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NO CHANGE IN FLUVIAL STYLE ACROSS A SEQUENCE BOUNDARY, CRETACEOUS BLACKHAWK AND CASTLEGATE FORMATIONS OF CENTRAL UTAH, U.S.A.

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Abstract: **Nonmarine sequence stratigraphic models are based largely on studies of fluvial units in the Cretaceous Western Interior of North America, including the Blackhawk and Castlegate formations of central Utah. These models suggest that fluvial units should show a transition from mudstone-prone, isolated meander-belt deposits of the transgressive and highstand systems tract into amalgamated braided-stream sandstones of the lowstand systems tract. These mudstone-rich fluvial strata are largely assumed, rather than documented, to represent the deposits of isolated meander-belt deposits, despite recent work that suggests that there is no simple relationship between the proportion of preserved floodplain mud and fluvial style.**

There are numerous studies documenting the braided character of the sandstone-rich Castlegate Formation, but there are no corresponding studies that document the internal fluvial facies architecture within the Blackhawk Formation to support the interpretation that the Blackhawk comprises the deposits of a meandering-stream system. We test the validity of the sequence stratigraphic model by comparing dimensions and styles of associated bar and channel deposits, as well as cross-stratal thicknesses, between the Blackhawk and Castlegate formations along Salina Canyon in Utah.

Data compiled from 24 measured sections and 6 photomosaics show that the Blackhawk Formation comprises isolated sandy channel-belt sheet sandstones, 5–8 m thick, contained within thick floodplain mudstones, whereas the Castlegate Formation consists of about 80 m of amalgamated sandy channel-belt sheets, 4–7 m thick, with only minor mudstone. The average height of cross-sets is 13 cm in the Castlegate Formation and 14 cm in the Blackhawk Formation and formative dune height is estimated to be 38 cm for the Castlegate Formation and 45 cm for the Blackhawk Formation. Average bar-accretion thicknesses are 2 m in both the Blackhawk and Castlegate formations. Corresponding water depths are estimated to be 2.5–4.1 m for the Blackhawk and 2.3–3.8 m for the Castlegate. The correlation of master bedding planes in the Blackhawk Formation shows overlapping lens-shaped bar deposits and channel fills. Bar tops appear to dip in several directions, indicating both lateral and downstream accretion of mid-channel braid bars.

While there is some indication that Castlegate rivers were slightly shallower, the differences do not suggest a major change in fluvial style across the sequence boundary; both are braided. The lack of change in scale of channels also is not compatible with a hypothesized increase in aridity between the Blackhawk and the Castlegate. The difference in fluvial architecture between the two formations is interpreted to reflect changes in accommodation that were likely tectonic in origin. This supports that idea that preservation of thick successions of fine-grained overbank material is not a function of the plan-view channel geometry.

INTRODUCTION: NONMARINE SEQUENCE STRATIGRAPHY AND FLUVIAL STYLE

Nonmarine sequence stratigraphic models have largely been developed from studies of well exposed foreland-basin successions in Utah and Wyoming (Shanley et al. 1992; Shanley and McCabe 1994; Van Wagoner 1995). These models suggest that major unconformities, or sequence boundaries, are associated with a dramatic change in fluvial style from isolated, single story, meandering streams in the transgressive and highstand systems tract to amalgamated braided-stream systems in the lowstand systems tract. The transition between the Blackhawk and the overlying Castlegate sandstones in the Book Cliffs of central Utah has been interpreted as one such sequence-bounding unconformity, as have successions of similar age in the Kaiparowits Plateau several hundred kilometers to the south (Shanley et al. 1992; Shanley and McCabe 1994) and in the Ericson Formation in Wyoming to the north (Steel et al. 1999). Van Wagoner (1995, his figure 53) depicts the transgressive fluvial systems of the Blackhawk Formation as comprising "mud-dominated, single-story, laterally accreting point bars" and states that "In the highstand systems tract, alluvial valleys tend to be relatively narrow, dominated by meandering streams." Van Wagoner (1995) shows the lower lowstand systems tract as being deposited as multistory, braided sheet sandstones. On the basis of work on the Kaiparowits Plateau, Shanley and McCabe (1994) state that the highstand systems tract consists of "isolated, high-sinuosity fluvial channels" whereas the lowstand comprises amalgamated fluvial-channel deposits of low-sinuosity, high-gradient rivers. They demonstrate that channel deposits of the transgressive systems tract are commonly tidally influenced (Shanley et al. 1992; Shanley and McCabe 1994).

The term meandering has been applied to many fluvial successions that show high mudstone-to-sandstone ratios, whereas the term braided has been applied to many successions in which the proportion of floodplain mudstones is low (e.g., Moody-Stuart 1966; Friend 1983; Allen 1984; Galloway and Hobday 1996; Nichols 1999). There has been a significant challenge to this bipartite classification of ancient fluvial systems into "meandering" versus "braided" endmembers, in large part because these are not mutually exclusive categories (Miall 1985; Bridge 1993b, 2003, p.147). In modern systems, water discharge, valley slope, sediment flux, and grain size determine channel patterns (Bridge 2003, p.155). Gradational differences within and among these variables result in a continuum of channel patterns (e.g., Bridge 1985; Brierley and Hickin 1991; Bridge 2003).

Determination of the plan-view morphology of ancient rivers requires detailed analysis of the bedding geometry of channel and bar deposits with respect to paleocurrent data, a task ideally suited to the excellent outcrops in Utah, although exceedingly difficult in subsurface applications (Miall and Tyler 1991; Bridge 1993). While there are many published examples of these types of analyses of other ancient fluvial outcrops (e.g., Willis 1993b; Bridge 1993a; Miall 1994; Holbrook 2001),

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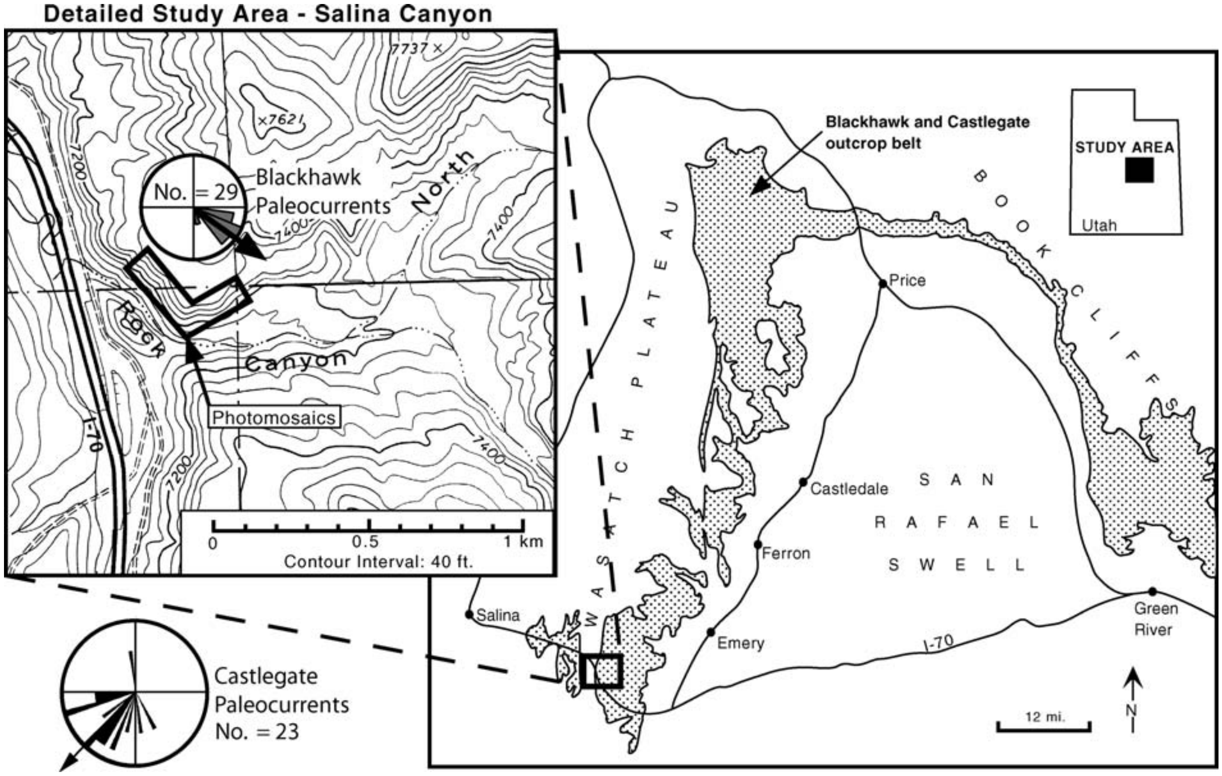

FIG. 1.—Location of the Study Area. Stippled area shows the location of the Blackhawk and Castlegate outcrop belt. Inset shows topographic map of Rock Canyon area. Rose diagrams show paleocurrent data from the Castlegate and the Blackhawk formations in the study area.

there have been no studies on the Blackhawk Formation, and only a few on the Castlegate Formation (Miall 1993,1994; Olsen et al. 1995), despite the extensive regional sequence stratigraphic work (e.g., Van Wagoner et al. 1990; Olsen et al. 1995; Van Wagoner 1995). The lack of such a study represents an opportunity to test the predicted changes in fluvial style across a sequence boundary by documenting the channel paleohydraulics and river type across the Blackhawk–Castlegate transition. We suspect that the Blackhawk has been assumed to be meandering, largely because it exhibits a high mud-to-sand ratio (e.g., Van Wagoner 1995) rather than because of any detailed work that documents the types of bars or channels in these systems.

In this study, we attempt to distinguish whether Blackhawk channel bars are attached to the sides of a single channel (i.e., point bars or alternate bars), or if they occur between adjacent active channels, thus defining a braided system. The transition between the Blackhawk and Castlegate has also been hypothesized to correlate with an increase in aridity reflecting climate changes in the basin (Van Wagoner 1995). A more detailed analysis of the paleohydraulics of the two systems will also allow us to test this hypothesis as well.

