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The problem of paleo-planforms

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ABSTRACT

Reconstructing river planform is crucial to understanding ancient fluvial systems on Earth and other planets. Paleo-planform is typically interpreted from qualitative facies interpretations of fluvial strata, but these can be inconsistent with quantitative approaches. We tested three well-known hydraulic planform predictors in Cretaceous fluvial strata (in Utah, USA) where there is a facies-derived consensus on paleo-planform. However, the results of each predictor are inconsistent with facies interpretations and with each other. We found that one of these predictors is analytically best suited for geologic application but favors single-thread planforms. Given that this predictor was originally tested using just 53 data points from natural rivers, we compiled a new data set of hydraulic geometries in natural rivers ($n = 1688$), which spanned >550 globally widespread, sand- and gravel-bed rivers from various climate and vegetative regimes. We found that the existing criteria misclassified 65% of multithread rivers in our data set, but modification resulted in a useful predictor. We show that depth/width (H/W) ratio alone is sufficient to discriminate between single-thread ($H/W > 0.02$) and multithread ($H/W < 0.02$) rivers, suggesting bank cohesion may be a critical determinant of planform. Further, we show that the slope/Froude (S/Fr) ratio is useful to discriminate process in multithread rivers; i.e., whether generation of new threads is an avulsion-dominated (anastomosing) or bifurcation-dominated (braided) process. Multithread rivers are likely to be anastomosing when S/Fr < 0.003 (shallower slopes) and braided when S/Fr > 0.003 (steeper slopes). Our criteria successfully discriminate planform in modern rivers and our geologic examples, and they offer an effective approach to predict planform in the geologic past on Earth and on other planets.

INTRODUCTION

River planforms constitute a fundamental element of fluvial landscapes and reflect the quasi-equilibrium form of channels in response to water discharge, sediment flux, and slope. In ancient fluvial systems, their reconstruction is crucial to determine river response to climate and land-cover change (Gibling and Davies, 2012; Gibling et al., 2014; Colombera et al., 2017), water, sediment, and biogeochemical fluxes (Ganti et al., 2019; Lyster et al., 2021), and pre-vegetation landscape dynamics on Earth and other planets (Ielpi and Rainbird, 2016; Ielpi et al., 2018; Ganti et al., 2019; Ielpi and Lapôtre, 2019a; Lapôtre et al., 2019; Lapôtre and Ielpi, 2020). In fluvial strata, facies interpretations provide qualitative insights into paleo-planform (e.g., Miall, 1993, 1994; Adams and Bhattacharya, 2005; Hampson et al., 2013); however, quantitative planform predictors are important complements to these approaches. They are particularly important where exposure of fluvial strata is limited (Fielding et al., 2018; Chamberlin and Hajek, 2019), where paleohydraulic calculations are required (Lyster et. al., 2021), and where facies interpretations may be equivocal (Fielding et al., 2018). Recent debates about the implication of "sheet-braided" facies models for pre-vegetation rivers underscore this latter issue (Gibling and Davies, 2012; Gibling et al., 2014; Ielpi and Rainbird, 2016; Ganti et al., 2019).

Planform predictors include empirical relationships (e.g., van den Berg, 1995) and theoretical approaches, where the onset of meandering and braiding is predicted by mathematical models of channel stability and bar formation (e.g., Parker, 1976; Crosato and Mosselman, 2009). However, insights from these predictors can contrast stratigraphic interpretations (Ganti et al., 2019; Lyster et al., 2021). In stratigraphy, the discriminatory power of these predictors is unclear because (1) they are tested on modern data sets that lack natural river data (relative to experimental and man-made channels) and are biased toward North American and gravel-bed rivers; and (2) they often discriminate only single-thread and multithread rivers, neglecting to distinguish between anastomosing and braided planforms (Schumm, 1985; Church, 2006; Church and Ferguson, 2015).

We assessed how the predictors postulated by Parker (1976), Crosato and Mosselman (2009), and van den Berg (1995) performed when applied to fluvial strata with consensus facies interpretations of planform, and we established the approach that is most suitable for geologic application. We then compiled a new data set of hydraulic geometries in natural rivers and used these data to propose new criteria for paleo-planform prediction.

