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Field evidence for disequilibrium dynamics in preserved fluvial cross-strata: A record of discharge variability or morphodynamic hierarchy?

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Abstract

Bedforms preserved in the rock record can provide detailed information on the morphologies and hydrodynamics of ancient fluvial systems on Earth and other planets. Existing process–product relations for bedform preservation assume that fluvial cross strata reflect conditions under which bedforms were equilibrated with the prevailing flow, i.e., steady-state conditions. However, recent theoretical and experimental observations indicate that enhanced bedform preservation can occur in non-steady state, or disequilibrium, conditions, and it is currently unclear how prevalent disequilibrium dynamics are in preserved fluvial strata at outcrop scale. Here we explore whether steady-state assumptions are appropriate for ancient fluvial systems by evaluating the nature of bedform preservation in well studied fluvial deposits of three Late Cretaceous (Turonian and Campanian) geologic formations in central Utah, USA: the Blackhawk Formation, Castlegate Sandstone, and Ferron Sandstone. In the field, we made systematic measurements of dune-scale cross-strata to quantify the extent to which preserved cross-sets reflect dune preservation in steady-state conditions. Across the three formations, consistently low coefficients of variation in preserved cross-set thicknesses of 0.25–0.5 are inconsistent with bedform preservation in steady-state conditions, and instead point to fluvial systems in which enhanced bedform preservation occurred in disequilibrium conditions.

Enhanced bedform preservation in dune-scale cross-stratification can be explained by two independent hypotheses: the effect of flashy flood hydrographs on bedform preservation (flood hypothesis) or bedform preservation in the presence of larger migrating barforms (hierarchy hypothesis). We estimated bedform turnover timescales to quantitatively assess these competing hypotheses and contextualize their implications. Under the flood hypothesis, field measurements are consistent with enhanced bedform preservation driven by flashy flood hydrographs with flood durations ranging on the order of hours to a few days, which are consistent with perennial fluvial systems subject to heavy rains and tropical storms. Alternatively, under the hierarchy hypothesis, field measurements are consistent with bedform climb angles that range from 10^{-2} to 10^{-1}, reflecting rapid bar migration. Our work provides a novel way of investigating fluvial discharge variability in the geologic past, and we

outline the potential next steps to disentangle the relative controls of flow variability and hierarchy in controlling bedform preservation in ancient fluvial systems.

Keywords

Fluvial systems; Bedforms; Cross strata; Hydrodynamics; Morphodynamics; Discharge variability

1. Introduction

Quantitative reconstructions of palaeohydraulics from fluvial stratigraphy complement qualitative observations of sedimentary facies to build more complete pictures of palaeo-landscapes on Earth and other planets. In fluvial strata, preserved bedforms, which include ripples, dunes, and unit bars, are crucial to these reconstructions. Bedforms are readily formed on riverbeds across a range of grain sizes (e.g., Carling, 1999; Best, 2005) and their evolution generates cross-stratification — the resultant cross-strata are a fundamental building block of alluvium on planetary surfaces (e.g., Allen, 1982; Edgar et al., 2018). Cross-strata provide a window to formative conditions in ancient fluvial systems and are routinely used to reconstruct morphologies and hydrodynamics (Holbrook & Wanas, 2014; Ganti et al., 2019; Wang et al., 2020; Lyster et al., 2021); for instance, measurements of dune-scale cross-set thicknesses provide a mechanism to estimate the sizes of dunes active on ancient riverbeds and, therefore, palaeoflow depths (Leclair & Bridge, 2001; Bradley & Venditti, 2017). Moreover, bedform kinematics respond to spatial and temporal changes in flow and sediment transport conditions (e.g., Ten Brinke et al., 1999; Martin & Jerolmack, 2013; Wu et al., 2020), and recent research has highlighted that these changes may be recorded in preserved cross-set geometries (Leary & Ganti, 2020). If we can use geometries of cross-stratification to extract information about water and sediment discharge variability, this would significantly improve our understanding of ancient fluvial systems, including river response to climatic perturbation (e.g., Foreman et al., 2012; Colombera et al., 2017). However, a crucial outstanding challenge in this field of research involves adapting engineering-scale insights, which are typically founded in precisely defined boundary conditions (and which underpin palaeohydraulic reconstructions), to geological scales over which more variability in environmental conditions is typically assumed due to issues of time-averaging and temporal incompleteness in the rock record (e.g., Romans et al., 2016; Straub et al., 2020).

Process–product relationships between bedform evolution and cross-stratal geometries have primarily been studied using small-scale physical experiments and numerical models (Paola & Borgman, 1991; Bridge, 1997; Leclair, 2002; Jerolmack & Mohrig, 2005; Ganti et al., 2013; Wu et al., 2020). Existing models that relate cross-set thicknesses to original bedform heights rely on the assumption that the formative train of bedforms evolved in steady-state conditions under no-net aggradation or with a small bedform climb angle ($<10^{-2}$; gradient in terms of y/x)

(Paola & Borgman, 1991; Jerolmack & Mohrig, 2005). For a range of these formative conditions, theory, numerical models and experimental observations suggest the bedform preservation ratio — defined as the ratio of the average preserved cross-set thicknesses and the average original bedform heights — is a near-constant value of 0.3 (Paola & Borgman, 1991; Leclair & Bridge, 2001; Leclair, 2002; Jerolmack & Mohrig, 2005). Further, these models predict that the coefficient of variation, *CV*, of cross-set thicknesses has a constant value of 0.88 (Paola & Borgman, 1991; Leclair & Bridge, 2001; Leclair, 2002; Jerolmack & Mohrig, 2005), with Bridge (1997) suggesting that the steady-state model for bedform preservation can be applied so long as the *CV* of cross-set thicknesses is bounded by 0.88±0.30. While these insights have primarily been supported by numerical and experimental studies under steady-state conditions (e.g., Leclair, 2002; Ganti et al., 2013; Leary & Ganti, 2020), they are widely applied in field-scale palaeohydrological studies (e.g., Holbrook & Wanas, 2014; Ganti et al., 2019; Wang et al., 2020; Lyster et al., 2021).

However, steady-state conditions, strictly defined, are not commonly observed in natural systems when discharge is variable (e.g., Fielding et al., 2018; Ghinassi et al., 2018; Herbert et al., 2020), or under relatively constant flow conditions in which spontaneously developed features, such as bars, establish complex and locally variable flow conditions that change as bars shift and channels migrate (Reesink et al., 2015; Chamberlin & Hajek, 2019; Ganti et al., 2020; Wysocki & Hajek, 2021). These non-steady, or disequilibrium, conditions are increasingly recognized to be fundamental controls on fluvial behaviour and stratigraphic architecture (Plink-Björklund, 2015; Reesink et al., 2015; Fielding et al., 2018; Ghinassi et al., 2018; Ganti et al., 2020; Herbert et al., 2020; Leary & Ganti, 2020; Wysocki & Hajek, 2021). At the bedform scale, recent theoretical and experimental observations indicate that fluvial cross-strata may preferentially record bedform dynamics in disequilibrium conditions (Reesink et al., 2015; Ganti et al., 2020; Leary & Ganti, 2020), i.e., when flow and bedform evolution are out of phase (c.f. Myrow et al., 2018). Bedform disequilibrium conditions are characterized by localized increase in sedimentation rates relative to bedform migration rates, which enhances the preservation of bedforms (Reesink et al., 2015; Ganti et al., 2020; Leary & Ganti, 2020). Cross-sets preserved in disequilibrium conditions have diagnostic geometries that deviate from cross-sets preserved in steady-state conditions: a) restricted range of cross-set thickness distributions such that $CV<0.88$ and b) elevated bedform preservation ratios (>0.3) such that a larger fraction of the formative topography is preserved in the stratigraphy (Jerolmack & Mohrig, 2005; Leary & Ganti, 2020; Wu et al., 2020).

Two distinct disequilibrium conditions lead to enhanced bedform preservation. First, Leary and Ganti (2020) used experimental data to show that characteristic patterns of dune preservation are found under different conditions of formative flow variability (i.e., the near-instantaneous short-term discharge variability associated with the magnitudes and timescales of individual floods). They demonstrated that dune preservation preferentially occurs during flood recession, and that preserved cross-sets only have geometries that are consistent with steady-state conditions when the formative flow duration (T_f), i.e. the flood recession, is greater than the bedform turnover timescale (T_t) — defined as the time it takes to displace the volume of sediment in a bedform (Myrow et al., 2018). Conversely, when the flood recession is shorter than the bedform turnover timescale, the larger peak flood-equilibrated dunes get abandoned and are minimally reworked during the flood recession and subsequent low flow conditions, which results in a high bedform preservation ratio and low *CV* for preserved cross-sets (Leary & Ganti, 2020). These conditions are typical in rivers with flashy flood hydrographs, which are characterised by rapid flow deceleration and, therefore, short flood recessions. We term this the *flood hypothesis* for enhanced bedform preservation. Moreover, Leary and Ganti (2020) showed that it is possible to estimate formative flow durations from preserved cross-sets — this may enable quantitative reconstructions of flood variability from the rock record and augment traditional qualitative methods that rely on facies and architectural models (e.g., Plink-Björklund, 2015). Alternatively, the self-organization of fluvial systems into a morphodynamic hierarchy (e.g., dunes, bars, channels, channel belts) can also result in enhanced preservation of the topography associated with each hierarchical level (Ganti et al., 2020). In this scenario, high bedform preservation ratio and low *CV* can occur due to localized increase in the angle of climb of bedforms associated with, for example, concurrent migration of dunes and bars (Jerolmack & Mohrig, 2005; Ganti et al., 2013; Reesink et al., 2015; Ganti et al., 2020), which include both unit bars and longer-lived compound bar features. We term this the *hierarchy hypothesis* for enhanced bedform preservation. In both of these scenarios, cross-strata are expected to encode more detailed information about morphodynamic conditions in ancient fluvial systems, which are not accounted for in models that assume bedform preservation occurred in steady-state conditions.

Despite advances in understanding bedform dynamics, the prevalence of bedform disequilibrium dynamics in preserved fluvial strata is currently unclear, partly because we lack detailed field measurements of cross-set geometries and their statistical nature. While a handful of field studies have documented low *CV* (0.3–0.7) in fluvial cross-strata (Jerolmack & Mohrig, 2005; Colombera et al., 2017; Cardenas et al., 2020; Wang et al., 2020), consistent with bedform disequilibrium dynamics, these data are usually limited to a few outcrop observations for individual geologic formations. Here, we systematically characterize the geometries and statistical nature of dune-scale cross-strata for three Late Cretaceous geologic formations in central Utah, USA (Figs 1,2), to assess the nature of dune preservation. Across all three formations, we show that dune-scale cross-strata are dominated by the preservation of bedform disequilibrium dynamics, which calls into question the use of steady-state assumptions in palaeohydraulic reconstructions. Using these field observations, we reconstruct bedform kinematics (i.e., turnover timescales) and quantify the formative conditions that are consistent with field data under both the flood and hierarchy hypotheses (i.e., flood durations, migration rates). Finally, we evaluate whether it is possible to deconvolve the relative roles of flow variability and morphodynamic hierarchy on enhanced bedform preservation, which may provide a potentially powerful pathway to reconstruct flood variability in ancient fluvial systems, and to evaluate the nature of interactions between dunes, bars, channel migration and channel avulsion in palaeo-channel networks.