REGIONAL SETTING AND STRATIGRAPHY

The Blackhawk and Castlegate formations are part of an upper Campanian clastic wedge deposited in the Cretaceous Western Interior Seaway during the late Sevier Orogeny (Figs. 1, 2, 3). The Blackhawk and Star Point formations make up the lower section of the Mesaverde Group and are composed of coastal-plain, marginal marine, and marine deposits (Fig. 2). The upper section of the Mesaverde Group comprises coastal-plain deposits of the Castlegate and overlying Price Canyon formations.

The Blackhawk Formation in the southern Wasatch Plateau is 200–300 m thick (Hintze 1988) and comprises interbedded coal, mudstone, shale, siltstone, and sandstone. It is a mud-prone unit containing single-story channel belt deposits (Fig. 3). Abundant coals and poorly developed gleysols (Fig. 4) show that the Blackhawk Formation was deposited in wet conditions with overall drainage-basin discharge partitioned among a few active rivers (Flores et al. 1982; Van Wagoner et al. 1990; Van Wagoner 1995). Near Price Canyon, the Blackhawk fluvial channels typically form 1-meter-thick single-story belts associated with thick coals deposited in humid alluvial and coastal plain environments (Olsen et al. 1995). Eastward in the Book Cliffs, the coastal-plain facies grade into nearshore deposits and the Blackhawk is divided into six members representing a stacking of progradational to aggradational shoreface and deltaic sandstones (Fig. 2). Farther downdip these sandstone members ultimately grade into the distal basin mudstones of the Mancos Shale (Fouch et al. 1983).

The Castlegate Formation is a dominant cliff-forming sandstone unit throughout the Wasatch Plateau and the Book Cliffs (Fig. 3). It has been the subject of numerous studies (e.g., Young 1955; Van de Graaff 1972; Fouch et al. 1983; Van Wagoner et al. 1990; Van Wagoner 1995; Miall 1993; Yoshida et al. 1996; Black 2000; McLaurin and Steel 2000; Miall and Arush 2001). Most previous studies have focused on the eastern outcrop belt along the Book Cliffs. In contrast, there have been virtually no detailed studies of the superb outcrops along Salina Canyon and the Wasatch Plateau.

At its type locality in Price Canyon, the Castlegate is 190 m thick and is composed of a lower sandy fluvial facies member, a middle fluvial member, which has an increased preservation of fines and grades downdip into marine facies, and the upper Bluecastle tongue, which is similar to the lower member (Fouch et al. 1983; Chan and Pfaff 1991; Olsen et al. 1995; McLaurin and Steel 2000). These divisions are generally not traceable to the study area along Salina Canyon in the southern Wasatch Plateau (Franczyk and Pitman 1991). In Salina Canyon, the

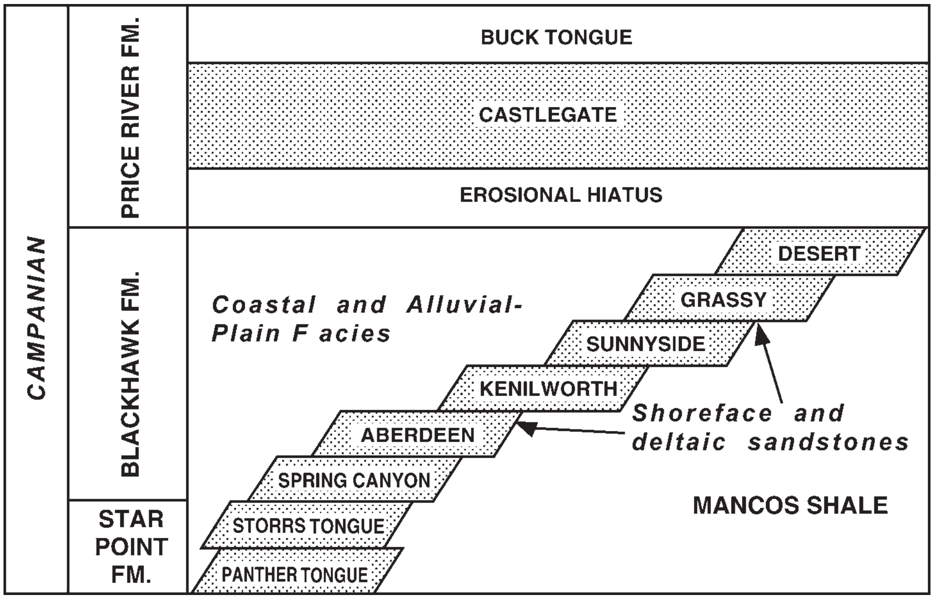

FIG. 2.—Schematic west-to-east Blackhawk–Castlegate stratigraphy (Taylor and Lovell 1995, modified from Young 1955).

Castlegate thins dramatically to 70–80 m thick, reflecting lower accommodation and/or postdepositional erosion (Franczyk and Pitman 1991).

The Castlegate Formation overlies the Blackhawk across an easily recognized and regionally traceable contact (Fig. 3). Erosion at the base of the Castlegate does not exceed more than one channel story in any single outcrop location, although more extensive regional erosion has been proposed farther east (e.g., Van Wagoner et al. 1990; Van Wagoner 1995; Yoshida et al. 1996). Van Wagoner et al. (1990) and Van Wagoner (1995) interpreted this erosion surface as a sequence boundary on the basis of a basinward shift in facies in the downdip areas, regional valley-scale truncation of underlying Blackhawk strata, and evidence of onlap. Although this surface shows different facies relationships at different points in the basin, in the nonmarine section the contact has been interpreted to represent a transition from a meander-belt deposit of the Blackhawk into a braided-stream terminal fan of the Castlegate (Van Wagoner 1995). This work is largely based on the correlation of down-dip marine facies into the up-dip nonmarine section. Correlations of Van Wagoner (1995) show the marine-to-nonmarine transition as a single throughgoing erosion surface, although this interpretation has been criticized (Yoshida et al. 1998; Van Wagoner 1998; McLaurin and Steel 2000; Miall and Arush 2001). Recent work relates a major petrographic change from lithic arenites in the Blackhawk to quartz arenites in the Castlegate to rejuvenated tectonic uplift in the Wasatch thrust belt (Horton et al. 2004).

The updip equivalent of both the Blackhawk and Castlegate formations, exposed 60 km to the north, is the conglomeratic Sixmile Canyon Formation of the Indianola Group (Lawton 1986a, 1986b). These conglomeratic facies are interpreted to represent the proximal deposits of sheetflood-dominated alluvial fan facies shed from the advancing Sevier thrust front.

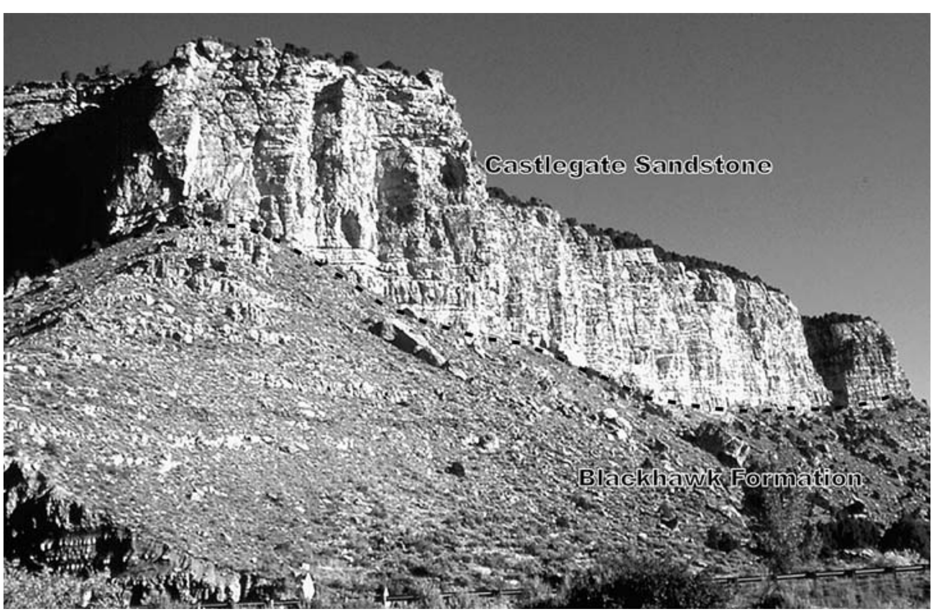

FIG. 3.—Oblique photograph of the Blackhawk and Castlegate on the north side of I-70, near Salina Canyon. The Castlegate forms the prominent 80-meter cliff comprising amalgamated channels. The slope-forming Blackhawk Formation comprises a muddy fluvial succession containing weathered sandstone pods, interpreted as channels. As seen in the photograph, the contact between the Blackhawk and the Castlegate appears to be sharp. The apparent undulations in the contact are due to parallax.

