MODEST CHANGE IN FLUVIAL STYLE WITH VARYING ACCOMMODATION IN REGRESSIVE ALLUVIAL-TO-COASTAL-PLAIN WEDGE: UPPER CRETACEOUS BLACKHAWK FORMATION, WASATCH PLATEAU, CENTRAL UTAH, U.S.A.

GARY J. HAMPSON, THOMAS O. JEWELL,* NAWAZISH IRFAN, M. ROYHAN GANI, AND BRYAN BRACKEN

ABSTRACT: Concept-driven sequence stratigraphic models of alluvial-to-coastal-plain successions suggest that fluvial architecture and style should transition from isolated, single-story, channelized sandbodies deposited by single-thread (typically meandering) rivers in mudstone-prone, high-accommodation intervals into densely stacked, amalgamated sandbodies deposited by multiple-thread (typically braided) rivers in low-accommodation intervals. Model predictions of changing fluvial style are tested by comparing the facies character, internal architecture, dimensions, and formative paleohydraulic conditions of representative, major fluvial sandbodies developed at different stratigraphic levels of an alluvial-to-coastal-plain succession developed under a progressively decreasing rate of accommodation creation (Late Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, USA).

The major fluvial sandbodies have a similar facies composition, and consist mainly of cross-bedded, medium-grained sandstone with subordinate mudclast conglomerate, folded sandstone, and inclined sandstones and intercalated siltstones. Facies are arranged within a hierarchy of architectural components. Channel stories (mean width and depth of 90 m and 7.2 m, respectively) represent the migration of a paleochannel segment and adjacent bar, and they are amalgamated laterally into channel belts (mean width and depth of 400 m and 9.2 m, respectively) that in turn are stacked vertically into channel-belt complexes (mean width and depth of 400 m and 20 m, respectively). Channel stories and belts were deposited by a combination of three paleochannel types that occur together in most major sandbodies: (1) single-thread “cut-and-fill” channels; (2) single-thread, laterally accreting channels of low-to-moderate sinuosity; and (3) multiple-thread, wandering-to-braided channels. Estimated paleochannel slopes are uniformly low (< 0.04°), most sandbodies contain sparse, potential marine indicators (e.g., Teredolites-bored logs and tidally modulated? carbonaceous drapes along cross-bed foresets), and paleodischarge estimates imply that multiple-thread channels may have narrowed and branched downstream to form distributary networks. All of these features are consistent with a delta-plain setting.

Channel story and belt stacking patterns within each major sandbody (channel-belt complex) are highly non-uniform, such that (1) there are no systematic trends shared by the sandbodies, (2) sandbodies do not result from systematic, short-term changes in accommodation, such as those associated with the incision and fill of coastal incised valleys, and (3) variability within each sandbody is more pronounced than variability between sandbodies. These results suggest that local variations in sediment flux and transport capacity, combined with local avulsion history, were the principal controls on the architecture and dimensions of the major sandbodies. The similarities in architecture between major fluvial sandbodies imply that these controls were not predominantly governed by proximity to the coeval shoreline (c. 40–100 km) or by long-term tectonic subsidence rate (c. 80–700 m/Myr), which controlled creation of accommodation.

INTRODUCTION

Current sequence stratigraphic models of alluvial-to-coastal-plain successions (Wright and Marriott 1993; Shanley and McCabe 1994; Richards 1996) suggest that fluvial style should vary predictably within unconformity-bounded sequences. Sequence boundaries characterized by incision and well-developed interfluve paleosols are overlain by amalgamated, multiple-thread (typically braided) channel sandbodies in the lowstand systems tract and isolated, single-story, single-thread (typically meandering) channel sandbodies in the transgressive and highstand systems tracts. The transition between transgressive and highstand systems tracts (cf. maximum flooding surface) may be marked by subtle marine influence (Shanley et al. 1992) or by coal-prone successions (e.g., Cross 1988; Bohacs and Suter 1997). These changes in fluvial style are interpreted to be driven by various allocenic controls on base level and
sediment flux, including relative sea level, basin subsidence, climate, and hinterland tectonism (e.g., Shanley and McCabe 1994; Holbrook et al. 2006). Geomorphic studies of modern rivers and floodplains, and physical experiments and numerical models imply that stratigraphic architectures driven by allocigenic controls may be substantially modified or overprinted by the autogenic response(s) of fluvial systems, such as avulsion, to these controls (e.g., Westcott 1993; Mackey and Bridge 1995; Jerolmack and Paola 2007; Sheets et al. 2007; Hajek et al. 2010; Wang et al. 2011).

The alluvial-to-coastal plain strata of the Cretaceous Blackhawk Formation, Wasatch Plateau, central Utah, offer an important test against a high-quality outcrop dataset of both sequence stratigraphic and avulsion-based models of fluvial style and stratigraphic architecture. These strata form part of a progradational siliciclastic wedge where the shallow-marine component has been extensively studied in the nearby Book Cliffs (e.g., Balsley 1980). Here, the shallow-marine Blackhawk Formation is interpreted to contain multiple high-frequency sequences of c. 0.2–1.0 Myr duration stacked within a low-frequency highelevation systems tract of c. 2.0–3.0 Myr duration (Fig. 2) (e.g., Howell and Flint 2003; Hampson 2010 and references therein). The Blackhawk Formation is overlain by the Castlegate Sandstone across a regional erosion surface, interpreted as a major, low-frequency sequence boundary (e.g., Van Wagoner 1995), which is associated with angular truncation in the westernmost Book Cliffs (Yoshida et al. 1996; Miall and Arush 2001) and potentially also in the Wasatch Plateau (Hampson et al. 2012). Recent mapping of large-scale stratigraphic architecture and sandbody distributions in the alluvial-to-coastal-plain Blackhawk Formation of the Wasatch Plateau indicates that stratigraphic organization of the type implied by sequence stratigraphic models is rare and cryptic (Hampson et al. 2012). In the lower c. 50 m of the Blackhawk Formation, stratigraphic cycles bounded by major, regionally extensive coal zones are identified. The coal zones correspond to parasequence-bounding flooding surfaces in coeval shallow-marine strata (e.g., Flores et al. 1984; Dubiel et al. 2000; Hampson et al. 2011), implying that the stratigraphic cycles can be attributed to cyclic, high-frequency (< 0.1 Myr duration) relative sea-level changes (Hampson et al. 2012). Similar coal zones and stratigraphic cycles are absent in the upper Blackhawk Formation. In the Wasatch Plateau as a whole, there are upward-increasing trends in sandbody size and abundance from base to top of the Blackhawk Formation, consistent with the formation being assigned to a low-frequency (c. 2.0–3.0 Myr duration) highstand systems tract in coeval shallow-marine strata. There is also an abrupt increase in sandbody abundance and amalgamation across the base of the Castlegate Sandstone, consistent with the interpretation of this contact as a major sequence boundary. Adams and Bhattacharya (2005) documented that fluvial style was uniform in the uppermost Blackhawk Formation and Castlegate Sandstone. However, no work has been carried out to date on the facies character and internal architectures of fluvial sandbodies in the remainder of the Blackhawk Formation, and as a result their fluvial styles and potential relationships with stratigraphic architecture are unknown.

The aims of the paper are threefold: (1) to document the facies character and internal architectures of representative fluvial sandbodies developed at a number of stratigraphic levels throughout the Blackhawk Formation, (2) to reconstruct the plan-view morphology and fluvial style of the Blackhawk rivers, and (3) to evaluate controls on fluvial style and alluvial-to-coastal-plain stratigraphic architecture in the Blackhawk Formation. The results have broad applications to our understanding of alluvial-to-coastal plane rivers and their preservation in the stratigraphic record, and specific applications to predicting hydrocarbon recovery from alluvial-to-coastal-plain reservoirs. Sandbody connectivity and reservoir drainage are strongly controlled by the spatial organization of fluvial sandbodies (e.g., Larue and Hovadik 2006), hence it is important to establish the degree to which such organization can be related to fluvial style.

STRATIGRAPHIC AND PALEOGEOGRAPHIC SETTING

The studied alluvial-to-coastal-plain strata lie within the nonmarine Blackhawk Formation, which was deposited along the western margin of the Cretaceous North American Western Interior Seaway (e.g., Krystinik and DeJarnett 1995; inset map in Fig. 1). The nonmarine Blackhawk Formation overlies and interfingers to the east with shallow-marine sandstones of the Star Point Sandstone and various shallow-marine members of the Blackhawk Formation, and it underlies fluvial sandstones of the lower Castlegate Sandstone (Fig. 2; Speier and Reeside 1925; Young 1955). In combination, these lithostratigraphic units form an eastward-thinning siliciclastic wedge of early and middle Campanian age (Fouch et al. 1983) that passes basinward into the offshore deposits of the Mancos Shale (Young 1955) and represents a duration of 3.5–4.0 Myr (Krystinik and DeJarnett 1995). The sediment within this wedge was derived from the Sevier Orogen (Fig. 1), probably from the Canyon Range Culmination c. 80 km west of the Wasatch Plateau outcrop belt (DeCelles and Coogan 2006). The study area lay within the flexurally subsiding foredeep of the Sevier Orogen, but also experienced subsidence driven by dynamic topography across the entire seaway (e.g., Liu and Nummedal 2004). It occupied a paleolatitude of approximately 42°N (Kauffman and Caldwell 1993), and flora from the nonmarine Blackhawk Formation indicate that the climate was seasonal and warm temperate to subtropical (Parker 1976).

