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Erosional surfaces in the Upper Cretaceous Castlegate Sandstone (Utah, USA): Sequence boundaries or autogenic scour from backwater hydrodynamics?

Elizabeth J. Trower[1], Vamsi Ganti[2], Woodward W. Fischer[3], and Michael P. Lamb[3]
[1]Department of Geological Sciences, University of Colorado Boulder, Boulder, Colorado 80309, USA
[2]Department of Geography, University of California Santa Barbara, Santa Barbara, California 93106, USA
[3]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA

ABSTRACT

Sequence stratigraphy relies on the identification of unconformity-bound sedimentary packages in order to understand variations in sediment supply, subsidence, and eustasy, which are themselves controlled by external (allogenic) drivers such as climate and tectonics. However, intrinsic (autogenic) river dynamics can also create a rich stratigraphic architecture in the absence of allogenic changes. Here, we outline scaling relationships for the expected depth and length scales of autogenic scour resulting from non-uniform flows in coastal rivers, and apply these relationships to the Upper Cretaceous Castlegate Sandstone—a classic fluvial sandstone unit in the Book Cliffs of Utah (USA). Theoretical and experimental work suggests that hydrodynamics within the backwater reach of coastal rivers—the zone of non-uniform flow that extends upstream of the river mouth—causes spatially extensive erosion during floods; this in turn creates erosional surfaces within fluvio-deltaic stratigraphy that may appear similar to sequence boundaries. Results demonstrate that scour patterns within the Castlegate Sandstone are consistent with the predictions of backwater-induced scours, and show how allogenic versus autogenic erosional surfaces can be parsed within fluvio-deltaic stratigraphy.

INTRODUCTION

Sequence stratigraphy is based on the identification of genetically related rock sequences contained between major erosional unconformities referred to as "sequence boundaries" (e.g., Van Wagoner et al., 1987; Catuneanu and Zecchin, 2013; Ainsworth et al., 2017). Sequence boundaries are often interpreted as signals of relative sea-level fall, which results in incision and the formation of significant erosional surfaces (Fig. 1A). Variations in sediment supply, subsidence, and eustasy can contribute to the development of a sequence boundary; these are thought to be controlled primarily by allogenic forces—climate and tectonics (Schlager, 1993). However, recent studies have demonstrated that autogenic dynamics in fluvio-deltaic systems can mask or overprint allogenic signals (Best and Ashworth, 1997; Jerolmack and Paola, 2010; Ganti et al., 2014b; Mikeš et al., 2015; Li et al., 2016), and there is growing recognition of the role that autogenic processes (e.g., delta-lobe switching, auto-retreat) may play in determining stratigraphic architecture (e.g., Strong and Paola, 2008; Catuneanu and Zecchin, 2013; Hampson, 2016). This presents a significant challenge for fluvial sequence stratigraphy: the erosional unconformities that define sequences might be generated by allogenic and/or autogenic processes. It is therefore critical to understand the conditions under which allogenic and autogenic signals overlap in order to untangle them in the rock record.

Non-uniform flows affect sediment transport and erosional patterns in coastal rivers. The backwater reach of a river is the distal zone of non-uniform flow due to the boundary condition of near constant water surface elevation at the river mouth (Lane, 1957), which can extend hundreds of kilometers inland for large, low gradient rivers (Lamb et al., 2012). Recent field, experimental and theoretical work demonstrate that backwater hydrodynamics significantly affect sediment dispersal (Lamb et al., 2012; Nittrouer et al., 2012), river avulsion locations (Jerolmack and Swenson, 2007; Chatanantavet et al., 2012; Ganti et al., 2014a), and river lateral migration (Lamb et al., 2012; Fernandes et al., 2016); these ideas are beginning to be incorporated into conceptual models and interpretations of stratigraphic architecture (Blum et al., 2013; Colombera et al., 2016; Fernandes et al., 2016; Durkin et al., 2017). However, workers have yet to address the stratigraphic implications for the observation that coastal rivers may scour deeply within the backwater zone during large floods (Lamb et al., 2012; Chatanantavet and Lamb, 2014), potentially leaving widespread erosional surfaces.