2. Study area

In the Late Cretaceous North American continent, rivers draining the Sevier orogenic fold-and-thrust belt delivered sediment to the Western Interior Seaway (WIS) (e.g., Kauffman & Caldwell, 1993) (Fig. 1). We focus on well-studied fluvial strata of the Late Cretaceous Blackhawk Formation, Castlegate Sandstone and Ferron Sandstone in central Utah, USA (Figs 1,2) (c.f. Lyster et al., 2021). These strata have distinct architectures and are interpreted to preserve differing fluvial styles; the Ferron Sandstone preserves major meandering trunk channels (Cotter, 1971; Chidsey et al., 2004), while, at the Blackhawk–Castlegate transition, single- and multi-thread channels of the Blackhawk Formation (Adams & Bhattacharya, 2005; Hampson et al., 2013; Flood & Hampson, 2014) are capped by predominantly braided channels of the Castlegate Sandstone (e.g., Miall, 1993, 1994) (Fig. 1,2). Moreover, these systems are potentially linked with a monsoonal climate (Fricke et al., 2010; Sewall & Fricke, 2013).

2.1 Blackhawk Formation and Castlegate Sandstone, Mesaverde Group

The Campanian Blackhawk Formation and Castlegate Sandstone (Figs 1,2) represent a series of transverse fluvial systems draining the Sevier orogenic front to the WIS (Pettit et al., 2019), with an additional longitudinal component of drainage from the south-southwest (e.g., Szwarc et al., 2015; Pettit et al., 2019) (Fig. 1b). The lower–middle Campanian Blackhawk Formation is a ledge-forming succession characterized by large fluvial channelized sandstone bodies and abundant floodplain sediments (e.g., Adams & Bhattacharya, 2005; Hampson et al., 2013; Flood & Hampson, 2014) (Fig. 2a–c). These sandstone bodies represent both single- and multi-thread systems, as interpreted from bar architectures (Adams & Bhattacharya, 2005; Hampson et al., 2013). Meanwhile the middle–upper Campanian Castlegate Sandstone is a cliff-forming succession situated above the Blackhawk Formation (Fig. 2a) and is characterized by amalgamated fluvial channel-belt deposits, which are interpreted to preserve braided rivers, and are less amalgamated in the middle with interbedded mudstones, which are interpreted to preserve more sinuous/meandering channels (e.g., Miall, 1993, 1994). We collected data for the Blackhawk Formation and Castlegate Sandstone from five canyons along the eastern Wasatch Plateau front (Fig. 1a; c.f. Lyster et al. (2021)). Dune-scale cross-strata in the Blackhawk Formation are generally associated with bar deposits, as well as lower bar, channel floor or thalweg deposits, whereas dune-scale cross-strata in the Castlegate Sandstone are predominantly associated with bar deposits (Miall, 1993, 1994; Adams & Bhattacharya, 2005; Hampson et al., 2013; Flood & Hampson, 2014).

2.2 Ferron Sandstone, Mancos Shale

The Turonian Ferron Sandstone comprises three deltaic clastic wedges (Cotter, 1971; Chidsey et al., 2004) (Fig. 1b). These deltas were fed by rivers draining the Sevier orogenic front to the WIS and may have also featured an additional/intermittent longitudinal component of drainage from the south-southwest, as observed for the Blackhawk Formation–Castlegate Sandstone succession (e.g., Szwarc et al., 2015; Pettit et al., 2019). We focus on the Last Chance deltaic complex, using data from three canyons in southwestern Castle Valley (Fig. 1). These canyons preserve the most palaeo-landward terrestrial fluvial facies of the Last Chance delta and are characterized by major channelized sandstone bodies and abundant floodplain sediments and palaeosols (Cotter, 1971; Chidsey et al., 2004) (Fig. 2d–f). These strata preserve the major meandering trunk channels that fed the Last Chance delta, which is evidenced by abundant laterally accreted point bar deposits (Cotter, 1971; Chidsey et al., 2004) (Fig. 2f). Dune-scale cross-strata in the Ferron Sandstone are generally associated with point bar deposits, as well as lower bar, channel floor or thalweg deposits (Cotter, 1971; Chidsey et al., 2004).

3. Methods

At field localities, we measured the geometries of dune-scale cross-sets. Trough and planar cross-sets occurred predominantly in sand-grade sediments and occasionally in coarser granule-grade sediments (Fig. 3). To measure the distribution of thicknesses within individual cross-sets we delineated cross-set boundaries (i.e., the lower, asymptotic bounding surface and the upper, erosional bounding surface) and measured cross-set thickness with a vertical precision of ±5 mm at regular intervals along the entire width of the cross-set dip-section (n=5–15 measurements) (Fig. 3e,f), in line with methods outlined in Paola and Borgman (1991), Ganti et al. (2019) and Lyster et al. (2021). We then estimated the median grain-size (D_{50}) using size terms of the Wentworth (1922) classification (Fig. 3a,b). When converted to numerical values, we assigned the middle value for each size term or, where grain-size straddled two size terms, we used the boundary value, e.g., D_{50} of medium-grade sand = 0.375 mm and medium–coarse-grade sand = 0.5 mm (Wentworth, 1922). We repeated this for multiple cross-sets within co-sets. Having measured thickness distributions within individual cross-sets, we then measured a sample of maximum cross-set thicknesses (i.e., the maximum distance between lower and upper bounding surfaces) of cross-sets at each locality (n=~25–75). These cross-sets were all related, spanning multiple co-sets that were confined, where possible, to a single channelized sandstone body.

For each individual cross-set, we calculated the mean cross-set thickness, h_{xs}, the maximum thickness, and the CV of the internal thickness distribution ($CV(h_{xs})$) — a key parameter to test whether the bedforms are preserved in steady-state or disequilibrium conditions. For each sample of maximum cross-set thicknesses, we similarly calculated the mean maximum cross-set thickness, h_p, and the CV of the entire sample ($CV(h_p)$), and we additionally analysed the shape of each distribution.

We then propagated mean thicknesses of individually measured cross-sets (and their respective grain-sizes) through a well-established quantitative framework (c.f. Ganti et al., (2019), Lyster et al., (2021); Supplementary Methods) to reconstruct bedform turnover timescales — we can use these values to contextualise the implications of the flood and hierarchy hypotheses. For instance, under the flood hypothesis we expect waning flow durations to be shorter than turnover timescales, whereas under the hierarchy hypothesis we expect bars to be migrating on timescales that approach bedform turnover timescales. We reconstructed turnover timescales, T_t, i.e., the time taken to displace the volume of sediment of the bedform (per unit width), following Martin and Jerolmack (2013) and Myrow et al. (2018), as:

$$T_t = \frac{\lambda h_d \beta}{q_b}, \qquad \text{[Eq. 1]}$$

where λ is bedform wavelength, which we estimated using the depth scaling relation of van Rijn (1984), h_d is bedform (i.e., dune) height, β ~0.55 is the bedform shape factor and q_b is the unit bedload flux, which we calculated following Mahon and McElroy (2018) (Supplementary Methods). As the exact error margins of palaeohydraulic inversion methods are unknown, we used a Monte Carlo uncertainty propagation method to estimate uncertainty, which yielded 10^6 values of T_t per cross-set (Supplementary Methods). From these estimates we extracted median T_t, the 25–75 percentile range of T_t, and the 10–90 percentile range of T_t. For each cross-set, we suggest that the 10–90 percentile range of T_t offers a plausible minimum and maximum value for mean T_t, and that the 25–75 percentile range of T_t offers the bounds in which the true value of mean T_t is most likely to occur.

Reconstruction of T_t requires a priori knowledge of the bedform preservation ratio (h_{xs}/h_d), which itself is a function of whether bedforms were preserved in steady-state or disequilibrium conditions. To evaluate a maximum T_t value, we used h_{xs}/h_d = 0.3, which reflects steady-state preservation under low bedform climb angle. We then assessed the sensitivity of T_t to h_{xs}/h_d by repeating the methodology outlined above for h_{xs}/h_d values from 0 to 1. In the absence of preserved formsets that reflect $h_{xs}/h_d \geq 1.0$ (Reesink et al., 2015), enhanced bedform preservation is characterized by $0.3 < h_{xs}/h_d \leq 0.7$ (Supplementary Information; Jerolmack and Mohrig (2005); Reesink et al. (2015); Ganti et al. (2020); Leary and Ganti (2020)). For the sensitivity analyses, we used the h_{xs} and D_{50} of each measured cross-set and calculated the overall mean h_{xs} and mean D_{50} for the Blackhawk Formation, Castlegate Sandstone and Ferron Sandstone, respectively.

4. Results

4.1 Cross-set geometries

We present results aggregated at the formation scale, with no spatial or temporal reference frame, as ancillary field observations suggest there is little variation between field sites (see

Supplementary Information and Lyster et al., (2021)). We measured >400 individual dune-scale cross-sets of the Blackhawk Formation (n = 81), Castlegate Sandstone (n = 146) and Ferron Sandstone (n = 190) (Fig. 4), with ~5–15 height measurements per cross-set, totalling >3800 measurements. For each cross-set we recorded grain-size, which is reported in the Supplementary Information, and we calculated the mean thickness and the maximum thickness. Distributions of mean cross-set thicknesses are similar for the Blackhawk Formation and Castlegate Sandstone (two-sample t-test; $p = 0.067$; test statistic = -1.838, degrees of freedom = 225); distributions have median values of ~0.13–0.14 m and 10–90 percentile ranges of 0.1–0.2 m. Distributions of maximum cross-set thicknesses for the Blackhawk Formation and Castlegate Sandstone generally have medians of 0.17–0.18 m and 10–90 percentile ranges of 0.13–0.27 m (Fig. 4a,b). Whereas for the Ferron Sandstone, cross-sets are larger with broader percentile ranges. The distribution of mean cross-set thicknesses has a median of 0.15 m and a 10–90 percentile range of 0.08–0.25 m, and the distribution of maximum cross-set thicknesses has a median of 0.22 m and a 10–90 percentile range of 0.12–0.45 m (Fig. 4c).

We also measured maximum thicknesses of >3000 dune-scale cross-sets across the Blackhawk Formation (801 measurements across 26 samples), Castlegate Sandstone (1015 measurements across 27 samples) and Ferron Sandstone (1257 measurements across 21 samples), with between 25–75 measurements per sample (Fig. 5). For each formation, distributions of maximum thicknesses of cross-sets have median values of ~0.2 m (Fig. 5); these values are consistent with maximum values extracted from individually measured cross-sets (Fig. 4). For the Blackhawk Formation and Castlegate Sandstone, 90% of maximum cross-set thicknesses are between ~0.15–0.3 m, and the upper 10% of maximum cross-set thicknesses are markedly larger (≤0.5–0.6 m) (Fig. 5a,c). Meanwhile, for the Ferron Sandstone, 90% of maximum cross-set thicknesses are between ~0.15–0.35 m and the upper 10% of maximum cross-set thicknesses are also markedly larger (≤ 0.7 m) (Fig. 5e). These distributions of maximum cross-set thicknesses across all cross-set samples are generally mirrored in individual cross-set samples (Fig. 5b,d,f), with median values of ~0.2 m, suggesting they are not from a limited subset of locations. Most samples of maximum cross-set thicknesses demonstrate positively-skewed, long-tailed distributions wherein relatively few large cross-sets exist among abundant smaller cross-sets (Fig 5b,d,f). The kurtosis of distributions varies for each formation, such that distributions in the Castlegate Sandstone and Ferron Sandstone are more long-tailed than in the Blackhawk Formation (Fig 5b,d,f).