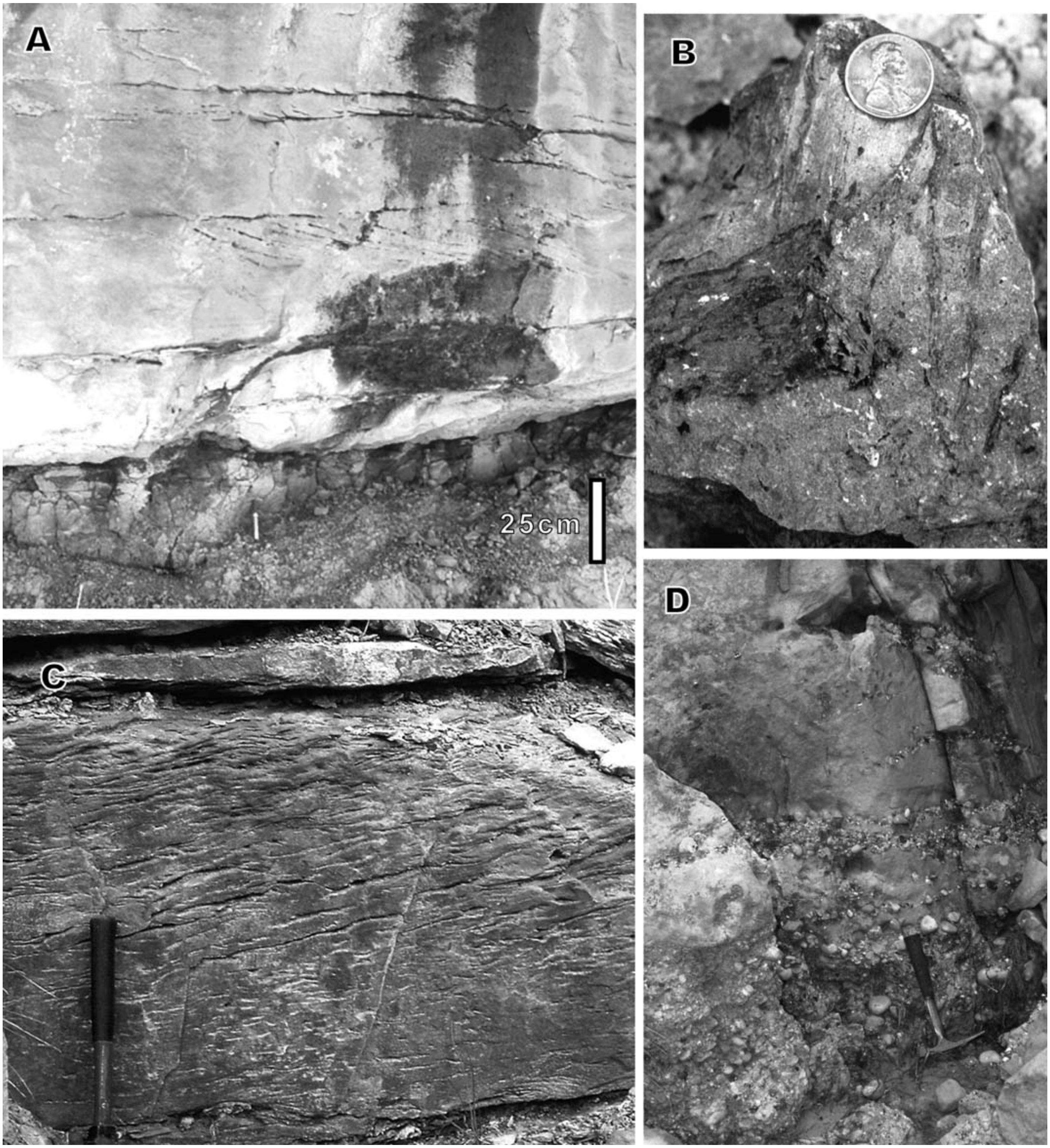

FIG. 4.—Photographs of facies, **A)** base of a Blackhawk channel showing dune-scale cross-bedded sandstones eroding into underlying gray floodplain mudstones. **B)** Close-up of mudstones showing root traces and preserved organic plant material. Penny for scale. **C)** Climbing-ripple sandstones within Blackhawk floodplain, interpreted as crevasse-splay deposits. Note hammer for scale. **D)** Pebble conglomerate grading into dune-scale cross-bedded sandstones within the Castlegate. Note hammer for scale.

Did the Castlegate Rivers Dry Out?

The regional correlations and paleogeographic maps of Van Wagoner (1995) show that Castlegate lowstand river deposits ended landward of underlying highstand shorefaces of the Blackhawk. Consequently, the Castlegate sandstone has been interpreted as a terminal alluvial megafan consisting of braided ephemeral streams in a semihumid to arid climate (Van Wagoner 1995). To justify the idea that Castlegate rivers dried out before they reached the sea, Van Wagoner suggested that water was both absorbed into underlying older marine sands and evaporated as a consequence of the hypothesized overall increase in aridity. Hematite-coated iron oolites, in a more distal position within the Mancos Shale but directly above the Castlegate sequence boundary, and the presence of a transgressively reworked thin red sandstone at the top of the Castlegate, were also cited as reflecting arid eolian conditions (Van Wagoner 1995). Van Wagoner recognized that lacustrine and coally marsh facies within the Caslegate suggest that the climate could not have been arid all the time and postulated climate cycles with cyclicity of thousands to hundreds of thousand of years.

On the basis of an arid-model hypothesis we predict that individual Castlegate channels should show evidence of shallower flow depths and higher width-to-depth ratios than the more humid, widely spaced single-thread "meandering" rivers assumed to form the Blackhawk channel belts. The aridity hypothesis would also require thicker channel stories, thicker dune-scale cross stratification, and thicker bars, associated with the fewer but larger, and thus deeper, Blackhawk rivers. Because aridity decreases the chemical weathering of labile grains (e.g., carbonates), the aridity-hypothesis would also predict that Castlegate sandstones should have a higher percentage of labile rock fragments than Blackhawk sandstones, given the similar west-derived source terrain. There is also a problem with sediment budget, and particularly the fate of mud that the Castlegate rivers probably carried, especially if the rivers died out on the floodplain. The low proportion of muddy facies in the Castlegate needs some explanation. There is clearly some controversy as to whether there was a major climate change between the Blackhawk and Castlegate, and, if so, what the magnitude of the change was.

This paper thus evaluates two aspects of the Blackhawk–Castlegate transition. First we evaluate the validity of the idea that the Blackhawk is a meandering-stream deposit, with the consequent implications for assumptions about mud-prone fluvial systems and the implications for sequence stratigraphic models. Second, we evaluate the paleohydraulics of the Castlegate and Blackhawk to determine whether there is evidence for a significant lowering of discharge that might be expected as a consequence of the hypothesized change to a more arid climate. Our approach focuses on documenting the fluvial style by detailed analysis of the bar and channel geometry, cross-stratal thickness, facies analysis, and petrography of the Blackhawk and Castlegate formations in a more proximal location than most previous studies.

STUDY AREA AND METHODS

The outcrops chosen for our detailed study are located in Rock Canyon, immediately west of the San Rafael Swell on I-70 along Salina Canyon (Figs. 1, 5). Here post-Cretaceous normal faults have brought the Mesaverde stratigraphy, typically exposed high in the Book Cliffs, down to road level, allowing easy access for detailed study. These outcrops present exposures of the upper Blackhawk and lower Castlegate formations at angles approximating depositional strike and dip (Figs. 1, 5), which allow us to constrain the 3-D geometry of these deposits with a focus on the channel and bar types. The view perpendicular to flow is critical in determining bar types and thus fluvial style (Bridge 1993; Bristow 1993b). Our data include 24 measured sections of Blackhawk and Castlegate channel-belt sandstones and floodplain facies, regional and detailed photomosaics, and hand samples collected for petrographic analysis.

We constructed photomosaics at two scales to analyze both overall channel-belt architecture and detailed internal bedding. The photomosaics of the entire cliff face (Fig. 5) were used to map the channel belts and floodplain mudstones and show the boundary between the Blackhawk and the Castlegate. More detailed photomosaics of individual channel belts in the Blackhawk (Figs. 6, 7) were used to analyze the internal facies architecture of stacked bar and channel deposits using techniques outlined by Miall (1985), Bridge (1985), Bridge (1993b), Bristow (1993b), and Holbrook (2001).

We used a hierarchical approach to determine the scale of the architectural elements. The smallest scale of surface mapped are the cross-set boundaries (master surfaces), which are interpreted to represent bar accretion surfaces (i.e., macroforms of Miall 1985). The termination of these bar accretion surfaces outline the higher-order bar deposits. Bar accretion surfaces either downlap onto channel floors or are truncated at the tops of preexisting bars (Fig. 6). Bedset boundaries typically correlate with major bar forms. Truncation surfaces define the bases of major channels, and the contact between rippled sandstones and silts and thick mudstones at the top of the sand body and is taken to be the top of the channel belt (Figs. 6, 7). Lower order scours may represent confluence zones associated with braid bars or chute channels.

By integrating the geometry of bar forms, mapped on the photomosaics, with paleocurrent data (collected primarily from dune-scale cross strata), it was possible to interpret bar types. In particular, strike-oriented exposures allow the distinction of bank-attached, laterally migrating point bars, commonly associated with single-thread meandering rivers, from braid bars, which typically show bidirectional downlap. The strike-oriented data allow us to reconstruct the original river plan form and to determine whether the fluvial systems were deposited by braided or single-thread meandering streams. Our analysis allowed accurate mapping of barforms and channels using a hierarchical scheme (Figs. 5, 6, 7).

Bar-top drapes are the best features to identify and map bars. Bar drapes were identified in measured sections as rippled sandstone and siltstone beds capping fining-upward bedsets within the channel belts. The fine-grained bar drapes preferentially weather out in outcrop, allowing us to map bar forms onto the photomosaics (Figs. 6, 7). In areas where the fines have been eroded by later deposition, the erosion surface between successive bar deposits may be indicated by a change in grain size or cross-set thickness. Within the bars, cross-set boundaries are used as the basis for mapping inter-bar accretion surfaces.

To further evaluate estimated water depths, we compared our data to various empirically derived formulas based on modern and ancient data (Bridge 1993b; Leclair and Bridge 2001; Bridge 2003). Cross-set thickness in fluvial deposits has been shown to be controlled primarily by formative dune height, with changes in aggradation rate having a negligible influence on cross-set thickness (Leclair et al. 1997; Leclair and Bridge 2001). Average dune heights, in turn, typically scale to 6–10 times flow depth (Allen 1984; Bridge and Tye 2000).

Analysis of data on cross-set thickness collected in our measured sections allows us to estimate flow depths (Fig. 8, Table 1). This requires using as many cross-set thickness (s) measurements as possible to calculate the mean, s_m, and standard deviation, s_{sd}. s_{sd}/s_m should be approximately equal to 0.88 ($\pm$ 0.3). If this holds true, then the mean dune height, h_m, can be calculated by the following equation (methodology from Bridge and Tye 2000):

$$h_m = 5.3\beta + 0.001\beta^2 \quad \text{where } \beta \approx s_m/1.8 \tag{1}$$

The thickness of completely preserved channel stories, as seen in the measured sections and photomosaics, can also be used to estimate channel flow depth (Bridge 2003). Lastly, bar height is typically about 80–90% of flow depth (Bridge 2003), and thickness of bar accretionary units can thus also be used to estimate water depth. These multiple techniques allow us to compare the flow depths of Blackhawk and Castlegate channels to evaluate whether a significant decrease in discharge occurred.