Most previous work on the nonmarine Blackhawk Formation has focused on characterizing coal resources in the Wasatch Plateau coalfield (e.g., Speier 1931; Doelling 1972; Hayes and Sanchez 1979; Sanchez et al. 1983; Dubiel et al. 2000; Quick et al. 2005). Coal seams are thickest and most abundant in the lower part of the Blackhawk Formation, where they define a high-resolution stratigraphic framework (e.g., Flores et al. 1984; Dubiel et al. 2000; Hampson et al. 2012). However, most of the Blackhawk Formation consists of a variety of channelized fluvial and sheet-like crevasse-splay sandbodies surrounded by floodplain shales, supplemented by lagoonal shales in the lower part of the formation (Marley et al. 1979; Flores et al. 1984; Hampson et al. 2012). These deposits represent an overall alluvial-to-coastal-plain setting that lay behind a series of approximately north–south-trending, wave-dominated shorelines represented by the Star Point Sandstone in the Wasatch Plateau (Figs. 1, 2) (Flores et al. 1984; Dubiel et al. 2000; Hampson et al. 2011) and shallow-marine members of the Blackhawk Formation in the Book Cliffs (Fig. 1) (e.g., Balsley 1980; Hampson and Howell 2005).

Both regionally, across the eastern Wasatch Plateau (over an area of 1500 km²), and locally, in the 150 km² area surrounding Link Canyon, channelized fluvial sandbodies increase in size and abundance from the base to the top of the Blackhawk Formation (Marley et al. 1979; Hampson et al. 2012). The regional proportion of channelized sandbodies varies from c. 10% in the lower Blackhawk Formation to c. 30% in the upper Blackhawk Formation (Hampson et al. 2012), and then increases abruptly to > 90% in the lower Castlegate Sandstone (Miall 1993; Adams and Bhattacharya 2005; McLaurin and Steel 2007; Hajek and Heller 2012). The upward increase in sandbody abundance coincides with a decrease in tectonic subsidence rate during deposition of the upper Blackhawk Formation and lower Castlegate Sandstone, inferred from a progressive decrease in aggradation rate of shallow-marine strata in the Blackhawk–Castlegate clastic wedge (based on regional outcrop and subsurface mapping tied to dated ammonite biozones; Hampson 2010), and with a progressive increase in distance from the coeval shoreline (Fig. 2) (based on regional mapping at outcrop of successive shorelines in the Star Point Sandstone and Blackhawk Formation; e.g., Kamola and Hunttenoon 1995; Taylor and Lovell 1995; Hampson 2010; Hampson et al. 2011). Sequence stratigraphic interpretations in the Book Cliffs assign the Blackhawk Formation to a low-frequency highstand systems tract (c. 2.0–3.0 Myr duration) truncated by a sequence boundary at the base of the
lower Castlegate Sandstone, which constitutes a low-frequency lowstand systems tract (Taylor and Lovell 1995; Van Wagoner 1995; Yoshiida 2000; Howell and Flint 2003). Multiple high-frequency sequences (c. 0.2–1.0 Myr duration) are superimposed on the low-frequency highstand and lowstand systems tracts (e.g., Van Wagoner 1995; Yoshiida 2000; Howell and Flint 2003; Hampson 2010). Detailed architectural analysis in an area south of Link Canyon (labeled Salina Canyon in Figs. 1, 2) suggests that fluvial sandbodies in the uppermost Blackhawk Formation were deposited by braided river systems of style similar to those that formed the overlying Castlegate Sandstone, but sandbodies in the latter are much more strongly amalgamated (Adams and Bhattacharya 2005), supporting a reduction in accommodation across a low-frequency sequence boundary at the base of the Castlegate Sandstone. Detailed architectural analyses of the lower Castlegate Sandstone in the Book Cliffs provide some three-dimensional control on the exposed stratigraphic architecture (Fig. 3B).

The dataset comprises 21 measured sections and a comprehensive set of high-resolution photomontages collected from six major sandbodies and three minor sandbodies developed at different stratigraphic levels within the Blackhawk Formation (major sandbodies are numbered 1–6 in Fig. 3; minor sandbodies lie below major sandbody 5). The measured sections record lithology, grain size and sorting, sedimentary structures, paleocurrents, body fossils, and trace fossils, and they have been studied using conventional facies analysis. Photomontages have been used to construct bedding diagrams that have enabled identification of a hierarchy of architectural units and their bounding surfaces within each sandbody (cf. architectural-element analysis of Miall 1985, 1988 and Holbrook 2001). The cliff-face geometry around Link Canyon provides some three-dimensional control on the exposed stratigraphic architecture (Fig. 3B).

FACIES ANALYSIS

Seven facies have been identified in the studied sandbodies and surrounding fine-grained deposits (Table 1). In combination, these facies belong to two facies associations documented in previous work on the gross stratigraphic architecture of the Blackhawk Formation (Fluvial Sandbodies and Aggradational Floodplain facies associations of Hampson et al. 2012).

Fluvial Sandbodies Facies Association

The fluvial sandbodies facies association of Hampson et al. (2012) consists of laterally discontinuous, erosional based, channelized
sandbodies of variable dimensions (5–25 m thick, 50–6000 m wide over the entire Wasatch Plateau outcrop belt). The association has four constituent facies (F1–F4), and corresponds to the Type III sandstones of Marley et al. (1979).

**Description.**—Prominent erosion surfaces within and at the base of channelized sandbodies are lined by thin (< 1 m), laterally discontinuous (< 50 m) sheets of moderately to poorly sorted, medium- to coarse-grained sandstone containing abundant rounded mudclasts, and wood and carbonaceous plant fragments (facies F1; Fig. 4A–C). Some wood fragments contain *Teredolites* borings (Fig. 4C). These mudclast conglomerates constitute only a small proportion (< 5%) of the total sandbody volume.

Mudclast conglomerates (facies F1) are overlain by moderately sorted, medium-grained sandstones containing abundant trough and tabular cross-bedding, with subordinated planar-parallel lamination and structureless beds (facies F2; Fig. 4D). Cross-bedded, medium-grained sandstones contain minor intercalations of fine-grained sandstone and siltstones, but lack upward-fining or upward-coarsening trends. They occur as channelized and lenticular bodies up to 6.0 m thick and 200 m wide. Scattered mudclasts are present along cross-set bases and foresets, and carbonaceous drapes occur along the foresets and toesets of a small number of cross-sets (Fig. 4E). Cross-sets are up to 1.0 m thick, and are stacked into cosets that are 0.8–3.0 m thick. Cross-set boundaries in some cosets dip in the same direction as foreset within the constituent cross-sets (Fig. 4D), whereas in others they are horizontal or inclined nearly perpendicular to foreset dip. Cosets are arranged into larger architectural units, which have a range of internal organizations and are bounded by erosion surfaces, some lined by mudstone conglomerates (facies F1). Cross-bedded, medium-grained sandstones constitute most (70–95%) of the total volume of the major sandbodies (numbered 1–6 in Fig. 3) but are absent in some minor sandbodies (not shown in Fig. 3, but located below major sandbody 5).

Mudclast conglomerates (facies F1) and cross-bedded, medium-grained sandstones (facies F2) enclose regions of moderately sorted, medium-grained sandstone characterized by meter-scale soft-sediment folds (facies F3; Fig. 4F). These deformed, folded regions have highly variable geometry, and are up to 3.5 m thick and 20 m wide. They constitute a
small proportion (5% to 20%) of the total volume of any particular sandbody.

In several sandbodies, cross-bedded, medium-grained sandstones (facies F2) pass gradationally upward and laterally into upward-fining successions of moderately sorted, medium- to fine-grained sandstone beds and intercalated siltstones (facies F4; upper part of sandbody, containing prominent inclined surfaces, in Fig. 4G). Sandstone beds in these latter successions are predominantly current-ripple cross-stratified and planar-parallel laminated, with some thin (0.3 m) cross-beds (Fig. 4H). Cross-stratification is unidirectional, and paleocurrents have a unimodal distribution. Siltstones thicken and become more abundant upward (Fig. 4G), with no apparent rhythmicity. Intercalated sandstones and siltstones (facies F4) are inclined at a low angle (20°), and strike subparallel to perpendicular to paleocurrents indicated by current ripples. The tops of some successions are sparsely penetrated by rootlets. Inclined, intercalated sandstones and siltstones form a small proportion (5% to 20%) of the total volume of the major sandbodies (numbered 1–6 in Fig. 3) but may constitute almost all (> 95%) of the total volume of minor sandbodies (not shown in Fig. 3, but located below major sandbody 5).

**Interpretation.**—The facies association as a whole is considered to consist of the sandstone deposits of river channel systems in an alluvial-to-coastal-plain setting (Marley et al. 1979; Flores et al. 1984; Dubiel et al. 2000; Hampson et al. 2012; Rittersbacher et al. in press). In this context, mudstone conglomerates (facies F1) are interpreted as lag deposits lining erosion surfaces at the bases of channels and their constituent architectural elements (channel stories, bars and bar-growth increments in Figs. 5, 6). The abundance of mudstone clasts and wood fragments indicates erosion of a vegetated, cohesive, mudstone-rich substrate, represented by the aggradational floodplain facies association (facies AF1–AF3). Where present, rare *Teredolites*-bored wood fragments (Fig. 4C) may indicate either marine or freshwater conditions, both of which are consistent with the coastal-plain setting (e.g., Bromley et al. 1984; Plint and Pickerill 1985).