Our data show that CV values of cross-set thicknesses are significantly lower than the expected steady-state values of 0.88 (Fig. 6). We found low CV of thicknesses within individual cross-sets ($CV(h_{xs})$), as well as low CV of thicknesses for a sample of measured cross-sets within related co-sets ($CV(h_p)$) (Fig. 6). In the Blackhawk Formation and Castlegate Sandstone, median $CV(h_{xs})$ is 0.3 with a 25–75 percentile range of ~0.25–0.38, and maximum $CV(h_{xs})$ extends to 0.45–0.55 (Fig. 6a,b). The Ferron Sandstone $CV(h_{xs})$ values are also low (relative to steady-state) but are higher than in the Blackhawk–Castlegate succession. For the Ferron

Sandstone, median $CV(h_{xs})$ is 0.4 with a broader 25–75 percentile range of ~0.3–0.5, and maximum $CV(h_{xs})$ extends to 0.6–0.75 (Fig. 6c). We found that none of the measured $CV(h_{xs})$ values were consistent with the proposed empirical range of 0.88±0.30 for steady-state preservation (Bridge, 1997) in the Blackhawk–Castlegate succession; however, 6% of the measurements were within this range for the Ferron Sandstone. For $CV(h_p)$, recovered values are even lower. In the Blackhawk Formation and Castlegate Sandstone median $CV(h_p)$ is 0.2, with 25–75 percentile ranges of ~0.15–0.25 (Fig. 6a,b), and in the Ferron Sandstone median $CV(h_p)$ is 0.3, with a 25–75 percentile range of ~0.25–0.35 (Fig. 6c).

4.2 Maximum bedform turnover timescales

We first present results for reconstructed T_t values for each formation using a bedform preservation ratio of 0.3, and then explore the sensitivity of T_t to $h_{xs}/h_d > 0.3$ which is expected for the preservation of bedforms under high angles of local bedform climb. The geometries and grain-sizes of measured cross-sets imply that T_t values typically span 1–10 days, with a median value of 2–4 days (Fig. 7). The overall distributions of T_t vary between the geologic formations (Fig. 7). For the Castlegate Sandstone median T_t is 2.5–3 days, with a 10–90 percentile range of 1–7 days (Fig. 7a). For the Blackhawk Formation, values are marginally higher with a median T_t of 3–3.5 days, and a 10–90 percentile range of 1.5–8 days (Fig. 7b). While the Ferron Sandstone has a similar median T_t of 3–3.5 days, it has a much broader 10–90 percentile range spanning <1–15 days (Fig. 7c).

We recovered 10^6 values of T_t for each cross-set using a Monte Carlo approach (see Methods and Supplementary Methods) and the results described above present the cumulative distribution function (CDF) of median T_t values for each cross-set (Fig. 7). We also computed the CDFs for the 10^{th}, 25^{th}, 75^{th} and 90^{th} percentiles of T_t values of each cross-set to highlight the plausible range of values that are consistent with field observations. These CDFs demonstrate that, despite uncertainty in T_t of up to one order of magnitude, the majority of possible T_t values are between 1 and 10 days (Fig. 7). These T_t values suggest that floods with typical recessions >10 days would have fully equilibrated bedforms, similar to observations in relatively shallow modern rivers (Leary & Ganti, 2020). Further, the estimated maximum T_t of 2–4 days, with an overall span of 1–10 days (Fig. 7) for dune-scale cross-strata in the Blackhawk-Castlegate succession and the Ferron sandstone are consistent with dune migration in modern natural rivers (e.g., Hajek & Straub, 2017; Leary & Ganti, 2020).

4.3 Sensitivity of bedform turnover timescales to bedform preservation ratio

To assess the sensitivity of T_t to h_{xs}/h_d, we systematically varied h_{xs}/h_d for each formation from 0 to 1 (Fig. 8), where the former indicates no preservation and the latter implies complete preservation of formsets. An increase in h_{xs}/h_d corresponds analytically with a decrease in T_t (see Supplementary Methods). For example, increasing h_{xs}/h_d by a factor of 2, from 0.3 to 0.6, reduces T_t by a factor of 5–6 (Fig. 8). Compared to results for h_{xs}/h_d=~0.3, the median T_t values for the Castlegate Sandstone and the Blackhawk Formation are smaller by a factor of 5, with median T_t of 0.7 days (~17 hours) and 1 day, respectively (Figs. 8a, b). For the Ferron Sandstone, h_{xs}/h_d=0.6 reduces the median T_t by a factor of 6 to ~1 day, when compared to h_{xs}/h_d=~0.3 (Fig. 8c). In all cases, extreme dune preservation with h_{xs}/h_d=1 yielded T_t <0.1 days, and extremely low values of h_{xs}/h_d << 0.3 yielded unrealistic T_t values as high as 10^5 days (Fig. 8). Experimental bedform preservation under steady and unsteady flows indicates that the h_{xs}/h_d may likely span 0.3 and 0.7 (grey bars, Fig. 8; Supplementary Information) in the absence of evidence for formset preservation (Leary & Ganti, 2020).

5. Discussion

From >400 individually measured dune-scale cross-sets (n=5–15 measurements per cross-set) across the three geologic formations, our results indicated that estimated $CV(h_{xs})$ was always lower than 0.88 and ranged from ~0.25–0.5 (Fig. 6). Across these formations, only 3% of the estimated $CV(h_{xs})$ were consistent with the empirical range of 0.88±0.30 expected for bedform preservation under steady-state conditions (Bridge, 1997). Low $CV(h_{xs})$ is inconsistent with steady-state preservation of bedforms and does not support generation of cross-sets by random variability in scour depths through time (Paola & Borgman, 1991; Leclair & Bridge, 2001; Leclair, 2002; Jerolmack & Mohrig, 2005). Instead, our observations provide evidence for enhanced bedform preservation driven by localized increase in sedimentation rates relative to the bedform migration rates (Jerolmack & Mohrig, 2005; Ganti et al., 2020; Leary & Ganti, 2020), suggesting that river dune deposits of the Blackhawk Formation, Castlegate Sandstone, and Ferron Sandstone are dominated by bedform disequilibrium dynamics. Below we discuss the implications of these observations under the flood and hierarchy hypotheses and delineate potential approaches to disentangle their relative roles in ancient fluvial systems.

5.1 Implications of the flood hypothesis for bedform preservation

Using physical experiments, Leary and Ganti (2020) showed that, where bedform disequilibrium dynamics are only controlled by formative flow variability, low $CV(h_{xs})$ indicates a scenario in which the formative flow duration (T_f), i.e. the flood recession, is significantly less than the bedform turnover timescale (T_t). Bedform disequilibrium dynamics associated with formative flow variability typically manifest in rivers with flashy flood hydrographs, in which river discharge is characterized by floods with a short flood recession period relative to T_t (Leary & Ganti, 2020) — the rapid decline in water discharge following peak flood minimizes bedform reworking and enhances bedform preservation (Leary & Ganti, 2020). Under the flood hypothesis, the documented low $CV(h_{xs})$ is consistent with T_f values that are a factor of 10 smaller than T_t (assuming the ratio of T_f to T_t is ~0.1; c.f. Leary and Ganti (2020)). As the maximum T_t values fall between 1–10 days for our field data, the estimated $CV(h_{xs})$ indicates typical T_f values spanning 0.1–1 day (2.4–24 hours) for h_{xs}/h_d=~0.3. The range of plausible T_f values consistent with experimentally observed bedform preservation ratios and field-estimated $CV(h_{xs})$ is on the order of 0.1 days for all the geologic formations considered here (Fig. 8).

Under the flood hypothesis, our field data unanimously indicate that flood recessions did not exceed a few hours to a day for these Late Cretaceous fluvial systems. Given the typical shape of flashy flood hydrographs, we also anticipate that total flood durations did not exceed a few hours to a few days. Our estimated flood durations are plausible and consistent with recent (decadal-scale) observations of modern rivers in sub-tropical and/or mid-latitude regions (e.g., Serinaldi et al., 2018). Moreover, compilations of global flood data indicate that, for flood durations on the order of hours to days, the main causes are: heavy rain, brief torrential rain, tropical storms, and extra-tropical storms (Serinaldi et al., 2018). These flood durations, and associated causes, are typical of perennial discharge regimes. While the Blackhawk Formation, Castlegate Sandstone and Ferron Sandstone have not been explicitly studied in terms of variable discharge facies models, existing facies analyses of these formations have typically described sedimentary and architectural structures associated with perennial rivers (see review by Plink-Björklund, 2015). These include abundant Froude subcritical structures (i.e., cross-sets from which we collected data; Fig. 3) and well-developed macroforms (i.e., bars and accretion sets) (Cotter, 1971; Miall, 1994; Chidsey et al., 2004; Adams & Bhattacharya, 2005; Hampson et al., 2013; Flood & Hampson, 2014; Chamberlin & Hajek, 2019).

Independent modelling and proxy studies of palaeoclimate in Late Cretaceous central Utah suggest the region was subject to a sub-tropical/monsoonal climate with monsoonal precipitation and frequent seasonal flooding in low-lying alluvial plains (e.g., Fricke et al., 2010; Sewall & Fricke, 2013). However, floods caused by monsoonal rains typically have long durations spanning ~5–25 days (Serinaldi et al., 2018). Additionally, an abundance of features associated with monsoonal systems, e.g., in-channel mud layers, abundant soft-sediment deformation, soft-sediment clast conglomerates (see review by Plink-Björklund, 2015), have not been reported in the literature for these formations or observed at our field localities. Given that our reconstructed flood durations and existing facies models indicate perennial discharge regimes, the flood hypothesis indicates that these river dune deposits could record bedform adjustment to flooding associated with storm events as opposed to sustained monsoonal flooding.

5.2 Implications of the hierarchy hypothesis for bedform preservation

Under the alternative hierarchy hypothesis, enhanced bedform preservation is facilitated by self-organization of fluvial systems into a series of hierarchical elements (Ganti et al., 2020), where the nature of preservation of topography within a given hierarchical level is solely controlled by the next level in the morphodynamic hierarchy. The presence of bars — the higher-order hierarchical elements of dunes — will locally enhance preservation of river dunes because the bars both provide accommodation for bedforms and increase bedform climb angles (Reesink et al., 2015; Ganti et al., 2020). Cardenas et al. (2020) observed low $CV(h_{xs})$ for dune-scale cross-strata on the stoss and lee slopes of point bar and free bar deposits, when compared to dune-scale cross-strata in thalweg deposits of the Cretaceous Cedar Mountain Formation, Utah, which is consistent with the hierarchy hypothesis for bedform preservation. Numerical models indicate that observed low $CV(h_{xs})$ values are associated with rapid sedimentation rates relative to bedform migration rates such that the bedform climb angle is of the order of 10^{-2} to 10^{-1} (Jerolmack & Mohrig, 2005). Given that the local angle of climb for bedforms is influenced by the relative rates of dune migration to bar migration (Ganti et al., 2020), these results suggest low $CV(h_{xs})$ values measured in the field are consistent with timescales of bar migration on the order of days to months.

