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# BASE-LEVEL BUFFERS AND BUTTRESSES: A MODEL FOR UPSTREAM VERSUS DOWNSTREAM CONTROL ON FLUVIAL GEOMETRY AND ARCHITECTURE WITHIN SEQUENCES

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ABSTRACT: **The effects of downstream base-level control on fluvial architecture and geometry are well explored in several broadly similar sequence-stratigraphic models. Cretaceous Dakota Group strata, U.S. Western Interior, have characteristics reflecting combined downstream and upstream base-level controls that these models cannot address. Particularly, three layers of amalgamated channel-belt sandstone within this group thicken and are continuous for distances ($\leq$ 300 km) along dip that stretch the reasonable lengths for which these models are intended to apply. As well, architecture in up-dip reaches records repeated valley-scale cut-and-fill cycles. This contrasts with equivalent strata down dip which record channel-scale lateral migration with no such valley-scale cycles apparent.**

**We here introduce the concept of "buffers and buttresses" to address these observations. We assume that river longitudinal profiles are each anchored down dip to some physical barrier (e.g., the sea strand, etc.) that we refer to as a "buttress." Buttress shift is considered the primary downstream control on base level. Profiles extrapolated up dip from the buttress over any modeled duration of buttress shift can range widely because of high-frequency variability in upstream base-level controls (e.g., discharge, etc.). All these potential profiles however are bounded above by the profile of highest possible aggradation, and below by the profile of maximum possible incision. These upper and lower profiles are "buffers," and they envelop the available fluvial preservation space. Thickness of the buffer zone is determined by variability in upstream controls and should increase up dip to the limit of downstream profile dominance. Dakota valley-scale surfaces record repeated cut-and-fill cycles driven by up-dip controls and are confined between thick stable buffers. Equivalent strata down dip record lateral reworking within a thinner channel-scale buffer zone that was positioned by downstream controls. Regression exposed slopes similar to the buffer zone, thus buffers were stable for long distances and durations. This prompted dip-extensive lateral reworking of strata into upstream valley-scale and downstream channel-scale sheets.**

**Buffers and buttresses provide a broadly applicable model for fluvial preservation that captures upstream vs. downstream base-level controls on geometry and architecture. The model lends general insights into dip-oriented variations in fluvial architecture, production of sheet vs. lens geometry, total preservation volumes for fluvial systems, and variations in these factors related to contrasting climatic conditions and basin physiography. The model can be amended to existing sequence stratigraphic approaches in order to capture dip-oriented variations in sequence architecture.**

## INTRODUCTION

The geomorphic concept of river base level (Powell 1875) and the outgrowth that rivers will aggrade or degrade as they strive for an equilibrium or "graded" longitudinal profile (Gilbert 1877; Bull 1991) have endured as pivotal concepts for elucidating fluvial response to external forcing factors like climate and sea level. Local shifts in base-level elevation may be caused by changes related to either downstream (e.g., sea-level drop, etc.) or upstream (e.g., increased rainfall, etc.) conditions. These changes will propagate in the drainage, usually with diminishing effect, because each river segment must adjust to changes in the adjacent segments (Mackin 1948). Regional impacts of local base-level shifts are thus captured by the resulting cumulative adjustments in the longitudinal profile (Mackin 1948).

Relative impact of downstream base-level controls, particularly sea level, on the longitudinal profile is well explored. Posamentier and Vail (1988) argued that because sea level is ultimate base level, the full longitudinal profile of a shore-reaching river should rise or fall proportionally with sea-level change. This should force a fluvial sea-level signature, through aggradation or degradation, well up valley from the strand. Closer scrutiny resulted in criticisms. Others soon noted that transgression and regression across a shelf does not always significantly change overall slope of coeval river profiles, and thus does not universally require an aggradational or degradational response (Schumm 1993; Wescott 1993). Furthermore, several authors showed that the downstream influence of sea level on river grade is indeed strong near the strand but decreases with distance up dip as more upstream controls like climate and tectonics gain the principal influence on river profile (Blum 1993; Shanley and McCabe 1994; Guccione 1994; Törnqvist 1998). Downstream base-level effects like sea-level change thus rarely propagate more than a few tens to a couple of hundreds of kilometers up dip (Blum and Törnqvist 2000).

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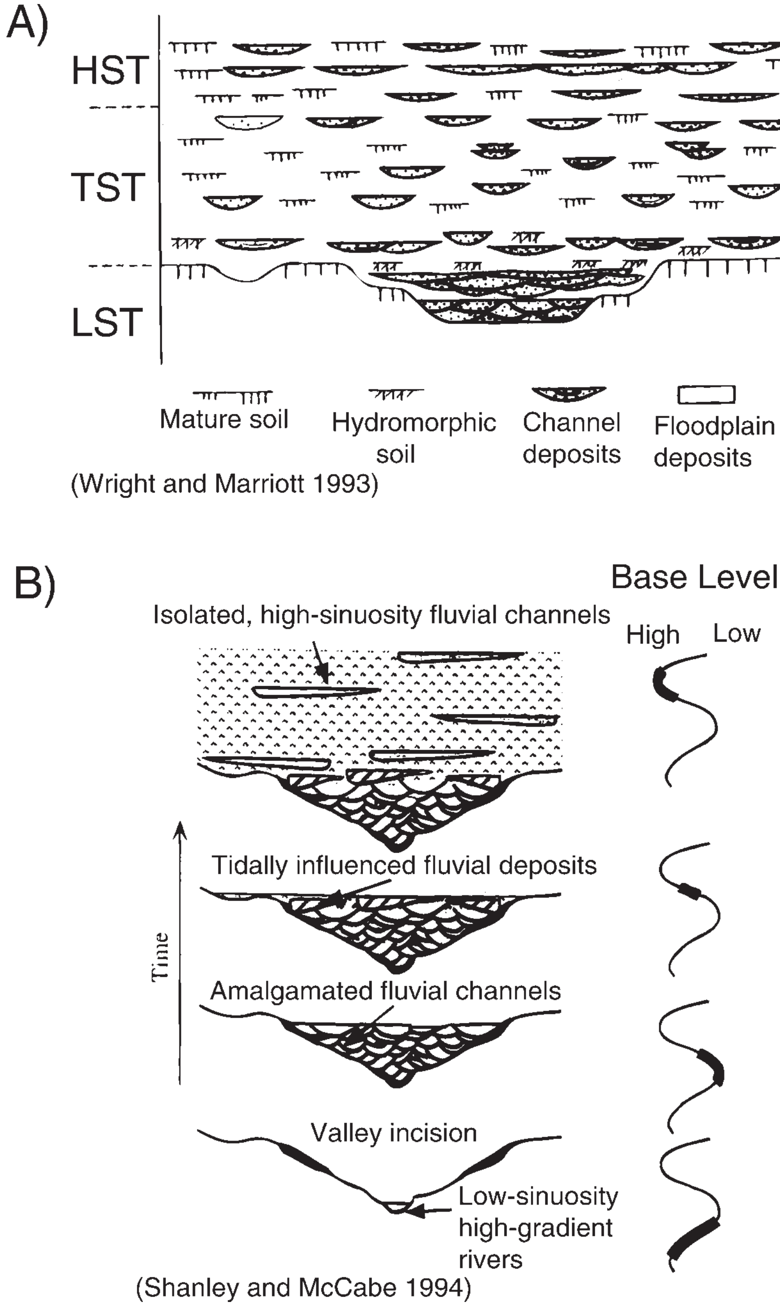


FIG. 1.—Two representative models (A, B) for fluvial aggradation and incision in response to downstream base-level shift, and associated systems tracts commonly applied when these models are used in a sequence stratigraphic context. Both models predict tight packing of sandy channel and channel-belt strata, relative to muddy floodplain strata during periods of slow aggradation compared to sediment supply (i.e. lowstand systems tract (LST)), and vice versa (i.e., transgressive systems tract (TST)). In both cases, slow aggradation rate is considered reflective of slow base-level rise, and vice versa.

These discussions evolved into a collection of broadly similar fluvial sequence-stratigraphic models that predict downstream base-level controls on fluvial architecture and geometry (Wright and Marriott 1993; Legarreta et al. 1993; Shanley and McCabe 1994; Currie 1997; Martinsen et al. 1999) (Fig. 1). In these models fluvial systems are still assumed to incise or aggrade with fall and rise, respectively, of sea level (or other downstream base-level controls) when and where a coeval adjustment in the longitudinal profile is triggered. Further, channel belts deposited by aggradation are generally predicted to develop high connectivity when the rate of accommodation caused by base-level rise is slow compared to sediment supply (e.g., sea-level lowstand conditions), and low connectivity if the ratio of accommodation to sediment supply is high (e.g., transgression) (Fig. 1). Recent works do argue, however, that these predictions may oversimplify the relationship between aggradational conditions and channel-belt architecture because they do not capture potential spatial variations in the aggradational response to downstream base-level rise (Mackey and Bridge 1995; Bridge 2003; Strong et al. 2005).