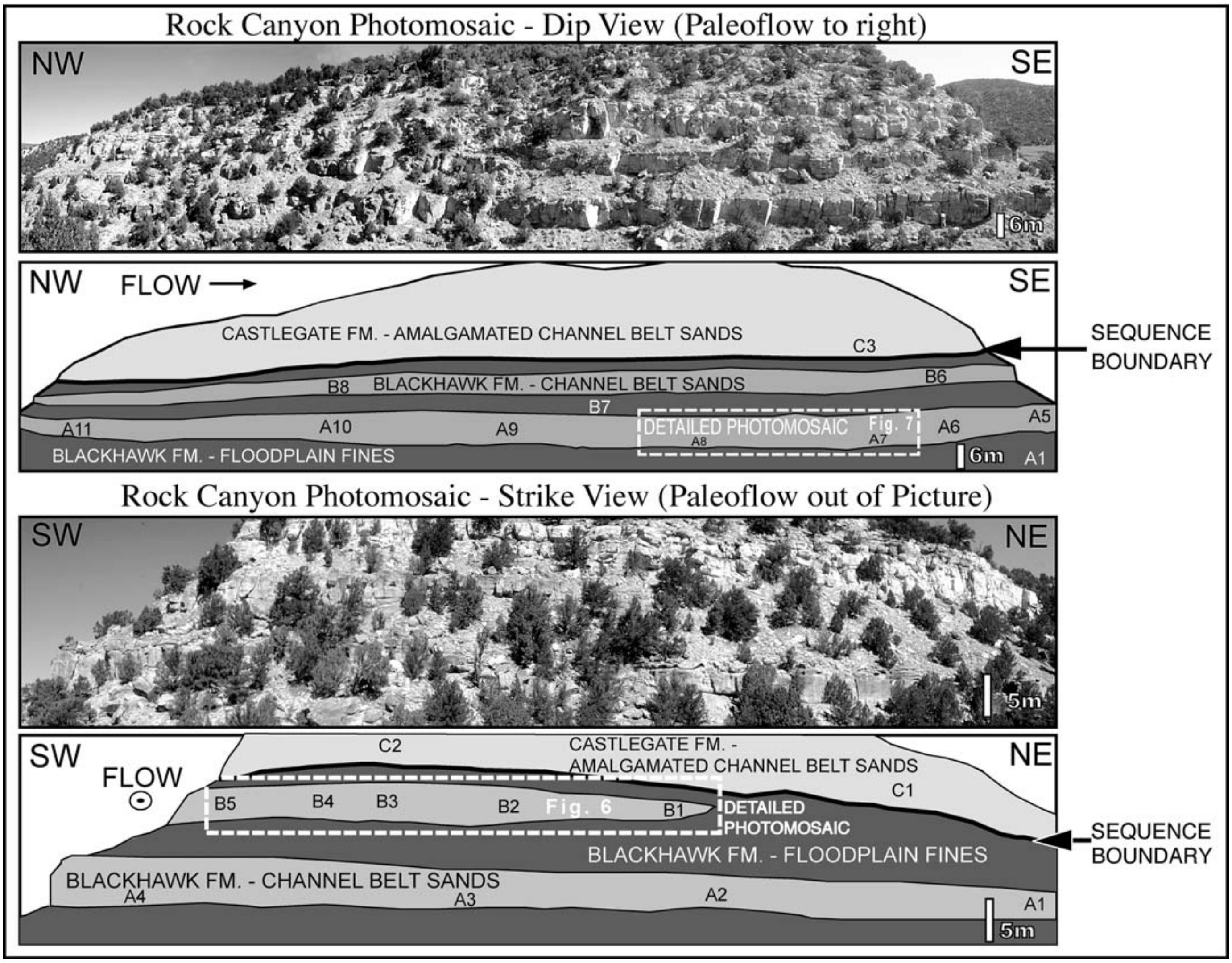

FIG. 5.— Regional depositional dip- and strike-oriented photomosaics with interpretations of channel-belt sandstones and floodplain facies. Amalgamated channel belts at the top of the outcrop represent the Castlegate sandstone. Channel belts in the Blackhawk are single story and average about 5 m thick. Individual segments of the channel belts were selected for detailed analysis of bar and bedding geometry (see Figs. 6, 7). A1, B1 etc. represent locations of measured sections. Locations of photomosaics are shown in Figure 1.

RESULTS: STRATIGRAPHIC RELATIONSHIPS, FACIES, BEDDING ARCHTIECTURE, AND PETROGRAPHY

Blackhawk Facies

The regional photomosaic (Fig. 5) and measured sections (Fig. 9) show that the Blackhawk indeed consists of isolated channel-belt sandbodies encased in fine-grained floodplain mudstones and thin sandstones. The Blackhawk channel belts are unconnected vertically, and the sand/shale ratio is approximately 50%. The Blackhawk channel-belt sandbodies are 5–8 m thick. Perpendicular to flow, the channel belts appear to be on the order of hundreds of meters, although only the uppermost Blackhawk sandbody shows a pinchout on the strike-oriented photomosaic (Fig. 5). The width-to-depth ratio of the Blackhawk channel belt is estimated to be over 15:1, and these sand bodies are thus classified as sheet sandstones rather than shoestring sandstones (Friend 1983).

Internally, the Blackhawk sand bodies show sharp to erosional bases and comprise mostly fine-grained, trough cross-bedded and fine- to very fine-grained cross-laminated sandstones, with common discontinuous mud drapes (Figs. 4A, 6, 7, 9). Trough cross sets range from 5 to 45 cm with an average thickness of about 14 cm (Fig. 8). Paleocurrent data from 29 cross beds in the Blackhawk show a dominant southeast trend (Fig. 1). Mud-chip rip-up clasts and fluid-escape features also occur throughout the sand bodies. Sandbodies are usually capped by a fining-upward succession of thinly interbedded, very fine-grained cross-laminated sands, silts, and mud (Fig. 8). Fining-upward bedsets (bar deposits in Fig. 9) range from 50 cm up to about 2 m in thickness.

The Blackhawk sand bodies are separated by a thick, fine-grained facies comprising interbedded, very fine-grained, climbing-ripple cross-laminated sandstones and silty mudstones (Figs. 4C, 5, 9). In places, sandstones fill elongate, wedge-shaped depressions, thought to be casts of dinosaur footprints. The silty mudstones are predominantly gray, green, brown, black, or mottled in color, contain root traces (Figs. 4A, B), abundant carbonaceous material and variably oriented slickensides. They also contain variable amounts of quartz and detrital silts, along with brown clays and organic material (Fig. 10E). Thin coal zones are also present. The rare soil horizons are classified as immature histosols and gleysols (Mack et al. 1993).

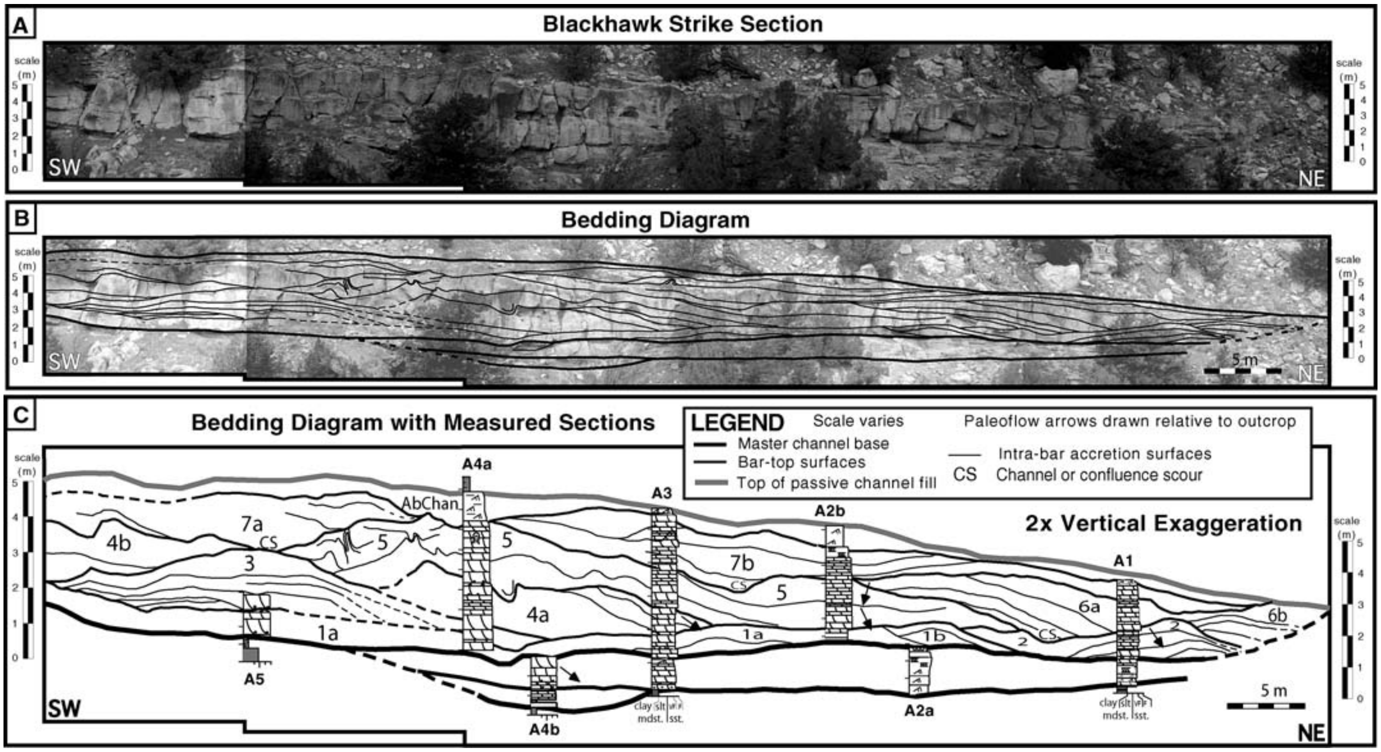

FIG. 6.—Strike-oriented bedding diagram showing interpretation of bars and channels. Mounded geometries clearly indicate braid bars. Bars are numbered 1 to 7. Measured sections in the lowest panel show vertical facies successions. Measured sections are in meters. Arrows represent paleocurrents. Down is towards viewer, up is away from viewer, and left and right represent flow to the left or right, respectively. Legend for measured sections is provided in Figure 9. Location of photomosaic is shown in Figure 5. See text for further explanation.