METHODS

Paleo-Planform Reconstruction

We focused on three Cretaceous formations in Utah, USA (Fig. 1A), where distinct planforms have been interpreted from facies analyses and plan-view exposures: (1) the Ferron Sandstone preserves meandering trunk channels (Fig. 1B; Cotter, 1971; Wu et al., 2015; Bhattacharyya et al., 2015); (2) the Blackhawk Formation preserves single-thread and multithread channels (Fig. 1C; Adams and Bhattacharya, 2005; Hampson et al., 2013); and (3) the Castlegate Sandstone preserves mostly braided channels (Fig. 1C; Miall, 1993, 1994).

For individual cross-sets in the Blackhawk Formation ($n = 81$), Castlegate Sandstone ($n = 146$), and Ferron Sandstone ($n = 190$), we determined mean cross-set thickness, h_{xs}, and median grain size, D_{50} (Figs. 1D and 1E), and we used an established quantitative framework (cf. Lyster et al., 2021; see the Supplemental Material[1]) to reconstruct flow depth (H), slope (S), flow velocity (U),

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[1]Supplemental Material. Extended methodological details, information on dataset compilation and how to access the dataset, and a list of field localities. Please visit https://doi.org/10.1130/GEOL.S.19424360 to access the supplemental material, and contact editing@geosociety.org with any questions.

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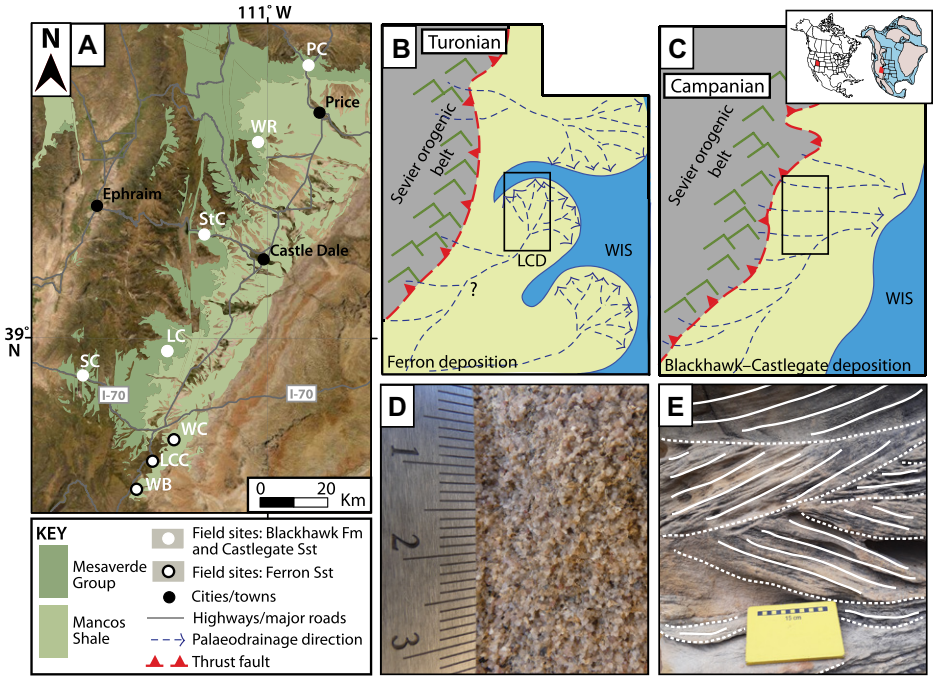

Figure 1. (A) Central Utah field sites in the western United States: Last Chance Creek (LCC); Link Canyon (LC); Price Canyon (PC); Salina Canyon (SC); Straight Canyon (StC); Wattis Road (WR); Willow Basin (WB); and Willow Creek (WC). (B,C) Utah paleogeography in the Turonian (B) and Campanian (C). Black boxes indicate the position of A. Inset indicates the position of Utah (red) relative to modern (left) and Cretaceous (right) North America. (D,E) For each cross-set, we measured median grain size (D) and mean cross-set thickness (E). Dotted and solid white lines indicate bounding surfaces and individual foresets, respectively. LCD—Last Chance delta; WIS—Western Interior Seaway; Fm—Formation; Sst—Sandstone.

and Froude number (Fr). We also required wetted channel width (W), which is difficult to constrain from geologic outcrops. To address this, we (1) implemented plausible lower and upper values of W (W_{min} and W_{max}) based on published estimates; and (2) evaluated the sensitivity of each predictor to uncertainty in channel aspect ratio (H/W) using identical data inputs for h_{xs} and D_{50} and using a Monte Carlo method to estimate error (see the Supplemental Material).