Sequences within the mid-Cretaceous Dakota Group of the southern U.S. High Plains contain fluvial architectural characteristics that are not accounted for by downstream-focused fluvial sequence-stratigraphic models. Numerous measured and photopanoramic sections (Fig. 2) reveal three contiguous Dakota fluvial sandstone layers that lie above respective sequence-bounding unconformities (lower and upper members of the Mesa Rica Sandstone and the Romeroville Sandstone; Fig. 3). Each of these layers records high amalgamation of fluvial channel-belt sandstone within continuous sheets and discrete valleys, and could be interpreted from Figure 1 to record deposition under conditions of slow sea-level rise. This characteristic of high amalgamation, however, can be

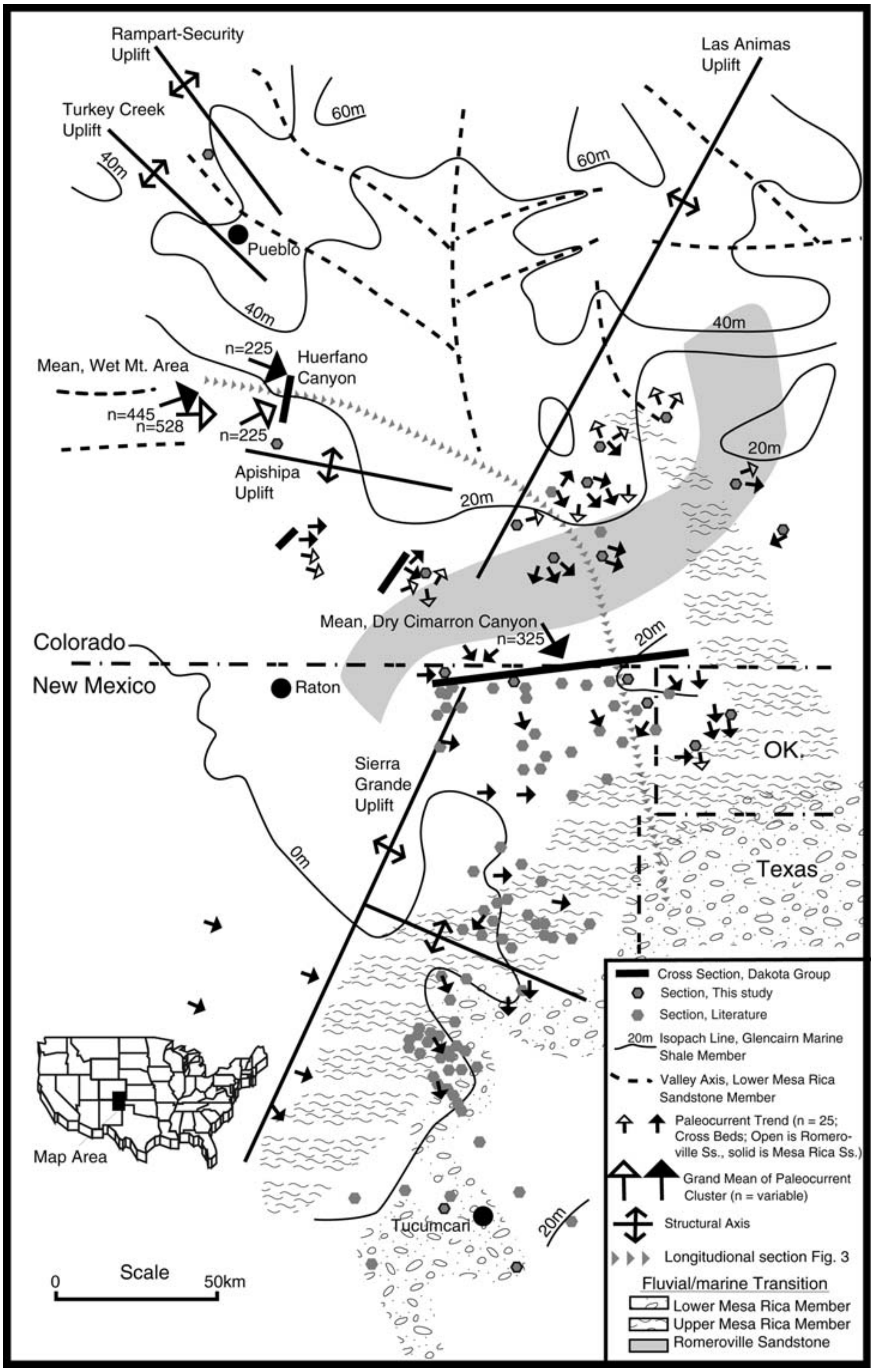


FIG. 2.—Locations of data used in this study, including: extended photopanoramic cross sections, measured sections with shorter accompanying photpans, and measured sections from the literature (Holbrook 1988; Holbrook and Wright Dunbar 1992; Holbrook 1992; Holbrook 1996). Also included are major drainages for lower Mesa Rica Sandstone, paleocurrent trends for Mesa Rica and Romeroville sandstone, major basement structures, and the zone of transition from fluvial to marine and deltaic strata for lower and upper Mesa Rica and Romeroville sandstone. The location of the longitudinal cross section in Figure 3 is indicated as well. Grand mean of paleocurrents from Wet Mountains is from Odien (1997), (after Holbrook 2001).

traced continuously from the contemporary marine strand to as far as 300 km up dip. These distances stretch the limits of up-dip effect from a downstream base-level change, and likely overextend the applicability of downstream-focused models. Furthermore, the more up-dip parts of each individual layer have a complex internal architecture that reflects deposition during repetitive valley-scale cycles of aggradation and incision. These incision–aggradation cycles are not expressed individually within the lower reaches, and thus appear to reflect base-level changes caused by upstream controls. Current sequence models cannot account for upstream-controlled incision–aggradation cycles that have no similar counterpart downstream.

The purpose of this paper is to offer a general model for fluvial sequence preservation that can account for both downstream and upstream base-level control on fluvial architecture and geometry. This model is referred to here as the concept of ''base-level buffers and buttresses,'' and will be defined and discussed in more detail later in this

