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Research Article

Fine-sediment Supply Can Control Fluvial Deposit Architecture: An Example From the Blackhawk Formation-Castlegate Sandstone Transition, Upper Cretaceous, Utah, USA

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The arrangement of channel and floodplain deposits in alluvial basins reflects the balance of subsidence, sediment supply, and channel avulsion behavior during accumulation. Approaches for reconstructing tectonic and climatic histories from alluvial architecture generally assume that floodplain preservation is primarily a function of channel mobility relative to long-term sediment-accumulation rate; however, the amount of mud supplied to a river network can significantly impact the baseline accumulation of fine-grained deposits in alluvial basins. Here we evaluate preserved fine-sediment volume fractions at the bedform, reach, and outcrop scale across the transition from the mudstone-dominated Blackhawk Formation to the sandstone-dominated Lower Castlegate Sandstone (Upper Cretaceous, Utah, USA). Results show a nearly 50% decrease in mud abundance across the Blackhawk-Castlegate transition at a range of morphodynamic scales (mud percent in bed material: 28.4% to 14.1%, interbar fine deposits: 39.6% to 22.1%, and outcrop architecture: 58% to 16%). This decrease in fine-grained sediment coincides with an abrupt increase in quartz abundance from Blackhawk to Castlegate sands, suggesting that unroofing quartz-rich source rock caused significant regional changes in the alluvial deposits. This result shows that changes in sediment supply grain size are detectable from bed to landscape scales and can cause major changes in stratigraphic architecture. This method of comparing sand-to-mud ratios can be broadly applied in other fluvial successions and in source-to-sink transects to better reconstruct mud fluxes through ancient fluvial networks and to investigate how rivers respond to changes in fine-sediment availability.

INTRODUCTION

The supply of fine sediment to an alluvial basin is an important control on stratigraphic architecture, but it is difficult to estimate from the rock record because fine-grained sediment is often bypassed downstream. Overall, the stratigraphic architecture of fluvial deposits is controlled by accommodation (the space available to accumulate sediments, controlled by subsidence and sea level), sediment supply, and landscape processes (such as river migration and avulsion; e.g., Leeder, 1978; Straub & Esposito, 2013). Studies have shown how total sediment supply can impact alluvial architecture, particularly through relationships between sediment supply, channel mobility, and basin-filling rate (e.g., Hampson et al., 2014; Heller & Paola, 1996; Lyster et al., 2020). However, most alluvial architecture interpretations implicitly assume the supply of fine sediment and the potential for overbank deposition is constant. Understanding whether changes in fine-sediment supply can cause observable shifts in alluvial architecture is important for reconstructing paleochannel mobility, predicting subsurface reservoir and aquifer connectivity, and constraining system-wide sediment budgets in ancient systems (e.g., Hampson et al., 2014; Holbrook & Wanas, 2014; Robinson & Slingerland, 1998).

Estimating the relative amount of fine sediment (diameter <63 microns) supplied to a sandy paleochannel is challenging because most fine particles are bypassed downstream, especially during times of rapid reworking due to low accommodation and/or highly mobile rivers (e.g., Leeder, 1978; Straub & Esposito, 2013); however, some fraction of the fines are deposited across multiple spatial and temporal scales within the fluvial network, even during sediment-bypass conditions. At the bedform scale, which reflects short term, local flow dynamics, fine sediment is trapped within the pore space of individual bedforms (such as dunes) and as drapes between bedforms (Wysocki & Hajek, 2021). This channel-bed deposition of fines increases with fines concentration in the river and is enhanced by flocculation and discharge variability (Lamb et al., 2020; Plink-Björklund, 2015; Wysocki & Hajek, 2021). At the reach scale, fine sediment can be deposited in zones of slow flow created by bars and channel bends (e.g., Durkin et al.,