Cross-bedded, medium-grained sandstones (facies F2) record deposition from straight- and sinuous-crested dunes that migrated in response to unidirectional currents. Carbonaceous drapes along the foresets and toesets of a few cross-sets indicate settling of abundant carbonaceous flakes from suspension during periods of low flow velocity; where such drapes are organized periodically, they may indicate tidal influence (e.g., Nio and Yang 1991). The stacking of cross-sets into cosets records the superposition of migrating dunes on to larger bars. The inclination of cross-sets within cosets records downstream accretion of bars, where set boundaries are inclined in the same direction as foresets within cross-sets (Fig. 4D), or lateral-to-oblique bar accretion, where set boundaries are inclined nearly perpendicular to foreset dip (cf. Miall 1994). The

---

**Fig. 3.**—A) Panel showing mapped stratigraphy and facies architecture in the Blackhawk Formation along the cliff line around the Link Canyon study area (Figs. 1, 2, 3B) (after Hampson et al. 2012). The Knight and Accord lakes coal zones in the lower Blackhawk Formation (after Hayes and Sanchez 1979; Sanchez et al. 1983) and the projected positions of the Bear Canyon and Kenilworth–Castlegate D coal zones, which are used to subdivide the Blackhawk Formation into gross intervals (Hampson et al. 2012), are shown. B) Geologic map of the Link Canyon study area. Both the panel and the map highlight the positions of six major fluvial sandbodies, numbered 1–6, whose internal architecture has been characterized in this study.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Lithology and Sedimentary Structures</th>
<th>Bioturbation</th>
<th>Geometry and Dimensions</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fluvial Sandbodies Facies Association</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1: Mudclast conglomerate</td>
<td>Moderately to poorly sorted, medium- to coarse-grained sandstone containing abundant mudclasts, and wood and carbonaceous plant fragments. Facies occurs as a local, discontinuous lining above erosion surfaces.</td>
<td>Absent (BI = 0)</td>
<td>Discontinuous sheet: 0.1-1.0 m thick, up to 50 m wide</td>
<td>Lags lining the bases of channel stories, bars, and bar-growth increments.</td>
</tr>
<tr>
<td>F2: Thick, channelized, cross-bedded sandstone</td>
<td>Moderately sorted, medium-grained sandstone units containing cosets of trough and tabular cross-beds, and structureless beds. Minor intercalations of fine-grained sandstone and siltstones, and scattered mudclasts along cross-set bases and foresets. Cross-sets are up to 1.0 m thick, and are organized into a variety of patterns within cosets (0.8-30 m thick). Grain size is uniform; facies lacks upward-fining or upward-coarsening trends. Sandstone units have channelized geometries.</td>
<td>Absent to sparse (BI = 0-1); non-diagnostic assemblage (Planolites)</td>
<td>Lenses: up to 6.0 m thick, up to 200 m wide</td>
<td>Bar and channel-fill sandstone. Cross-set organizational patterns within cosets define lateral-to-oblique accretion, downstream accretion and vertical accretion (&quot;cut-and-fill&quot;) architectural elements.</td>
</tr>
<tr>
<td>F3: Folded sandstone</td>
<td>Moderately sorted, medium-grained sandstone containing meter-scale soft-sediment folds, which deform mudclast conglomerate beds (facies F1) and cross-strata (facies F2).</td>
<td>Absent (BI = 0)</td>
<td>Highly variable: up to 3.5 m thick, up to 20 m wide</td>
<td>Bar and channel-fill sandstone deformed by water escape.</td>
</tr>
<tr>
<td>F4: Inclined sandstones and intercalated siltstones</td>
<td>Upward-fining successions of moderately sorted, medium- to fine-grained sandstone beds and intercalated siltstones. Sandstone beds are predominantly current-ripple cross-stratified and planar-parallel laminated, with some thin (&lt; 0.3 m) cross-beds. Siltstones thicken and become more abundant upward. Strata are inclined at a low angle (&lt; 20°), and strike subparallel to perpendicular to paleocurrents indicated by current ripples. Gradationally overlies and passes laterally into cross-bedded sandstones (facies F2).</td>
<td>Absent to sparse (BI = 0-1); rootlets</td>
<td>Lenses: up to 4.3 m thick, up to 190 m wide</td>
<td>Channel-fill sandstone and heteroliths. Organizational pattern of dipping strata defines lateral-to-oblique accretion or downstream accretion. Lateral and vertical facies relationships indicate that facies F4 records channel and channel-belt abandonment.</td>
</tr>
<tr>
<td><strong>Aggradational Floodplain Facies Association</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AF1: Thin, tabular, cross-bedded sandstone</td>
<td>Erosionally based, moderately sorted, medium- to fine-grained sandstone units containing thin (&lt; 0.3 m) trough and tabular cross-sets, current-ripple cross-stratified and planar-parallel laminated beds. Sandstone units have tabular and channelized geometries, and occur encased within root-penetrated siltstones (facies AF2).</td>
<td>Absent to sparse (BI = 0-1); rootlets</td>
<td>Sheets and lenses: up to 2.2 m thick, up to 50 m wide</td>
<td>Crevasse channels (lenticular sandbody geometry) and crevasse-splay lobes (tabular sandbody geometry).</td>
</tr>
<tr>
<td>AF2: Root-penetrated siltstones</td>
<td>Siltstones with sparse, thin (&lt; 0.2 m) beds of very fine- to fine-grained sandstone. Sandstone beds are current-ripple cross-stratified and planar-parallel laminated. Siltstones are generally penetrated by rootlets and variably destratified by pedogenesis; where primary structures are preserved, siltstones are parallel laminated.</td>
<td>Absent to moderate (BI = 0-4); rootlets</td>
<td>Poorly exposed</td>
<td>Floodplain.</td>
</tr>
<tr>
<td>AF3: Coal</td>
<td>Laminated coal and carbonaceous shale.</td>
<td>Absent (BI = 0)</td>
<td>Sheets: up to 0.2 m thick</td>
<td>Mire.</td>
</tr>
</tbody>
</table>
organization of cross-sets into cosets and larger units defines a hierarchy of architectural units (Fig. 5), which are interpreted in a later section.

Folded sandstones (facies F3) are interpreted to record deformation of bar and channel-fill sandstones by water escape. The abundance of meter-scale soft-sediment folds indicates liquefaction and fluidization under high pore-fluid pressures, most likely caused by loading in response to rapid but spatially uneven sand deposition (e.g., Owen 1986).

Inclined, intercalated sandstones and siltstones (facies F4) were deposited by intermittent unidirectional currents, which generated and drove the migration of current ripples and small dunes to result in the sandstone beds. Siltstone interbeds record deposition from suspension during periods of low flow velocity. The inclination of the strata define components of both lateral accretion, where strata strike perpendicular to paleocurrents indicated by current ripples, and downstream accretion, where strata strike subparallel to paleoflow. The fine grain size and small cross-strata in this facies, relative to the cross-bedded, medium-grained sandstones (facies F2), indicate decreased flow velocities. By implication, the facies records abandonment of the channels represented by the cross-bedded, medium-grained sandstones (facies F2) that lie gradationally below and lateral to it. The apparent lack of rhythmicity, predominance of unimodal paleocurrent distributions, and absence of bioturbation support deposition of inclined, intercalated sandstones and siltstones (facies F4) in rivers lacking tidal influence, where they record lateral migration of point bars in high-sinuosity, meandering rivers or of side-attached and mid-channel bars in low-sinuosity rivers (Thomas et al. 1987).

**Fig. 4.—Photographs illustrating facies in the studied sandbodies and adjacent deposits.**

A) Mudclast-conglomerate lag (facies F1) with pitted weathering appearance, lining erosion surface at channel-story base (story 3 in major sandbody 1; log 1.3 in Fig. 7). The lag and underlying erosion surface have been folded, due to water escape. B) Log and C) *Teredolites*-bored log, indicating possible marine influence, within mudclast-conglomerate lag (facies F1) lining erosion surface at base of channel-belt complex (major sandbody 5; log 5.2 in Fig. 11). D) Tabular cross-beds in cosets up to 1 m thick within channelized, cross-bedded sandstone (facies F2) (belt 2 of major sandbody 6; between logs 6.4 and 6.5 in Fig. 12). Inclined cosets indicate downstream accretion of a bar. E) Periodically spaced carbonaceous drapes along foresets in channelized, cross-bedded sandstone (facies F2), indicating potential tidal influence (story 3 of major sandbody 3; log 3.2 in Fig. 9). F) Large soft-sediment fold within sandbody (facies F3) (belt 2 in major sandbody 6; log 6.2 in Fig. 12). G) Inclined sandstones and intercalated siltstones (facies F4) gradationally overlying cross-bedded, medium-grained sandstone (facies F2) in channel story (story 3 of major sandbody 1; between logs 1.3 and 1.4 in Fig. 7), which is amalgamated with an underlying channel-belt sandstone. H) Climbing-current-ripple cross-stratification in fine-grained sandstone bed occurring within inclined sandstones and intercalated siltstones (facies F4) (story 3 of major sandbody 1; log 1.1 in Fig. 7). I) Margin of channelized, cross-bedded sandstone (facies F2) (belt 1 in major sandbody 6; log 6.3 in Fig. 12), which passes laterally (to the right) into a thin, cross-bedded sandstone sheet (facies AF1). J) Cross-bedded and current-ripple cross-laminated sandstone sheet penetrated by deep roots (facies AF1), overlain by root-penetrated siltstones containing rhizocretions (facies AF2) that are capped by a thin coal (facies AF3) (directly below story 2 of major sandbody 3; log 3.1 in Fig. 9).
Aggradational Floodplain Facies Association

The aggradational floodplain facies association of Hampson et al. (2012) consists of interbedded thin sandstones, siltstones, mudstones, and coals that encase the channelized sandbodies of the fluvial sandbodies facies association. The association has three constituent facies (AF1–AF3), but is generally poorly exposed, such that the proportions of these three facies cannot be estimated reliably.

Description.—The facies association contains thin (< 2.2 m), erosionally based, moderately sorted, medium- to fine-grained sandstone units with tabular and narrow, channelized (< 50 m) geometries (facies AF1). Thin, tabular and channelized sandbodies correspond respectively to the Type I and Type II sandstones of Marley et al. (1979). Some of the tabular sandstone units are observed to form the lateral extension of fluvial sandbodies (facies F1–F4; Fig. 4I), and all sandstone units are underlain and overlain by root-penetrated siltstones (facies AF2). The sandstone units contain thin (< 0.3 m) trough and tabular cross-sets, current-ripple cross-stratified beds, and planar-parallel laminated beds (Fig. 4J). Many have root-penetrated tops.

Thin, cross-bedded sandstone units (facies AF1) are encased within siltstones containing rare, thin (< 0.2 m) beds of very fine- to fine-grained sandstone (facies AF2). Sandstone beds are current-ripple cross-stratified and planar-parallel laminated. Siltstones are generally penetrated by rootlets and variably destratified by pedogenesis (Fig. 4J); where primary structures are preserved, siltstones are parallel laminated.