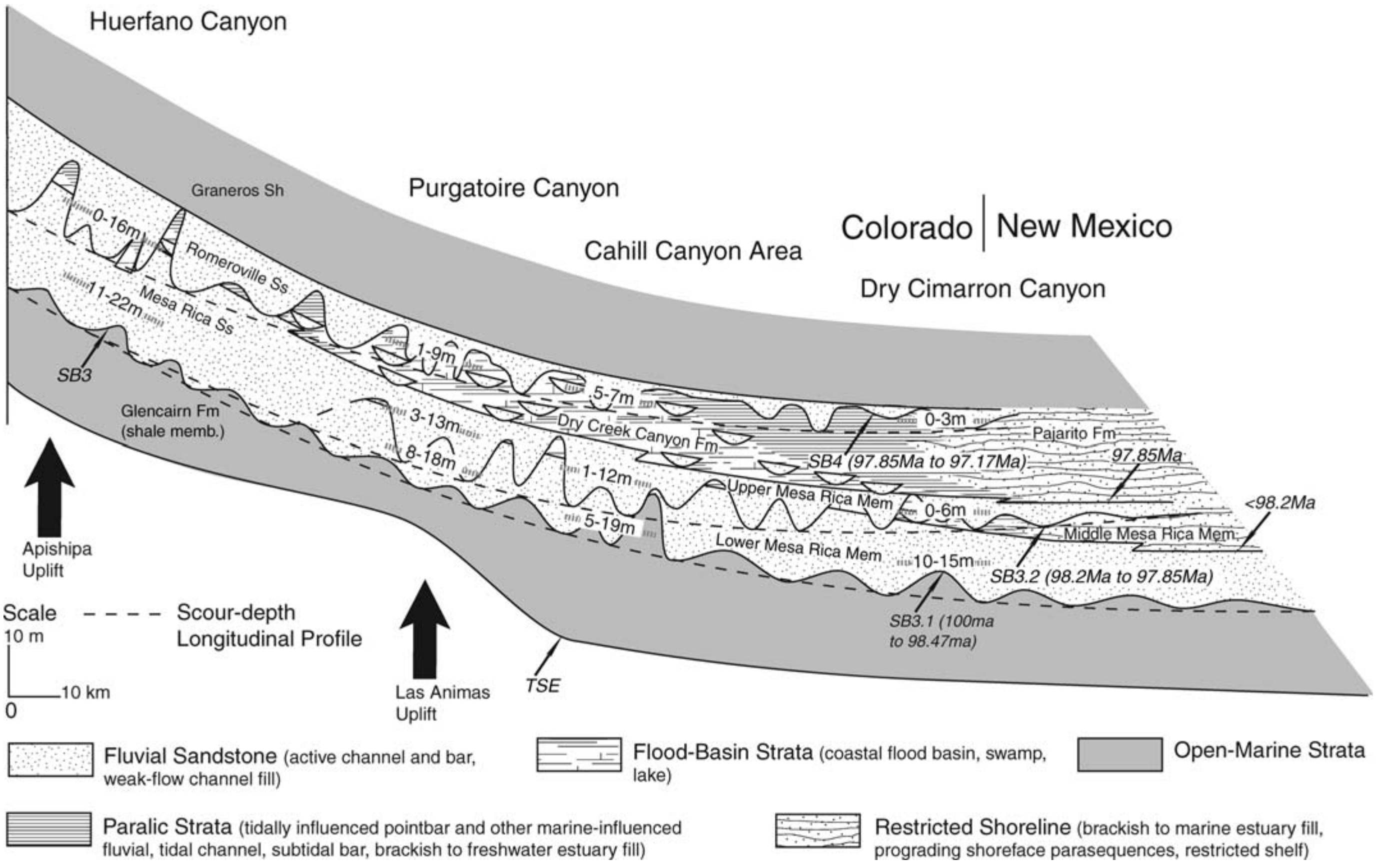


FIG. 3.— Longitudinal section through Dakota Group strata (all units in between Glencairn Formation and Graneros Shale) illustrating thickness trends and lithofacies associations of Mesa Rica and Romeroville fluvial sandstone layers. Posted thicknesses for these units are from four areas (Huerfano Canyon, Purgatoire Canyon, Cahill Canyon, and Dry Cimarron Canyon) where sufficient exposure in photopans and measured section permitted an accurate estimate of the full thickness range. Thicknesses of enveloping marine- and paralic-dominated formations are drawn to scale. Sequence boundaries are numbered following Weimer (1984) and Holbrook and Wright Dunbar (1992). The original slope of longitudinal profiles cannot be measured directly and is shown schematically with assumed vertical exaggeration. The profile location is shown in Figure 2. Modern erosion removes much of the southern terminus of the lower Mesa Rica Sandstone within the profile. Its terminus is considered to be 50 to 100 km farther south on the basis of extrapolations from lithofacies trends observed slightly to the west by Holbrook and Wright Dunbar (1992). Dates are based on graphic correlation and are elaborated in Scott et al. (2004). On the basis of these dates, surface SB3.1 formed between 100 Ma and 98.47 Ma. Middle Mesa Rica transgression began at $<$ 98.2 Ma. SB3.2 formed between 98.2 Ma and 97.85 Ma. Dry Creek Canyon transgression began at 97.85 Ma, and SB4 eroded after 97.85 Ma and near 97.17 Ma. Error of these dates is based on the collective error of the radiometric dates used to establish time ranges for biota within the applied database, and the number of biota used in assessment. Error for each of the above dates is estimated at $\pm$ 0.05 Ma. The Thatcher limestone member of the Graneros Shale is approximately 15 meters above the Romeroville–Graneros contact and is dated at 95.78 $\pm$ 0.61 Ma on the basis of a bentonite layer 90 cm below this member at Pueblo, Colorado (Obradovich 1993).

paper. The model expands upon current fluvial sequence-stratigraphic models (e.g., Fig. 1) in order to incorporate dip-oriented complexities in Dakota sandstone layers that these models presently cannot address. Though derived particularly to explain features in Dakota deposits, the buffers-and-buttresses model should be generally applicable to modeling of geometry, architecture, and preservation potential for any fluvial unit.

## GENERAL LITHOSTRATIGRAPHIC AND SEQUENCE STRATIGRAPHIC FRAMEWORK FOR DAKOTA GROUP STRATA

Middle Cretaceous (upper Albian through lowermost Cenomanian) strata of the Dakota Group in southeastern Colorado, northeastern New Mexico, and the Oklahoma panhandle comprise, in ascending order, lower, middle, and upper members of the Mesa Rica, the correlative Dry Creek Canyon and Pajarito, and the Romeroville formations (Fig. 3). These strata record three small transgressive–regressive events that generated three sequences, collectively recording an overall retreating shoreline. This three-sequence bundle is the lower transgressive part of a larger sequence recording the second-order Greenhorn marine cycle (Figs. 2, 3). The following discussion outlines the regional depositional framework for these strata and is drawn mostly from Holbrook and Wright Dunbar (1992), Holbrook (1996), and Holbrook (2001).

Latest Early Cretaceous (late Albian) regression and lowstand of the Kiowa–Skull Creek marine cycle (Kauffman 1977) resulted in widespread erosion of sequence boundary SB3.1 above marine strata of the prior Kiowa–Skull Creek flooding event (Glencairn Formation). This surface is overlain by fluvial sheet sandstone of the lower member of the Mesa Rica Sandstone (Fig. 3). Lower Mesa Rica strata record fluvial deposition of an extensive sandstone sheet during regression through early transgression and have a lowstand marine shoreline in east-central New Mexico (Fig. 2). A short transgression that followed laid a thin veneer of paralic and floodplain strata (Mesa Rica middle member) above the southern Mesa Rica lower member. A minor regression followed which caused local incision of middle and lower Mesa Rica strata. This surface is preserved over the middle half of the study area as sequence boundary SB3.2 and is overlain by regressive fluvial sandstone of the Mesa Rica

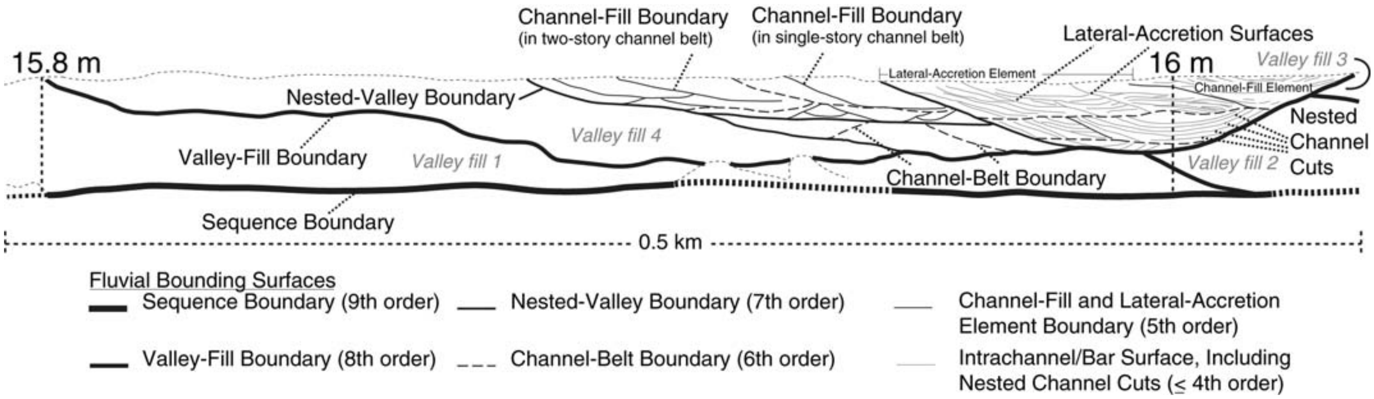


FIG. 4.—Simplified photopan of Romeroville Sandstone schematically revealing representative architecture of multivalley sheets (cf., Holbrook 2001) common to both the Mesa Rica Sandstone and the Romeroville Sandstone in the Huerfano Canyon. Mesa Rica and Romeroville sandstone layers are both complexly partitioned in this up-dip area by a range of bounding surfaces. Each surface is assigned an order and interpreted according to architectural-element analysis. General rules for identifying surfaces and assigning orders within fluvial strata are defined in Holbrook (2001, p. 183), and criteria for interpreting these surfaces are outlined in Miall (1996). In short, bedding surfaces binding individual cross-lamina sets are defined as first-order surfaces. Surfaces mapped in outcrop that bundle and confine sets of first-order surfaces are ranked as second-order. Surfaces bundling second-order surfaces are third-order, and so forth. Origins of surfaces are then interpreted on the basis of order, surface morphology, and analogy with modern systems. Lower-order (≤ 5) surfaces that are flat to convex up occur as bar surfaces in modern systems. Concave-up surfaces at approximately fifth-order are typically primary channel scours binding bar sets and smaller cut-and-fill surfaces, and higher-order surfaces typically record channel belts, valleys, and regional unconformities (see Miall 1988, 1996 for further details). The orders and interpretations assigned here follow these criteria and are detailed in Holbrook (2001). The scours recording valley-scale incision (eighth-order) are typically near the complete thickness of the unit, having an average thickness of 15 m or more and crosscutting each other laterally in multiple generations to form a multivalley sheet roughly one valley fill thick. Four laterally crosscutting valleys are identified in this example. Valleys are architecturally defined as containing multiple channel-belt stories (cf. Dalrymple et al. 1994), and are also partitioned here by nested-valley scours. The underlying sequence boundary records the composite scour of multiple laterally juxtaposed valleys.

upper member (Fig. 3). The lowstand marine deposits of this unit are in east-central New Mexico and southeastern Colorado (Fig. 2). The upper and lower Mesa Rica Sandstone merge into a single sandstone sheet to the north. Surfaces SB3.1 and SB3.2 merge as well, and no distinctions between these surfaces are recognizable there (Fig. 3) (Holbrook 2001).

Flooding of the Mesa Rica upper member resulted in deposition of a section of intercalated fluvial, paralic, and floodplain deposits know as the Pajarito Formation in New Mexico and the Dry Creek Canyon Formation in Colorado. These strata extend northward beyond the study area and record a substantial transgression that introduced fossiliferous marine shale deposits locally into the southern and eastern extremities of the study area. This transgression apparently resulted in brief connection of the southern Tethyan and northern Boreal seas (Holbrook et al. 1998). Subsequent regression generated sequence boundary SB4 above these strata. Surface SB4 is overlain by the fluvial Romeoville Sandstone (Fig. 3), which passes into marine equivalents in northeastern New Mexico and the Oklahoma panhandle (Fig 2). Transgression over the fluvial Romeroville Sandstone resulted in onlap of open marine and minor intervening coastal deposits of the Graneros Shale. This records the long-term regional flooding of the Greenhorn transgression (Fig. 3), which formed a stable marine connection between the northern Boreal and southern Tethyan seas by the deposition of the Thatcher member (Scott et al. 2004).

## ARCHITECTURE, GEOMETRY, AND LITHOFACIES OF DAKOTA FLUVIAL STRATA

This section extracts lithofacies and architectural data from extensive descriptions in the literature, and augments these data with observations from this study (Fig. 2). Extensive (approx. 1 km) photopanoramic cross sections of continuous canyon-wall exposures in the Huerfano Canyon are applied from Holbrook (2001) and Holbrook and Oboh-Ikuenobe (2002). These detail architectural and thickness trends of Dakota strata in up-dip areas. Similarly, photopans from Holbrook (1996) define architecture of the Lower Mesa Rica Sandstone in the down-dip reaches of the Dry Cimarron Canyon. Additional photopans are added in intervening areas in this study, as well as photopans of Romeoville and upper Mesa Rica sandstones in the Dry Cimarron Canyon. Architectural data were captured in all photopans using techniques of architectural-element analysis (Miall 1985, 1988, 1996). Several local stratigraphic sections were also collected from the literature and during this study to better constrain regional lithofacies trends.