The nature of stratigraphic architecture, particularly of barform deposits, is well-documented for the Blackhawk Formation, Castlegate Sandstone and Ferron Sandstone (Cotter, 1971; Miall, 1993, 1994; Chidsey et al., 2004; Adams & Bhattacharya, 2005; Hampson et al., 2013; Flood & Hampson, 2014; Chamberlin & Hajek, 2019; Lyster et al., 2021). The Castlegate Sandstone comprises amalgamated fluvial channel-belt deposits which, architecturally, are dominated by barforms (e.g., mid-channel bars) (Miall, 1993, 1994; Chamberlin & Hajek, 2019). Therefore, dune-scale cross-sets that we measured in the Castlegate Sandstone likely preserve dunes that were influenced by bar migration, and it is possible that low $CV(h_{xs})$ values observed in these cross-sets reflect bedform disequilibrium dynamics associated with the hierarchy hypothesis, especially given that unit bar migration typical of braided rivers can be comparable to dune migration rates (Strick et al., 2019). Conversely, fluvial strata of the Blackhawk Formation and Ferron Sandstone comprise major channelized sandstone bodies (Cotter, 1971; Chidsey et al., 2004; Adams & Bhattacharya, 2005; Hampson et al., 2013; Flood & Hampson, 2014) which, while abundant in barforms (e.g., laterally accreted point bar deposits; Fig. 2f), also likely preserve a much larger proportion of channel deposits that are devoid of barform architecture and which may reflect thalweg deposits. Cardenas et al. (2020) hypothesized that thalweg strata represent aggradation in channel beds during the final flood event prior to channel avulsion. We therefore consider that enhanced bedform preservation in thalweg deposits of the Blackhawk Formation and Ferron Sandstone is less likely to reflect bedform preservation in the presence of rapid bar migration and, instead, is more likely to reflect formative flow variability.

5.3 Detangling flood versus hierarchy controls on bedform preservation

While both the flood hypothesis and the hierarchy hypothesis explain the observed dominance of enhanced bedform preservation, disentangling their relative roles in controlling bedform preservation is currently non-trivial. We hypothesize that spatially contextualizing the observed deposits may be critical for evaluating the controls on bedform preservation. For example, it is likely that dunes preserved in channel-thalweg deposits of single-thread rivers are not influenced by the presence of bars and, therefore, may reflect the formative flood variability. This scenario may be similar to physical experiments that do not exhibit the multiple morphodynamic hierarchical levels that typify natural rivers. We hypothesise that, where low $CV(h_{xs})$ values are observed in dune-scale cross-sets associated with thalweg deposits, we can use estimated bedform turnover timescales to constrain formative flow durations. Similarly, field observations indicate that dunes preserved in the presence of bars are likely to be better preserved than expected under steady-state conditions (Reesink et al., 2015; Cardenas et al., 2020). In this scenario, $CV(h_{xs})$ may yield insight into the relative rates at which bedforms and barforms migrated in ancient fluvial systems.

Together, single-thread river deposits may display a larger range of $CV(h_{xs})$ that reflects both formative flow variability and the relative kinematic rates of evolution of successive hierarchical levels in the morphodynamic hierarchy. In contrast, braided rivers are characterized by relatively rapid migration of unit bars and free bars in the presence of river dunes (e.g., Strick et al., 2019) and detangling the role of morphodynamic hierarchy and flood variability may be more difficult. Our results are consistent with this expectation as we observe a larger range of $CV(h_{xs})$ for single-thread river deposits of the Ferron Sandstone compared to the predominantly braided river deposits of the Castlegate Sandstone (Fig. 6). Nonetheless, this work provides a basis for further testing the roles of flow variability and morphodynamic hierarchy on the preservation of bedform dynamics, including other causes of non-uniform flow such as channel abandonment and backwater hydraulics (e.g., Wu et al., 2020).

In terms of cross-set geometries, a promising avenue to decipher the dominant control on bedform disequilibrium dynamics is to compare population statistics of related cross-sets, measured in the field, with those from experimental observations. For instance, Leary and Ganti (2020) showed that, in flashy flood hydrographs, the rapid decline of water discharge associated with short waning-flow durations enhances preservation of relatively larger, peak-flood equilibrated, dunes (Leary & Ganti, 2020). In this scenario, we expect maximum cross-set thicknesses to have a positively skewed long-tailed distribution with large cross-sets interspersed with relatively smaller cross-sets (Leary & Ganti, 2020). Whereas bedform preservation in steady-state conditions, or under a broad flood hydrograph, will likely result in maximum cross-set thicknesses that have a short-tailed distribution, with a much higher frequency of smaller cross-sets, as longer waning-flow durations enable reworking of larger dunes such that the preservation potential of peak-flood equilibrated dunes is low (Leclair, 2011; Leary & Ganti, 2020). Across our measured samples, distributions of maximum cross-set thicknesses are consistent with bedform preservation under the flood hypothesis; most samples have long-tailed, positively skewed distributions (Figs 5b,d,f). Based on these considerations, we judge it plausible that fluvial stratigraphy in the Blackhawk Formation and Ferron Sandstone may record bedform disequilibrium dynamics driven by formative flow variability, associated with the magnitudes and timescales of individual discharge events on the timescale of hours to days. Future experimental and modelling work should investigate whether and how bedform preservation ratios and the statistical nature of preserved cross-sets differs between systems in which bedform disequilibrium dynamics are driven by flashy flood hydrographs versus coevolution of dunes and bars, respectively. We advocate that this is the next step in determining the extent to which discharge variability can be quantitatively reconstructed from stratigraphic observations.

Ultimately, despite sampling a variety of fluvial planform styles across large geographic regions, our results indicate that measured dune-scale cross-sets do not demonstrate the geometries expected for bedform preservation under steady-state conditions, which routinely underpin palaeohydraulic investigations of ancient fluvial systems. This indicates that application of bedform preservation ratios of ~0.3 to fluvial strata may result in overestimation of true palaeoflow depths (c.f. Leclair & Bridge, 2001) and consequently underestimate palaeoslopes. We argue that systematic measurements of cross-set geometries and, where possible, bedform preservation ratios should be a routine tool to facilitate and contextualize palaeohydraulic reconstructions, and to test for the presence of bedform disequilibrium dynamics.

6. Conclusions

We made systematic measurements of dune-scale cross-set geometries and grain-sizes in fluvial strata of three Late Cretaceous geologic formations in central Utah, USA: the Blackhawk Formation, Castlegate Sandstone, and Ferron Sandstone. Across all three formations, we documented unanimously low $CV(h_{xs})$ in preserved cross-set thicknesses of 0.25–0.5. These field observations are inconsistent with the steady-state bedform preservation model that assumes cross-sets are generated by random variability in scour depth with time (Paola & Borgman, 1991; Leclair & Bridge, 2001). Instead, our observations add to the growing recognition that bedform preservation is dominated by disequilibrium dynamics (Reesink et al., 2015; Ganti et al., 2020; Leary & Ganti, 2020), resulting in higher bedform preservation ratios and the deposition of cross-sets which preserve a relatively narrow distribution of thicknesses ($CV(h_{xs})<<0.88$).

We considered two independent hypotheses that lead to enhanced bedform preservation in disequilibrium conditions. Under the flood hypothesis, our data indicate that the flood durations that typify these deposits likely ranged from hours to days, which are reflective of heavy rain and tropical storms in these ancient fluvial landscapes. Under the hierarchy hypothesis, the observed low $CV(h_{xs})$ is consistent with bedform deposits preserved with rapidly evolving bars whose timescale of migration likely spans days to months. Detangling the flood versus hierarchy controls on bedform preservation may be possible through the spatial contextualization of preserved deposits of single-thread rivers, with flow variability potentially the dominant control on the nature of bedform preservation in channel-thalweg deposits, such as those observed in the Ferron Sandstone and Blackhawk Formation. However, detangling these relative controls may be difficult in the deposits of braided rivers, such as the Castlegate Sandstone, that are characterized by migration of unit bars and braid bars that can lead to the enhanced bedform preservation.

Where low $CV(h_{xs})$ reflects enhanced bedform preservation associated with formative flow variability, the approaches presented in this paper have significant implications for investigating discharge variability in the geologic past, particularly the magnitudes, transport capacities, and durations of individual flood events generated during short-period climatic perturbations. Meanwhile, where low $CV(h_{xs})$ reflects enhanced bedform preservation associated with the presence of a morphodynamic hierarchy, these results have implications for evaluating the nature of interactions between dunes, bars, channel migration and channel avulsion in palaeo-channel networks. We advocate that quantifying cross-set geometries should become a standard approach in future studies to improve and contextualize palaeohydrological reconstructions from ancient fluvial deposits.

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Data Availability

Field data available in the Supplementary Information.

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Figures

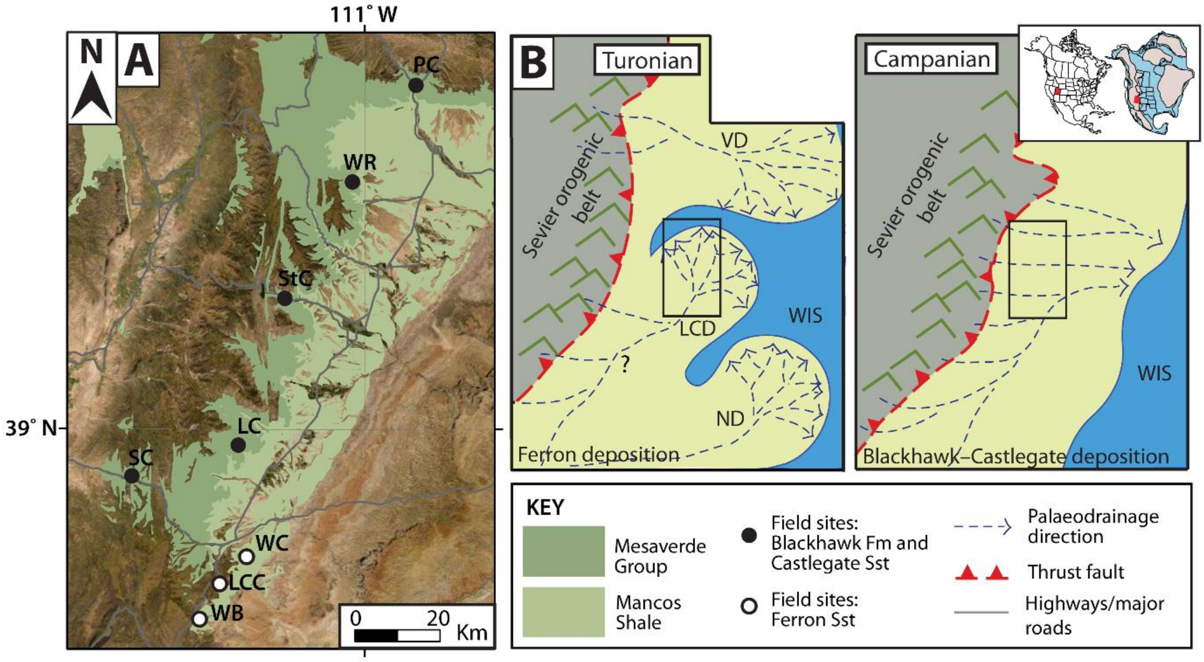

Figure 1: Study area. A) Field areas in central Utah, U.S.A., which include Last Chance Creek (LCC), Link Canyon (LC), Price Canyon (PC), Salina Canyon (SC), Straight Canyon (StC), Wattis Road (WR), Willow Basin (WB) and Willow Creek (WC). LC, PC, SC, StC and WR are field sites from which we obtained data for the Blackhawk Formation and Castlegate Sandstone (Mesaverde Group; black-filled circles). LCC, WB and WC are field sites from which we obtained data for the Ferron Sandstone (Mancos Shale; white-filled circles). B) A conceptual diagram of Utah palaeogeography and palaeodrainage in both the Turonian (left) and Campanian (right). Likely palaeodrainage configurations (and delta progradation) are indicated by dashed blue lines with arrows. The black outlined box in the centre of each palaeogeography indicates the study area (i.e., the approximate position and extent of A). The location of Utah relative to the modern North American continent (left) and the Late Cretaceous North American continent (right) is shown in the inset figure — Utah is highlighted as a red box. LCD = Last Chance delta; ND = Notom delta; VD = Vernal delta; WIS = Western Interior Seaway. Figure adapted from Lyster et al. (2021). [2 column figure]