We hypothesized that autogenic scour resulting from river floods in backwater zones can produce an identifiable stratigraphic fingerprint and developed predictive relationships for the spatial scales of these autogenic scours. We evaluated this hypothesis through examination of Cretaceous fluvio-deltaic deposits of the Castlegate Sandstone in the Book Cliffs of Utah (USA)—a locality where modern concepts in fluvial sequence stratigraphy were developed (e.g., Van Wagoner, 1991, 1995).

EROSIONAL SCOURS FROM BACKWATER HYDRODYNAMICS

The backwater reach is characterized by non-uniform flows, where during low water discharge, the flow decelerates toward the river mouth leading to net deposition; and during large floods, the flow accelerates toward the river mouth leading to net erosion (Lane, 1957; Lamb et al., 2012; Nittrouer et al., 2012). The length of the backwater zone (L_b) scales with the characteristic bankfull flow depth (h_c) and the river bed slope (S): $L_b \sim h_c/S$ (e.g., Jerolmack and Swenson,

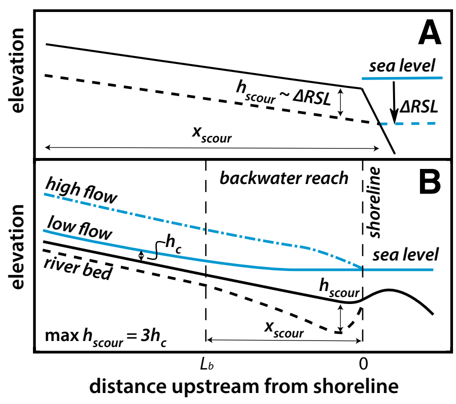

Figure 1. Schematics of scour patterns predicted for relative sea-level (RSL) fall (A) and in the backwater reach under variable flow conditions (B). Black lines indicate width-averaged river bed elevation prior to (solid line) and after (dashed line) scour by either RSL fall (A) or backwater-induced scour (B) driven by changes in water surface elevation (blue lines; solid line—prior to scour, dashed line—condition driving scour).

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2007), where h_c and S are evaluated upstream in a reach of normal flow (Fig. 1B). The backwater zone vacillates between periods of deposition and erosion because floods are short-lived relative to the timescale (years to decades) needed for the river bed to reach topographic equilibrium with a given flow discharge (Chatanantavet and Lamb, 2014). Thus, a region of transient bed adjustment (i.e., episodic deposition and scour) tied to the backwater reach is expected, rather than the normal-flow conditions that are often assumed in basin filling models.

Field, experimental, and theoretical work showed that during large floods (> bankfull), the water surface elevation in the backwater zone is drawn down at the river mouth to match sea level, resulting in a zone of spatial flow acceleration that extends ~$L_b/2$ upstream of the river mouth (Chatanantavet et al., 2012; Lamb et al., 2012; Nittrouer et al., 2012) (Fig. 1B). During these events, intense river bed scour occurs near the river mouth and rapidly propagates upstream to ~$L_b/2$ (Chatanantavet and Lamb, 2014; Ganti et al., 2016). Thus, the scour depth is deepest near the river mouth and shallows upstream to ~$L_b/2$ becoming characteristic of normal flow conditions at L_b (Fig. 1B).

The maximum backwater-induced scour at the river mouth is related to the flood regime; through deposition and erosion, the river bed attempts to adjust to a given flow, so that maximum scour depth (h_{scour}) scales with the difference in the normal flow depths between typical low and high flows: $h_{scour} \propto \Delta h$ (Chatanantavet and Lamb, 2014). A compilation of modern rivers shows that Δh scales with h_c by a factor of 0.5–3 (Ganti et al., 2014a), indicating that $0.5h_c \leq h_{scour} \leq 3h_c$ for backwater-induced scours. Upstream of the backwater zone, channel scour depths are expected to be $<h_c$ and can form due to channel lateral migration or channel avulsion and reoccupation (Mohrig et al., 2000). The reduction in lateral migration rates of rivers within the backwater zone (Lamb et al., 2012; Fernandes et al., 2016; Durkin et al., 2017) suggests that backwater-induced scours may be preferentially localized near the shoreline. Backwater-induced scours should have a stratigraphic expression: the largest floods scour deeply but infrequently, allowing time for the scoured surface to be buried by subsequent low-discharge events and preserved via subsidence and compaction.