### *Lower, Middle, and Upper Mesa Rica Sandstone and Pajarito–Dry Creek Canyon Formations*

The upper and lower members of the Mesa Rica Sandstone form two distinct layers in the south where they are parted by the middle Mesa Rica member, but merge up dip into one sandstone unit near Huerfano Canyon (Figs. 2, 3). Lithofacies of the two layers, and the merged unit, are very similar and dominated by medium-grained, well-sorted, planar and trough cross-bedded quartz arenite (Fig. 4). These strata are interpreted to record active channel filling and fluvial bar deposition (Long 1966; Holbrook and Wright Dunbar 1992; Odien 1997). The lower Mesa Rica member unconformably overlies marine shale and shoreface sandstone of the Glencairn Formation, and the upper Mesa Rica member unconformably incises middle Mesa Rica and/or lower Mesa Rica strata (Fig. 3). Middle Mesa Rica member strata comprise lenses of fluvial channel sandstone typical of upper and lower members, but are more commonly floodplain siltstone and mudstone with paleosols and/or tidally influenced estuarine mudstone and sandstone (Holbrook 2001; Akins 2003). Middle and lower member strata of the Mesa Rica are conformable. Middle member fluvial sandstone lenses range widely in thickness (1 m–10 m), are well dispersed with minimal interconnectivity, and constitute between 10% and 50% of the unit regionally.

Figure 2 indicates the areas over which Mesa Rica fluvial strata pass into correlative lowstand marine units. Preserved remnants of the lowstand deltaic deposits for the fluvial lower Mesa Rica are encapsulated in equivalent Mesa Rica deltaic strata of east-central New Mexico. Here, the lower Mesa Rica sheet disperses into progressively smaller distributary belts and channels above delta-front strata starting just south of the

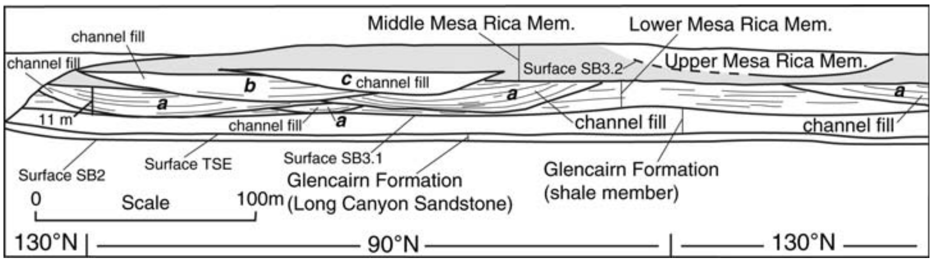


FIG. 5.—Architecture of a channel sheet (cf., Holbrook 2001) in lower Mesa Rica Sandstone of the Dry Cimarron Canyon. Channel scours here are of equivalent order to channel fills farther up dip in the Huerfano Canyon; however, enveloped fills are typically two or three times as thick. Surfaces within channels binding cross-lamina sets and bars also envelop proportionally thicker stratal sections. Channel level "a" records preservation of a continuous sandstone sheet one channel thick throughout the area, whereas levels "b" and "c" record later aggradation of channels from this sheet. The higher-order surfaces recording valleys and nested valleys that are observed in up-dip areas of the Huerfano Canyon are not observed here.

latitude of the Texas–Oklahoma border (Fig. 2; from Holbrook and Wright Dunbar 1992, and this study). The Pajarito Formation is entirely paralic to marine strata above underlying lower Mesa Rica fluvial sandstone near the southern end of the field area (32 km southeast of Tucumcari). Upper Mesa Rica Sandstone transitions from fluvial to marine between this locality and the southernmost unambiguous fluvial exposures of this unit near the Oklahoma–Texas border. In the far southeastern corner of Colorado, the upper Mesa Rica disassociates into an amalgamated series of well-defined estuary fills recording marine lowstand deposition there.

The upper and lower Mesa Rica have some distinction in thickness trend (Fig. 3). The lower Mesa Rica has continuous sheet geometry with minimal local thickness variation south of about Pueblo, Colorado (Figs. 2, 3) but becomes more discontinuous farther to the north (Weimer 1984; Holbrook 1992, Odien 1997). In the Dry Cimarron area, where this sheet is continuous and clearly distinguishable from the upper Mesa Rica, it ranges between 10 and 15 m thick. The upper Mesa Rica is lithologically similar to the lower Mesa Rica Sandstone but is less continuous and commonly confined to localized sheets. The upper Mesa Rica unit ranges from 0 to 6 m thick where distinguished (Fig. 3). In the Huerfano Canyon area, and to approximately 50 km down dip, the upper and lower Mesa Rica are indistinguishable. These two units merge rather than stack here, and the two combined units form a continuous sheet 11 to 22 m thick (Fig. 3).

The architecture of the sandstone sheet that forms the merged upper and lower Mesa Rica members within the Huerfano Canyon is highly complex (Fig. 4). Here, channel fills (up to 4.5 m thick) are tightly amalgamated, are bundled into single and multistory belts, and are generally incomplete owing to truncation by overlying channel fills. Channel belts are stacked and truncated within thicker valley fills. These are typically complex valley fills (cf., Holbrook 2001), bundling multiple nested-valley fills. Valley fills (15 m or more) are mostly near the complete thickness of the unit, and crosscut each other laterally in multiple generations. The result is a multivalley sheet (cf., Holbrook 2001) that is roughly one valley fill thick (Fig. 4).

The architecture of the distinguishable upper and lower Mesa Rica members is less complex (Figs. 5, 6). The lower Mesa Rica member in the Dry Cimarron Canyon lacks the partitioning by valley and nested-valley architectural surfaces seen up dip in the Huerfano Canyon. Channel fills are also thicker (10–12 m) and are approximately the same thickness as the encompassing sandstone member (Fig. 5). Though locally coupled with an adjacent lateral-accretion element, channel fills are generally singular (Holbrook 1996). Channels are amalgamated laterally here into a sheet over 84 km wide along strike with negligible vertical channel stacking (Holbrook 1996). The upper Mesa Rica member shows a similar, but not identical, architecture in down-dip areas of the Dry Cimarron Canyon (Fig. 6). The larger channel fills here are locally the same thickness as the upper Mesa Rica member (0–6 m), but most channel fills are about half this thickness. Channel fills are typically stacked two or three stories high. Nested-valley fills and valley fills, however, are similarly absent from these local sheets.

Upper Mesa Rica, and merged upper and lower Mesa Rica, strata grade conformably upward into Pajarito–Dry Creek Canyon strata. These overlying strata contain a complex of channel and floodplain-to-paralic deposits that are similar to those of the middle Mesa Rica, and are described in detail and interpreted in Long (1966), Holbrook (2001), and Akins (2003). Because the Pajarito–Dry Creek Canyon section is thicker and more extensive than the middle Mesa Rica, regional trends are more apparent. These strata include lenses of cross-bedded fluvial strata with scale and internal architecture like discrete valley fills and channel belts within locally underlying Mesa Rica Sandstone. In up-dip areas, these sandstone lenses are encased by nonmarine floodbasin deposits with

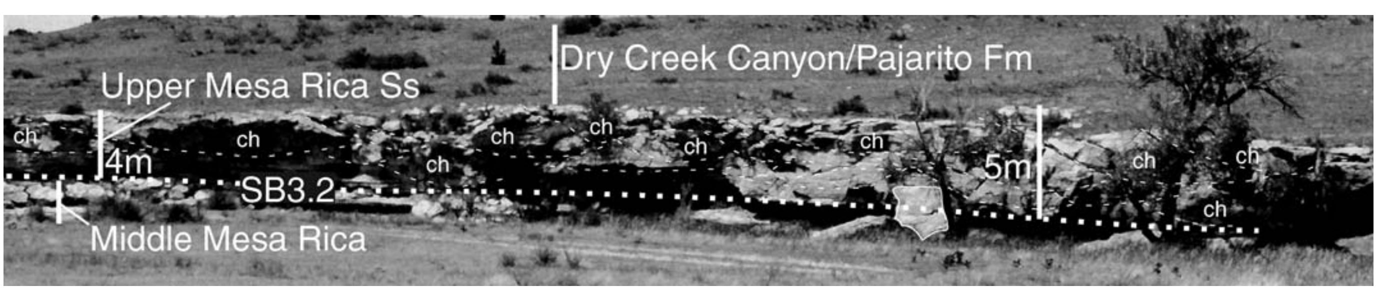


FIG. 6.—Architecture of channel sheet in upper Mesa Rica Sandstone in the Dry Cimarron Canyon. This sandstone is discontinuous here, ranges up to 6 m thick, and comprises mostly amalgamated channel fills. Channel fills are generally a little over half the maximum thickness of the unit, and rarely up to near the full unit thickness. Channel fills here are thus between one and two times the thickness of equivalent channel fills within the Huerfano Canyon. These strata lie within shallow locally incised valleys indented into the underlying sequence boundary (SB 3.2). Available exposure did not reveal higher-order valley and nested-valley surfaces within these strata.

interspersed paleosols. These strata give way down dip to more paralic units wherein sandstone lenses are less commonly developed (Fig. 3).