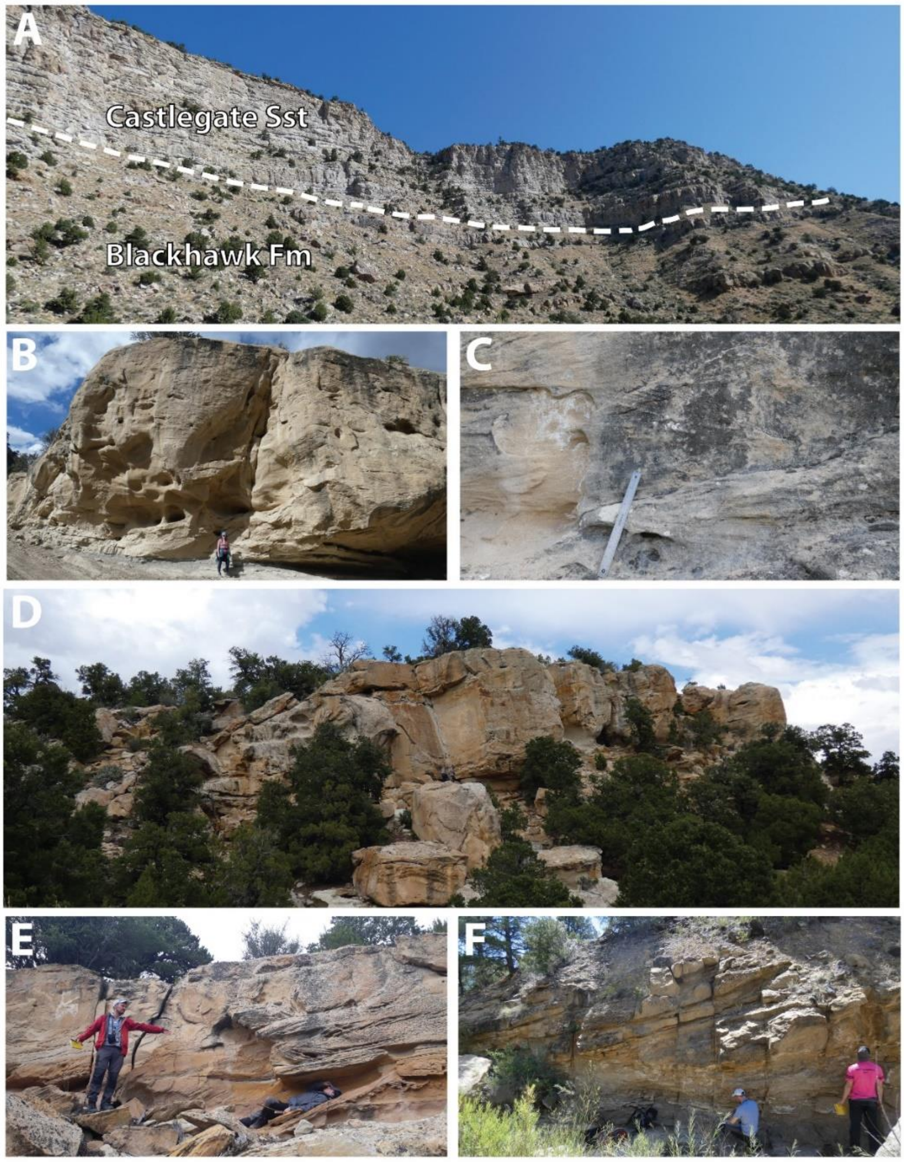

Figure 2: An overview of Upper Cretaceous fluvial strata from which we collected field data in central Utah, USA. A) Example of typical exposure of the Blackhawk Formation and Castlegate Sandstone (at Salina Canyon; SC; Fig. 1) which crops out in canyons along the eastern Wasatch front. Dashed white line indicates the lithostratigraphic boundary between the Blackhawk Formation and Castlegate Sandstone. Thickness of the Castlegate Sandstone is *ca* 85 m. B) Example of a major channelized fluvial sandstone body of the Blackhawk Formation at Link Canyon (LC; Fig. 1). C) Crude cross-stratification of amalgamated fluvial deposits of the Castlegate Sandstone at Price Canyon (PC; Fig. 1). D) Example of a major channelized sandstone body of the Ferron Sandstone at Last Chance Creek (LCC; Fig. 1). Persons for scale in centre of image. Thickness of channelized sandstone body in centre of image is *ca* 12 m. E) Cross-stratified fluvial strata of the Ferron Sandstone at LCC (with some soft-sediment deformation apparent). F) Laterally accreted point bar deposits of the Ferron Sandstone at LCC. [2 column figure]

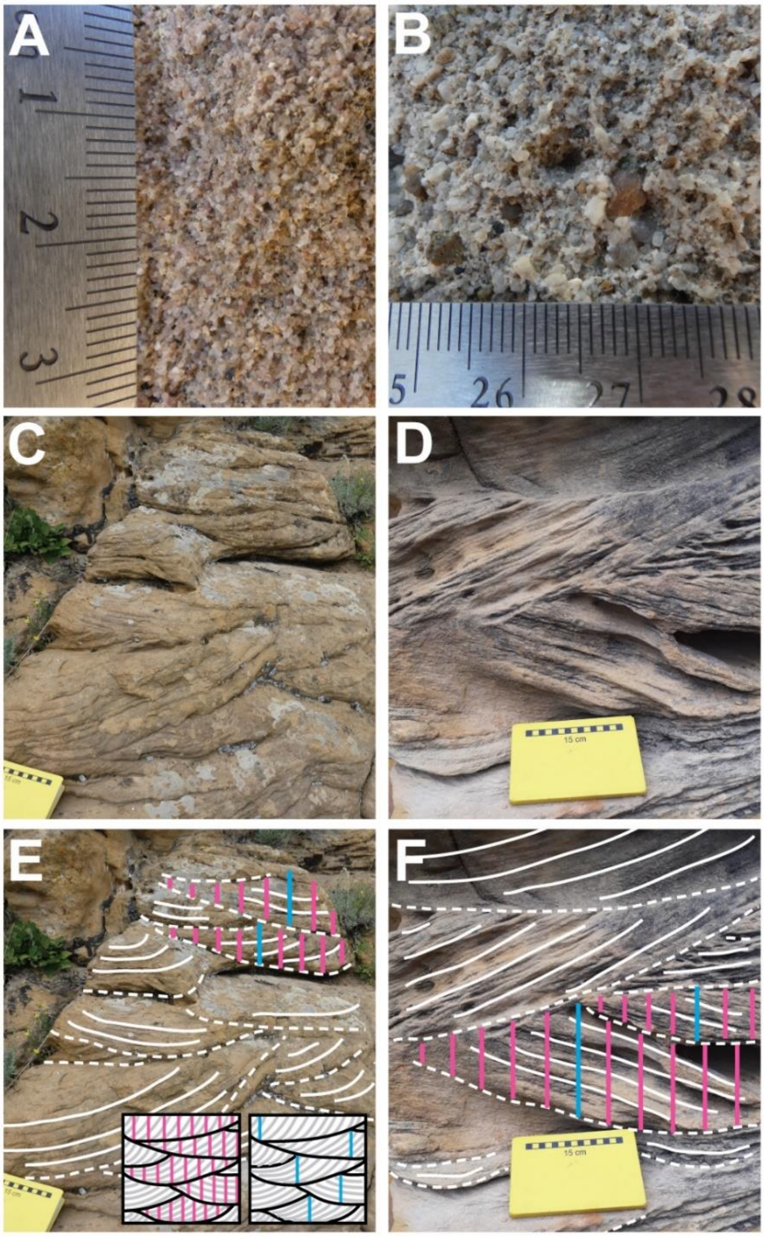

Figure 3: Field methods. A,B) For each measured cross-set, grain-size was assigned using the Wentworth (1922) classification. C,D) Examples of cross-sets from which distributions of cross-set heights were measured. E,F) Interpreted versions of the images in C,D. Dashed white lines indicate bounding surfaces between cross-sets and solid white lines indicate individual foresets within cross-sets. To exemplify how cross-sets were measured, pink vertical lines indicate the regular spacing within individual cross-sets at which heights were measured, and blue vertical lines indicate where maximum cross-set heights would have been measured for a population of cross-sets within co-sets at each locality. Insets in E are schematic representations of these two methods of data collection from cross-sets using pink and blue lines, respectively. Figure adapted from Lyster et al. (2021). [1 or 1.5 column figure]