Beds of laminated coal and carbonaceous shale (facies AF3) are intercalated with root-penetrated siltstones (facies AF2), above intensely root-penetrated and pedogenically modified intervals (Fig. 4J). Coals and carbonaceous shale are thicker and more abundant in the lower part of the Blackhawk Formation (e.g., Hayes and Sanchez 1979; Sanchez et al. 1983).

Interpretation.—Cross-stratified, medium- to fine-grained sandstone units (facies AF1) record deposition from dunes and ripples that migrated in response to unidirectional currents. The geometry and small thickness of these tabular and channelized units, combined with their distribution adjacent to and extending from channelized fluvial sandbodies (facies F1–F4; Fig. 4I), implies that they represent crevasse-splay lobes and crevasse channels, respectively (Marley et al. 1979; Flores et al. 1984). Root-penetrated siltstones (facies AF2) that encase the thin sandstone units (facies AF1) are interpreted as vegetated floodplain deposits. Variations in the intensity of pedogenesis and abundance of roots in these siltstones reflect spatial and temporal variations in sedimentation rate (cf. Bown and Kraus 1987). Coal and carbonaceous shale (facies AF3) record the accumulation and preservation of plant material in waterlogged mires.
MODEST CHANGE IN FLUVIAL STYLE WITHIN REGRESSIVE CLASTIC WEDGE

(A) Northwest

Inclined heterolithic strata (facies FA4) defining lateral accretion of point bar, interpreted as bedset. Internal surfaces marked by erosional truncation and/or lapout bound bedset growth increments.

(B) Inclined heterolithic strata (facies FA4) defining point-bar accretion

(C) Bedset: heterolithic strata (facies FA4) defining point-bar accretion

(D) Southwest

 preserved remnant of channel belt, containing lateral-accretion, downstream-accretion and channel-fill bedsets

(E) Five vertically stacked, erosionally amalgamated channel belts within channel-belt complex

Legend:
- Set and coset boundaries (1st- and 2nd-order bounding surfaces) & bed boundaries of indeterminate status
- Surfaces of macroform accretion and macroform boundaries (3rd- and 4th-order bounding surfaces)
- Channel-story and channel-belt boundaries (5th- and 6th-order bounding surfaces)

- F1: mudclast conglomerate
- F2: thick, channelized, cross-bedded sandstone
- F3: folded sandstone
- F4: inclined, interbedded sandstones and siltstones
- AF1: thin, cross-bedded sandstone
- AF2: root-penetrated siltstones
- AF3: coal
which requires sustained conditions of high water table and clastic-sediment starvation (Bohacs and Suter 1996). In the lower Blackhawk Formation, laterally extensive coal zones generally formed during transgression in a broad, coastline-parallel belt (Dubiel et al. 2000; Hampson et al. 2012).

ARCHITECTURAL ANALYSIS OF FLUVIAL SANDBODIES

Architectural units are identified in the studied channelized fluvial sandbodies using the geometry, extent, and crosscutting relationships of erosion surfaces, combined with the lateral and vertical arrangement of facies (F1–F4) (cf. architectural-element analysis of Miall 1985, 1988), following the rules for hierarchical ordering of surfaces established by Holbrook (2001, p. 183). We use a hierarchical scheme synthesized from previous work (McKee and Weir 1953; Allen 1983; Bridge and Diemer 1983; Miall 1988, 1991; Bridge 1993; Hajek et al. 2010; Payenberg et al. 2011) to describe and interpret the arrangement of architectural units within sandbodies, and also the stacking arrangement of sandbodies into larger architectural patterns (Figs. 5, 6). Our focus here is on larger units within the hierarchical scheme (channel stories, channel belts, channel-belt complexes as defined in Fig. 5; cf. Payenberg et al. 2011), although units at intermediate scales (bedset growth increments, bedsets) and their constituent smaller elements (cross-bed sets and cosets) are used to interpret channel and bar types and their behaviors. Below we describe the criteria that have been applied to interpret channel stories, channel belts, and channel-belt complexes in the study dataset.

Both channel stories and channel belts (levels 5 and 6, respectively, of architectural hierarchy in Fig. 5) occur as channelized sandbodies with a basal erosion surface that may be lined with a discontinuous mudclast lag. Their distinction is based on the degree of architectural complexity within the sandbodies. Each interpreted channel story has a relatively simple internal architecture that comprises the deposits of a single bar
measured sections; B amalgamated to form a multilateral body (deposits of multiple bar macroforms and channel fills that are laterally approximate stratigraphic level. Thus, each channel belt contains the deposits of multiple bar macroforms and channel fills that are laterally amalgamated to form a multistory complex (level 7 of architectural hierarchy in Fig. 5). Complexes and their constituent stories and belts may be confined above a deep, “master” erosion surface of composite character (e.g., within a paleovalley). Alternatively, near the margins of a complex that lacks a “master” erosion surface at its base, it may be possible to identify preserved intervals of aggradational floodplain deposits (facies AF1–AF3) in between the basal erosion surfaces of individual stories and belts. The latter architecture allows more confident interpretation of channel-belt complexes, because architectural relationships between their constituent stories and belts are more fully preserved.

Architecture of Major Sandbody 1

Major sandbody 1 is exposed throughout the study area (Figs. 3, 7A). Laterally extensive erosion surfaces lined by discontinuous mudclast lags (facies F1) define the base of channel-story and channel-belt architectural units (cf. Fig. 5). Channel belt 1 is strongly erosionally truncated (Fig. 7C), and the preserved remnant consists principally of cross-bedded, medium-grained sandstones (facies F2). Channel belt 2 comprises cross-bedded, medium-grained sandstones (facies F2) with isolated bodies of folded sandstone (facies F3), which grade upward into poorly preserved, inclined, intercalated sandstones and siltstones (facies F4) (Fig. 7C) that record lateral accretion relative to local paleoflow (Fig. 7D). Channel story 3 comprises mainly inclined, intercalated sandstones and siltstones (facies F4), which record the northeastward advance of a barform with flanks that built out to the north and south (i.e., obliquely downstream relative to local paleoflow; Fig. 7C, D). Channel story 4 cuts down from a similar stratigraphic level, and may be contiguous with channel story 3 (Fig. 7C). It consists of cross-bedded, medium-grained sandstones (facies F2) that pass laterally and upward...
into inclined, intercalated sandstones and siltstones (facies F4) (Fig. 7C) recording lateral accretion (Fig. 7D). The story has an asymmetric cross-sectional profile, with the steep cutbank offset by a series of growth faults (Fig. 7C). Channel stories 5 and 6 both comprise cross-bedded, medium-grained sandstones (facies F2) that grade upward into laterally accreted, inclined, intercalated sandstones and siltstones (facies F4) (Fig. 7C, D). Channel belts 1, 2, and channel story 3 are vertically stacked with minor aggradation in the western part of the study area, whereas channel stories 4–6 exhibit more pronounced vertical stacking and are progressively offset laterally towards the northeast (Fig. 7C, D). The bases of channel belts 1 and 2 are amalgamated into a composite erosion surface (Fig. 7C), whereas channel stories 3–6 pass laterally into poorly exposed aggradational floodplain deposits (facies AF1–AF3) (Fig. 7C). Major sandbody 1 is poorly exposed on the east face of Link Canyon, and the internal architecture of the sandbody has not been documented here.

**Architecture of Major Sandbody 2**

Major sandbody 2 pinches out to the west and east in the study area (Figs. 3, 8A), and consists of a single channel-story unit. Channel story 1 comprises cross-bedded, medium-grained sandstones (facies F2) with isolated bodies of folded sandstone (facies F3), which grade upward into inclined, intercalated sandstones and siltstones (facies F4) (Fig. 8B, C) that record lateral accretion relative to local paleoflow (Fig. 8D). The upper part of the story in the west-southwest likely consists of an asymmetric, fine-grained body that is not exposed (Fig. 8C); this body may represent a fine-grained channel plug.

**Architecture of Major Sandbody 3**

Major sandbody 3 pinches out to the south and north in the west face of Link Canyon (Figs. 3, 9A), and consists of four, vertically stacked channel-story units (1–4 in Fig. 9C, D). The preserved remnant of channel story 1 and fully preserved channel story 4 both consist almost exclusively of cross-bedded, medium-grained sandstones (facies F2). Channel stories 2 and 3 both mainly comprise cross-bedded, medium-grained sandstones (facies F2) that grade upward into inclined, intercalated sandstones and siltstones (facies F4) (Fig. 9C) recording lateral accretion relative to local paleoflow (Fig. 9D). The inclined sandstones and siltstones in both stories are capped by rootlets (Fig. 9B). Channel stories 2–4 pass laterally into, and are intercalated with, aggradational floodplain deposits (facies AF1–AF3), although the basal surfaces of channel stories 1 and 2 are amalgamated into a composite erosion surface (Fig. 9C).

**Architecture of Major Sandbody 4**

Major sandbody 4 pinches out to the southwest in the study area, and its northeast pinchout is poorly exposed (Figs. 3, 10A). The sandbody consists of one channel-story unit (channel story 1 in Fig. 10C, D) overlain by two channel-belt units (channel belts 2, 3 in Fig. 10C, D). All three channel-story and channel-belt units comprise discontinuous mudclast lags (facies F1) overlain by cross-bedded, medium-grained sandstones (facies F2) with isolated bodies of folded sandstone (facies F3) (Fig. 10C). Channel belt 3 contains a mounded bedset that downlaps the basal erosion surface of the belt towards the west-southwest and east-northeast (between logs 4.1 and 4.2 in Fig. 10C), implying a mid-channel barform in an orientation perpendicular to local paleoflow (Fig. 13). The base of major sandbody 4 is defined by the nearly planar erosion surface at the base of channel belt 2, with deep (c. 7 m), localized erosional relief where channel story 1 is present (Fig. 10C).