### *The Romeroville Sandstone*

The Romeroville Sandstone bears several similarities with the upper and lower Mesa Rica Sandstone in terms of lithology, thickness trends, and architecture. Most particularly, the lithofacies constituting the Romeroville are also those constituting the upper and lower Mesa Rica. The Romeroville Sandstone unconformably overlies the Dry Creek Canyon Formation and is onlapped above by marine Graneros Shale across a locally disconformable transgressive surface (Odien 1997; Holbrook 2001) (Fig. 3). The Romeroville Sandstone forms both local sheets and discrete lenses in the up-dip areas of Huerfano Canyon, where it ranges from 0 to 16 m thick (Fig. 3). It retains this discontinuous distribution as it thins down dip into localized channel complexes (0–3 m) above deltaic strata of the Romeroville lowstand wedge within Dry Creek Canyon–Pajarito strata of the Dry Cimarron Canyon.

The architecture of the Romeroville Sandstone closely resembles that of the underlying Mesa Rica. Channel fills are similarly stacked within larger nested-valley fills and valley fills throughout the Huerfano Canyon area (Fig. 4). Romeroville Sandstone here also bears the same general coincidence between thickness of valley fills and total unit thickness that is preserved in underling Mesa Rica strata. Lateral amalgamation of valley fills is not as thorough, however, and the Romeroville Sandstone includes both laterally amalgamated multivalley sheets as well as singular complex valley fills (cf. Holbrook 2001). Sandstone lenses near the terminus of Romeroville exposure in the Dry Cimarron Canyon constitute narrow ($\ll$ 1 km) and thin ($\leq$ 3 m) localized channel belts approximately one to three channel stories thick. Channel belts lack well-developed valley and nested-valley surfaces as in strand-proximal Mesa Rica strata. Channel fills here are thin ($\leq$ 2 m). Long continuous exposures of Romeroville Sandstone are absent between Huerfano Canyon and the Dry Cimarron Canyon, and information here must rely on localized exposures that escaped modern erosion. Those found do not reveal sufficient length of exposure to fully constrain channel-fill scours and other scours of higher order. Individual cross-lamina sets preserved in local outcrop pinnacles just north of, but near, the Dry Cimarron Canyon, however, are roughly twice as thick (average 40–60 cm) on average as cross-lamina sets within other Romeroville exposures. Cross sets of this mean thickness are exclusive to channel fills $\geq$ 7 m thick throughout Dakota strata. Average cross-bed thickness is closely related to channel-fill thickness (LeClair and Bridge 2001; Bridge 2003). Channel fills here are thus likely near 7 m as well, which is roughly the maximum thickness of the Romeroville Sandstone locally.

## BASE-LEVEL BUFFERS AND BUTTRESSES

Mesa Rica and Romeroville sandstone layers record intense vertical and lateral reworking in up-dip areas because of repetitive incision–aggradation cycles at valley-fill scales. These cycles were confined within discrete, long-standing, and extensive upper and lower limits that are recorded by the upper and lower boundaries of each respective sandstone layer. Enveloped channel fills are considerably thinner than the space between these limits. Channels were thus able to migrate freely both vertically and laterally within these confines, resulting in multistory ($\leq$ 8; Holbrook 2001) stacking and lateral amalgamation of single and multistory channel belts. This differs from equivalent exposures down depositional dip where valley-scale incision cycles are not locally expressed and channel-fill stacking is minimal. The vertical space between limits here was thinner than in up-dip areas both numerically and in comparison to encased channels. Stable vertical limits on aggradation and incision down dip promoted lateral reworking of channels with minimal stacking, locally producing sandstone sheets only one or two channel stories thick (Holbrook 1996). These contrasting architectures apparently record dip-oriented variance in preservation by individual river systems. A generalized model is needed to account for this contrast. We here introduce the concept of base-level buffers and buttresses, and then use this as a vehicle to explain these observations.

### *General Concepts*

**Defining Features.—**Rivers are prone to aggrade or incise as they strive to acquire the local elevation of the optimal longitudinal profile (Gilbert 1877; Mackin 1948; Merrits et al. 1994; Howard et al. 1994; Tebbins et al. 2000). This profile is determined by the interplay between the ability of the stream to transport sediment (controlled by stream power) and the local influx of sediment to be moved (sediment supply). Streams thus aggrade if the sediment supply exceeds the stream power, and vice versa, until the two are balanced at an elevation which is by definition that of the graded longitudinal profile (Lane 1955; Schumm 1977; Blum and Törnqvist 2000) (Fig. 7). The profile is also a function of uplift rate and erodibility of underlying strata because these can strongly influence the rate of incision, particularly in bedrock-controlled systems (Merrits et al. 1994; Howard et al. 1994).

Rivers each eventually encounter some down-dip barrier below which the river cannot substantially cut, and above which the river cannot substantially build. The longitudinal profile is anchored at the elevation and location set by this barrier, and this point serves as ultimate base level (Gilbert 1887; Mackin 1948). Most downstream effects on base level can be attributed to shifts in this barrier (Mackin 1948). Such a barrier could be local (e.g., cataracts, tributary junctions, lake strands, etc.) but ultimately is the ocean strand in most cases. These physical erosional barriers that anchor profiles, and to which the point of ultimate base level is set, are here referred to collectively as "buttresses" (Fig. 7).

Studies of Quaternary fluvial deposits reveal that upstream profile controls (i.e., water discharge, sediment influx, and short-term variations in local uplift rate) commonly cause $10^0$–$10^1$ m of profile adjustment within the same drainage over time scales of $10^2$ to $10^5$ years (Hall 1990; Autin et al. 1991; Blum and Price 1998; Goodbred and Kuehl 2000; Blum and Törnqvist 2000; Schumm et al. 2000; Harvey 2002). These adjustments are driven largely by coeval variations in climate and tectonics, and typically force profile change on time scales at least an order of magnitude shorter than downstream adjustments driven by shift in a buttress (e.g., sea-level change) (see Harvey 2002). Large variations in sediment supply and discharge caused by upstream controls can propagate down dip though areas where downstream controls are active, but their control on profile position decreases as the buttress is approached and downstream profile controls become dominant (e.g., Blum and Valastro 1994; Goodbred et al. 2003). Quaternary stratigraphers often succeed in sorting these complex upstream and downstream controls on profile variability within a drainage by reconstructing and interpreting a battery of sequential representative profiles from data preserved in remnants of coexistent terraced or buried floodplain surfaces (e.g., Woodridge and Linton 1955; Gibbard 1985; Blum and Price 1998; Veldkamp and van Dijk 2000; Cohen et al. 2002). This is usually an impractical technique to apply in ancient deposits because the inherently poorer exposure and lower age resolution is not conducive to the requisite detailed sorting of terrace fragments. Thus, an amended approach is required.

An alternative method for capturing profile variability derived from upstream controls over an episode of downstream buttress shift is offered here in the concept of base-level "buffers." Assume a representative episode of buttress shift (e.g., a slow buttress drop, etc.). A continuum of many potential profiles may be inferred up dip from the buttress while it undergoes this representative shift because of potentially higher-frequency variability in discharge, sediment supply, and uplift rate that