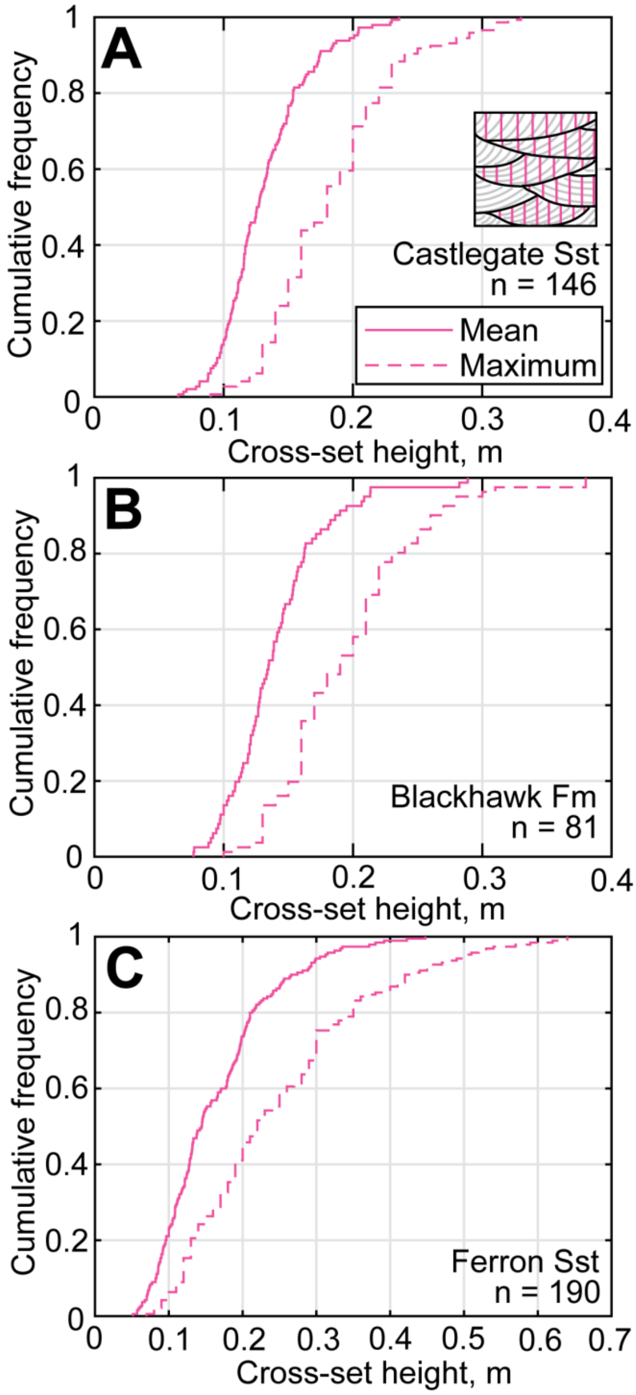

Figure 4: The cumulative frequency of the mean, median and maximum cross-set thickness for (A) the Castlegate Sandstone, (B) the Blackhawk Formation, and (C) the Ferron Sandstone. The solid pink line indicates the measured mean and the dashed pink line indicates the measured maximum. n indicates the number of cross-sets in which height distributions were measured, and therefore the number of cross-sets from which a mean and maximum were subsequently extracted. The inset in A is a schematic representation of how height distributions were measured within each cross-set. [1 column figure]

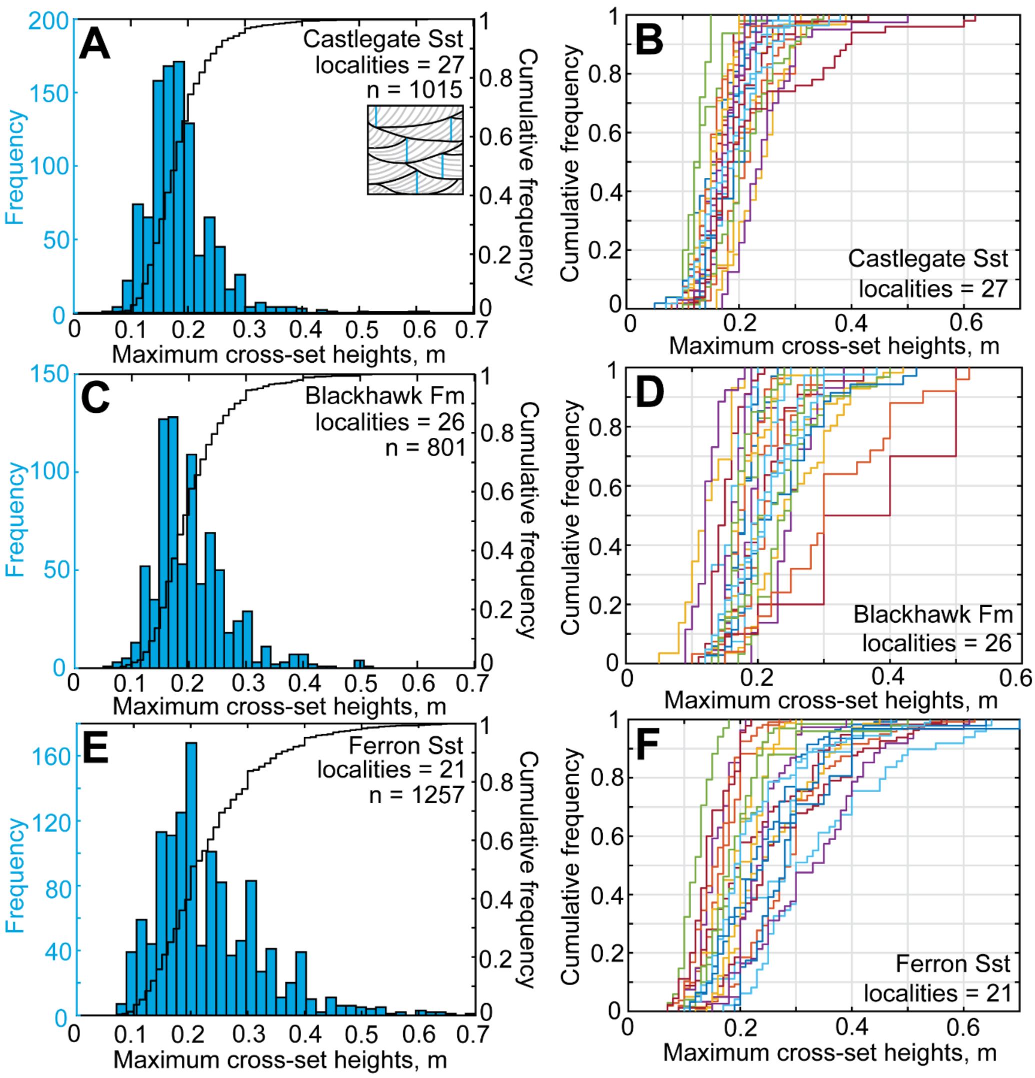

Figure 5: A) The frequency (left y axis; blue) and cumulative frequency (right y axis; black) of maximum cross-set heights measured across the Castlegate Sandstone. n indicates the total number of cross-sets measured for the entire formation, and the number of localities refers to the field sites across which these measurements were made. Measurements at each locality were for a population of related cross-sets within cosets, and typically comprised ~25–75 measurements. B) The cumulative frequency of maximum cross-set heights for each locality within the Castlegate Sandstone. C) The frequency and cumulative frequency of maximum cross-set heights measured across the Blackhawk Formation. D) The cumulative frequency of maximum cross-set heights for each locality within the Blackhawk Formation. E) The frequency and cumulative frequency of maximum cross-set heights measured across the Ferron Sandstone. F) The cumulative frequency of maximum cross-set heights for each locality within the Ferron Sandstone. The inset in A is a schematic representation of how maximum heights were measured across populations of cross-sets. [1.5 or 2 column figure]

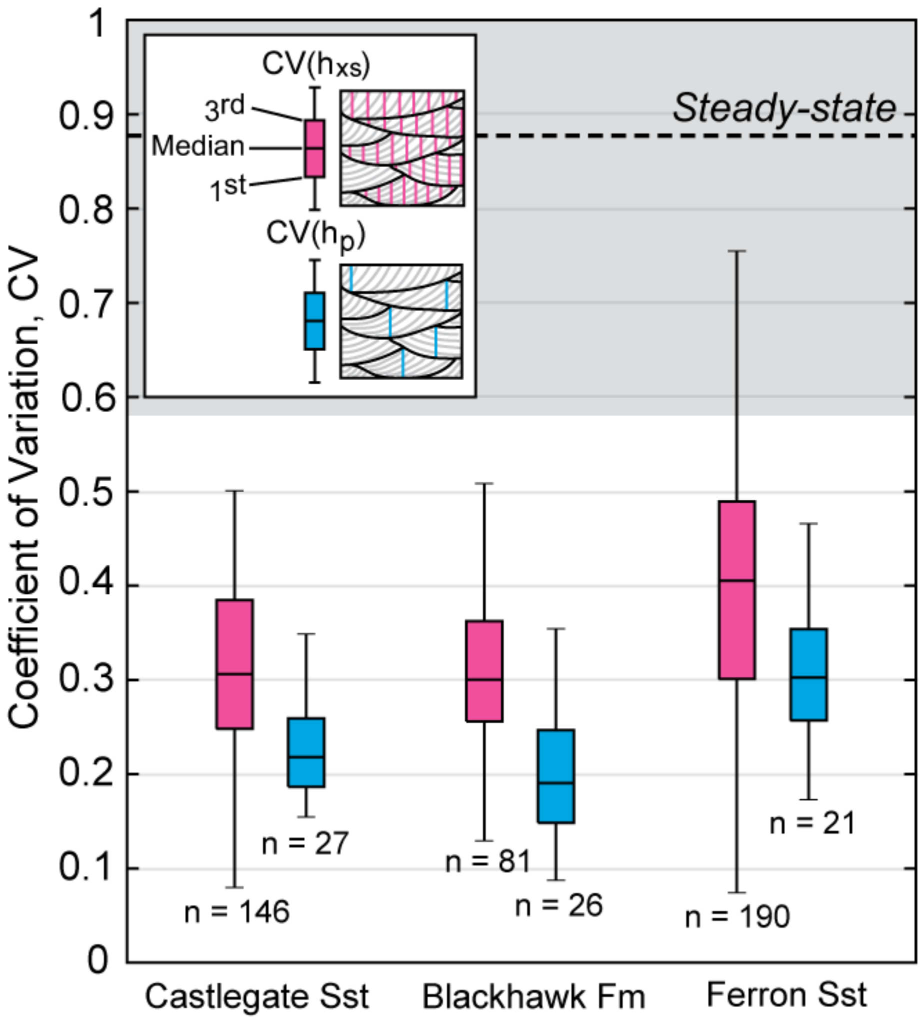

Figure 6: The coefficient of variation, CV, of cross-set heights measured in the Castlegate Sandstone, Blackhawk Formation, and Ferron Sandstone. Pink boxes indicate CVs of height distributions within individually measured cross-sets ($CV(h_{xs})$, with n indicating the number of individually measured cross-sets. The blue boxes indicate CVs of height distributions across a population of (related) cross-sets ($CV(h_p)$, with n indicating the number of field localities at which a population of cross-set heights was measured. At each locality, the population of measured cross-sets typically included ~25–75 cross-sets. Insets within the key demonstrate, schematically, how heights would have been measured for both $CV(h_{xs})$ and $CV(h_p)$ respectively (see Methods). The central mark of each box indicates the median estimate, and the bottom and top edges of each box indicate the 1st and 3rd quartiles (or 25^{th} and 75^{th} percentiles), respectively. The whiskers extend to the most extreme values of CV that are not considered to be outliers. The dashed black line indicates the theoretical steady-state CV of 0.88, following Paola and Borgman (1991), and the grey shaded region indicates the empirical steady-state CV of 0.88±0.30, following Bridge (1997). [1.5 column figure]