Blackhawk Facies Interpretation

The major sandstone bodies in the upper Blackhawk are interpreted as single-story fluvial channel belts separated by floodplain fines (Fig. 9). The abundance of trough cross strata and southeast paleocurrents confirm unidirectional flow in a fluvial channel. Fining-upward bedsets are interpreted as stacked bar deposits (following technique of Bridge and Tye 2000; Bridge 2003). Finer-grained rippled sandstone caps are interpreted as abandoned channel fills (Fig. 9). Thinner intra-belt mudstones and rippled sandstones are interpreted as bar drapes. When exposed during low river stage, these mud drapes may become desiccated, compacted, and resistant to erosion, increasing the likelihood of preservation. Through cracking they may be incorporated into subsequent flows as mud-chip horizons.

The climbing-current-rippled sandstone beds within the mudstones (Fig. 4C and at 4 m, 5 m, and 26 m in Fig. 9) are interpreted as overbank splay deposits. Sandstone-filled depressions at the bases of some of these rippled beds are interpreted to be molds of vertebrate (dinosaur) footprints. Dinosaur footprints have been extensively documented within downdip Blackhawk coal beds near Price, and have been interpreted to be associated with a swamp environment (Balsley 1980). The presence of immature saturated paleosols with histic subhorizons and a lack of evidence of caliche beds or significant oxidation suggest that the Blackhawk rivers flowed across a well vegetated, rapidly accreting wet floodplain with poorly developed soil horizons.

Bedding Architecture within Blackhawk Channel Belts

Figure 6 is a detailed view of the uppermost Blackhawk sand body that includes the channel-belt pinch-out margin (located in Fig. 5B). The outcrop in this view is oriented perpendicular to paleocurrent direction. The thick black lines delineate the extent of the erosional channel floors. Three stacked sandstone bodies are shown, interpreted as channel bodies within the channel belt. The lower two channel deposits are less than about 1 m thick, suggesting poor preservation and erosion by the overlying channels.

The upper channel body is the thickest and contains seven major bar deposits (1 to 7). In several cases, bars at the same stratigraphic level could be distinguished, and these are designated with an a or b (e.g., Bars 1a–1b, 4a–4b, 6a–6b, and 7a–7b, in Fig. 6). Bar deposits are remarkably uniform in their maximum thickness, which is about 1–2 meters, although the bars lower in the section average about 1 m thick (e.g., bars 1a, 1b). Bar widths are far more variable, but range from as little as 8 m (Bar 1b) up to about 50 m (e.g., bars 5 and 7b). Bar-top drapes are identified and mapped, as at the top of bar 6a in Section 1 (A1) or the top of bar 4b in Section 4a (3 m level in A4a, Fig. 6). Locally, mud drapes are partially eroded by the base of younger overlapping or overriding sandstones, resulting in a sand-on-sand contact commonly floored by mud chips. Cross-set boundaries are interpreted as intra-bar-accretion surfaces.

Several bars show a very distinctive lens-shaped geometry with internal bar accretion surfaces that dip in two directions. This is best observed in bars 2, 3, and 6b. Bar 6a shows preferred lateral accretion, with beds dipping toward the cutbank, although bar 6b shows vertical accretion and bidirectional downlap. Several bars show both bidirectional downlap of beds and a preferred migration, such as bar 5. It is less clear in what direction the youngest bars, 7a and 7b, are accreting.

A total of about 32 intra-bar accretion surfaces can be identified. Of these, about 17 show bidirectional dip, 9 dip toward the cutbank, and the rest are indeterminate. Several of the bars (e.g., 6a, 7a, and 7b, in Fig. 6) show scours at the base. The top of the unit is capped by a finer-

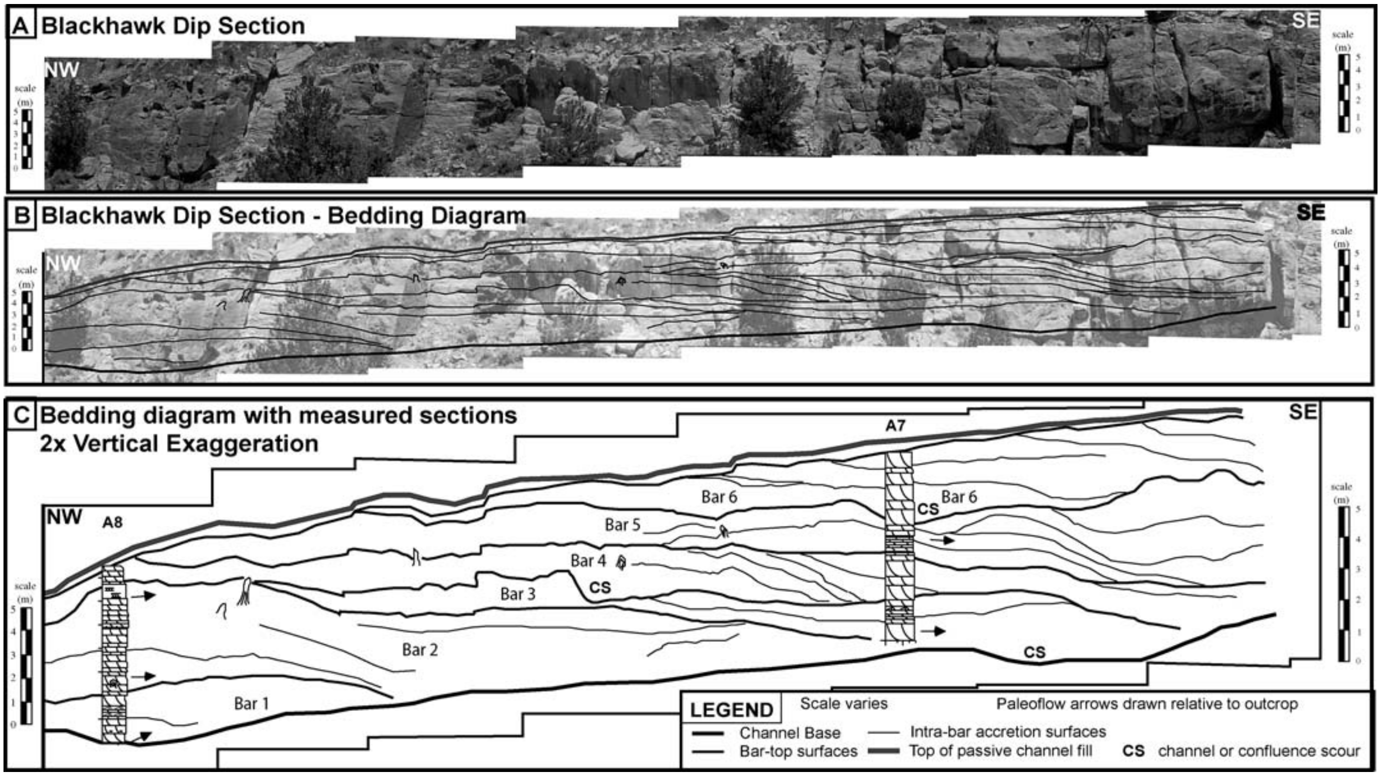

FIG. 7.—Dip-oriented bedding diagram showing interpretation of bars and channels. Downstream dipping surfaces indicate downstream accreting bars. CS refers to interpreted channel or confluence scours. Measured sections in lowest panel show vertical facies successions. Measured sections are in meters. Arrows represent paleocurrents. Down is towards viewer, up is away from viewer, and left and right represent flow to the left or right, respectively. Legend for measured sections is provided in Figure 9. Location of photomosaic is shown in Figure 5. See text for further explanation.

grained rippled sandstone and siltstone up to 1 m thick. Comparing sections A2b, A3, and A4a this facies is distinctly thicker on alternate sides of bar 7b.

An expanded view of the lower Blackhawk channel-belt sand body in the dip view, approximately parallel to paleoflow, is shown in Figure 7. Correlation of master bedding planes show six offlapping bar deposits (Bar 1–Bar 6, Fig. 7C). For the most part, bar surfaces and inter-bar accretion surfaces dip downstream, although dip magnitudes are variable. Cross-stratal set boundaries in younger bars downlap onto the tops of older bars. There are several bars that show local scours with up to 1

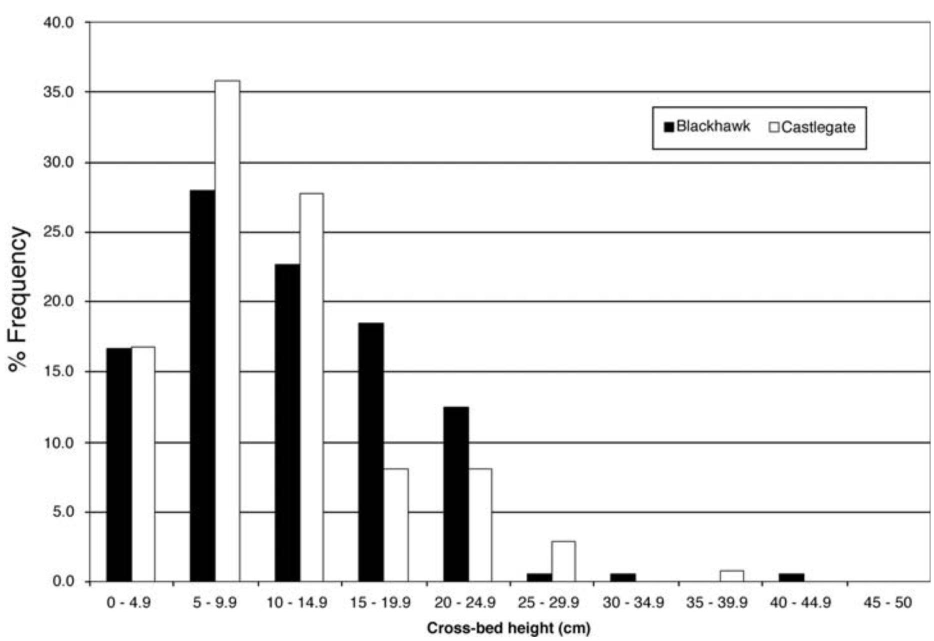

FIG. 8.—Histograms of cross-stratal thicknesses between Blackhawk and Castlegate channels.