For each cross-set, we used three predictors to reconstruct planform (Table 1). First, we used the predictor of Parker (1976), where the planform parameter (ε) is <1 for single-thread rivers, $\varepsilon > 1$ for multithread rivers with 1–10 threads, and $\varepsilon > 10$ for multithread rivers with >10 threads (Equation 1 in Table 1). Second, we used the predictor of Crosato and Mosselman (2009) to estimate the bar mode (m) of rivers, where $m \leq 1.5$ for single-thread rivers, $m \geq 2.5$ for multithread rivers, and $1.5 < m < 2.5$ for transitional rivers (Equation 2 in Table 1). Third, we used the predictor of van den Berg (1995) to estimate a specific stream power parameter (ω) to discriminate between single-thread and multithread rivers (Equation 3 in Table 1).

Validating Planform Predictors

We compiled data on hydraulic geometries in natural rivers. We focused on appropriate modern analogues for ancient rivers, i.e., rivers that can plausibly be preserved in the rock record, including globally widespread sand- and gravel-bed rivers from various climate and vegetative regimes (see the Supplemental Material). We included rivers with reported values of W, H, S, U, and discharge (Q); we calculated Fr (see the Supplemental Material). Our data set contained 1688 data points for more than 550 rivers from 87 sources, with 758 observations of multithread rivers, including braided ($n = 402$), anastomosing ($n = 124$), and transitional ($n = 232$) planforms, which represent meandering–anastomosing and sinuous–braided transitions, and 930 observations of single-thread rivers, which represent meandering and sinuous planforms. With these data, we tested existing predictors, and we analyzed data distributions to propose new criteria that honor both modern and stratigraphic observations.

RESULTS

Paleo-Planform Reconstruction

For each formation, we present the planforms implied using W_{min} and W_{max} (Fig. 2; Table 1). We found that the Parker (1976) predictor favored single-thread planforms, even for W_{max} (Figs. 2A–2C), which is inconsistent with interpretations of multithread Blackhawk and Castlegate channels. The Crosato and Mosselman (2009) predictor strongly favored multithread planforms (Figs. 2E–2G), which is inconsistent with interpretations of single-thread Blackhawk and Ferron channels. Finally, the van den Berg (1995) predictor also favored single-thread planforms (Figs. 2I and 2J), which, for W_{min}, is inconsistent with multithread Blackhawk and Castlegate channels. Ultimately, the predictors were inconsistent with one another, and no predictor was consistent with stratigraphic consensus for all three geologic examples.

We evaluated the sensitivity of each predictor to H/W to demonstrate how the implied planform (y axis) varied with uncertainty in H/W (x axis; Figs. 2D, 2H, and 2L). Despite identical data inputs, we found that the threshold H/W between multithread and single-thread rivers

TABLE 1. PLANFORMS RECONSTRUCTED FOR THE BLACKHAWK FORMATION, CASTLEGATE SANDSTONE, AND FERRON SANDSTONE, UTAH, USA

Planform predictor*		Equation 1 Parker (1976) $\varepsilon = \frac{S}{Fr}\frac{H}{W}$		Equation 2 Crosato and Mosselman (2009) $m^2 = 0.17g\frac{b-3}{\sqrt{RD_{50}}}\frac{W^3S}{CQ}$			Equation 3 van den Berg (1995) $\omega = 2.1S\sqrt{Q}$	
Planform reconstructed		Single-thread	Multithread	Single-thread	Transitional	Multithread	Single-thread	Multithread
Blackhawk Formation	W_{min}†	100%#	0%	2.5%	44.5%	53%	100%	0%
	W_{max}§	91%	9%	0%	0%	100%	9%	91%
Castlegate Sandstone	W_{min}	100%	0%	0%	0%	100%	100%	0%
	W_{max}	51%	49%	0%	0%	100%	29%	71%
Ferron Sandstone	W_{min}	100%	0%	7%	31.5%	61.5%	99%	1%
	W_{max}	100%	0%	1%	10%	89%	94%	6%

*Listed variables: ε—planform parameter; S—slope; H—flow depth; Fr—Froude number; W—channel width; m—bar mode; g—acceleration due to gravity; b—degree of nonlinearity of the dependence of sediment transport on flow velocity, assumed to be 4 in sand-bed rivers; R—submerged specific density of sediment; D_{50}—median grain size; C—Chézy friction coefficient; Q—total water discharge (see the Supplemental Material [see text footnote 1]).ω—a potential specific stream power parameter.
†Planforms reconstructed using a minimum plausible channel width, W_{min} (see Fig. 2; see the Supplemental Material).
§Planforms reconstructed using a maximum plausible channel width, W_{max} (see Fig. 2; see the Supplemental Material).
#Percentage of measured cross-sets that produce results consistent with the planform stated in the column header.