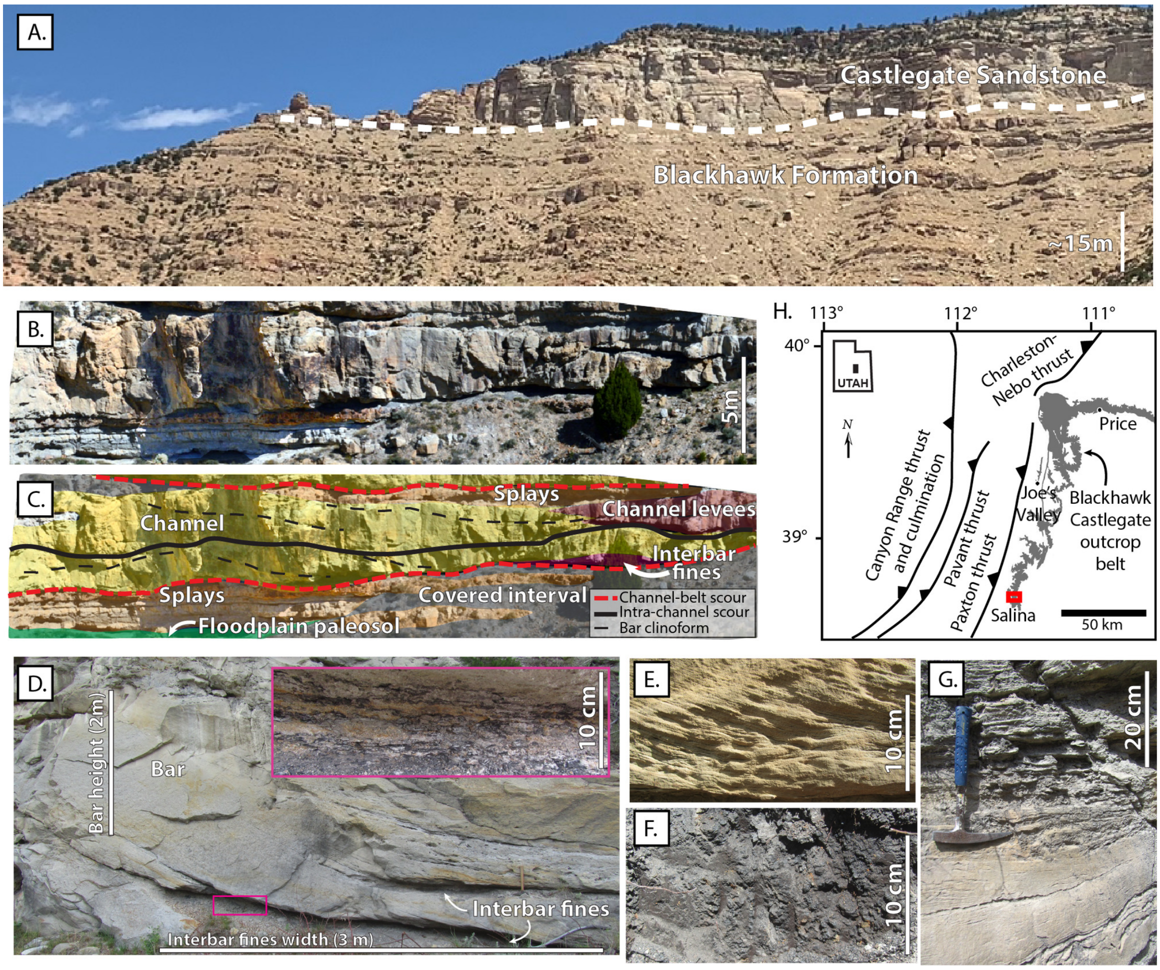

Figure 1. Fine sediment is stored at different scales within fluvial stratigraphy, from landscape (A), to reach (B-C), to bedform-scale storage (D-G). A: Outcrop photograph showing the transition from mudstone-dominated Blackhawk Formation to sandstone-dominated Lower Castlegate Sandstone; white dashed line shows formation contact. B-C: Photo of a Blackhawk Formation channel belt and surrounding floodplain deposit, with annotations in (C) showing key lithofacies packages and surfaces mapped in the field. D-G: Examples of bedform-scale storage of fine-grained sediment, including D: Castlegate bar with interbar fines at the toe; E: Blackhawk trough cross-beds with clay drapes; F: clay and organic-rich Blackhawk paleosol; G: rippled Castlegate levee. H: Study area map modified from Hampson et al. (2013).