TABLE 1.—*Analysis of formative dune heights and flow depths for the Castlegate versus the Blackhawk rivers based on measured cross-set thicknesses.*

	Average Cross-set Thickness	Average Dune Height	Estimated Water Depth	Maximum Channel Deposit Thickness
Blackhawk	16 cm	48 cm	2.9–4.8 m	5 m
Castlegate	12 cm	36 cm	2.2–3.6 m	5.5 m

Average formative dune height is calculated to be about 3 times average cross-set thickness. Water depth is estimated to be 6 to 10 times formative dune height (Leclair and Bridge 2001). Maximum channel thickness is taken from measured sections.

meter of relief (CS in Fig. 7), such as associated with bars 4 and 6. Measured section 7 (A7, Fig. 7) shows a thicker than usual cross-bed set at 4 m associated with the scour in bar 6.

Facies and Bedding Architecture within the Castlegate

The Castlegate forms a sandstone to conglomeratic unit that is variably exposed across the upper portion of the outcrops (Fig. 5). There is less than 5% mudstone within the Castlegate. The lowermost Castlegate channels lie on an erosional surface and internally comprise fining-upward channel stories consisting of trough cross-bedded fine-grained sand, very fine-grained cross lamination, common discontinuous mud drapes, mud-chip rip-up clasts, and features diagnostic of soft-sediment deformation, such as fluid-escape features and overturned cross-bedding (Fig. 9). Dune-scale cross strata average 13 cm in thickness (Fig. 8) and paleocurrents from 23 cross beds show a dramatic paleoflow reorientation to the southwest (Fig. 1).

Approximately 22 meters above the base of the Castlegate, there is a sudden grain-size increase from fine-grained sandstones to a matrix-supported pebble and cobble conglomeratic facies (Fig. 4D). The pebbles and cobbles occur along bedding planes and trough cross-beds. The matrix consists of fine-grained through very coarse-grained sand. Very fine-grained, cross-laminated sand also occurs in the conglomeratic facies.

Unfortunately, the exposure of the Castlegate at Rock Canyon precluded a detailed analysis of the bedding and bar geometry, although the outcrop quality improves dramatically a few miles north of our study area (Fig. 3). A detailed study of Castlegate bedding geometry, conducted by Black (2000) in these better exposed outcrops, show tabular channel-belt sand bodies with stories that vary in average thickness from 4 to 6 m. Black (2000) found downstream-accreting bar forms and channel-fill deposits ranging from less then 1 m to a maximum of 3 m in height, with an average of 1 m.

Blackhawk and Castlegate Petrography

Examination of Blackhawk sandstones in thin section reveals a composition dominated by monocrystalline quartz (approximately 60% bulk volume) and detrital carbonate (approximately 26% bulk

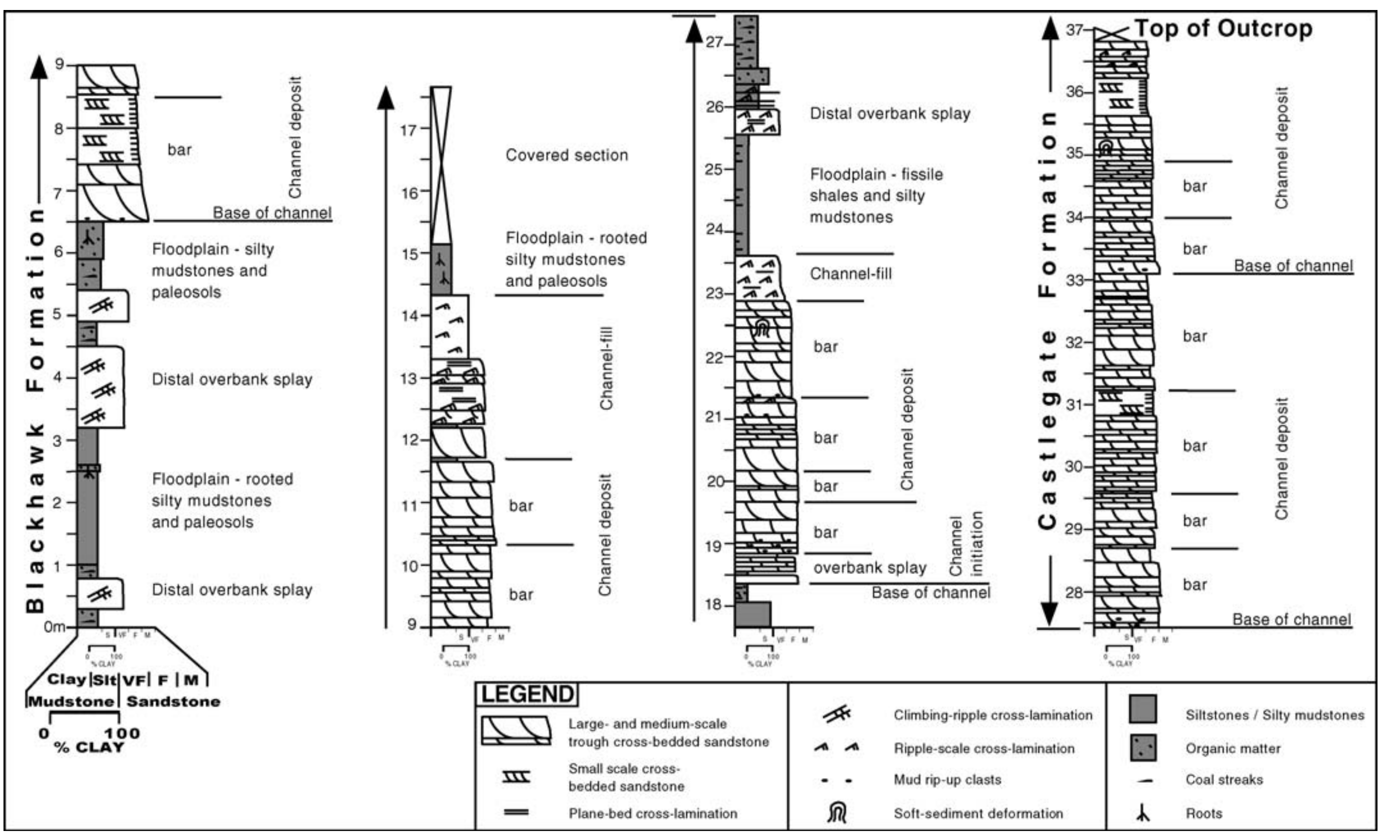

FIG. 9.—Measured section of entire outcrop, showing alternation of channel and floodplain facies. Upper 9 meters represents lower Castlegate Formation.