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varied for each predictor. For Parker (1976), Crosato and Mosselman (2009), and van den Berg (1995), these *H*/*W* values were ~0.002, ~0.03, and ~0.005, respectively (or *W*/*H* values of ~500, ~33, and ~200; Figs. 2D, 2H, and 2L). This difference arises analytically: in Parker (1976), the threshold between multithread and single-thread rivers is dependent on *H*/*W*, whereas in Crosato and Mosselman (2009) and van den Berg (1995), it is independent of *H*/*W*, which implicitly assumes that *H*/*W* is known. This is not an issue in modern rivers, where *H*/*W* is known, but it is problematic in geologic applications, where *W* is hardly measurable.

For geologic applications, the Parker (1976) predictor is analytically most appropriate because it requires the fewest assumptions, and its threshold is dependent on *H*/*W* (Table 1). However, the Parker (1976) predictor favored single-thread planforms; we therefore tested this predictor with our new data set.

New Paleo-Planform Predictor

In our data set, the Parker (1976) predictor correctly predicted planform in 93% of single-thread rivers but only in 35% of multithread rivers (Fig. 3A), so the existing Parker (1976) calibration requires improvement. Significantly, for single-thread and multithread rivers, our data showed that *H*/*W* distributions are statistically distinct, whereas *S*/Fr distributions have similar medians and interquartile ranges. Consequently, a simple *H*/*W* threshold can effectively discriminate between single-thread ($H/W > 0.02$) and multithread ($H/W < 0.02$) rivers (Fig. 3A). This threshold correctly predicted planform in 82% of single-thread rivers (90% predicted by $H/W > 0.014$) and 84% of multithread rivers (90% predicted by $H/W < 0.027$) (Fig. 3A).

Further, the Parker (1976) predictor does not discriminate between braiding and anastomosing styles, but our data set enabled this kind of prediction. We found that braided and anastomosing rivers had similar median *H*/*W* but distinct *S*/Fr distributions (Fig. 3B). In braided rivers, *S*/Fr spans ~0.001–0.1, whereas in anastomosing rivers, *S*/Fr spans ~0.0001–0.001 (Fig. 3B). In transitional rivers, *S*/Fr values of ~0.001–0.01 overlap with braided and anastomosing rivers, as these data span sinuous–braided and meandering–anastomosing transitions. We found that a simple threshold could discriminate between braided ($S/\mathrm{Fr} > 0.003$) and anastomosing ($S/\mathrm{Fr} < 0.003$) rivers, which