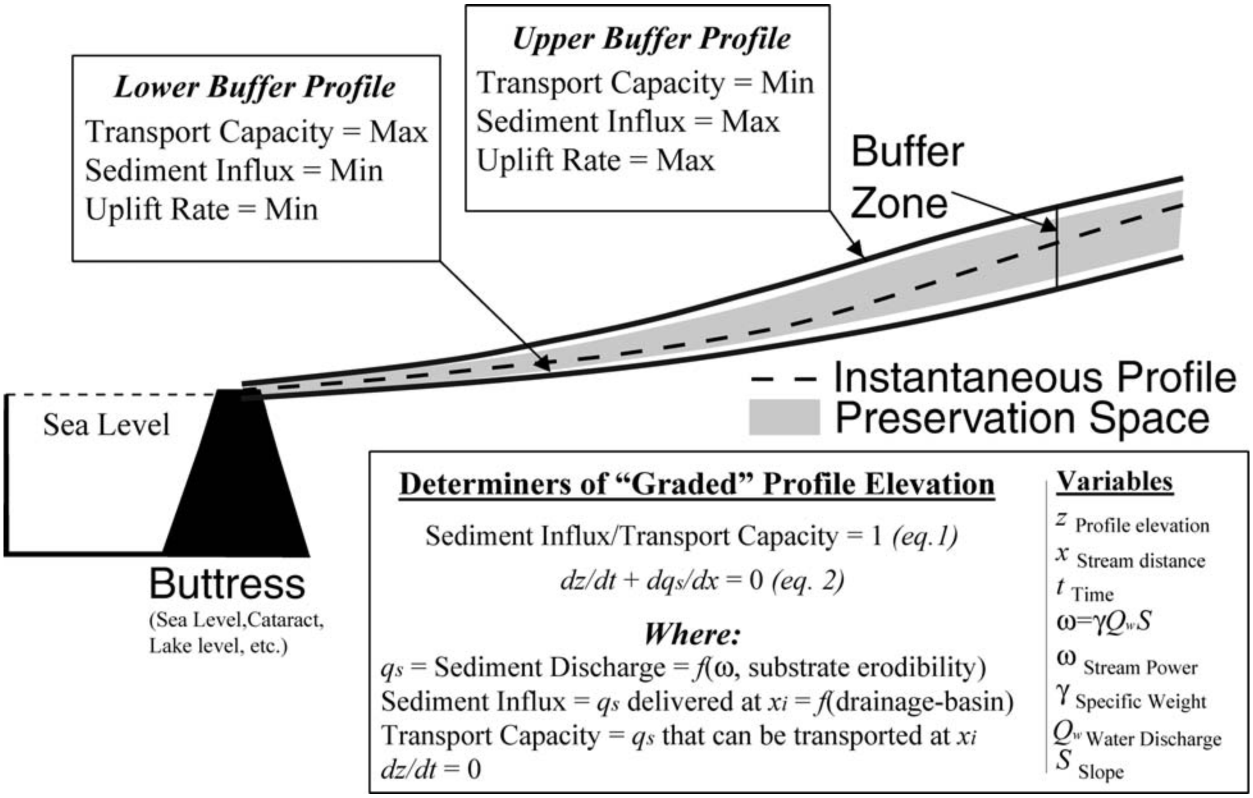


FIG. 7.— Diagrammatic explanation of buffers and buttresses. The upper and lower buffer profiles track the highest surface of aggradation and the lowest depth of incision, respectively, that a river could achieve during some modeled time interval (e.g., duration of a particular buttress shift, etc.). The upper buffer is thus a floodplain profile, and the lower buffer is a scour-depth profile. Buffer spacing (the "buffer zone") is determined by variability in upstream base-level controls during the modeled period. The instantaneous profile (the profile specific to any instance in time over the modeled period) for a river must be between the upper and lower buffers. The buffers are both assumed to represent graded profiles. They must therefore meet the conditions of equal sediment influx and outflux at each point $x_i$ along the profile (equation 1), and fulfill the continuity equation (equation 2) at the value where $dz/dt$, and thus $dq_s/dx$, is equal to 0 (Blum and Törnqvist 2000). Transport capacity is mostly controlled by stream power (Bagnold 1977); however, sediment influx is mostly controlled by several drainage-basin factors (e.g., vegetation, substrate lithology and erodibility, relief, etc.) not distinguished here. The primary independent variable controlling the position of both upper and lower buffers should be water discharge ($Q_w$). The "preservation space" records the space between the buffers within which the system is able to practically act within the time span used to define the buffers.

can intermittently disrupt equilibrium and force local profile adjustment. It is not practical to reconstruct all these potential profiles, nor is it accurate to represent this set with a single averaged equilibrium profile. It can be assumed, however, that at any instance during the buttress shift there will be a lowest and a highest possible profile attached to the buttress that will together envelop the reasonable range of potential profiles for this instance. The lowest profile records the maximum reasonable depth of profile incision and the highest profile follows the highest reasonable surface of aggradation. These reflect the highest and lowest ratio of transport capacity to sediment influx, respectively, produced by upstream variability in the system over some time of pertinent concern, for instance the period covered by the addressed buttress shift. Variables defining these profiles are elaborated in Figure 7. These hypothetical profiles define "buffers" between which the instantaneous profile (the unique profile for a single point in time) must be enclosed.

Because each of these buffers represent end-member conditions, they should become more difficult to reach as approached; thus, real streams cannot be practically expected to attain either the lower or upper buffer profile. There will thus be a "preservation space" between the buffers that defines the vertical space within which profiles actually varied (Fig. 7). This should be smaller than the full buffer zone, and defines the effective range of aggradation and incision where fluvial preservation may occur. The buffer zone and enveloped preservation space should also thicken some distance up dip from the buttress. This is because the buffers tend to diverge, owing to the general concavity of most river profiles (Mackin 1948; Hack 1973; Bagnold 1977; Snow and Slingerland 1987) and the requirement that these buffers join at the buttress yet accommodate increasing profile variability up dip (Fig. 7). This expected divergence applies only to the reach between the buttress and the up-dip limit of buttress dominance. Regional buffer trends beyond there are controlled by upstream effects and are not addressed. It is considered unlikely, however, that the vertical preservation space gained to this point is lost abruptly up dip.

**Effects of Buttress Shift.**—As the buttress moves, the buffers follow, with some modest adjustment to reflect the new and evolving conditions. The lowest and highest buffers that existed cumulatively during the life of the fluvial system define the space in which this system may eventually preserve strata (Fig. 8).

Vertical buttress shifts mostly affect modern river profiles near the buttress, and this effect dissipates up dip in favor of upstream profile controls (Leopold and Bull 1979; Schumm 1993; Blum 1993; Ethridge et al. 1998; van Heijst and Postma 2001). Buffer profiles are fundamentally river profiles, and should follow this behavior. Raising the buttress thus raises the buffers and enveloped preservation space for some distance up dip that is determined by local conditions. Fluvial sediments may potentially preserve within the lowest and highest preservation space generated, as well as in the space passed between (Fig. 8B). The buffers are unaffected by this shift farther up dip, and

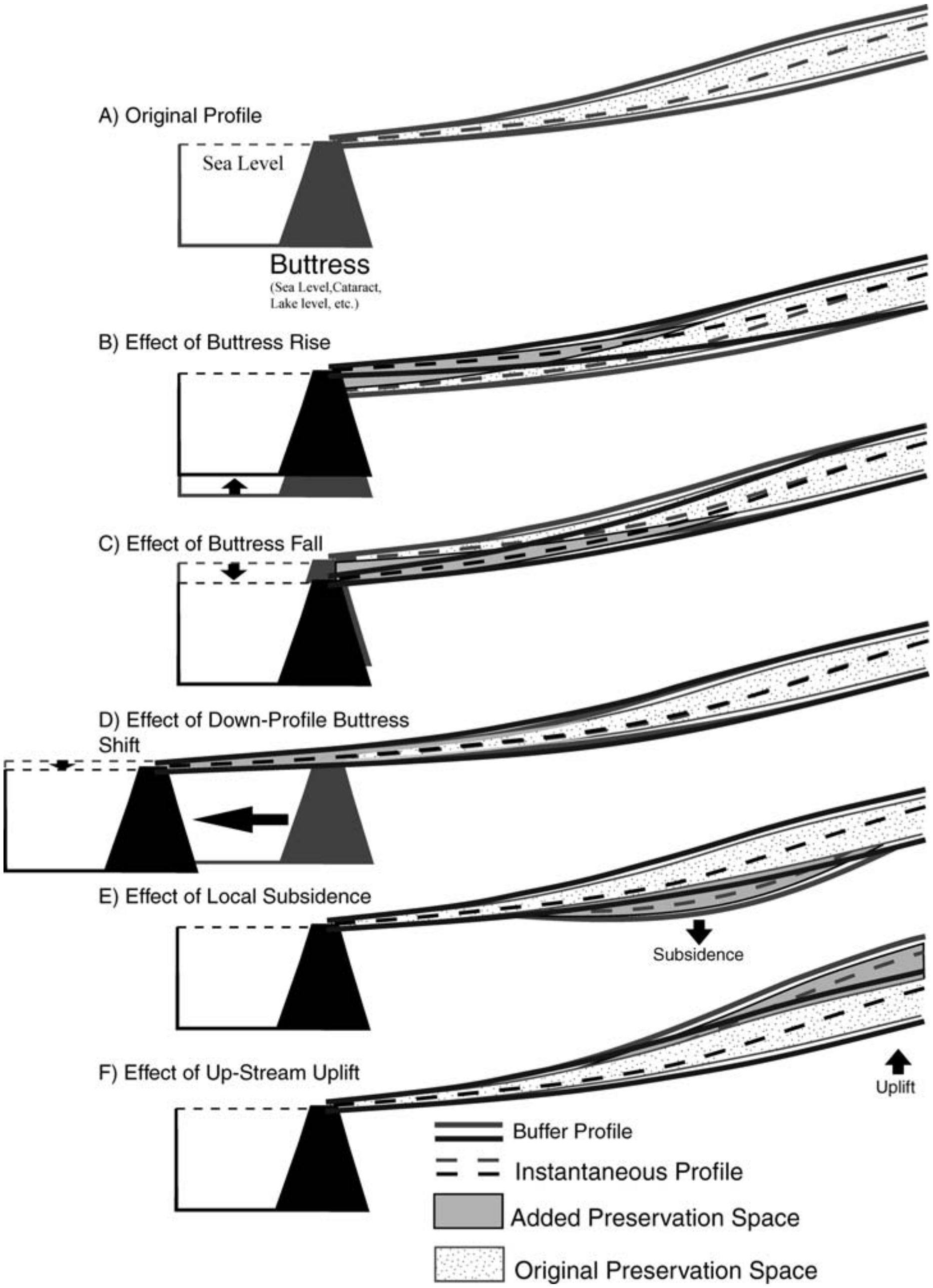


FIG. 8.—Preservation space added as a result of shift in initial buffer profiles **(A)** because of either buttress movement or tectonic adjustment. Fluvial preservation space may be added as a result of a simple buttress rise **(B)** or fall **(C)**. Sediments deposited in added preservation space resulting from a buttress fall (C) are generally sequestered as easily eroded terraces hanging from the valley wall. They thus tend to have less long-term preservation potential than deposits buried by aggradation during a buttress rise (B). Movement of the buttress along the trajectory of the original longitudinal profile **(D)** tends to lengthen preservation space, but otherwise adds minimal room for sediment accumulation. Subsidence beneath reaches of the lower buffer profile **(E)** tends to lower sediments deposited within the prior preservation space beneath active erosion. Long-term preservation potential of these sediments is high. Uplift beneath buffer profiles **(F)** tends to leave deposits from previous preservation spaces stranded as terraces where they could potentially be preserved long term, but have high probability of erosion before eventual burial. In each of the above cases B through F, the total space for potential accumulation of a fluvial unit is the integral of all preservation spaces produced over the period through which the depositing fluvial system was actively preserving sediment.

thus the preservation space there is unaffected. Similarly, a buttress drop shifts the buffers and will add preservation space only proximally (Fig 8C). Though sediment may still deposit within all added preservation space during a drop, sediment in the final lowest preservation space has better preservation potential. The other sediment is likely stranded as terraces along valley walls, where it tends to be eroded before eventual burial.