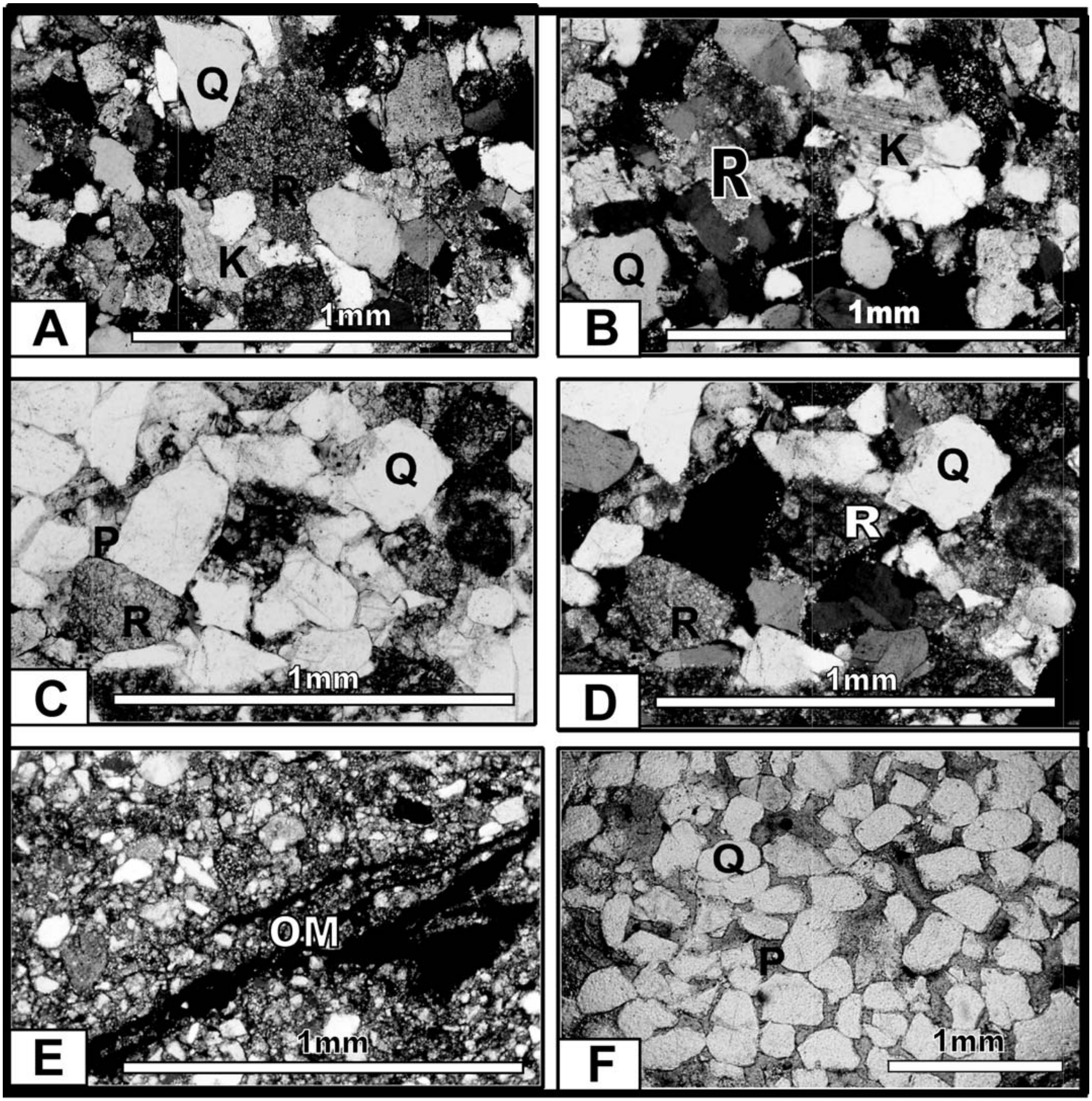

FIG. 10.—Photomicrographs of Blackhawk and Castlegate. Q = Quartz; K = Potassium Feldspar; R = Rock fragment; P = Pore space; OM = Organic matter. Scale bar is 1 mm. **A)** Blackhawk lith-arenite, showing moderate sorting and abundance of labile grains. Cross-polarized light. **B)** Blackhawk lithic felds-arenite, showing rock fragments and feldspars in cross-polarized light. **C)** Blackhawk lithic felds-arenite with carbonate and other sedimentary rock fragments in plane-polarized light. Note carbonate rhomb in the right rock fragments. Same slide as Part D. **D)** Blackhawk lithic felds-arenite in cross-polarized light. Same slide as in Part C. **E)** Blackhawk siltstone in crossed polarized light. Note large elongate fragment of dispersed organic matter. **F)** Castlegate quartz-arenite is composed predominantly of well-rounded quartz grains (plane-polarized light). Note high porosity and lack of labile grains. Quartz is assumed to be derived from the uplifted Permian–Pennsylvanian Oquirrh eolianites (Horton et al. 2004).

volume) (Fig. 10). Quartz grains commonly exhibit undulose extinction. Trace amounts of feldspar (1%), other sedimentary lithics (2.5%), organic matter (< 1%), and clays (1%) were also observed. Total porosity was approximately 10%. Blackhawk sandstones are classified as lithic arenites (terminology of Dott 1964). The carbonate fragments impart a tan color to the Blackhawk sandstones. The Blackhawk is petrographically distinctive from the clean white quartz arenite sandstones of the lower Castlegate (Fig. 10F) (Lawton 1986b; Horton et al. 2004).

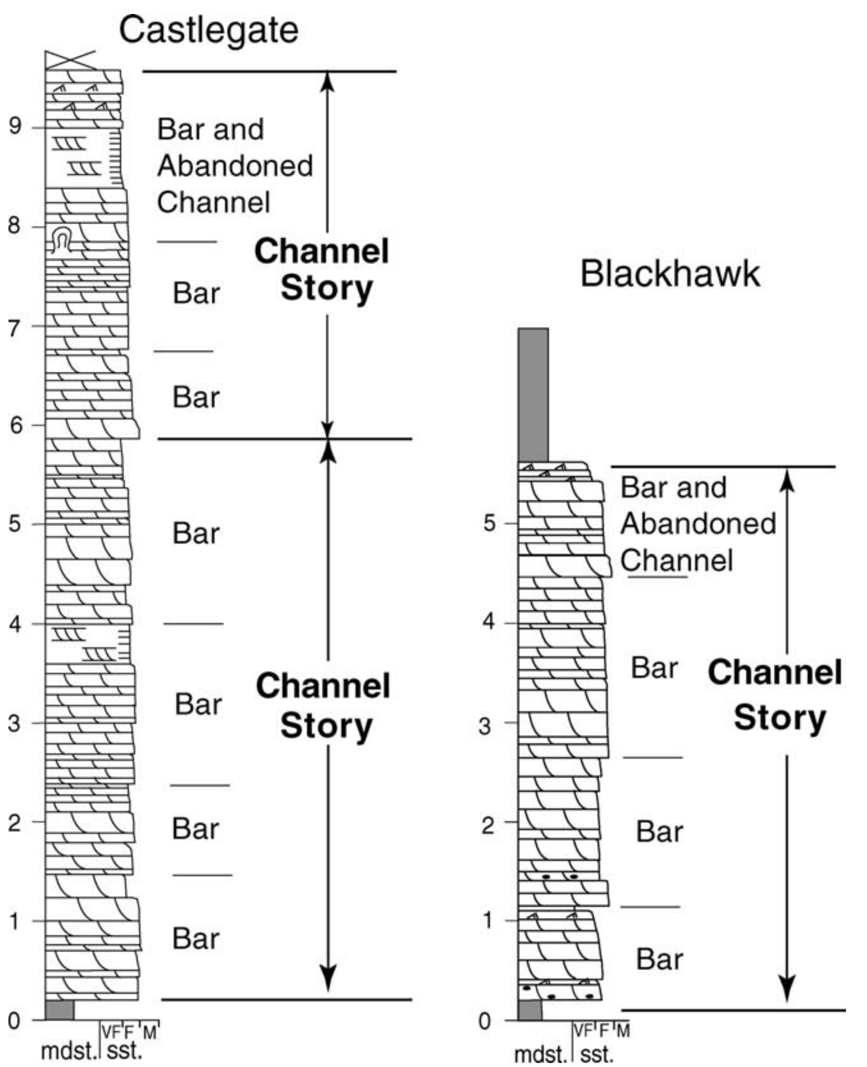

FIG. 11.—Side-by-side comparison of Blackhawk and Castlegate measured sections show extreme similarity in thicknesses of cross-sets, and bar and channel thicknesses. The Castlegate shows a greater degree of amalgamation of channels and channel belts.

Blackhawk and Castlegate Paleohydraulics

Visual comparison of Blackhawk and Castlegate measured sections illustrates the nearly identical scales of cross set, bar, and channel story elements (Fig. 11). In the Blackhawk Formation, bar accretionary units average 2 m in height, giving an estimated depth of Blackhawk rivers of approximately 2.5 m. Castlegate bar accretionary units in Rock Canyon also show values of about 1.5–2 m (Figs. 9, 11) and channel stories appear to be on the order of 3–5 m, similar to those mapped nearby by Black (2000). This supports the interpretation that Blackhawk and Castlegate rivers were not significantly different in depth.

A further demonstration of the similarity of fluvial style is illustrated by the use of techniques of quantitative analysis of Blackhawk and Castlegate cross-set thicknesses (Fig. 8, Table 1). Castlegate cross sets have a mean height of 13 cm versus a mean height of 14 cm for the Blackhawk (Fig. 8). Average formative dune heights are calculated to be 41 cm for the Blackhawk and 38 cm for the Castlegate (Table 1). This results in calculations for water depth of 2.49–4.15 m for Blackhawk rivers and 2.3–3.83 m for Castlegate rivers, which matches the measurements of story thickness and bar thickness (Figs. 9, 11). Calculations of channel width and channel-belt width are likewise similar for the two formations (Table 1). By these calculations, the Blackhawk and Castlegate rivers appear to be of the same scale. Although the Castlegate values are about 5% smaller, this difference is within the error of measurement and calculations and is not considered to be significant. In any case, the somewhat coarser nature of Castlegate rivers would also account for slightly smaller bars and bedforms given otherwise similar flow depths.

INTERPRETATIONS OF RESULTS

Interpretation of Blackhawk Channels as Braided

The strike oriented photomosaic (Fig. 6) shows three channel stories in the uppermost Blackhawk channel belt, although the lower two are very incompletely preserved. It was not possible to determine any details of the bedding geometry in these lower two stories.

Within the upper, thickest story, the Blackhawk bars show lens-shaped geometries that lack a preferred accretion direction, as opposed to uniformly dipping, laterally accreting bars that would define a point bar in a meandering stream. The strike view (Fig. 6) illustrates laterally amalgamated bars with tops dipping in multiple directions and a lack of clearly defined channel margins, indicating multiple active channels within the master channel. The silty rippled facies at the top of the channel belt is interpreted as an abandoned-channel fill. The fact that this fill is thicker on either side of bar 7b is evidence that bars were separated by multiple active channels. The mounded, lens-shaped forms with bidirectional downlap are diagnostic of braid bars (e.g., Bridge 1993a; Bristow 1993b). It seems clear that the Blackhawk rivers were dominated by numerous mid-channel bars

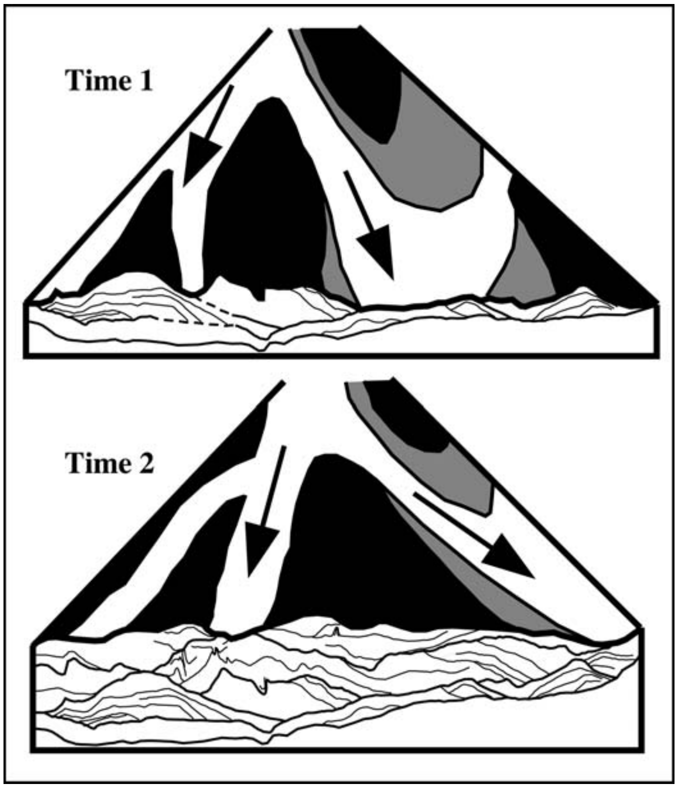

FIG. 12.— Reconstruction of Blackhawk braid bars based on strike bedding diagram (Fig. 6). Time 1 depicts deposition associated with bars 1–4a, and time 2 depicts deposition associated with bars 7a and 7b. Note overlapping and alternating bar stacking pattern. Black represents subaerial bar, light gray represents subaqueous bar.

indicative of more braided systems, as opposed to lateral bank-attached that would indicate a meandering system.