**Architecture of Minor Sandbodies 1–3 below Major Sandbody 5**

Minor sandbodies 1–3 lie beneath major sandbody 5, and are laterally discontinuous, although their margins are only partly exposed (Fig. 11A). Each sandbody comprises a single channel-story unit (Fig. 11E). Minor sandbody 1 consists solely of cross-bedded, medium-grained sandstones (facies F2), whereas minor sandbodies 2 and 3 predominantly comprise inclined, intercalated sandstones and siltstones (facies F4) (Figs. 6A–C, 11C, E) that record lateral accretion relative to local paleoflow (Fig. 11F). Minor sandbody 2 is oriented west-southwest to east-northeast and records lateral accretion towards the north-northeast; in contrast, minor sandbody 3 is oriented southwest to northeast and records lateral accretion towards the southeast (Fig. 11F). Minor sandbodies 1–3 are encased in poorly exposed aggradational floodplain deposits (facies AF1–AF3) (Fig. 11E).

**Architecture of Major Sandbody 5**

Major sandbody 5 pinches out to the west on the back wall of Link Canyon, but extends outside of the study area to the east (Figs. 3, 11B). The sandbody consists of a lower channel-story unit (channel story 1 in Fig. 11E, G) overlain by two channel-belt units (channel belts 2, 5 in Fig. 11E, G), the lower of which contains two distinct channel-story units (channel stories 3, 4 in Fig. 11E, G). Channel belt 2 consists principally of cross-bedded, medium-grained sandstones (facies F2), and contains several prominent southward-dipping erosion surfaces that define the northern margins of horizontal-bedded bedsets (Fig. 11E, G). Channel stories 3 and 4 comprise discontinuous mudclast lags (facies F1) overlain by cross-bedded, medium-grained sandstones (facies F2) that grade upward into laterally accreted, inclined, intercalated sandstones and siltstones (facies F4) (Fig. 11E, G). Only the southern margins of these two stories are exposed (Fig. 11G). Channel belt 5 consists of a basal mudclast lag (facies F1) overlain by cross-bedded, medium-grained sandstones (facies F2), and contains erosion surfaces and bedsets that dip towards the southwest and northeast (Fig. 11E, G), implying development and accretion of a mid-channel barform. The base of major sandbody 5 is a nearly planar, composite erosion surface at the base of channel-belt units 2 and 3, but exhibits deep (c. 8 m), localized erosional relief where channel story 1 is present (Fig. 11E).

**Architecture of Major Sandbody 6**

Major sandbody 6 is continuously exposed across the study area (Figs. 3, 12A), and consists of six, vertically stacked channel belts (1–6 in Fig. 12C, D) overlain by a channel-story unit (7 in Fig. 12C, D). Each channel belt is variably preserved, due to deep erosion at the base of overlying units (Fig. 12C). They each mainly comprise cross-bedded, medium-grained sandstones (facies F2), but locally grade laterally and vertically into poorly preserved, inclined, intercalated sandstones and siltstones (facies F4) (Fig. 12C). Channel belts 2, 4, 5, and 6 contain bedsets of cross-bedded, medium-grained sandstones (facies F2) and/or...
intercalated sandstones and siltstones (facies F4) that are generally inclined perpendicular to paleoflow, indicating lateral accretion (Fig. 12C–D). Channel belt 2 also contains a downstream-accreted bedset of cross-bedded, medium-grained sandstones (facies F2) (Fig. 12C–D). Channel story 3 comprises a discontinuous mudclast lag (facies F1) overlain by cross-bedded, medium-grained sandstones (facies F2) with isolated bodies of folded sandstone (facies F3). Many of the channel belts and stories pass laterally into, or are intercalated with,
aggradational floodplain deposits (facies AF1–AF3) (Figs. 4I, 6D–F, 12C), such that the base of the sandbody does not define a “master” erosion surface composed of erosionally amalgamated channel-story and channel-belt bases.

INTERPRETATION OF FLUVIAL SANDBODY ARCHITECTURES

The six major sandbodies described above (Figs. 7–12) have qualitatively similar internal architectures. Each major sandbody consists of the same facies in similar proportions, and contains architectural units of the same style and hierarchical level (cf. Fig. 5). Architectural elements within channel-story units are typically incompletely preserved, but include the deposits of laterally, obliquely, and downstream-accreted bars, and both tabular and channelized cross-bedded-sandstone elements. Upstream accretion is not observed. Nearly horizontal sandstone strata that onlap channelized erosion surfaces are interpreted to record an active “cut and fill” style of channel infilling characterized by vertical accretion. Interpretation of paleochannel morphology from outcrop data is fraught with challenges (e.g., Bridge 1985; Ethridge 2011). Nevertheless, in combination, the various architectural elements described above suggest that the sandbodies were deposited by river channels and bars that exhibited components of straight, meandering, wandering, and braided fluvial styles (sensu Rust 1978; Church 1983). We cannot discount anastomosing or anabranching channel-planform patterns, with multiple coeval channels of the type described above separated by vegetated, semipermanent islands (cf. Knighton and Nanson 1993), particularly at areal scales larger than that of the study area (Fig. 3B). We interpret that stories with a simple “cut-and-fill” architecture, and stories and belts containing pervasive lateral-to-oblique accretion with a consistent direction were deposited by a single-thread, straight-to-meandering channel. In contrast, belts containing downstream-accreted elements and mid-channel barforms are interpreted to have been deposited by

**Fig. 11.—Summary of outcrop data constraining the internal architecture of minor sandbodies 1–3 and major sandbody 5 within the study area (Fig. 3): maps showing outcrop and measured sections of A) minor sandbodies 1–3 and B) major sandbody 5; measured sections through C) minor sandbodies 1–3 and D) major sandbody 5; E) bedding diagram constructed from interpreted cliff-face photomontages (e.g., Fig. 6A–C) tied to measured sections, showing interpreted channel-story and channel-belt units (cf. Fig. 5); and map-view reconstructions of F) minor sandbodies 1–3, each consisting of a channel-story unit, and G) map-view reconstructions of channel-story and channel-belt units 1–5 in major sandbody 5.**
FIG. 12.—Summary of outcrop data constraining the internal architecture of major sandbody 6 within the study area (Fig. 3): A) map showing sandbody outcrop and measured sections; B) measured sections; C) bedding diagram constructed from interpreted cliff-face photomontages (e.g., Fig. 6D–F) tied to measured sections, showing interpreted channel-story and channel-belt units 1–7 (cf. Fig. 5); and D) map-view reconstructions of channel-story and channel-belt units 1–7.
multiple-thread, wandering-to-braided channels. Sandbodies in the uppermost Blackhawk Formation and lower Castlegate Sandstone have previously been interpreted as the deposits of multiple-thread, braided channels on the basis of architectural analysis and barform reconstructions (Miall 1993, 1994; Adams and Bhattacharya 2005; McLaurin and Steel 2007). The three minor sandbodies each comprise a single story, two of which are dominated by lateral accretion with a consistent direction (stories 2, 3) and one by tabular cross-bedded-sandstone elements (story 1) (Fig. 12). These three sandbodies are interpreted to have been deposited by single-thread channels. Below we assess quantitative aspects of the sandbodies and the architectural units that comprise them, and interpret the paleohydraulic conditions under which they were deposited.

Variation in Dimensions of Sandbodies and Their Architectural Components

Thicknesses of the major and minor sandbodies, and of their architectural components, are taken from measured sections (Figs. 7B, 8B, 9B, 10B, 11C, 11D, 12B) and bedding diagrams (Figs. 7C, 8C, 9C, 10C, 11E, 11D, 12C). Sandbody widths are taken from map-view reconstructions (Figs. 7D, 8D, 9D, 10D, 11F, 11G, 12D), and are measured perpendicular to the interpreted trend of one or both sandbody margins, where the margins are constrained by the available data (i.e., true sandbody width is measured). Where sandbody margins are poorly constrained, their apparent widths are measured perpendicular to the mean paleocurrent direction within the sandbody. Major sandbodies 1, 5, and 6 extend outside of the Link Canyon study area (Figs. 3B, 7, 11, 12); their widths are estimated from a subregional stratigraphic panel (Fig. 3A), assuming that the complexes have axes trending in the orientation N150E. This orientation is reasonably well constrained by the mapped distribution of the three sandbodies in cliff faces adjacent to the Link Canyon study area, and it is also broadly consistent with the orientation and paleocurrent data of at least some architectural components in each sandbody (Figs. 7D, 11G, 12D) and with the orientation of major sandbodies 2, 3, and 4 (Figs. 8D, 9D, 10D). All sandbodies are assumed to be linear in map view over the short along-axis distances used to estimate their widths (100–1000 m for major sandbodies, < 50 m for minor sandbodies). The estimated dimensions of the sandbodies and their architectural components are accurate to approximately ±10%.

Channel-story, channel-belt, and channel-belt-complex sandbodies have distinctly different ranges of width and thickness, with some degree of overlap (Fig. 14). Channel-story sandbodies are generally narrow (mean ± standard deviation of 90 ± 80 m) and thin (7 ± 4 m) (Fig. 14A). Channel-belt sandbodies are wider (400 ± 220 m) but of similar thickness (9 ± 4 m) (Fig. 14B). Channel-belt-complex sandbodies are of similar width to channel-belt sandbodies (400 ± 160 m), but are thicker than the latter (20 ± 7 m) (Fig. 14C). These relative ranges of sandbody dimensions are unsurprising, since they reflect the diagnostic criteria and interpreted origin of channel-story, channel-belt, and channel-belt-complex sandbodies: channel stories are amalgamated laterally to form multilateral channel belts, and channel belts are stacked vertically to form multistory channel-belt complexes (Fig. 5). Using data from nearby localities (Salina Canyon and Castle Gate localities; Figs. 1, 2), similar thicknesses have been documented for channel-story sandbodies in the lower Castlegate Sandstone (1–8 m, Miall 1993; 2–12 m, McLaurin and Steel 2007), channel-belt sandbodies in the uppermost Blackhawk Formation (5–8 m, Adams and Bhattacharya 2005) and lower Castlegate Sandstone (4–7 m, Adams and Bhattacharya 2005; 2–16 m, McLaurin and Steel 2007, Hajek and Heller 2012), and channel-belt-complex sandbodies in the lower Castlegate Sandstone (17–40 m, McLaurin and Steel 2007). The widths of channel-story, channel-belt, and channel-belt-complex sandbodies are poorly constrained in these previous studies (Miall 1993; Adams and Bhattacharya 2005; McLaurin and Steel 2007), principally because fully preserved examples of these architectural units are sparse or absent in the lower Castlegate Sandstone.