The slope of the surface exposed by buttress shift also has an effect on direction and extent of profile adjustment and in some cases may result in no effective vertical profile adjustment. For instance, in most systems where regression and transgression occur over plate interiors and shelves, as is the case in this study, the gradient of the land surface exposed or covered by shoreline migration can be similar to a profile in the existing preservation space. In such cases, the profile is substantially lengthened or shortened as sea-level change exposes or drowns the profile, but no vertical profile shift need occur (Fig. 8D) (Schumm 1993; Wescott 1993; Ethridge et al. 1998; Muto and Swenson 2005). The buffers and the preservation space similarly do not change vertical position dramatically in such instances, though they may lengthen and thicken or shorten and thin somewhat as the buttress retreats or approaches, respectively.

Lastly, local tectonics beneath buffer profiles can also affect long-term fluvial preservation (Holbrook and Schumm 1999; Schumm et al. 2000). If local subsidence is sufficient to lower previous fluvial deposits below the active preservation space, these strata are now removed completely from the interval of active fluvial erosion, and thus have high preservation potential (Fig 8E). Continued local uplift however will draw fluvial sediment that was deposited in the active preservation space above the maximum buffer profile (Fig 8F). These sediments will tend to be stranded as terrace fragments on valley walls and have limited long-term preservation potential.

### *Field Observations from Dakota Strata in the Context of the Buffers and Buttresses Model*

**Local Impact of Buffer Profiles.—**Architecture of Mesa Rica and Romeroville sandstone in up-dip areas of Huerfano Canyon is complex, and both layers reflect multiple episodes of valley-scale cut and fill within strict upper and lower limits. These limits are here proposed to reflect vertical constraint by enduring base-level buffers. Up to seven remnants of crosscutting valley fills are documented in single Mesa Rica and Romeroville exposures, each recording an independent and sequential episode of valley cutting and filling (Holbrook 2001). Most of these valleys have nested valleys within, recording smaller cut-and-fill events within valley confines (Fig. 4). In each case, the depth of valley incision and the height of valley aggradation were similarly confined to a 22 m (Mesa Rica) or 16 m (Romeroville) interval, reflecting strong and enduring upper and lower limits to the elevation range of channel aggradation and degradation. These limits appear to reflect emplacement of stable buffers, within which channels avulsed and cut/filled freely for between 0.62 and 2.15 $\pm$ 0.05 My (Mesa Rica) and 0.78 and 2.68 $\pm$ 0.05 My (Romeroville) years (Scott et al. 2004) without leaving these vertical confines. Singular complex valleys formed where sediment storage was minimal. Multivalley sheets (Fig. 4) formed where need for sediment storage greatly exceeded accommodation within single valleys and rapid and/or long-lasting lateral reworking resulted.

Architecture of upper and lower Mesa Rica members in down-dip regions of the Dry Cimarron Canyon contrasts with that of equivalent Mesa Rica strata up-dip within the Huerfano Canyon. Here, architecture records enduring lateral channel migration within thin channel-scale buffer zones, and the high-amplitude cycles that cut and filled complex valleys in equivalent deposits farther up dip are not evident. This is best exemplified by the lower Mesa Rica member. These strata record planar lateral migration of channels near the lowstand shoreline, eventually forming a laterally continuous sandstone sheet only one channel fill thick (Holbrook 1996). This is interpreted to reflect stability of a buffer zone as thin as one channel fill for a long period that was inversely proportional in duration to the rate of avulsion. Upper Mesa Rica channels underwent an episode of lateral reworking within a thin buffer zone that was similar to that of the lower Mesa Rica member. Reworking was not as protracted in this case, however, and resulted in sheets that are more laterally discontinuous (Fig. 3). Upper Mesa Rica channel fills are also thinner, are slightly more stacked, and do not reflect the large degree of down-dip increase in size typical of lower Mesa Rica channel fills. Larger channel size likely records an increased incorporation of tributary drainages down dip by lower Mesa Rica rivers that did not occur during later upper Mesa Rica deposition.

Romeroville Sandstone architecture in the Dry Cimarron Canyon area appears to mimic architecture of underlying Mesa Rica Sandstone. As with the upper Mesa Rica member, the Romeroville Sandstone here lies atop, and incises, a section comprising discrete channel belts that are dispersed within flood-basin strata. Channel fills within the Romeroville Sandstone also show a relationship between channel fill and unit thickness that is similar to the upper Mesa Rica member (Fig. 6). Romeroville channel fills of the Dry Cimarron Canyon area are only slightly stacked, form local sheets, are highly amalgamated, and are not partitioned by valley and nested-valley surfaces. Similarly, the Romeroville Sandstone here appears to record substantial lateral reworking between thinly spaced, but stable, buffers that did not last long enough to produce an expansive contiguous sheet.

**Drainage-Scale Impact of Buffers and Buttresses.—**Regional geometric characteristics of Dakota strata, and the relationship between contrasting up-dip and down-dip architecture within these strata, can be explained within the context of buffer and buttress model variations provided in Figure 8. These strata particularly have characteristics consistent with models in Figure 8D and 8B.

The upper and lower Mesa Rica and the Romeroville sandstone each record layers of amalgamated channel strata deposited during modest to extensive regressions across the U.S. Western Interior (Figs. 2, 3). The model in Figure 8D offers insights into why each regressive sandstone layer is continuous from coastal to distant up-dip sections. We here assume that the slope of the continental interior across which sea level fell was close to the slope of some typical river profile confinable within the respective preservation space for each of the three layers. While this assumption cannot be confirmed, it is considered feasible because each surface across which regression occurred was a profile sculpted by channels during a prior lowstand that was potentially modified only somewhat by marine onlap and/or local tectonics during the intervening transgression. Regression across such slopes would have lengthened the buffer profiles and potentially varied their spacing, but would not have greatly altered their averaged elevation once established. The preservation space set by these buffer profiles would thus have changed little over the depositional duration of respective upper and lower Mesa Rica and Romeroville sandstone layers. Accordingly, strata preserved within each of these layers record confinement between roughly stable upper and lower limits throughout regressive distance and duration, and thus form continuous dip-oriented units.

The model (Fig. 8D) also predicts that these layers may thicken up dip away from the buttress, which is the case in each instance (Fig. 3). The muting of this buffer-related thickening trend in the lower Mesa Rica member suggests a countervailing effect. Namely, channels, and thus channel fills, tend to become deeper down dip as discharge increases. The preservation space must accommodate one channel-fill thickness as a minimum. The trend toward thicker coastal channel fills within the lower Mesa Rica thus works against the down-dip thinning trend normally imposed by thinning of the preservation space.

The model in Figure 8D also lends insight into the dip-oriented architectural contrasts observed within lower and upper Mesa Rica and Romeroville sandstone layers. Where rivers approached the coast, they existed within a thin buffer zone that confined a thinner preservation space. Rivers also tend to enlarge in depth and cross section as they approach the strand. The depth of coastal rivers would have been close to the total thickness of the preservation space, and they would have had minimal opportunity to aggrade or degrade much more than their channel-fill thickness. The near coincidence of unit thickness and channel-fill thickness observed in these layers in down-dip areas is consistent with this prediction, as is the dearth of high-amplitude valley-scale surfaces within these strata. In contrast, strata in up-dip regions were deposited by generally smaller channels within a thicker buffer zone. Variations in upstream base-level controls, driven largely by climate variations (Holbrook 2001), caused streams to aggrade and incise freely at the valley scale within this comparatively thicker preservation space. This resulted in sandstone with a more complex architecture, which included thick valley fills and nested-valley fills. Predicted reworking of sediments between stable buffers would also explain favored preservation of the coarser sandy lithofacies typical of these layers in both up-dip and down-dip areas.

The model in Figure 8B more aptly explains the interrelationships between upper and lower Mesa Rica and Romeroville sandstone layers, as well as the architecture of the intervening units. Relative sea-level rise caused lifting of the sea-level buttress after regressive deposition of each of these sandstone layers. This caused aggradation of channels first within and then above these sandstone deposits as conjoined buffers rose in response. Lenses of fluvial channel-fill strata dispersed within muddy flood-basin and paralic deposits that lie above each of the three regressive sandstone layers preserve aggradation from respective buttress rise. This dispersion of channel strata above amalgamated channel fills is consistent with transgressive models in Figure 1, and these deposits are best preserved as the middle Mesa Rica member and the Dry Creek Canyon Formation. Such deposits exist above the Romeroville Sandstone as well but are almost entirely removed by ravinement associated with transgressive deposition of the Graneros Shale (Odien 1997; Holbrook 2001). The model also notes that transgression causes aggradation only for some limited distance up dip, beyond which the buffers are not lifted by downstream base-level rise. Transgression that caused aggradation of the middle Mesa Rica member did not alter buffer positions beyond approximately 120 km up dip of coeval maximum-transgressive marine strata (Fig. 3). Mesa Rica strata in up-dip areas of the Huerfano Canyon thus preserve unabated deposition within the same stable buffer zone despite transgressive splitting of the unit farther down dip. The transgression prompting Dry Creek Canyon deposition did propagate into the Huerfano Canyon area, and caused the buffers there to rise above the level they occupied during prior Mesa Rica deposition. The Mesa Rica and Romeroville sandstone layers thus split there, but clearly converge from wider spacing down dip (Fig. 3). These units likely merge farther up dip in a fashion similar to the lower and upper Mesa Rica members, but modern erosion of more hinterland strata prevents us from confirming this assertion.