Thus, despite the mud-prone nature of the Blackhawk fluvial system, the photomosaic interpretations demonstrate bar geometries diagnostic of a braided river. The local scours, seen in both dip and strike orientations, may represent confluence zones where two channels meet at the downstream end of a braid bar. The general uniformity in the maximum thickness of bars and their overall appearance suggests that the Blackhawk rivers did not experience extreme variations in discharge.

The dip-oriented view (Fig. 7) illustrates downstream accretion of bars in an aggradational regime. Downstream accretion has been interpreted to be diagnostic of braid bars (Miall 1985) although point bars may also show downstream accretion (Willis 1993a). We emphasize that it is the strike geometry that is truly diagnostic. The dip-oriented section also does not show large ranges of scales of bars or channels, suggesting relatively uniform flow conditions.

A planform reconstruction of the Blackhawk channels, based on the strike-oriented bedding diagrams in Figure 6, is presented in Figure 12. Typically, mid-channel barforms migrate by lateral accretion along their flanks, gradationally changing to downstream accretion at the downstream end (Bristow 1987, 1993a). The resulting bar tops dip in different directions. The Blackhawk braided-river deposits show evidence of both types of accretion. Additionally, Blackhawk measured sections show trough cross-beds of relatively consistent thickness. This implies a fairly steady discharge typical of perennial rivers.

The paleocurrent spread in the Blackhawk is also quite tight, which is also suggestive of relatively straight flow paths. In meandering streams, paleocurrents typically show a much wider spread of data related to the extreme sinuosity of flow paths. The paleocurrents provide further evidence that the Blackhawk channels were not especially sinuous, which further supports a braided plan form.

DISCUSSION

Implications for Alluvial Facies Models

This study shows that the Blackhawk rivers at Rock Canyon have a braided character, despite high preservation of fine-grained, vertical-accretion floodplain facies. Similar braided-channel-belt sands within low net-to-gross fluvial systems have been described within extensional basins of the Rio Grande Rift in the U.S.A. (Mack and Seager 1990; Mack and James 1993), in the South Pyrenean foreland basin (Bentham et al. 1993), and in the Potwar Plateau of the Himalayan foreland in Pakistan (Willis 1993b). These studies challenge classic fluvial facies models that have used the lack of muddy vertical accretion deposits as a diagnostic criterion for the identification of ancient braided systems (Friend 1983; Walker and Cant 1984).

Recent work shows that the proportion of channel-belt sandstones versus floodplain fines is a function of the rate at which a river avulses, the rate at which channels migrate across and cannibalize a floodplain, and the overall subsidence rate of the basin, rather than the plan form of the river (Bristow and Best 1993). A single-thread meandering river may produce a sheet-like sandstone if subsidence is low and if avulsion frequency and rates of channel migration are high (e.g., Holbrook 1996). A braided river may show numerous active channels and bars within the river, but if the river does not migrate as a whole, then isolated channel-belt sandstones encased in floodplain fines may result (Bentham et al. 1993; Willis 1993b). This study confirms the idea that sandstone/mudstone proportions and sandstone body geometry are poor predictors of the plan-form geometry of the associated rivers.

Implication for Arid Terminal-Fan Model

In the Salina area, there is no indication of facies characteristic of an alluvial-fan environment, such as sheet-flood or debris-flow deposits (e.g., Blair and McPherson 1994), or of eolian sandstones that might indicate an arid-alluvial mega-fan. The fan deposits of the Indianola are generally interpreted as humid-sheetflood type deposits but also do not show evidence of arid conditions. The abundance of carbonate rock fragments in the Blackhawk versus the Castlegate is also the opposite of that predicted by the aridity hypothesis. However, the increase in quartz-rich lithologies in the Castlegate is interpreted by Horton et al. (2004) to reflect influx of newly uplifted quartz-arenite lithologies of the eolian Pennsylvanian–Permian Oquirrh Formation, to the northwest. There is thus no evidence in the more proximal part of the basin to support a significant climate change across the Blackhawk–Castlegate transition, as recorded by the rocks along Salina Canyon.

The aridity hypothesis was based largely on the sequence stratigraphic assumption that the base of the Castlegate sandstones are everywhere younger than the Blackhawk, which then requires the water in the Castlegate rivers to never have debouched into the Cretaceous Seaway. If the base of the Castlegate is not chronostratigraphically significant, and if the lower Castlegate fluvial facies are in fact the time equivalents of basin-distal Blackhawk shorefaces, then the paleogeographic reconstructions of Van Wagoner (1995) must be revised. Given the historical importance of these rocks in the development of nonmarine sequence stratigraphic models, it seems that a basin-scale reevaluation is clearly warranted.

Implication for Sequence Stratigraphy

In Rock Canyon, the Blackhawk–Castlegate contact is characterized by a dramatic change in the proportion of sand to mud, a change in sandstone petrology, and a change in paleocurrent direction (Figs. 1, 3, 5, 9). Despite this, neither the grain size nor the plan-form fluvial style can be shown to change appreciably across the contact (Figs. 9, 12). A grain-size increase does occur about 22 m above the base of the Castlegate (Fig. 4D), suggesting a basinward shift in facies within the Castlegate. This invites the question of where, exactly, the sequence boundary is located. Miall and Arush (2001) identified an increase in grain size and change in petrography within the Castlegate at the type section north of Price, Utah (Fig. 1) and postulated an intraformational sequence boundary. Van Wagoner (1995), also showed two internal sequence boundaries within the Castlegate, although he did not allow correlation of proximal Castlegate fluvial channels with distal Blackhawk shorefaces (his figure 54), which would place some of the distal Blackhawk shorefaces in the lowstand or falling-stage systems tract, as opposed to the highstand. Such a correlation would actually resolve the problem of having all of the lowstand sediments deposited landward of the highstand. This would also resolve the sediment-budget difficulty, because in the present correlation it is unclear where all of the mud that presumably would have been carried by the Castlegate rivers now resides. Van Wagoner (1995, his figure 54) specifically rejects this view as representing a lithostratigraphic approach, a notion with which we disagree. Unfortunately, resolving the dilemma of placing the sequence boundary requires either new regional correlations or better chronometric control, both of which are far beyond the scope of this paper.

The fact that the present study indicates a braided fluvial style for the highstand Blackhawk fluvial strata in a unit that has been key in developing nonmarine sequence stratigraphic models suggests that generalized classification of fluvial style within many nonmarine sequence stratigraphic models may need to be reevaluated. Our results indicate no change in plan-view fluvial geometry across the Blackhawk–Castlegate sequence boundary in this more proximal location. In exposures of the Blackhawk fluvial deposits at Price Canyon, which have not been correlated back to Salina Canyon, lateral accretion elements within single-story, lens-shaped channel fills have been documented (Olsen et al. 1995). However, these channels are considerably smaller than the Blackhawk channels exposed along Salina canyon, perhaps reflecting a transition to smaller distributary channels in more distal or lateral exposures. This could be a result of lower slopes and lower discharge that characterize distributive systems downdip, or it could result from being along strike and outside the fluvial axis of deposition.

Incorrect assumptions about the relationship between plan-view channel shapes and sandbody characteristics as a function of systems tracts can lead to substantial errors when working in the subsurface. Notably, single-channel meandering systems have different internal heterogeneities than braided systems (Bridge 1993a). Sequence identification should focus on channel belt stacking patterns caused by changes in the ratio of accommodation to sediment supply (A/S ratio) (Wright and Marriott 1993; Shanley and McCabe 1994; Olsen et al 1995). This concept predicts that amalgamated sheet sandstones characterize low ratios of accommodation to sediment supply, and that more isolated and unconnected channel belts characterize higher ratios, regardless of plan-view channel shape.

A question remains whether the change in stacking patterns and proportion of preserved mudstone observed between the Blackhawk and Castlegate is driven by eustatic, tectonic, or climate-driven change in discharge. Our results suggest that a major change in climate regime can be discounted. More recent work by Horton et al. (2004) shows that the appearance of quartz-dominated lithologies in the Castlegate reflects renewed uplift of the Santaquin Culmination, which exposed quartz-rich lithologies of the Paleozoic Oquirrh Formation, a few hundred kilometers to the northwest. They suggest that the Blackhawk–Castlegate transition correlates with a major tectonic uplift event in the foreland, versus representing a eustatic or climate-driven change. The paleocurrent data also show a significant change in paleoflow. The Blackhawk rivers flowed to the southeast, whereas the Castlegate rivers flowed southwest. This 90° change in the orientation of the basin slope requires tectonic uplift and corroborates a tectonic control on the Castlegate.

CONCLUSIONS

Facies analysis of channels, bars, and bedforms in the Blackhawk and Castlegate formations along Salina Canyon, Utah, show that the rivers were the same scale and type, indicating no major change in fluvial style across the contact, despite the dramatic change in the preservation of floodplain deposits. Both Blackhawk and Castlegate rivers were braided. The difference in fluvial architecture likely reflects changes in accommodation rather than changes in fluvial style. Preservation of thick successions of fine-grained overbank material is thus not a function of plan-view channel geometry.

There is no evidence for major climate change or increase in aridity across the Blackhawk–Castlegate contact along Salina Canyon. The change in Castlegate provenance and paleoflow direction is interpreted to reflect the rejuvenation of the Sevier thrust belt. The Blackhawk–Castlegate transition is thus likely related to tectonic changes in accommodation and is unrelated to a change in climate or eustatic sea level.

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