2015; Hajek et al., 2010; Miall, 1988) (Figure 1B-1D). At the landscape scale, most fine sediment storage takes place in floodplains where fines settle out of suspension after floods (e.g., Pizzuto, 1987). The long-term storage of floodplain deposits is limited when channel mobility is high relative to accommodation creation rate, due to increased reworking of overbank material (e.g., Allen, 1978; Barefoot et al., 2022; Bridge & Leeder, 1979; Chamberlin & Hajek, 2019; Leeder, 1978).

We propose a new method to reconstruct the relative proportion of fines available to ancient rivers by combining observations across morphodynamic scales: bed-material sediments that reflect local, instantaneous sediment-transport conditions; bar-scale deposits that encompass channel migration processes; and outcrop-scale channel-floodplain ratios that integrate the balance of long-term basin filling and channel-reworking trends. We propose that a change in supplied fine-sediment flux would be detectable across these morphodynamic scales, from the bed-material to the outcrop scale, while changes in fine sediment preservation due to reworking (e.g., via channel migration and avulsion during times of low accommodation) would cause a decrease in fine-sediment abundance only at the landscape (outcrop) scale, and changes in the physical mechanisms promoting fines deposition in channels (e.g., changes in flow variability) would cause a change in fines content only at the bed scale. As a test case, we evaluated bed-, reach-, and outcrop-scale grain-size distributions from deposits of similar architectural style and context in the uppermost Blackhawk Formation and Lower Castlegate Sandstone in Salina Canyon (Upper Cretaceous, Utah, USA; Figure 1), where the composition, channel architecture, outcrop architecture, and landscape processes have been characterized in detail in previous studies (e.g., Adams & Bhattacharya, 2005; Chamberlin & Hajek, 2019; Flood & Hampson, 2014; Franczyk & Pitman, 1991; Lyster et al., 2020).

STUDY AREA

The Desert Member of the Blackhawk Formation and the Lower Castlegate Sandstone comprise fluvial and coastal plain deposits from rivers draining the Sevier fold-and-thrust belt into the Cretaceous Western Interior Seaway (e.g., Adams & Bhattacharya, 2005; Hampson et al., 2014; Van Wagoner, 1995; Van Wagoner et al., 1990; Figure 1H). There is a significant shift from isolated channel sandstones surrounded by fine-grained floodplain deposits in the Blackhawk Formation to sandstone-dominated channel deposits with limited mudstones in the Castlegate Sandstone (e.g., Adams & Bhattacharya, 2005; Figure 1A). Foundational studies in non-marine sequence stratigraphy interpreted this shift as representing an abrupt decrease in relative accommodation-creation rate (e.g., Miall & Arush, 2000; Van Wagoner, 1995; Yoshida, 2000). However, recent high-resolution correlations have shown that there is no single erosional surface between these formations and there are a range of possible auto- and allogenic controls on the stratal architecture of this interval (e.g., Pattison, 2019). Along with the overall shift to channel-sandstone dominated architecture, there is a petrographic change from calcite-cemented Blackhawk lithic arenites (including carbonate lithic grains) to silica-cemented quartz arenites of the Lower Castlegate, which has been connected to thrusting of quartz-rich source rocks in the fold-and-thrust-belt (e.g., along the Charleston-Nebo and Paxton thrust systems; Decelles & Coogan, 2006; Horton et al., 2004; Pujols et al., 2020). Additionally, Castlegate bars are exceptionally well-preserved, suggesting they were not routinely reworked via channel migration and avulsion processes; instead, either mud-poor sediment supply limited floodplain deposition during high accommodation conditions or floodplain mudstones were preferentially reworked downstream (e.g., during channel avulsion) under relatively low accommodation-creation rates (Chamberlin & Hajek, 2019). Other variables that could influence fine sediment deposition at the bed and reach scales, such as changes in the discharge variability, tidal influence, or fluvial style are assumed to be constant across this interval, because the climatic regime was constant (Kauffman & Caldwell, 1993), there is no sedimentologic evidence for tidal influence at the outcrops in Salina Canyon, and channels in the Blackhawk and Castlegate Sandstone were likely multi-threaded (e.g., braided) (Adams & Bhattacharya, 2005; Lyster et al., 2022). Furthermore, there is no evidence for significantly different flow variability or morphodynamic processes between these units (Lyster et al., 2021). Therefore, we expect that consistent changes in mud preservation across observation scales reflect changes in mud supply between the units.