![Image](56x467 to 568x726)

**Fig. 13.**—A) Uninterpreted and B) interpreted sections of a photopan illustrating two channel belts stacked within a channel-belt complex (major sandbody 4; Fig. 10). The upper channel belt (belt 2) contains a bedset that records vertical and lateral accretion in opposite directions of a mounded, mid-channel bar within a multiple-thread channel system. Note that surfaces bounding channel stories and channel belts in Parts B and C are shown using the same line weight.
Stratigraphic variations in the dimensions of the fluvial sandbodies and their constituent architectural components have also been analyzed (Fig. 15). There are no consistent stratigraphic trends in either width or thickness of the channel-belt-complex sandbodies (major sandbodies 1, 3, 4, 5, 6), although the youngest complex (major sandbody 6) is markedly wider (1260 m) than the four older complexes (270–620 m) (Fig. 15). This increased width is partly a reflection of wider channel belts in major sandbody 6 (250–740 m) relative to those in older complexes (120–390 m in major sandbodies 1, 3, 4, 5) (Fig. 15), and partly due to greater lateral offsets between the channel stories and belts stacked within major sandbody 6 (Fig. 12C, D).

Channel-story and channel-belt dimensions and stacking patterns within each major sandbody are highly variable (Fig. 15), such that: (1) there are no systematic trends shared by the sandbodies, and (2) variability within each sandbody is comparable in magnitude to the variability between sandbodies. Composite erosion surfaces at the bases of major sandbodies 1, 4, and 5 (Figs. 7, 10, 11) can be interpreted as unconformities at the base of stratigraphic valleys (sensu Strong and Paola 2008). However, the internal architecture of the sandbodies lacks the two diagnostic features of incised-valley fills formed by relative sea-level change in coastal-plain settings (e.g., Zaitlin et al. 1994): (1) an upward increase in preserved channel-story and channel-belt thickness, reflecting increasing accommodation during valley filling, and (2) an upward change in fluvial style that reflects progressively decreasing channel slope (e.g., low- to high-sinuosity) or increasing marine influence during transgressive backfilling of the valley. The erosional bases of these major sandbodies cannot also be mapped or correlated to define a regional network of paleovalleys developed at an incisional surface, as for coastal incised-valley fills (e.g., in the lowermost Blackhawk Formation north of the Link Canyon study area; figs. 12C, D, 13 in Hampson et al. 2012). Instead, stratigraphic valleys may have been cut and filled in response to local changes in the balance of sediment flux and transport capacity, within the limits set by base-level buffers driven by upstream controls (Holbrook et al. 2006). Architectures within such valley fills may appear disorganized, and principally reflect a combination of high-frequency climatic controls and autogenic responses related to internal and geomorphic thresholds (e.g., Westcott 1993; Holbrook 2001; Holbrook et al. 2006; Gibling et al. 2011). Major sandbodies 3 and 6 (Figs. 9, 12) lack composite, valley-form erosion surfaces at their bases, but instead comprise vertically stacked channel stories and channel belts whose margins are offset laterally and separated vertically by floodplain deposits. These sandbodies do not represent stratigraphic valleys, but the stacking of their constituent channel stories and channel belts is attributed to a combination of avulsion and local variations in sediment flux and transport capacity, as in the candidate stratigraphic valleys of major sandbodies 1, 4, and 5.

Fig. 14.—Graphs illustrating the width and thickness of A) channel-story, B) channel-belt, and C) channel-belt-complex sandbodies (Figs. 5–12). Black points are tightly constrained by outcrop data in the Link Canyon study area, whereas gray points are poorly constrained due to incomplete exposure and represent minimum widths and thicknesses. Channel-story sandbody 4 in major sandbody 1 may be overthickened by growth faults (Fig. 7C), and is indicated by an asterisk in Part A. Best-fit linear-regression lines with coefficients of determination ($R^2$ values) are shown. Correlations are strong for $R^2 > 0.8$, moderate for $0.8 > R^2 > 0.5$, and weak for $0.5 > R^2$. In Part A, best-fit regression lines are shown for tightly and poorly constrained data in black and gray, respectively.
Major sandbody 2 (Fig. 8) consists of a single channel story. Each of the minor sandbodies 1–3 comprises a single, small channel story (30–50 m wide, 4–5 m thick), comparable in scale to the smallest stories in major sandbodies 1–6 (Fig. 15). Thus, the minor sandbodies appear to have been deposited by rivers that were at least partly comparable in scale to those that deposited the major sandbodies.

**Paleohydraulic Analysis**

Based on the dimensions, architectural style, and grain-size patterns of the fluvial sandbodies and their architectural components, we reconstruct paleochannel forms and estimate the paleohydraulic conditions of the rivers that deposited them. Estimated paleochannel dimensions and paleohydraulic conditions are plotted in Figure 16 for each sandbody and its constituent architectural components, with sandbodies arranged in stratigraphic order, from oldest at the base (major sandbody 1; Fig. 7) to youngest at the top (major sandbody 6; Fig. 12).

(Figs. 7, 10, 11). Major sandbody 2 (Fig. 8) consists of a single channel story.

Each of the minor sandbodies 1–3 comprises a single, small channel story (30–50 m wide, 4–5 m thick), comparable in scale to the smallest stories in major sandbodies 1–6 (Fig. 15). Thus, the minor sandbodies appear to have been deposited by rivers that were at least partly comparable in scale to those that deposited the major sandbodies.

**FIG. 15.**—Graphs illustrating the width and thickness of channel-story and channel-belt sandbodies (narrow, shaded bars) and the channel-belt complexes that contain them (wide, unshaded bars). Black bars are tightly constrained by outcrop data in the Link Canyon study area, whereas gray bars are poorly constrained and represent minimum widths and thicknesses. Channel-story sandbody 4 in major sandbody 1 may be overthickened by growth faults (Fig. 7C), and is indicated by an asterisk. Most channel-belt complexes extend outside of the study area (major sandbodies 1, 5, and 6; Figs. 3B, 7, 11, 12), and their widths are estimated from a subregional stratigraphic panel (Fig. 3A), assuming that the complexes have axes trending in the orientation N150E. Data are arranged in stratigraphic order, from oldest at the base (major sandbody 1; Fig. 7) to youngest at the top (major sandbody 6; Fig. 12).
Methods.—Bankfull flow depth \( (D) \) is estimated from the measured thickness of a channel story or belt \( (h) \). Allowing for reduction of channel-story or channel-belt sandbody thickness by 10% during compaction,

\[
D = h/0.9 \tag{1}
\]

Ethridge and Schumm (1978) developed a different relationship for meandering channels, based on laboratory experiments in which bankfull flow depth was observed to be smaller than point-bar thickness (Khan 1971). Here, we use the thickness of channel-story and channel-belt sandbodies \( (h) \) as a proxy for compacted point-bar thickness, for sandbodies in which point bars are incompletely preserved:

\[
D = 0.585(h/0.9) \tag{2}
\]

In our analysis, we use Equation 1 to estimate bankfull flow depth in channel-story sandbodies lacking large-scale inclined surfaces (i.e., simple “cut-and-fill” sandbodies interpreted to record single-thread channels), and Equation 2 to estimate bankfull flow depth in channel-story and channel-belt sandbodies containing inclined surfaces that indicate lateral, oblique, or downstream bar accretion.

For channel-story and channel-belt sandbodies with a simple “cut-and-fill” architecture (i.e., lacking evidence of lateral, oblique, or downstream bar accretion), bankfull channel width \( (W) \) is estimated from measured sandbody thickness \( (h) \) and the dip angle of lateral-accretion surfaces \( (\beta) \) using the relationship proposed by Allen (1965) for meandering channels:

\[
W = 1.5(h / \tan \beta) \tag{3}
\]

The apparent dip angle of lateral-accretion surfaces measured in an outcrop face is corrected so that it is estimated perpendicular to mean
paleocurrent direction in the lateral-accretion bedset that contains them. For channel-belt sandbodies that contain downstream-accretion bedsets or mid-channel bars and are interpreted to have been deposited by multiple-thread channels, bankfull channel width is estimated from an empirical relationship with bankfull flow depth derived for modern braided rivers in the mid-continent USA (Leopold and Maddock 1953):

\[ W = 42 D^{1.11} \quad (4) \]

Sinuosity \((P)\) is estimated for channel-story and channel-belt sandbodies that contain lateral-accretion bedsets and are interpreted to have been deposited by single-thread channels, using the empirical relationship derived by Schumm (1972) for modern meandering rivers in the mid-continent USA:

\[ P = 3.5(W/D)^{-0.27} \quad (5) \]

In the same sandbodies, the ratio of observed lateral-accretion bedset width (i.e., extent of lateral point-bar accretion perpendicular to accretion-surface strike, using maps in Figs. 7D, 8D, 9D, 10D, 11F, 11G, 12D) to lateral-accretion surface width (i.e., width of accretionary channel bank) reflects a combination of sinuosity, meander wavelength, and downstream migration of the meander (e.g., Willis and Tang 2010). The quantity of measured paleocurrent data is insufficient to estimate sinuosity using statistical methods (e.g., Langbein and Leopold 1966; Le Roux 1992).

