, with some wave reworking of the surficial sediments (Rodriguez et al. 2000). The Baram River delta in NW Borneo has also been historically classified as wave-dominated, on the basis of its smooth-fronted plan-view shape, but recent studies of the internal facies show tide
The Burdekin delta also shows a smooth-fronted morphology that has caused it to be classified as “wave-dominated,” but detailed internal facies analysis show sharp-based river-dominated mouth bars that record river-flood processes (Fielding et al. 2005). Although the sandstone isolith map of the Burdekin delta (Fielding et al. 2005, their figure 20) shows a shore-parallel elongation, a considerably higher river influence was documented in cores and outcrops of this delta (Fielding et al. 2005). The plan-view morphology of any given modern delta reflects dominant surficial processes but may not necessarily reflect the short-lived constructional processes of river floods that dominate the internal facies architecture.

Similarly, the external shape of the Raptor Delta might be seen as controlled primarily by waves (Figs. 3, 9), but the internal facies architecture reveals a far more complex interaction of river, waves, storms, and tidal processes. For example, in any given vertical section, both river- and wave-dominated facies can vary laterally from 0 to 100 percent (Fig. 7). The estimated proportion of wave versus tidal versus river facies may change dramatically, depending on where vertical samples are taken. Worse, some of the facies changes are not clearly imaged by logs, and can be determined only where there is good outcrop or core control.

Rather than force-fitting the Raptor Delta into an end-member type of the tripartite delta classification (Galloway 1975), we prefer to described it as a “mixed-influenced delta” to indicate the complex delta-building processes that are reflected in the internal facies. Table 2 of Galloway (1975) suggested different framework facies for each of the three types of delta. However, in any given delta these framework facies are not mutually exclusive; hence, mixed-influenced deltas may be the norm rather than the exception. Like the modern Brazos Delta (Rodriguez et al. 2000) and the modern Burdekin Delta (Fielding et al. 2005), the main building phases of the Raptor Delta were likely seasonal to decadal river floods producing elements CH, FS, and BA. During intervening periods (e.g., between two floods) the delta was reworked by waves, storms, and tides, producing mainly SS, TM, and BM, which are reflected in the planform morphology (Fig. 9).

**Modern Analog and Morphological Elements**

Processes responsible for depositing the architectural elements in ancient deltaic deposits are better understood when comparison is made to modern deltaic systems. Although the sharp lateral facies change between the tidal and wave regime of the Raptor Delta (Fig. 6) can be compared with that of the modern Orinoco delta in NE Venezuela (Warne et al. 2002), the latter is almost an order of magnitude larger. The Burdekin Delta (∼ 40 km by 60 km) is thought to be the closest scaled analog for the ancient Raptor Delta (∼ 30 km by 60 km), particularly in terms of delta morphology and river-mouth processes. Like the Raptor Delta, wave- and storm-produced beach ridges lie on the flank of the Burdekin Delta away from the mouth of two main distributary channels (Fig. 10). Subaerial distributary channels extend subaqueously as
terminal distributary channels. These terminal channels (width < 100 m) meander gently on the delta front and taper basinward. Both mouth bars and in-channel bars coalesce to form bar assemblages close to the main distributary mouths. Tides produce a series of large dunes on bar fronts. The migration and/or growth of these morphological elements should produce architectural elements like those described in the Raptor Delta.

In fact, in all deltaic systems, major morphological elements include channels, bars, large bedwaves, beach-ridges/cheniers, and spays. Channel types include: trunk distributary, above first avulsion point; subaerial distributary; terminal distributary, below mean sea level; delta-front chute channel; and tidal creek and channel, both subaerial and subaqueous. Bars are associated with each of these channels. The number and size of mouth bars are directly proportional to the number and size of distributary channels, respectively. Beach-ridge/chenier plains develop when riverborne sediments accrete to the coast away from a river mouth but within the same river delta system. In the rock record, these morphological elements produce architectural elements similar to those described here.

CONCLUSIONS

This study, for the first time, develops an architectural-element model for open-marine deltaic deposits by investigating the Cretaceous Raptor Delta in the Wall Creek Member, Wyoming. High-resolution (centimeter scale) cliff mapping of bedding and facies reveals six architectural elements in the prodelta and delta-front deposits of a single prodessional parasequence—PF (prodelta fines), FS (frontal splay), CH (channel), SS (storm sheet), TM (tidally modulated deposit), and BA (bar accretion). Element CH represent subaqueous terminal or chute channels filled rapidly with deposits of sediment gravity flows showing lateral accretion surfaces. The depositional mechanism of these channels is probably analogous to that of laterally migrating channels in a submarine fan. The main building phases of the Raptor Delta were probably seasonal to decadal river floods producing elements CH, FS, and BA. During intervening periods, the delta was reworked by waves, storms, and tides producing mainly elements SS and TM. It is suggested that these elements are among the basic building blocks of all deltas, and can be used as a guideline for high-resolution object-based modeling of deltaic reservoirs and as a predictive tool in delineating internal geometry of modern and ancient deltas with limited subsurface data. However, the relative proportions, combinations, and bonding styles of these elements may vary from one system to another, and even within the same system depending on where vertical samples are taken. Vertical facies proportion curves may vary over kilometer spacing and should be considered when using these types of data for reservoir modeling and extrapolation of facies variability in a subsurface setting.

The sandstone isolith map of the Raptor Delta shows a lobate geometry with a slight shore-parallel elongation suggesting some wave influence. The smooth inferred plan-form morphology vs. the internal facies complexity of the Raptor Delta raises concern about the basic assumption of the tripartite classification of deltas. The well studied modern deltas of the Brazos, Baram–Trusan, and Burdekin show similar observations that the main constructional processes are not reflected in the external morphology of deltas. Therefore, only a detailed facies architectural analysis may reveal the complexity of interactive delta-building processes. Rather than force-fitting into an end-member type, the Raptor delta is classified as mixed-influenced to indicate its inherent complexity.

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Fig. 10.—ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images (3-2-1 band ratio) of modern Burdekin Delta (NE Australia) showing major morphological elements that produce architectural elements in the rock records, like those identified in the Cretaceous Raptor Delta (see text for discussion).

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