METHODS

To quantify the mud (clay and silt) fraction in Blackhawk and Castlegate deposits in Salina Canyon, we mapped outcrop exposures into channel, proximal overbank, and distal overbank facies associations following Adams and Bhattacharya (2005) and Chamberlin and Hajek (2019) (Figure 1; Supplement) and used these categories for targeted sampling across morphodynamic hierarchies in both formations. For bed-material grain size measurements, sandstone cross-sets at the base of bar deposits were sampled from each formation and disaggregated for particle size analysis. Co-located interbar fines immediately adjacent to the bar – lensoidal pockets of rippled mud to very-fine-sand packages at the toes of bars (sensu Lynds & Hajek, 2006) – were sampled and analyzed to constrain bar-scale fines deposition. These interbar fines, deposited in zones of low shear stress in the lee of bars, can be distinguished from other morphodynamic elements by their bar-adjacent location, lensoidal geometry, and sedimentary structures (Lynds & Hajek, 2006).

To assess outcrop-scale fine sediment fractions, we first estimated the relative proportions of each facies association in measured sections and photo panels (Figure 2, Supplement). For the Blackhawk Formation, outcrop-scale facies association estimates were based on three measured sections and two mapped outcropped panels from Flood and Hampson (2014) (Figure 2A; Supplement). We classified covered intervals within measured sections as distal overbank because finer-grained intervals form vegetation- and scree-covered slopes in the study area. For the Castlegate Formation, facies proportions were estimated from an interpreted cliff-face photo panorama from Chamberlin and Hajek (2019) (Supplement). This published mapped panel does not include distal overbank facies (Chamberlin & Hajek, 2019), but we observed distal overbank in very small amounts at other locations in the study area. We therefore estimated that 1% of the Castlegate Formation is distal overbank facies.

To estimate bulk grain-size distributions across facies, we selected the median grain-size distributions of samples across each facies association (i.e., channel, proximal overbank and distal overbank) for Blackhawk and Castlegate deposits (Supplement). We combined these grain-size distributions with outcrop-scale facies proportions to estimate the overall mud fraction in each formation. We note that this generalization does not account for minor fractions (<5% of the total cross-sectional area) of coarse lags in channel deposits or coal in overbank deposits.

Particle size analysis

To measure grain-size distributions of the bed-material and interbar-fine sediments, we mechanically disaggregated each sample with a mortar and pestle, and then we analyzed each sample using Penn State University's Malvern MasterSizer 3000, a laser particle size instrument that can measure grains from 0.1-3500 microns. Each sample was suspended in water, constantly stirred with a magnetic stir bar/plate and pipetted from a sample cup at an equal water depth to introduce the sample to the instrument.

Mechanical disaggregation of samples can introduce error via grain breaking or incomplete separation and because cements remain in the sample, either as coatings on grains or as disaggregated particles. However, chemical dissolution of calcite cements would have destroyed carbonate