Channel slope \((S)\) is estimated via two empirical relationships. The first relationship is derived from observed bankfull channel widths and depths for modern rivers in the mid-continent USA (Schumm 1972):

\[ S = 30 \left\{ \left( W/D \right)^{0.95} / W^{0.98} \right\} \quad (6) \]

The second relationship was proposed by Lynds (2005) for sand-beds rivers, following the form of a relationship for gravel-bed rivers given in Paola and Mohrig (1996):

\[ S = \left( T d_{\text{bedd}} \right) / D \quad (7) \]

where \(T\) is the product of an empirically derived coefficient (bankfull nondimensional shear stress) and sediment density, and is approximately equal to 2.7, and \(d_{\text{bedd}}\) is the median grain size of the bedload, taken as 0.25 mm (fine-to-medium sand). The first relationship (Equation 6) gives slope estimates that are generally 2–3 times steeper than the second relationship (Equation 7). However, the latter estimates are based on the critical shear stress of transport for the \(d_{\text{bedd}}\) grain size, which gives a minimum value of the slope required to transport bedload material of median grain size, and are accurate to within a factor of 2 (Paola and Mohrig 1996). Our estimates of channel slope thus lie approximately within the margin of error inherent to the two independent techniques used to derive them. It should be noted that in Figure 16, slope is plotted in degrees rather than the original units (i.e., feet per mile in Schumm 1972).

Peak discharge \((Q_p)\) is estimated using the method of Bhattacharya and Tye (2004), which multiplies bankfull channel cross-sectional area against peak flow velocity \((U_p)\):

\[ Q_p = 0.65 \left( \frac{W D}{U_p} \right) \quad (8) \]

Peak flow velocity is derived using the bedform-phase diagrams of Rubin and McCulloch (1980), and is estimated from three parameters: flow depth, median bedload grain size, and dominant bedform type. Flow depth is calculated using a combination of the experimental data of LeClair and Bridge (2001), which indicate that mean dune height is approximately 2.9 times mean cross-set thickness (0.2–0.3 m in the studied sandbodies), and the empirical relationship of Yalin (1964) that flow depth typically approximates 6–10 times mean dune height; thus flow depth is estimated at 3.5–8.7 m. Allen’s (1970) empirical relationship between flow depth, \(D\), and mean dune height, \(h_m\) (Equation 9) gives comparable values of estimated flow depth (7.3–10.3 m):

\[ D = 11.6 h_m^{0.84} \quad (9) \]

Using these estimates of flow depth, combined with the observed median grain size of the bedload (fine-to-medium sand) and dominant bedform type (3D dune, recorded by trough cross-bedding), peak flow velocity is estimated to have been 0.6—1.3 m s\(^{-1}\). This range of values is used to estimate peak discharge (Fig. 16). Estimates of peak discharge (Equation 8) are comparable (within \(\pm\)50\%) with those of mean annual flood discharge \((Q_{\text{ma}})\) estimated using the empirical relationship of Schumm (1972) for modern rivers in the mid-continent USA (Equation 10):

\[ Q_{\text{ma}} = 16 \left( \frac{W^{1.56}}{(W/D)^{0.66}} \right) \quad (10) \]

Estimates of peak discharge (Equation 8) are 1–10 times greater than estimates of mean annual discharge \((Q_{\text{ma}})\) using the empirical relationship of Schumm (1972) for modern rivers in the mid-continent USA (Equation 10):

\[ Q_{\text{ma}} = W^{2.41} \left\{ \left( \frac{18(W/D)^{1.13}}{\text{m}^2} \right) \right\} \quad (11) \]

Each of the major fluvial sandbodies characterized within the Link Canyon study area exhibits a similar range of interpreted paleohydraulic parameters, although this range is large and associated with significant uncertainty (Fig. 16). Four key results are highlighted below.

**Bankfull Channel Dimensions.**—Estimated bankfull widths and depths of various channel types are summarized below. Single-thread channels preserved as simple “cut-and-fill” bedsets \((n = 7)\); denoted as “single-thread, no lateral accretion” in Fig. 16) have estimated bankfull widths of 30—110 m (mean of 60 m) and bankfull depths of 4.0—9.9 m (mean of 5.7 m). Single-thread channels preserved adjacent to lateral-, oblique-, and downstream-accretion bedsets \((n = 13)\); denoted as “single-thread, no lateral accretion” in Fig. 16) have estimated bankfull widths of 20—320 m (mean of 130 m) and bankfull depths of 2.3—9.8 m (mean of 5.6 m). Multiple-thread channels \((n = 11)\); denoted as “multiple-thread” in Fig. 16), have estimated bankfull widths of 80—910 m (mean of 540 m) and bankfull depths of 2.1—14.2 m (mean of 8.8 m). The estimates of bankfull flow depth quoted above, which are derived from observed sandbody thicknesses (Equations 1 and 2; Ethridge and Schumm 1978), are consistent with values of 3.5—10.3 m derived from observations of mean cross-set thickness and inferred dune height (e.g., Equation 9; after Yalin 1964; Allen 1970; LeClair and Bridge 2001).

The occurrence of both single-thread and multiple-thread channel deposits within the same channel-belt complexes (e.g., major sandbodies 1, 4, 5, and 6; Figs. 15, 16) implies that both types of channel coexisted on the Blackhawk alluvial-to-coastal plain. Comparison of the estimated bankfull channel dimensions indicates that single-thread channels had a relatively small range of bankfull widths and depths, whereas multiple-thread channels were wider and deeper. There is relatively little stratigraphic variation in inferred bankfull channel dimensions, although the estimated bankfull width of multiple-thread channel belts generally increases upward within the Blackhawk Formation stratigraphy, from 110—340 m (belts 1—2 and story 3 in major sandbody 1; belts 2—3 in major sandbody 4) to 80—910 m (belts 2 and 5 in major sandbody 5; belts 1a, 2, 3, and 5 in major sandbody 6) (Fig. 16). This trend implies that multiple-
thread channel belts became wider with increasing distance from the coeval shoreline (Fig. 2); they likely defined downstream-branching networks of downstream-narrowing, trunk distributary channels on a delta plain (Marley et al. 1979; Flores et al. 1984; Rittersbacher et al. in press).

Channel Sinuosity.—Single-thread channels preserved adjacent to lateral- and oblique- and downstream-accretion bedsets in major fluvial sandbodies \( n = 14 \): belt 2 and stories 3–6 in major sandbody 1; story 1 in major sandbody 2; stories 2–3 in major sandbody 3; story 1 in major sandbody 4; stories 3–4 and 5 in major sandbody 5; and belts 4 and 6a in major sandbody 6 (Fig. 16) have low-to-moderate estimated sinuosities (1.1–1.9, mean of 1.5). Single-thread channels preserved adjacent to lateral-accretion bedsets in isolated, heterolithic channel stories \( n = 2 \); minor sandbodies 2–3; (Fig. 16) have moderate estimated sinuosities (1.6–2.1). There is only a weak correspondence between estimated channel sinuosity and the ratio between lateral-accretion-set width and lateral-accretion-surface width (Fig. 16), which likely reflects the influence of meander wavelength and downstream meander migration on this latter ratio, in addition to sinuosity (e.g., Willis and Tang 2010). These results suggest that single-thread channels were straight to moderately sinuous in planform, despite the observation that lateral-accretion bedsets are prominent architectural components of the Blackhawk Formation sandbodies.

Channel Slope.—Best estimates of channel slope are uniformly low (< 0.04%), although there is a large standard error associated with these values (e.g., wide bars in column showing channel-slope estimates, with values including standard errors reaching 0.2%; Fig. 16). Estimated values of channel slope show no trend with stratigraphic position (Fig. 16), and are comparable to modern coastal-plain and delta-plain gradients. Estimated values of channel slope are thus consistent with subtle marine influence in a coastal-plain setting (e.g., Teredolites-bored logs and tidally modulated? carbonaceous drapes along cross-bed foresets, Fig. 4C, E) at most stratigraphic levels (major channel stories 1–5).

Peak Discharge.—Estimates of peak discharge are derived in turn from estimates of peak flow velocity, bankfull channel width, and bankfull channel depth (Equation 8; Bhattacharya and Tye 2004). Similarly, estimates of mean annual discharge and mean annual flood discharge are derived from estimates of bankfull channel width and depth (Equations 10 and 11; Schumm 1972). Our estimated discharge values thus mimic the influence of meander wavelength and downstream meander migration on this latter ratio, in addition to sinuosity (e.g., Willis and Tang 2010). These results suggest that single-thread channels were straight to moderately sinuous in planform, despite the observation that lateral-accretion bedsets are prominent architectural components of the Blackhawk Formation sandbodies.

Controls on Fluvial Style and Stratigraphic Architecture

The six major fluvial sandbodies documented in this paper occur at different stratigraphic levels of the Blackhawk Formation in the Link Canyon study area (Fig. 3). Most of these major sandbodies are channel-belt complexes. They all consist of the same types of architectural components (Figs. 7–12), which have similar dimensions (Figs. 14, 15), and were deposited by three paleochannel types that varied little between sandbodies: (1) single-thread “cut-and-fill” channels that lack lateral accretion and were filled by vertical accretion; (2) single-thread, laterally accreting channels of low-to-moderate estimated sinuosity (1.1–2.1); and (3) multiple-thread, wandering-to-braided channels (Fig. 15). All three channel types are present within most of the major sandbodies, implying that they were developed penecontemporaneously on a low-gradient (< 0.04°) coastal plain that was subject to some marine influence. Multiple-thread channels reconstructed in the two upper major sandbodies (belts 2 and 5 in major sandbody 5; belts 1a, 2, 3, and 5 in major sandbody 6; Fig. 16) are estimated to have had higher paleodischarges than those in the underlying sandbodies (belts 1–2 and story 3 in major sandbody 1; belts 2–3 in major sandbody 4; Fig. 16), in part due to the wider paleochannels reconstructed in major sandbody 6 (Fig. 15). If these variations in estimated paleodischarge are attributed to channel position relative to the coeval paleoshoreline, then they imply that multiple-thread channels of high paleodischarge (e.g., represented by sandbodies 5–6, located c. 90–100 m from approximately coeval shoreline #10 in Figs. 1, 2) branched downstream to supply several multiple-thread channels of lower paleodischarge (e.g., represented by sandbodies 1–4, located c. 40–60 m from approximately coeval shorelines #3–7 in Figs. 1, 2). Thus, paleohydraulic discharge estimates imply that the major sandbodies may represent delta-plain distributary networks of downstream-narrowing channels, although his interpretation cannot yet be supported by independent evidence. However, the most striking feature of the six major sandbodies is their similarity in facies character, internal architectures, and interpreted paleochannel dimensions (Figs. 7–12, 16). Paleohydraulic conditions varied within a relatively small and uniform range during deposition of the six major sandbodies to result in this modest variation in fluvial style.