## SOME GENERAL IMPLICATIONS OF THE BUFFERS AND BUTTRESSES MODEL

### *Architecture and Geometry of Fluvial Strata*

Consideration of fluvial preservation in the context of buffers and buttresses permits some generalizations regarding fluvial geometry and architecture. Most of these are apparent in Dakota strata.

First, equivalent fluvial strata tend to bear dip-oriented contrasts in number and architecture (stacking and/or magnitude) of surfaces formed by incision–aggradation cycles. Rivers are more sensitive to buttress shift at the shore because they are confined within a thin channel-scale buffer zone. Any buttress shift that vertically moves these conjoined confining buffers forces the contemporary channel profile to soon follow. Architecture recording incision and stacking of discrete channel-belts in close concert with buttress shift is thus expected down dip. The buffers are not moved by buttress shift at some distance up dip (120 km for the middle Mesa Rica transgression), therefore surfaces cut by buttress-driven cycles need not all be distinguishable in these up-dip reaches (e.g., surface SB3.2; Fig. 3). During a buttress shift, contemporary channels up dip may undergo several cycles of valley-scale incision and aggradation within a thicker buffer zone because of more variable upstream base-level effects. Though these upstream effects may propagate downstream, their control on timing and magnitude of incision diminishes as downstream base-level controls gain dominance over profile position. Architecture, particularly stacking arrangement, of equivalent bounding surfaces may change down dip in response (Blum and Valastro 1994). Up-dip valley scours encasing multiple stacked channel belts may also be compressed down dip to the architectural magnitude of single channel belts as they are squeezed into a more channel-scale buffer zone. Multiple up-dip valley fills can thus pass down dip into an architecturally more simple set of aggrading or laterally amalgamating channel belts that collectively reflect a single buttress shift. This appears to be the case throughout the Dakota section.

Second, fluvial sandstone sheets generally record buffers that are stable over long durations, whereas discontinuous fluvial sandstone records comparatively mobile buffers. Rapid elevation of buffers proportionally increases aggradation rates. Increased aggradation relative to sediment supply favors filling of new preservation space with muddy (e.g., Aslan and Autin 1999) and/or peaty (e.g., Berendsen and Stouthamer 2001) flood-basin strata in lieu of channel belts (e.g., Dry Creek Canyon Formation). Construction of a strike-extensive sand sheet requires that the buffers instead remain stable for a long enough time to permit channels to laterally shift (by migration and avulsion) to all parts of the sheet and replace any prior deposits with channel-belt sand (e.g., lower Mesa Rica member). This duration is inversely proportional to lateral shift rates of formative channels and directly proportional to sheet strike extent. Local sheets can form sooner than regional sheets if avulsions are locally concentrated (e.g., confinement of river avulsions to incised valleys, concentration of avulsion at nodes, etc.). Thickness of sheets resulting from stationary buffers is determined by the thickness of the preservation space between the buffers. In cases where relative buffer rise is sufficiently slow as to maintain effective stability, younger sheet deposits continuously bury older sheet deposits. Aggradation may result in a composite sheet with thickness equal to the interval within and between its lowermost and uppermost preservation space. Because available sandy bedload tends to fill the upstream parts of the preservation space first (Strong et al. 2005), dip-oriented variations in the strike continuity of sheets are likely.

Third, total stratal volume accumulated over the life of a fluvial system can be quantified as the preservation volume generated within the initial and final buffer zones, plus the preservation volumes generated by migration in between, minus the material removed by subsequent or coeval erosion processes. Programs for simulating channel profiles are available (e.g., Tebbins et al. 2000) and could be used for simulating buffer profiles. Integration of preservation volumes between buffer profiles over the depositional span of a fluvial system is a potential approach to simulating fluvial stratigraphic geometry and architecture.

### *Effects of Setting on Model Variability*

Architecture and geometry of fluvial strata likely varies because of differences in greenhouse vs. icehouse settings. Both greenhouse (Pratt 1984; Carmo and Pratt 1999; Hoffman et al 1999) and icehouse (Hall 1990; Page et al. 1996; Blum and Valastro 1994) conditions are subject to climatic fluctuations that can alter upstream base-level controls on time scales of $10^3$ to $10^5$ years. Icehouse conditions are subject to high-amplitude glacioeustatic sea-level changes on time scales within this range ($10^4$ to $10^5$ years) but greenhouse sea-level changes of similar or greater amplitude tend to be more long term ($10^5$ to $10^6$ years) (e.g., Revelle 1990). Dakota strata record the greenhouse condition whereby large downstream base-level effects from sea level were on scales of $10^5$ to $10^6$ years. Shore-proximal areas at this time were typified by long-term lateral reworking of channel-belt sand between stable buffers. Conceivably, the more mobile sea-level buttress typical of icehouse conditions would provide for less stable coastal buffers. One would expect icehouse conditions to be less conducive to long-term lateral reworking and sheet formation on coastal plains (George Postma, personal communication). Coastal icehouse strata might be more typified by units reflecting mobile buffers. Closer similarity in frequency between up-dip and down-dip incisional cycles may also result in less contrast in architectural complexity between these areas during icehouse conditions.

Basin physiography and tectonics also have a profound effect on fluvial geometry and architecture. For instance, regression across low-sloping ramps tends to prompt lateral deposition preserving strike-continuous fluvial units that are floored by relatively flat erosional surfaces (Holbrook 1996; Wellner and Bartek 2003). This is because the buffer profiles here tend to experience little change during regression. Incision of deep discrete valleys by sea-level fall requires a net buttress drop that often may be accomplished only by regression beyond a topographic break (e.g., the shelf-slope break (Vail et al. 1977), etc.). Likewise, uplift and subsidence may move the land surface with respect to the buffer profiles. Possible responses are explored in Figure 8E and 8F.

### *Sequence Stratigraphy*

Sequence stratigraphic models (e.g., Fig. 1) could be improved by amending them to consider shifting of buffers in response to shifting of a buttress (i.e., sea level). This approach would aid in the integration of upstream base-level controls into these primarily downstream-oriented models. In particular, this would permit them to capture the architectural complexities related to higher-frequency incision–aggradation cycles gained in the up-dip direction because of increasing influence of primarily upstream controls like climate and tectonics.

Consideration of the buffers and buttresses model also helps elucidate the genesis and characteristics of ''lowstand'' fluvial sandstone. Fluvial sandstone layers composed of amalgamated channel belts that lie above erosional sequence boundaries are generally categorized as lowstand systems tract (LST; Fig. 1). Upper and lower Mesa Rica and Romeroville sandstone layers would each fit these general criteria, and could thus be defined as lowstand deposits in this context. The buffers and buttresses model argues, however, that these strata were each actually deposited throughout falling stage and lowstand and were still forming during the part of subsequent transgression that preceded local lifting of the buffers. Indeed, the Mesa Rica within the Huerfano Canyon might be labeled lowstand locally by the initial criteria, even though more regional study reveals that these strata incorporate deposits of an entire transgressive–regressive cycle that is well expressed farther down dip. Though a sand-rich fluvial deposit composed of amalgamated channel belts is common to the bases of most sequences, these strata may be deposited over various stages within the early part of a marine sea-level cycle. Lowstand is probably a misleading term for these strata. Likewise, these basal sandy units, and underlying sequence boundaries, tend to merge landward in all models in Figure 8 except 8E. Landward merging of these sandy basal strata is the case for Dakota sequences, and is likely the case for most sequences where subsidence does not increase up dip.

## CONCLUSIONS

Buffers and buttresses serves as a general model for preservation of fluvial strata that can elucidate geometry and architecture of fluvial strata in the context of both upstream and downstream base-level controls. The model considers fluvial preservation to be limited to some space between upper and lower maximum possible profiles, ''buffers,'' that move and/or alter shape with downstream base-level shifts. Downstream base level is considered to be controlled by movement of some physical ''buttress'' (e.g., sea level, etc.) below which streams cannot incise and above which streams cannot aggrade substantially. Upper and lower buffers are both anchored to this buttress, and may diverge for some distance up dip as profile variability is introduced by increasing influence of upstream base-level controls. Upstream controls like climate and tectonics primarily determine spacing trends between these upper and lower buffers. Geometry and architecture of fluvial strata accumulated during the depositional life of a fluvial system are primarily determined by the cumulative movement of the preservation space that is confined between the buffer profiles and the rate and fluctuation of sediment storage within this preservation space.

The buffers-and-buttresses model offers insights into observations from Dakota strata that are not well addressed by prior sequence-stratigraphic models. Namely, this model offers a more encompassing explanation for the dip-extensive ($\leq$ 300 km) and strike-extensive ($\leq$ 84 km) continuity, the up-dip increase of architectural complexity, and the up-dip thickness increase observed within amalgamated channel-belt strata of the upper and lower Mesa Rica and Romeroville sandstone layers. The model predicts that retreat of a sea-level buttress (regression) over a low-gradient ramp deposits a dip-extensive layer of sandstone between relatively stable buffers. Longer durations of buffer stability during regression favor storage of sand by lateral channel reworking and thus production of continuous strike-oriented sandstone sheets. Durations required for sheet production are inversely proportional to rates of lateral channel reworking. Furthermore, architectural complexity and thickness of these layers typically increase up dip as higher-frequency upstream base-level controls gain increasing influence over lower-frequency downstream controls. The buffers-and-buttresses model can be merged with existing sequence-stratigraphic models in the future in order to capture such complexities in fluvial geometry and architecture.

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