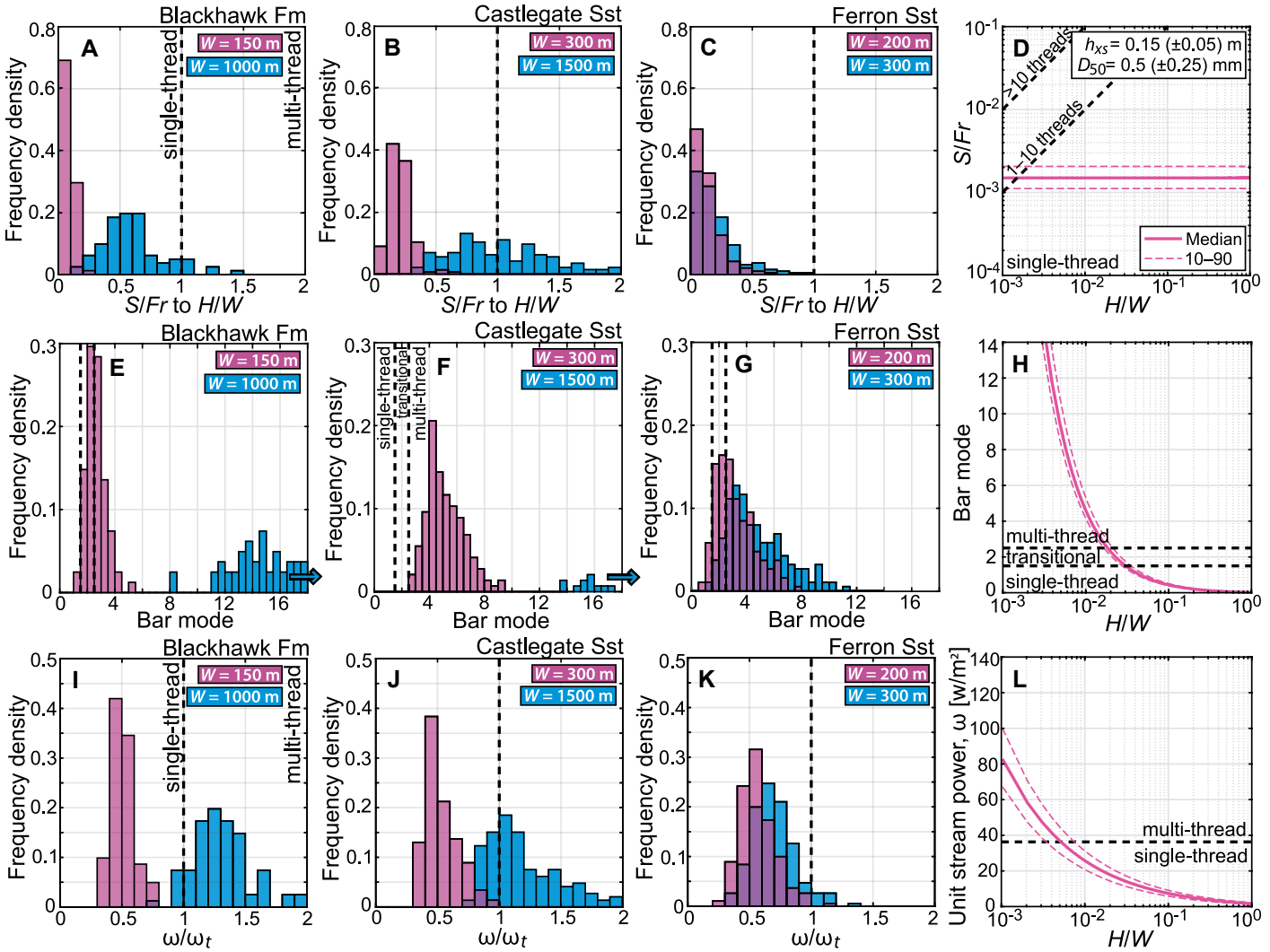

Figure 2. Planforms reconstructed for cross-sets in each studied formation, assuming end-member widths (pink and blue boxes). (A–C) Planforms reconstructed using Parker's (1976) approach for the Blackhawk Formation (A), Castlegate Sandstone (B), and Ferron Sandstone (C). (D) Sensitivity of Parker's (1976) approach to depth/width (*H*/*W*). (E–G) Planforms reconstructed using Crosato and Mosselman's (2009) approach for the Blackhawk Formation (E), Castlegate Sandstone (F), and Ferron Sandstone (G). (H) Sensitivity of Crosato and Mosselman's (2009) approach to *H*/*W*. (I–K) Planforms reconstructed using van den Berg's (1995) approach for the Blackhawk Formation (I), Castlegate Sandstone (J), and Ferron Sandstone (K). (L) Sensitivity of van den Berg's (1995) approach to *H*/*W*. See panel D for mean and standard deviation of cross-set thickness (h_{xs}) and grain size (D_{50}) used to evaluate sensitivity. *S*/Fr = slope/Froude; ω/ω_t = potential specific stream power/threshold stream power. Fm—Formation; Sst—Sandstone.