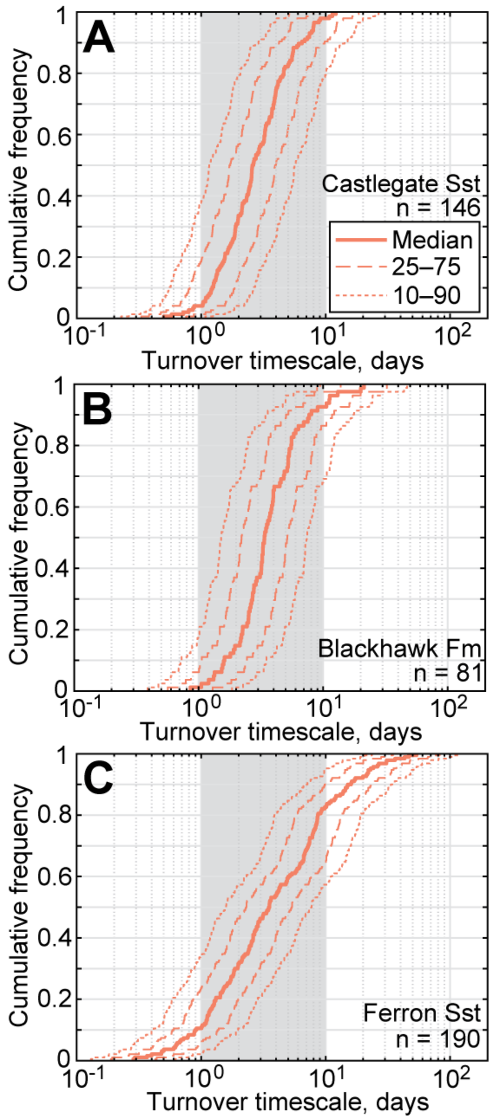

Figure 7: The cumulative frequency of estimated turnover timescales, T_t, calculated for (A) the Castlegate Sandstone, (B) the Blackhawk Formation, and (C) the Ferron Sandstone (see Supplementary Methods). T_t was calculated for each cross-set from which a cross-set height distribution was measured, using the mean height and the measured grain-size (Fig. 3; see Methods). n indicates the number of T_t values that were calculated (equal to the number of measured cross-set height distributions). The solid orange line indicates the median T_t reconstructed for each cross-set, the dashed orange lines indicate the 25th–75th percentile range of T_t values reconstructed for each cross-set, and the dotted orange lines indicate the 10th–90th percentile range of T_t values reconstructed for each cross-set, which we offer as plausible spreads of values for mean T_t (see Supplementary Methods). Grey shaded region indicates T_t values of 1–10 days; for the Castlegate Sandstone and Blackhawk Formation, ~90–95% of median T_t values fall within this range and, for the Ferron Sandstone, ~70% of median T_t values fall within this range. [1 column figure]

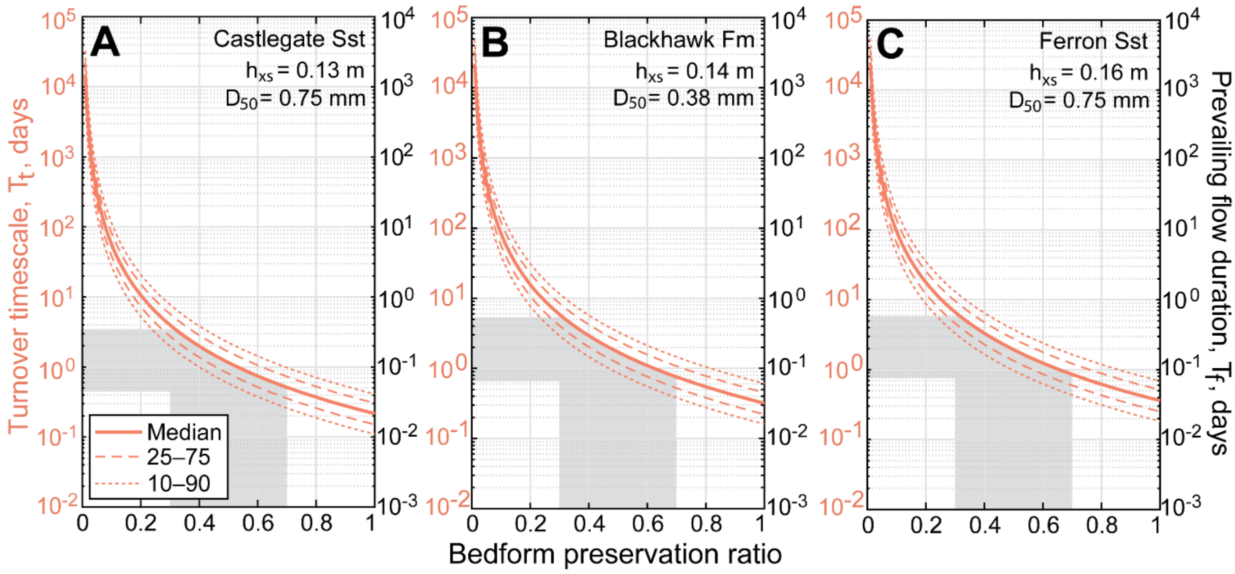

Figure 8: Turnover timescales, T_t, reconstructed for the Castlegate Sandstone, Blackhawk Formation and Ferron Sandstone using a range of preservation ratios. For these purposes, the mean cross-set height (h_{xs}) and median grain-size (D_{50}) for each geologic formation have been used (i.e., the mean and median across all measured cross-set distributions). The solid orange line indicates the median T_t reconstructed for each bedform preservation ratio, the dashed orange lines indicate the 25th–75th percentile range of T_t values reconstructed for each bedform preservation ratio, and the dotted orange lines indicate the 10th–90th percentile range of T_t values reconstructed for each bedform preservation ratio, which we offer as plausible spreads of values for mean T_t (see Supplementary Methods). The grey region highlights the range of median T_t values associated with a plausible range of bedform preservation ratios; steady-state bedform preservation ratios are ~0.3, and Leary and Ganti (2020) documented that higher bedform preservation ratios may extend up to ~0.7 during flash floods. On the right y axis, we show reconstructed prevailing flow durations, T_f, for the scenario in which T_f is a factor of 10 smaller than the reconstructed bedform turnover timescale. [2 column figure]

Supplement to *Field evidence for disequilibrium dynamics in preserved fluvial cross-strata: A record of discharge variability or morphodynamic hierarchy?*

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Contents:

S1. Field localities

Table S1: *Field localities visited in this study. Localities are grouped by field area (e.g., Price Canyon, Wattis Road; see Figure 1 in main text) and subdivided by formation (i.e., Blackhawk Formation, Castlegate Sandstone and Ferron Sandstone).*

Location and stratigraphic interval		**Field sites**	**Elevation, m (±3–4)**
Last Chance Creek	Ferron Sandstone	N38 40 18.9, W111 24 52.5	2255
		N38 40 20, W111 24 45.3	2241
		N38 40 21.7, W111 24 17.1	2218
		N38 40 17.5, W111 24 12	2209
		N38 40 12, W111 24 2.5	2190
		N38 40 7.7, W111 23 50.3	2179
		N38 40 9.1, W111 23 44.8	2187
		N38 40 8.9, W111 23 53.6	2215

Link Canyon	Blackhawk Formation	N38 57 42.1, W111 19 57.4	2363
		N38 57 39.7, W111 19 53.9	2383
		N38 57 41.4, W111 19 53.0	2398
		N38 57 44.3, W111 19 53.8	2421
		N38 57 48.4, W111 19 53.9	2473
		N38 57 58.3, W111 19 57.3	2538
		N38 57 52.8, W111 19 55.8	2509
		N38 57 51.4, W111 19 55.0	2500
	Castlegate Sandstone	N38 58 05.9, W111 19 56.6	2572
		N38 58 08.0, W111 19 55.8	2584
		N38 58 10.6, W111 19 54.2	2600
Price Canyon	Blackhawk Formation	N39 44 11.0, W110 50 47.7	1932
		N39 44 08.4, W110 50 46.9	1947
	Castlegate Sandstone	N39 45 05.1, W110 53 10.3	1920
		N39 44 48.5, W110 49 58.1	1969
		N39 44 52.6, W110 49 55.4	1983
		N39 45 01.3, W110 49 43.5	2000
		N39 45 03.0, W110 49 40.6	1999
		N39 45 10.5, W110 49 35.8	2008
		N39 45 12.0, W110 49 34.8	2003
Salina Canyon	Blackhawk Formation	N38 54 00.8, W111 39 53.8	1861
		N38 53 51.5, W111 39 02.3	1885
		N38 54 29.6, W111 41 46.8	1802
		N38 54 13.8, W111 39 05.9	1926
	Castlegate Sandstone	N38 54 52.9, W111 38 06.5	2036
		N38 54 52.3, W111 38 08.7	2017
		N38 54 50.6, W111 38 18.1	2009
		N38 54 52.6, W111 38 20.2	2030
		N38 54 53.7, W111 38~20.2	2035
		N38 54 33.0, W111 42 32.7	1779
		N38 54 57.1, W111 38 20.3	2076
		N38 54 59.4, W111 38 13.1	2111

Straight Canyon	Blackhawk Formation	N39 16 56.6, W111 13 58.0	2027
		N39 16 46.2, W111 13 41.9	2010
		N39 16 29.1, W111 13 11.9	1996
		N39 17 16.2, W111 14 37.5	2047
		N39 17 15.7, W111 14 30.4	2043
		N39 17 05.7, W111 14 10.5	2037
		N39 17 36.5, W111 16 16.7	2146
		N39 17 19.3, W111 16 00.0	2129
		N39 17 20.9, W111 15 19.8	2102
	Castlegate Sandstone	N39 17 51.9, W111 16 18.0	2161
		N39 18 28.6, W111 16 13.2	2181
		N39 18 55.2, W111 16 06.2	2238
Wattis Road	Blackhawk Formation	N39 31 45.5, W111 02 16.0	2577
		N39 31 11.9, W111 01 56.9	2692
		N39 31 19.8, W111 01 58.4	2655
		N39 31 20.7, W111 02 37.2	2798
		N39 31 14.3, W111 02 13.8	2765
	Castlegate Sandstone	N39 31 28.6, W111 02 44.9	2844
		N39 31 31.7, W111 02 50.6	2877
		N39 31 30.2, W111 02 46.4	2861
		N39 31 33.5, W111 02 53.2	2889
Willow Basin	Ferron Sandstone	N38 34 50.9, W111 28 6.2	2668
		N38 34 49, W111 28 6.5	2636
		N38 34 48.9, W111 28 4.5	2631
		N38 34 47.6, W111 28 5.4	2592
		N38 34 35.1, W111 27 48.4	2537
Willow Creek	Ferron Sandstone	N38 44 0.4, W111 18 47.2	1965
		N38 43 37.4, W111 18 46.5	1926
		N38 43 25.2, W111 18 45.9	1895

S2. Extended methodology: Estimation of bedform turnover timescale

We propagated mean thicknesses of individually measured cross-sets (and their respective grain-sizes) through a well-established quantitative framework (c.f. Ganti et al., 2019; Lyster et al., 2021) to reconstruct a variety of palaeohydraulic parameters and, eventually, bedform turnover timescales, T_t. We first reconstructed mean original bedform (i.e., dune) height, h_d, as a function of mean cross-set thickness, h_{xs}, using the relation of Leclair and Bridge (2001),

$$h_d = 2.9(\pm 0.7)h_{xs}, \qquad \text{[Eq. S1]}$$

where 2.9 is the mean (μ) and 0.7 is the standard deviation (σ). The above relation was experimentally derived for steady-state conditions, i.e., bedform preservation ratio (h_{xs}/h_d) of ~0.3. However, bedform preservation in disequilibrium conditions may imply that h_{xs}/h_d is higher (Jerolmack & Mohrig, 2005; Reesink et al., 2015; Ganti et al., 2020; Leary & Ganti, 2020). Initially, we assumed h_{xs}/h_d of ~0.3, which means that T_t estimates are maximum values. We subsequently evaluated the sensitivity of T_t to h_{xs}/h_d (see Methods in main text). Finally, we estimated likely values of h_{xs}/h_d for each geologic formation using available data (Section S3), which broadly range from 0.3–0.7, and used these values to contextualise the implications of this sensitivity on our results (Figure 8 in main text).