STUDY SITE AND METHODS

The Lower Castlegate Sandstone in the Book Cliffs of southern Utah is well exposed as cliff-forming fluvial sandstones that transition eastward into marine sandstones within the Mesaverde Group—a sequence of fluvial, coastal plain, deltaic, and shoreface-to-shelfal marine sedimentary rocks that accumulated along the western margin of the Cretaceous Western Interior Seaway (Van de Graaff, 1972).

Van Wagoner (1991, 1995) identified and interpreted scour surfaces in the lower Castlegate Sandstone as components of two sequence boundaries that separate shoreline and shelf facies representing beach parasequences and non-marine stream facies interpreted as incised-valley fills. These abrupt "basinward shifts in facies" were interpreted to reflect two rapid drops in relative sea-level (Van Wagoner, 1991, 1995). The controls on this base-level fall and its associated incision surfaces are a subject of ongoing debate (e.g., Miall and Arush, 2001, and references therein, suggesting that variability in paleocurrent directions and sediment provenance reflect a tectonic control), where the presumption is that Castlegate sequence boundaries are synchronous, regionally conformable surfaces recording abrupt base-level fall. However, Krystinik and DeJarnett (1995) correlated Western Interior Seaway sections from Arizona to Alberta using marine biostratigraphy and demonstrated that sequence stratigraphic surfaces were not regionally conformable, indicating that regional effects likely masked basin-wide eustatic signals. Furthermore, Pattison (2010) interpreted lower Castlegate channel scours as diachronous erosional surfaces resulting from multiple episodes of channel incision during sea-level fall punctuated by small-scale flooding events, during which channels were filled. These studies highlight inconsistencies between the predictions of allogenic changes and observations of the rock record.

We estimated the spatial scales of backwater-induced scours in paleo-Castlegate rivers by constraining paleo-channel bed slope (S), h_c, and L_b, and compared this with field observations of h_{scour}. Previous authors concluded that the paleo-shoreline was located between Sagers Canyon and Horse Pastures and oriented NNE, nearly normal to the trend of the modern Book Cliffs escarpment near Green River (Fig. 2A) (Van de Graaff, 1972; Petter, 2010). Paleo-current data indicate that Castlegate rivers flowed ESE, approximately normal to the inferred paleo-shoreline trend (Hampson, 2016 and references therein). In the field, we documented the sedimentology of Lower Castlegate units and measured bar heights and scour depths in a transect along the paleo-flow direction, including Price, Tusher, Crescent, West Blaze, Blaze, Sagers, and Sulfur Canyons. Bar height, median grain size, D_{50}, and h_{scour} data were also compiled from previous studies (Van Wagoner, 1995; Pattison, 2010; Petter, 2010). Paleo-flow depths were estimated from preserved bar clinoform heights (Mohrig et al., 2000) (Fig. DR1 in the GSA Data Repository[1]) and were used to constrain S by combining measurements of D_{50} and an empirical bankfull Shields relation from Trampush et al. (2014).

RESULTS

At Price and Tusher Canyons, the Lower Castlegate is composed of amalgamated sheet-like channel deposits (Fig. DR2), consistent with

[1]GSA Data Repository item 2018257, supplemental figures DR1–DR5 and Tables DR1 and DR2, is available online at http://www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org.