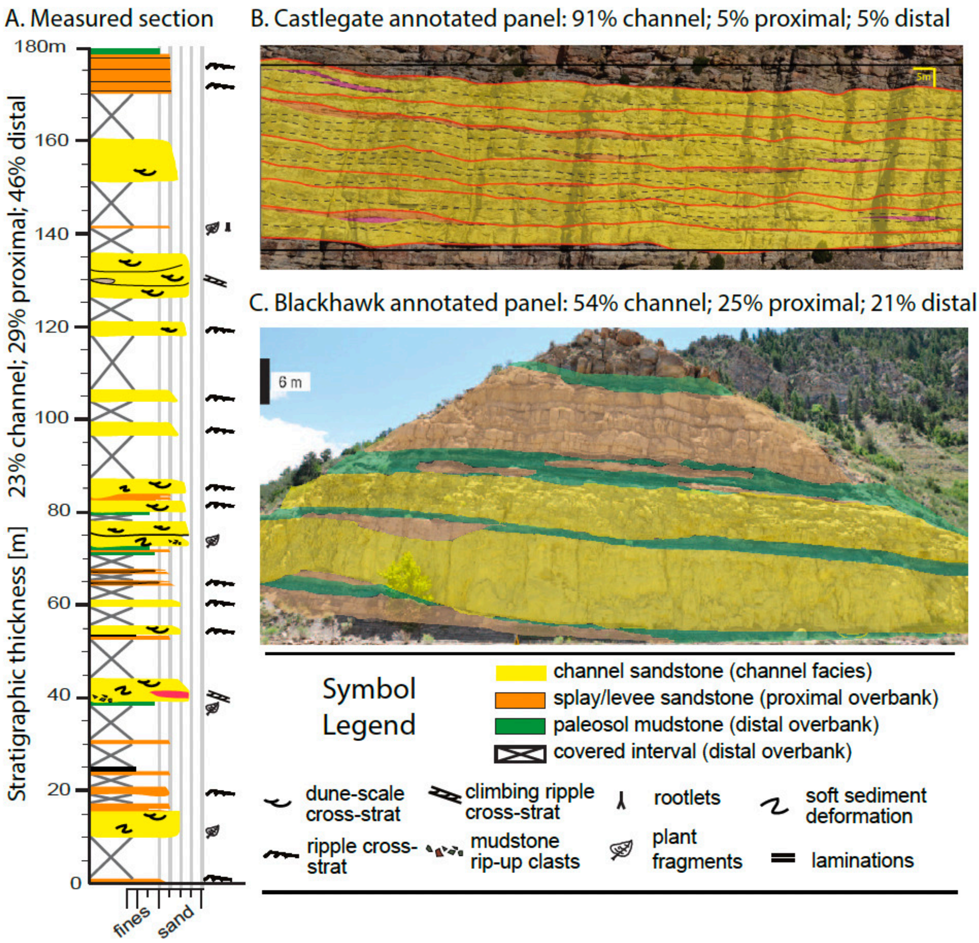

Figure 2. Examples of dataset types used to calculate outcrop-scale grain size estimates, including A) measured sections, B) an annotated photo panel of the Castlegate Sandstone modified from Chamberlin and Hajek (2019), and C) digitized Blackhawk Formation outcrop interpretations from Flood and Hampson (2014) (their locality SaC12).

lithic grains in Blackhawk Formation samples, and there is no simple disaggregation method for the silica-cemented Castlegate samples. To assess the potential impact of mechanical disaggregation on our particle-size analyses, we examined each sample with a binocular microscope at several intervals during the disaggregation process to ensure complete disaggregation and minimal broken grains. Additionally, we chemically disaggregated a subset of Blackhawk Formation samples in HCl without mechanical disaggregation to evaluate what fraction of fines in mechanically disaggregated samples might reflect ground-up cements rather than primary transported fines. Mechanically disaggregated bed material samples from the Blackhawk had 0.3% more fines on average than chemically dissolved samples, and mechanically disaggregated interbar fines samples had an average of 3.3% more fine sediment than chemically disaggregated samples. This indicates that the mechanical breakdown of cements could artificially increase the total transported fraction of fines in samples by up to approximately 3.5%.

RESULTS

Channel-bed material in both formations is predominantly trough cross-stratified fine- to medium-grained sandstone and is primarily deposited in bar clinoforms (Figure 1). We found that channel-belt and bar packages have a similar architecture in both formations (also documented by Adams & Bhattacharya, 2005), although Blackhawk channels have more abundant soft-sediment deformation and in some cases contain clay drapes along cross-bed and bed-set bounding surfaces, while Castlegate channels are more likely to contain granule lags at the base of preserved thalweg fills. Grain-size analysis shows a 50% decrease in bed-material fines (silt and clay) between the Blackhawk (28.4% by volume) and Castlegate formations (14.1%) (Figure 3a; Table 1). The tenth percentile (D_{10}) and median (D_{50}) grain-size diameters are finer in Blackhawk bed material samples than in the Castlegate, but the ninetieth percentile (D_{90}) diameters are similar (Table 1), suggesting that the differences in bed material grain-size distributions are primarily due to differences in the abundance of fines.

At the reach scale, interbar fines in both formations comprise sedimentologically similar ripple-laminated,

Table 1. Lithofacies-, reach-, and outcrop-scale grain size results for the Blackhawk and Castlegate formations.