We used a Monte Carlo uncertainty propagation method to estimate uncertainty (c.f. Lyster et al., 2021). In doing so, we offer plausible spreads of values for the median of each reconstructed parameter. From Equation S1, we generated 10^6 random samples of the model parameter between bounds defined by μ−σ and μ+σ. To avoid introduction of additional assumptions, we generated these samples from a uniform distribution as the shape and the scale of the full distribution of the data is unknown. These 10^6 samples were used to calculate 10^6 values of h_d, and these results were propagated through subsequent calculations. Given that Equation S1 assumes steady-state flow conditions and a h_{xs}/h_d value of ~0.3, and that we randomly sampled the model parameter between μ−σ and μ+σ, we note that our uncertainty analysis analytically accounts for some variability in h_{xs}/h_d, between ~0.28 and ~0.45.

To reconstruct formative flow depth, H, we used the bedform height−flow depth scaling relation of Bradley and Venditti (2017), which was derived using >380 empirical data. Bradley and Venditti (2017) presented a non-parametric relation which characterized their data, which did not assume an underlying distribution for the scaling parameter. In this relation, median H is given as

$$H = 6.7h_d, \qquad \text{[Eq. S2]}$$

with a probabilistic uncertainty estimator in which the 1st and 3rd quartiles of H are given by H=4.4h_d and H=10.1h_d, respectively (Bradley & Venditti, 2017). We generated 10^6 random samples between 4.4 and 10.1, again from a uniform distribution, and reconstructed 10^6 values of H in these ancient fluvial systems using Equation S2. These values were then used to estimate bedform wavelength, λ, as λ=7.3H, following van Rijn (1984).

To reconstruct palaeoslope, we used the empirical method of Trampush et al. (2014). Palaeoslopes may also be calculated by a Shields stress inversion where the dimensionless Shields stress is known (or where it can be estimated using, e.g., bedform stability diagrams; Carling (1999)). However, we implemented the method of Trampush et al. (2014) for consistency with the method that Mahon and McElroy (2018) used to derive Equations S4 and S5. In addition, previous studies have shown that both palaeoslope methods recover similar values for sand-grade grain-sizes (Ganti et al., 2019; Lyster et al., 2021). Trampush et al. (2014) expressed palaeoslope, S, as

$$\log S = \alpha_0 + \alpha_1 \log D_{50} + a_2 \log H, \qquad \text{[Eq. S3]}$$

where $\alpha_0 = -2.08 \pm 0.036$, $\alpha_1 = 0.254 \pm 0.016$, and $\alpha_2 = -1.09 \pm 0.044$ are constants. We randomly sampled 10^6 values of α_0, α_1, and α_2 (uniformly distributed between $\mu-\sigma$ and $\mu+\sigma$) and reconstructed 10^6 values of S.

To calculate characteristic bedform migration velocity, V_c, and therefore unit bedload flux, q_b, we used the bedform-scale (as opposed to grain-scale) approach of Mahon and McElroy (2018), in which q_b is estimated geometrically, per unit width, as a function of bedform migration velocity, V_c. These variables are given as:

$$\log V_c = \beta_0 + \beta_1 \log S, \qquad \text{[Eq. S4]}$$

$$q_b = (1-\varphi)\frac{h_d V_c}{2}, \qquad \text{[Eq. S5]}$$

where $\beta_0 = 0.6113 \pm 0.144$ and $\beta_1 = 1.305 \pm 0.0515$ are constants, and φ is a dimensionless bed porosity of 0.5 (Mahon & McElroy, 2018). To reconstruct V_c, we randomly sampled 10^6 values for the model parameters, β_0 and β_1, from a uniform distribution between bounds defined by $\mu-\sigma$ and $\mu+\sigma$. These values were then used to estimate q_b (Equation S5).

Having calculated 10^6 values of h_d, H, λ, S, V_c, and q_b, we reconstructed bedform turnover timescales, T_t, i.e., the time taken to displace the volume of sediment of the bedform (per unit width), following Martin and Jerolmack (2013) and Myrow et al. (2018), as:

$$T_t = \frac{\lambda h_d \beta}{q_b}, \qquad \text{[Eq. S6]}$$

where β ~0.55 is the bedform shape factor.

This recovered 10^6 values of T_t in units of seconds which we converted to days. From these values, we extracted median T_t, the 25–75 percentile range of T_t (or the 1st–3rd interquartile range of T_t), and the 10–90 percentile range of T_t. Given that the errors and uncertainties associated with Equations S2–S6 are propagated through the methodology, and that these errors and uncertainties are compounded on top of each other, we suggest that the 10–90 percentile range of T_t offers plausible minimum and maximum values for median T_t, with the 25–75 percentile range of T_t highlighting where true values of median T_t are most likely to occur between these bounds.

S3. Constraints on bedform preservation ratios

As discussed in the main text, and above, the scaling relation of Leclair and Bridge (2001) (Equation S1) is derived for steady-state conditions, which implies that reconstructed H values are also steady-state estimates. However, it is expected that h_{xs}/h_d is higher in disequilibrium conditions (see main text). The ability to constrain h_{xs}/h_d from geological outcrop would be useful for evaluating the nature of bedform preservation, however this is difficult in practice.

In order to accurately constrain h_{xs}/h_d, we ideally require systematic measurements of cross-set heights and knowledge of their original bedform heights, however it is not possible to know original bedform heights in ancient fluvial systems. Instead, we can contrast cross-set heights with independent proxies of H, e.g., barform heights. If H values reconstructed from mean cross-set heights using steady-state assumptions agree with independent proxies of H, then this might imply that h_{xs}/h_d was truly ~0.3. However, this approach requires us to assume the relationship between the original bedform height and the palaeoflow depth (Equation S2) in order to recover a value for h_{xs}/h_d. Reconstructions of h_{xs}/h_d are therefore estimates. Moreover, barform heights are a proxy for maximum bankfull depths which, given the possibility that mean bankfull depths are smaller, will act to decrease the estimated value of h_{xs}/h_d. This is particularly true where the heights of point bar deposits are used as independent proxies of H, as flow depths in meandering systems are typically greater on meander bends. One further issue with this approach is that the barforms themselves may not be fully preserved (Chamberlin & Hajek, 2019).

In this study, despite our detailed data collection, we do not have the desired spatiotemporal resolution of field measurements to accurately constrain h_{xs}/h_d., i.e., we do not have a mean cross-set height and the mean height of the associated barform for each measured cross-set. However, as a starting point, we compared mean cross-set heights across our field areas (Fig. 1 in main text) with mean barform heights in published literature. Based on stratigraphic observations, detailed below, we predict that values of h_{xs}/h_d likely ranged between 0.3 and 0.7. This suggests that uncertainty margins in Equation S1, which analytically account for variability in h_{xs}/h_d between ~0.28 and ~0.45, are reasonable. It is unlikely that h_{xs}/h_d is much smaller than ~0.3 because, as mentioned in the main text, if h_{xs}/h_d is much smaller than ~0.3 then T_t rapidly increases from 10^1 to 10^5 days (Eq. S1 and S2), which are implausible bedform migration timescales.

We recovered median values of h_{xs} equal to ~0.13–0.14 m for the Blackhawk Formation and Castlegate Sandstone, but which broadly span 0.1–0.2 m. H values reconstructed using steady-state assumptions have previously been verified for the Blackhawk Formation and Castlegate Sandstone by Lyster et al. (2021). The authors reconstructed median *H* values of 2–4 m from cross-sets spanning the Blackhawk Formation and Castlegate Sandstone at localities along the eastern front of the Wasatch Plateau (Lyster et al., 2021). These *H* values are in broad agreement with *H* values independently inferred from bar-scale clinoform heights, which have means of ~3–3.5 m, but which typically span 1–8 m (Adams & Bhattacharya, 2005; Lynds & Hajek, 2006; McLaurin & Steel, 2007; Hajek & Heller, 2012; Chamberlin & Hajek, 2019; Lyster et al., 2021). Assuming the model parameter in Equation S3 is true, we might expect values of h_{xs}/h_d up to 0.6–0.7.

Meanwhile, for the Ferron Sandstone, *H* values reconstructed using steady-state assumptions have not previously been verified. Here, from individually measured cross-sets (n=190), we recovered median values of 0.15 m for mean cross-set heights, which broadly span 0.1–0.3 m. Using Equation S3 we project median values for *H* of ~3 m, but which broadly span 1–10 m (Equation S3). Independent proxies of *H* are limited for the Ferron Sandstone. As such, in the field we obtained new measurements of independent *H* proxies, e.g., laterally accreted point bar deposit heights, which we made using a Haglof Laser Geo laser range finder to a precision of ±5 cm, and which we used to supplement limited secondary data (Table S2). In the Ferron Sandstone, previous work has documented channel-fill deposits and laterally accreted point bars with heights of order 8–9 m (Cotter, 1971; Gardner et al., 2004; Garrison & Bergh, 2004). Here we report a broader range of heights for independent *H* proxies (Table S2). Across 35 measurements of point bar/lateral accretion set heights (Table S2), we recover a mean height of 4.7 m, with a 1st–3rd interquartile range spanning 2.9–6.5 m. Minimum and maximum heights are 1.1 and 10 m, respectively (Table S2). Similarly, if we assume the model parameter in Equation S3 is true, then we might expect h_{xs}/h_d values up to 0.6–0.7.

Table S2: *Independent measurements of palaeoflow depth indicators in the Ferron Sandstone*

Palaeoflow depth proxy	Thickness (m)	Source
Laterally accreted point bar deposit	9.1	Cotter (1971)
Laterally accreted point bar deposit	<8	Gardner et al. (2004)
Maximum thickness of channel-fill deposits	~9	Gardner et al. (2004)
Maximum thickness of channel-fill deposits	~9	Garrison and Bergh (2004)
Laterally accreted point bar deposits	8, 7.5, 9, 3.2, 4.8, 3.6, 6.5, 7.5, 3.6, 4.1, 2.7, 6.4, 5.5, 2.8, 1.1, 1.9, 7.5, 2.7, 7.1, 1.2, 4.4, 3.7, 3.1, 3.4, 3, 2.5, 5.9, 2.5, 4.7, 10, 4.2, 1.6, 3, 6.5, 10	**This study**

Maximum thickness of single channel storeys	8.6, 11.1, 12.2, 9, 7.6, 7.1, 3.9, 5.6, 2.6, 7.3, 12, 9.3	**This study**

S4. Data tables

We provide a Microsoft Excel spreadsheet containing field results and a selection of reconstructed palaeohydrologic parameters for the Blackhawk Formation, Castlegate Sandstone and Ferron Sandstone. Field data and results are reported per field area (see Fig. 1 in main text).

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