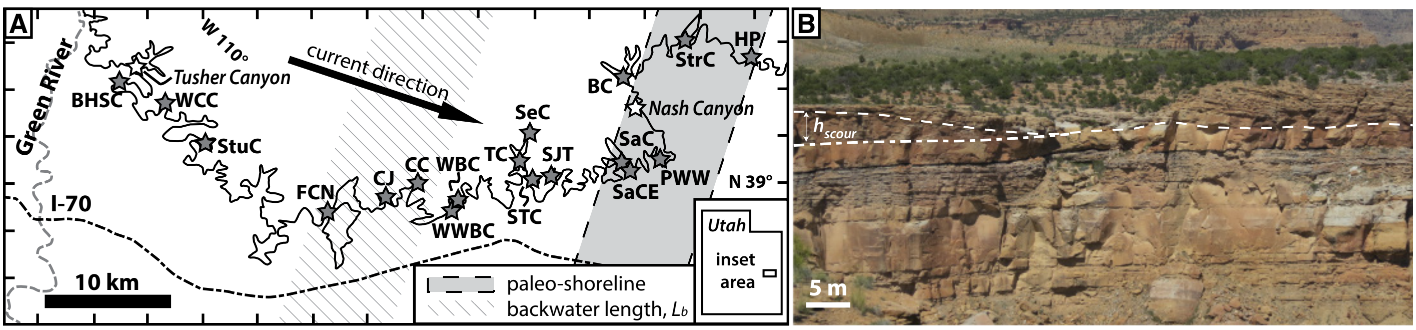

Figure 2. A: Location map of stratigraphic sections along the Book Cliffs (near Green River, Utah, USA), marked with gray stars. Approximate location of paleo-shoreline and backwater length shown in light gray and diagonal patterns, respectively. B: Scour surface (dashed line) in West Blaze Canyon. Section locations: BHSC—Big Horn Sheep Canyon, WCC—West Coal Canyon, StuC—Stubb Canyon, FC—Floy Canyon North, CJ—Crescent Junction, CC—Crescent Canyon, WWBC—West West Blaze Canyon, WBC—West Blaze Canyon, TC—Thompson Canyon, STC—South Thompson Canyon, SeC—Sego Canyon, SJT—Short Jeep Trail, SaC—Sagers Canyon, SaCE—Sagers Canyon East, PWW—Pinto Wash West, BC—Bull Canyon, StrC—Strychnine Canyon, HP—Horse Pastures. Latitude and longitude ticks indicate 3′ increments.

the facies association described by Petter (2010). Downstream at Crescent and West Blaze Canyons, the Lower Castlegate is characterized by multistory channel complexes and more substantial local instances of incision into the underlying Blackhawk Formation (Fig. 2B; Fig. DR3). Farther east beyond Blaze Canyon, channel sandstones are less amalgamated and interbedded with siltstones. Discrete oyster build-ups are present in Sagers Canyon (Fig. DR4), indicating proximity to the paleo-shoreline consistent with previous work, including: beach ridge deposits interbedded with oyster shell coquinas between Thompson and Nash Canyons (Van de Graaff, 1972) and a shoreface facies in Thompson and Sagers Canyons (Pattison et al., 2008). Symmetrical wave ripples indicative of a shallow marine environment occur at Sulfur Canyon, ~20 km further east from Horse Pastures (Fig. DR5).

From bar height data (Table DR1), we estimated $h_c = 3.8 \pm 2.2$ m from the more proximal Tusher Canyon (estimated to be within the normal-flow reach of the Castlegate rivers; Petter, 2010). Median grain sizes of channel fill deposits were estimated as $D_{50} = 163 \pm 41$ μm based on previous analyses by Petter (2010), and were used as inputs to the bankfull Shields number criteria (Trampush et al., 2014) to yield $S = 2 \times 10^{-4}$ (Table DR1). Thus, our estimate of L_b ~20 km for Castlegate rivers is consistent with Petter's (2010) estimate of L_b = 20–30 km. Constraints on h_c result in predicted maximum scour depth near the river mouth $h_{scour} = 3h_c$ = 11.4 m and these scour depths are expected to taper upstream to approach less than h_c (< 3.8 m) at ~20 km.

Measured scour depths for the Castlegate range from h_{scour} = 1–11 m (Table DR2). Mean scour depths are greatest at the distal Bull Canyon and Pinto Wash West locations, and decrease westward toward Crescent Junction (Fig. 3A). Upstream of the inferred backwater zone, scour depths are small and relatively consistent over the remaining sections to Big Horn Sheep Canyon (Fig. 3A).