		D10 (µm)	D50 (µm)	D90 (µm)	Percent <4 µm	Percent <63 µm
Bed-material measurements (bedform scale)	Blackhawk Formation	5.6	128	277	8.6	28.4
	Castlegate Sandstone	36.5	170	299	5.6	14.1
Interbar-fine measurements (reach scale)	Blackhawk Formation	4.3	80	178	9.8	39.6
	Castlegate Sandstone	12.5	104	194	7.6	22.1

		Facies	Outcrop proportion	Percent < 63 µm	Percent > 63 µm
Outcrop-scale estimates	Blackhawk Formation	*Channel*	0.26	28.4	71.6
		Proximal overbank	0.34	40	60
		Distal overbank	0.39	60	5
		Bulk outcrop	1.00	58	42
	Castlegate Sandstone	*Channel*	0.94	14	86
		Proximal overbank	0.05	40	60
		Distal overbank	0.01	90	10
		Bulk outcrop	1.00	16	84

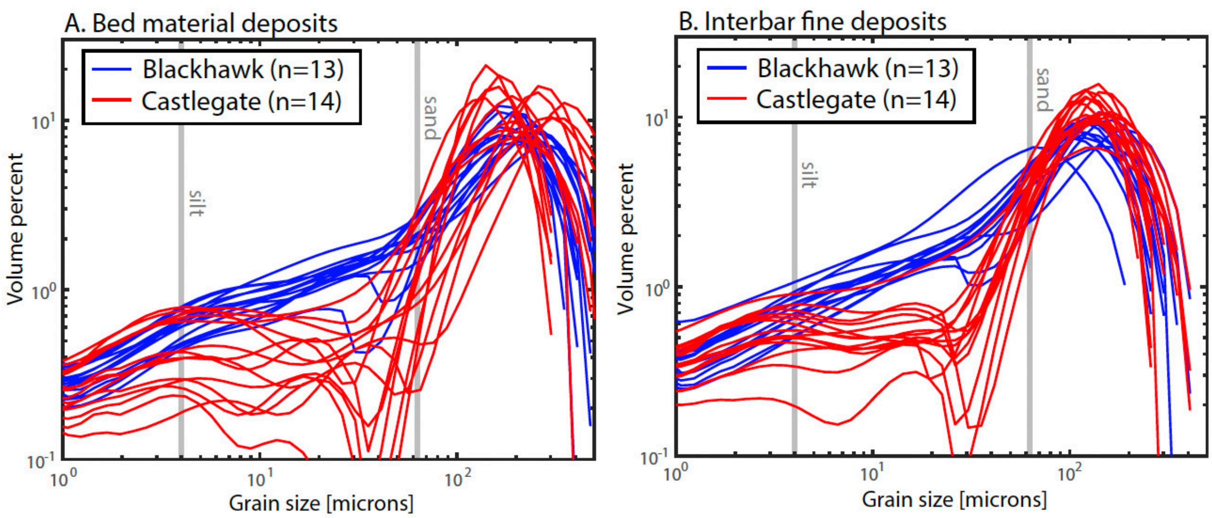

Figure 3. Log-log plots of measured grain size distributions for bed material (A) and interbar fine (B) samples. Blackhawk Formation samples have higher volume percentages of fines in both bar and interbar fine deposits, particularly in the silt range.

lensoidal pockets of interbedded silts and fine sands at the toes of bar clinoforms (Figure 1D). At their maximum extents, Blackhawk interbar fines range from 0.3-5m wide and 0.02-0.4m thick and Castlegate interbar fines are a comparable size (0.03-0.6m thick, 0.5-4m wide) (Supplement). Consistent with bed-material results, grain-size analysis shows that there is a 44% decrease in mud content between Blackhawk (39.6%) and Castlegate (22.1%) interbar fines (Figure 3B), along with a statistically significant decrease in the D_{10} and D_{50}, but not in the D_{90}, grain sizes (Table 1).