There are no systematic trends in the type or preservation of successive channel stories and belts within each of the channel-belt complexes, such that the internal architectures of the sandbodies do not result from systematic, short-term changes in accommodation such as those that characterize incised-valley fills formed by relative sea-level change in coastal-plain settings (e.g., Zaitlin et al. 1994). Major sandbodies 1, 4, and 5 have composite, valley-form erosion surfaces at their bases (Figs. 7, 10, 11), but their internal architectures appear to reflect local changes in the balance of sediment flux and transport capacity due to upstream controls, such as high-frequency climatic variations, and autogenic responses (e.g., Westcott 1993; Holbrook 2001; Holbrook et al. 2006; Gibling et al. 2011). Major sandbodies 2, 3, and 6 do not consist of vertically stacked channel stories and channel belts that are confined within composite, valley-form erosion surfaces (Figs. 8, 9, 12). Instead, the stacking of channel stories and channel belts within major sandbodies 3 and 6 is interpreted to reflect localized, autogenic behavior (e.g., avulsion). Major sandbody 2 consists of a single channel story. The similarity in stacking of architectural elements in the major fluvial sandbodies, whether confined to candidate valleys or not, implies that the same, localized autogenic processes operated under a relatively wide range of conditions (Fig. 2); (1) variable proximity to the coeval shoreline, from c. 40 km (major sandbody 1) to c. 100 km (major sandbody 6), based on regional mapping of shoreline positions at outcrop (Figs. 1, 2) (e.g., Kamola and Huntoon 1995; Taylor and Lovell 1995; Hampson 2010; Hampson et al. 2011); (2) variable sediment accumulation rate, which approximates tectonic subsidence rate, from c. 80–700 m/Myr, based on regional outcrop and subsurface mapping of stratigraphic surfaces tied to dated ammonite biozones (Hampson 2010); (3) broadly uniform distance (c. 80 km) from the highlands of the Canyon Range Culmination in the Sevier fold-and-thrust belt (Fig. 1), which was the likely sediment source (DeCelles and Coogan 2006); and (4) seasonal, warm temperate-to-subtropical climatic conditions, as implied by coal-seam flora (Parker
Local, autogenic behavior has been interpreted as the principal control on fluvial architecture at comparable scales in the Castlegate Sandstone, which overlies the Blackhawk Formation (McLaurin and Steel 2007; Hajek and Heller 2012).

The modest change in fluvial style between the major sandbodies and the dominance of upstream controls and autogenic patterns in their internal stratigraphic architecture do not conform to the predictions of sequence stratigraphic models of alluvial-to-coastal-plain successions (Wright and Marriott 1993; Shanley and McCabe 1994; Richards 1996), but are instead consistent with interpreted autogenic patterns in large-scale stratigraphic architecture of the Blackhawk Formation over the Wasatch Plateau outcrop belt (Fig. 1). At this large scale, the Blackhawk Formation exhibits subtle trends of increasing size, abundance, and interconnectedness of major fluvial sandbodies from its base to its top (cf. Fig. 3A; Hampson et al. 2012). While these overall trends are interpreted to reflect progressively decreasing tectonic subsidence, at least in the upper Blackhawk Formation and overlying Castlegate Sandstone (Adams and Bhattacharya 2005; Hampson et al. 2012), they are superimposed on an apparently random distribution of sandbodies which exhibits localized clustering that is independent of stratigraphic and paleogeographic position. This clustering pattern is tentatively attributed to large-scale avulsion (cf. Mackey and Bridge 1995; Hajek et al. 2010; Wang et al. 2011). However, it contrasts with the occurrence of relatively well-organized stratigraphic cycles bounded by major, regionally extensive coal zones in the lowermost Blackhawk Formation, which was deposited on the lower coastal plain up to 50 km from the coeval shoreline (Hampson et al. 2012). Thus autogenic behavior appears to have strongly influenced fluvial stratigraphic architecture at a range of scales in alluvial-to-upper-coastal-plain strata in the Blackhawk Formation. The modest variation in fluvial style between the major sandbodies documented in Link Canyon indicates that fluvial style in the Blackhawk Formation bears little relationship to stratigraphic organization and architecture predicted from sequence stratigraphic models for coastal-plain settings influenced by relative sea-level change. In particular, there is no overall change from single-story, single-thread (e.g., meandering) channel sandbodies to amalgamated, multiple-thread (e.g., braided) channel sandbodies from base to top of the Blackhawk Formation, despite a transition from aggradation to pronounced progradation of coeval shallow-marine deposits that are assigned to a highstand systems tract (e.g., Howell and Flint 2003; Hampson 2010 and references therein). These results support the findings of Adams and Bhattacharya (2005), who documented no change in fluvial style across an interpreted sequence boundary at the overlying Blackhawk-Formation-to-Castlegate-Sandstone transition.

CONCLUSIONS

The Link Canyon study area exposes six major sandbodies developed at different stratigraphic levels of the Blackhawk Formation. The fluvial sandbodies consist of four facies: (F1) mudclast conglomerate (< 5% of each sandbody); (F2) thick, channelized, cross-bedded, medium-grained sandstone (70–95%); (F3) folded sandstone (< 5% to 20%); and (F4) inclined sandstone and intercalated siltstones (< 5% to 20%). Fine-grained aggradational floodplain deposits that enclose the fluvial sandbodies consist of three facies: (AF1) thin, tabular cross-bedded sandstone; (AF2) root-penetrated siltstones; and (AF3) coal. In the major fluvial sandbodies, facies are arranged within a hierarchy of architectural components. Studied architectural components include, from small to large spatial scales, bedsets, channel stories, channel belts, and channel-belt complexes. Channel-story, channel-belt, and channel-belt-complex sandbodies have distinctly different ranges of width and thickness. Channel stories (n = 19) are 10–310 m wide (mean of 90 m) and 3.6–15.0 m thick (mean of 7.2 m). Channel stories are amalgamated laterally into channel belts (n = 12) that are 120–740 m wide (mean of 400 m) and 1.9–13.7 m thick (mean of 9.2 m). Channel belts are stacked vertically into channel-belt complexes (n = 5) that are 270–1300 m wide (mean of 400 m) and 9–28 m thick (mean of 20 m).

Channel stories and belts were deposited by three types of paleochannels: (1) single-thread ‘‘cut-and-fill’’ channels, preserved as simple channel-fill bedsets characterized by vertical accretion; (2) single-thread, laterally accreting channels of low-to-moderate sinuosity, preserved as channel stories containing lateral-to-oblique-accretion bedsets; and (3) multiple-thread, wandering-to-braided channels, preserved as channel belts containing lateral-accretion, oblique-accretion, downstream-accretion, and/or simple channel-fill bedsets. Estimated paleochannel slopes are uniformly low (< 0.04°), similar to modern coastal-plain and delta-plain gradients, which is consistent with evidence of potential marine influence (e.g., *Teredolites*-bored logs, rhythmic carbonate crusts along cross-bed foresets implying tidal influence) in most sandbodies. Paleo hydraulic discharge estimates imply that multiple-thread channels may have narrowed and branched downstream to form distributary networks, consistent with a delta-plain setting.

The fluvial style of the major sandbodies (channel-belt complexes), as reflected in their facies character and internal architectures, exhibits only minor variation with the stratigraphic position of the sandbodies. Channel-story and channel-belt dimensions and stacking patterns within each major sandbody are highly variable, such that: (1) there are no systematic trends shared by the sandbodies, (2) sandbody architectures do not result from high-frequency changes in accommodation, such as those associated with the incision and fill of coastal incised valleys, and (3) variability within each sandbody is more pronounced than variability between sandbodies. Thus, the stacking of channel stories and channel belts within channel-belt complexes is interpreted to reflect local variations in sediment flux and transport capacity, which may have resulted in valley formation, and localized, autogenic processes (e.g., avulsion). In turn, the geometry and dimensions of the major fluvial sandbodies principally reflect channel avulsion history rather than paleochannel morphology. The similarities in architecture between major fluvial sandbodies implies that the same local variations in sediment flux, transport capacity, and autogenic behavior operated under a range of proximities to the coeval shoreline (c. 40–100 km) and tectonic subsidence rates (c. 80–700 m/Myr), for a uniform distance to the sediment source area (c. 80 km) and seasonal, warm temperate-to-subtropical climate. Our results indicate that current sequence stratigraphic models are poor predictors of fluvial style within alluvial-to-coastal-plain strata, because the influence of accommodation is strongly overprinted by the effects of local variations in sediment flux and transport capacity, and by autogenic patterns.

ACKNOWLEDGMENTS

The authors thank Chevron Energy Technology Company for funding and support of this work. Additional support was provided by the Department of Earth Science and Engineering, Imperial College (Irfan, Jewell). We thank Chris Fielding, Adrian Hartley, John Howell, Howard Johnson, Andrew Ranson, Andreas Rittersbacher, Hiranya Sahoo, and Brian Willis for insightful discussions. The scholarly, astute, and constructive reviews and editorial comments of Frank Ethridge, John Holbrook, and Martin Gibling, and the meticulous copy editing of John Southard are gratefully acknowledged.

REFERENCES


Received 16 May 2012; accepted 28 October 2012.