DISCUSSION

Our scaling relationships indicate that allogenic scour depths must significantly exceed the bankfull flow depth ($h_{scour} > 3h_c$) and occur over a distance longer than L_b in order to unambiguously distinguish allogenic signals from backwater-induced scour. Within the backwater reach (L_b ≈20 km), Castlegate scour depths (h_{scour}) range from h_c to $3h_c$, maximum scour depths occur ≤ 10 km ≈L_b/2 from the paleoshoreline, and scour depths upstream of L_b/2 from the paleo-shoreline are less than h_c; each of these agrees well with the predictions for a backwater signature in the absence of allogenic changes (Fig. 3A) and suggests that Castlegate rivers were connected to the sea (Bhattacharya, 2011). The extent to which relative sea level cycles influenced distal Castlegate

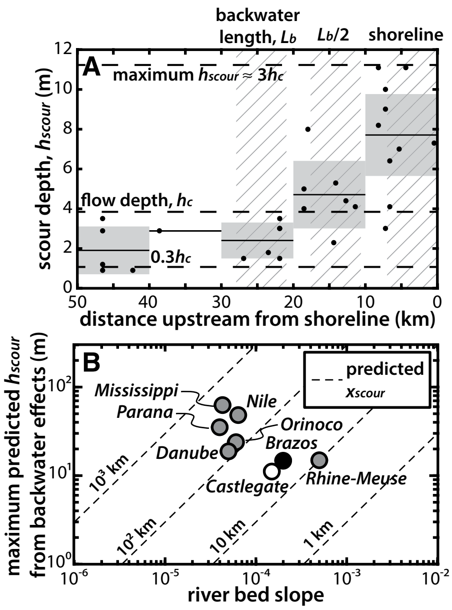

Figure 3. A: Castlegate (Utah, USA) scour depths versus upstream distance. Solid horizontal lines and gray boxes indicate mean and standard deviation of scour depth, respectively, for 10-km-long bins. Diagonal-lined regions indicate the uncertainty on the location of the paleo-shoreline and, consequently, the backwater length, L_b, and the upstream limit of backwater-induced scour, L_b/2. Horizontal dashed lines indicate upper and lower bounds on backwater-induced scours. B: Predicted depth and length of backwater-induced scours as a function of river bed slope compiled for modern rivers and the paleo-Castlegate and paleo-Brazos rivers (cf. Chatanantavet et al., 2012, their Table S1).

erosional surfaces is ambiguous owing to their consistency with backwater-induced scours. Nevertheless, marine to non-marine facies transitions in the Castlegate Sandstone are consistent with variations in relative sea level, whether resulting from allogenic changes or autogenic shifts in depocenters due to avulsion.

Our analysis constrains the depth and length of erosional scours resulting solely from autogenic backwater hydrodynamics and provides a framework to distinguish scour patterns that are necessarily allogenic from those that are plausibly autogenic. For example, Quaternary deposits of the paleo-Brazos River in Texas have 30–40 m deep incised valleys that extend for >100 km (Abdulah et al., 2004; Blum and Aslan, 2006) and have been attributed to sea-level fall driven by Pleistocene glaciation (Rohling et al., 2009). Given h_c ≈5 m (Sylvia and Galloway, 2006) and $S = 2 \times 10^{-4}$ (assuming a slope similar to the modern river; Phillips, 2015), we estimated L_b ~25 km for the paleo-Brazos River. In this case, the spatial scales of observed erosional scours (h_{scour} ~6–8h_c and $x_{scour} > 4L_b$) are 2-to-4 fold greater than backwater-induced scours; this analysis confirms that the observed incision was likely related to base-level change. For large, low sloping rivers, like the Mississippi, backwater-induced scour depths (h_{scour} ~$3h_c$ = ~75 m) might approach the largest Quaternary sea level cycles, scour lengths (x_{scour} ~L_b = ~450 km) can be regional in upstream extent, and channel width (~500 m) is large compared to typical scales of lateral continuity assessed in outcrop, which all present a challenge for assessing autogenic versus allogenic controls on sequence boundaries (Fig. 3B). In contrast, autogenic scours in smaller rivers will be spatially limited and may allow better separation of autogenic and allogenic stratigraphic signals (Jerolmack and Paola, 2010; Ganti et al., 2014b).

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