At the outcrop scale, there is a clear difference between the predominately covered, sloping Blackhawk Formation and the cliff-forming Castlegate Sandstone. In both formations, proximal overbank deposits comprise normally graded, current rippled very fine to fine-lower sandstones with tabular or lenticular shapes and lateral extents >10s of meters; in the Blackhawk Formation, organic rich, laminated siltstone interbeds are common. Distal overbank deposits in the Blackhawk comprise meter-thick packages of dark gray silty mudstones and coals with varying degrees of pedogenic development that can include slickensides, orange mottling, and root traces. In contrast, distal overbank facies in the Castlegate are <1m thick packages of interbedded, laminated gray siltstones and very fine sandstones with limited pedogenic features. At the outcrop scale, Blackhawk Formation deposits are approximately 26% channel, 34% proximal overbank, and 39% distal overbank facies, while the Castlegate Sandstone comprises approximately 94% channel, 5% proximal overbank, and 1% distal overbank facies. Combining the field-generated facies proportions and lab-generated grain-size datasets shows that the outcrop-scale mud fraction decreases from 58% in the Blackhawk Formation to 16% in the Castlegate (Table 1; Supplement). This is consistent with observed trends at the bed and reach scales, showing that the Castlegate has significantly less fine-grained sediment than the Blackhawk at all measurement scales.

DISCUSSION

We document a large reduction in mud across three morphodynamic scales, the magnitude of which is remarkably consistent with a basin-wide, source-to-sink estimate showing a regional 50% decrease in fine sediment across Blackhawk and Castlegate time (Hampson et al., 2014). This consistency across scales is coincident with an abrupt change in sandstone composition from carbonate-lithic-rich Blackhawk deposits to quartz arenite Castlegate sandstones (Adams & Bhattacharya, 2005; Franczyk & Pitman, 1991), and there is no evidence for increased deposit reworking across this interval (Chamberlin & Hajek, 2019). Overall, this suggests that the major architectural shift between the Blackhawk and Castlegate was driven by a reduction in the amount of mud supplied to the river networks. If the reduction in mudstones preserved in the Castlegate were instead the result of increased reworking of deposited floodplain sediments via channel migration and avulsion (e.g., Barefoot et al., 2022; Leeder, 1978; Miall & Arush, 2000), there is no reason the proportion of fines preserved in channel facies, and particularly channel bed-material, would change. Instead, we document a coincident and parallel reduction in the proportion of fines at the reach scale, where the abundance and fine-sediment fraction of intra-channel slackwater facies decreases, and within bed-material deposits, which have been shown to reflect the proportion of fine-sediment supplied to sand-bed systems (Wysocki & Hajek, 2021). This interpretation is consistent with bar-preservation observations and modeling predictions of Chamberlin and Hajek (2019), which show well-preserved bar deposits consistent with sufficiently high accommodation creation during Castlegate deposition in Salina Canyon.

This interpreted change in sediment supply grain size was likely due to the exhumation of quartzite-rich source rocks during thrusting in the Sevier fold-and-thrust belt (e.g., the Neoproterozoic-Cambrian Prospect Mountain Quartzite and the Pennsylvanian-Permian Oquirrh Formation; Decelles & Coogan, 2006; Horton et al., 2004; Pujols et al., 2020). Detrital zircon studies of Blackhawk-Castlegate sandstones show a consistent source area across this boundary (Pettit et al., 2019), and duplexing along the Paxton thrust likely exposed quartz-rich source rocks within the drainage basin (Decelles & Coogan, 2006; Horton et al., 2004; Lawton et al., 2007; Pujols et al., 2020). Paleocurrents are consistent across the formation boundary (Supplement; Franczyk & Pitman, 1991), and there is no change in fluvial style (Adams & Bhattacharya, 2005; Lyster et al., 2021, 2022), so it is unlikely that this shift represents a change from a transverse to longitudinal system at these sites in Salina Canyon. Quartz-rich source units are difficult to distinguish using detrital zircons (e.g., Lawton et al., 2010), which may explain why Pettit et al. (2019) did not identify a shift in source rock between these formations.

Overall, these results suggest that an incidental change in fine-sediment supply due to unroofing could result in significant alluvial architecture changes, which indicates that in some cases, changes in sediment supply grain size are as important for alluvial architecture as volumetric sediment supply, subsidence, and channel reworking (the suite of variables traditionally considered in sequence stratigraphic analysis). Differences in fine-sediment supply could explain the lack of correlation between channel deposit proportion and aggradation rate (Colombera et al., 2015), and should be incorporated into sequence stratigraphic frameworks. For the Blackhawk-Castlegate transition specifically, this new interpretation of a sediment-supply-driven change in architecture is inconsistent with the traditional interpretation of a sequence boundary at the base of the Castlegate (e.g., Miall & Arush, 2000; Van Wagoner et al., 1990; Yoshida, 2000), which requires a change in accommodation-creation rate relative to total sediment flux. Other recent studies have also reevaluated this sequence boundary from other perspectives, including a lack of evidence for large-scale incised valleys across this formation boundary (Pattison, 2019; Trower et al., 2018), and no evidence for reworking of Castlegate deposits (Chamberlin & Hajek, 2019). At a large scale, there are major tectonic and eustatic controls on architectural changes in these Sevier foreland basin deposits (e.g., Aschoff & Steel, 2011), but these results suggest that fine-sediment supply can cause major shifts in deposit architecture across formation boundaries within this larger framework.

A loss in mud supply could have significant impacts on the morphodynamics of a fluvial network. An overall coarser sediment load, lacking abundant fine silt and clay, might promote crevasse-splay development (i.e., "proximal overbank" facies) rather than distributed muddy floodplain deposition and abundant "distal overbank" facies (e.g., Millard et al., 2017; Nienhuis et al., 2018). Castlegate overbank facies are generally sandier than Blackhawk floodplain deposits (Figure 1), supporting the possibility that Castlegate floodplains were coarser overall. Additionally, the small, patchy nature of Castlegate floodplain deposits, and the lack of pedogenic development, suggest they were temporally less stable than Blackhawk floodplains. Decreasing the proportion of cohesive clay in floodplain sediments may lower floodplain erodibility thresholds, promoting wider (e.g., Dunne & Jerolmack, 2020) and more laterally mobile (e.g., Edmonds & Slingerland, 2010) channels. This is consistent with interpretations that Castlegate channel belts were wider and more multi-thread than Blackhawk rivers (e.g., Adams & Bhattacharya, 2005; Lyster et al., 2022).

The loss of fine sediment in Castlegate deposits is most pronounced in the range of 10-50 microns, where there is a distinct drop in relative abundance between the relatively flat, fine tail and coarser peak of sandy sediments in the bed-material and interbar fines grain-size distributions (Figure 3). Similar grain-size distributions have been observed in modern rivers and may indicate the role of flocculation in fine-sediment transport (Hajek et al., 2010). The mechanism through which changes in the fine-grained sediment flux are preserved in the deposit grain sizes across spatiotemporal scales remains unclear, but flume experiments do show that higher clay concentrations in the sediment flux leads to increased clay deposition in the bed, particularly during aggradational phases (Wysocki & Hajek, 2021), and clay flocculation and flow variability can also increase fine deposition in the bed (e.g., Bungartz & Wanner, 2004; Fielding et al., 2017; Lamb et al., 2020; Plink-Björklund, 2015). Thus, while flow hydraulics may be the dominant control on fine sediment deposition at any one location (Lamb et al., 2020), persistent changes in fine-grained sediment deposition across scales likely reflect broader, large-scale changes in sediment supply grain size.

Going forward, this technique could be applied to other ancient fluvial successions with vertical changes in alluvial architecture to investigate the role of fines supply, especially in intervals where a vertical change in net-to-gross has been used to interpret a sequence boundary. Additionally, future work is needed to constrain the number and distribution of samples required to robustly identify vertical changes in the fines supply.

CONCLUSIONS

This study shows an approximately 50% reduction in the fraction of mud in bedform-, reach-, and outcrop-scale measurements from the mudstone-dominated Blackhawk Formation to the sandstone-dominated Castlegate Sandstone, coincident with a marked increase in quartz composition in sandstones across this boundary. This suggests that a simple decrease in the proportion of fine sediment supplied to Castlegate rivers caused the major architectural change at the Blackhawk-Castlegate boundary. This contrasts with previous interpretations that outcrop-scale fluvial architecture primarily reflects tectonic-, climatic- or sea-level-driven changes in total sediment supply or accommodation creation. Measuring grain-size distributions across morphodynamic hierarchies in fluvial deposits can be a useful tool for investigating paleo-sediment supply in ancient source-to-sink networks, providing a constraint on paleo-sediment flux, sediment storage, and channel reworking in ancient fluvial networks.

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