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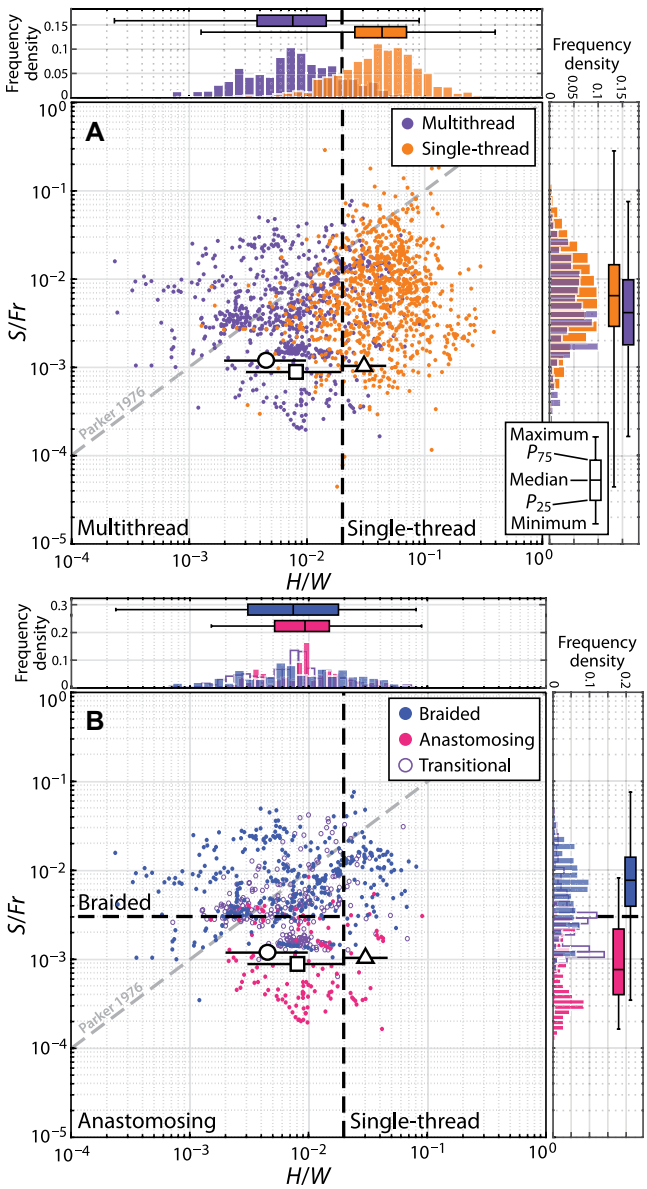

Figure 3. Observations of single-thread and multithread rivers (A); and braided, anastomosing, and transitional multithread rivers (B). *X*-axis histograms and box plots indicate frequency densities and distributions of depth/width (*H*/*W*) ratios, respectively. *Y*-axis histograms and box plots depict same but for slope/Froude ratios (*S*/Fr). See panel A for box-plot key (*Px* denotes *x*th percentile). Gray dashed lines indicate the single-thread to multithread threshold defined by Parker (1976). Black dashed lines indicate our new thresholds. Symbols indicate approximately where the Blackhawk (squares), Castlegate (circles), and Ferron (triangles) channels plot, assuming upper and lower *W* values (extent of line).

correctly predicted planform in 84% of braided rivers (90% predicted by $S/\mathrm{Fr} > 0.002$) and 85% of anastomosing rivers (90% predicted by $S/\mathrm{Fr} < 0.0034$) (Fig. 3B).

Using these thresholds together (i.e., $H/W < 0.02$ and $S/\mathrm{Fr} < 0.003$ for anastomosing rivers, $H/W < 0.02$ and $S/\mathrm{Fr} > 0.003$ for braided rivers, and $H/W > 0.02$ for single-thread rivers), we correctly predicted 70% of anastomosing rivers, 65% of braided rivers, and 82% of single-thread rivers in our data set.

Applying these criteria to our geologic data, Ferron rivers plotted as single-thread channels (triangles in Fig. 3), consistent with facies interpretations (Cotter, 1971; Wu et al., 2015), whereas Blackhawk and Castlegate rivers plotted as anastomosing channels (squares and bold open circles in Fig. 3B), which is inconsistent with interpretation of these multithread rivers as braided but consistent with them being characterized by sand beds, shallow slopes, high suspended sediment loads, and a propensity to avulsion (e.g., Miall, 1993, 1994; Chamberlin and Hajek, 2019; Lyster et al., 2021), features typical of anastomosing rivers. Further, assuming W_{min}, Blackhawk channels plotted on the single-thread transition, consistent with interpretations of single-thread Blackhawk channels (Hampson et al., 2013).

DISCUSSION AND CONCLUSIONS

For our geologic examples, we showed that existing planform predictors disagree with each other and with facies interpretations. While the Parker (1976) approach was the most suitable paleo-planform predictor, it favored single-thread planforms (Figs. 2A–2D) and incorrectly classified two thirds of multithread rivers in our data set (Fig. 3A). We note that theory-based predictors, such as the Parker (1976) predictor, often assume straight channels with rectangular cross sections and nonerodible banks. Consequently, they may not capture the wide variability of natural rivers, minimizing the potential importance of factors beyond this geometry. Moreover, the original data set used to validate the Parker (1976) predictor was small and heavily relied on experimental and man-made channels. In our new data set, H/W was the most important discriminator of planform, rather than S/Fr, with $H/W > 0.02$ in single-thread rivers and $H/W < 0.02$ in multithread rivers (Fig. 3A). We hypothesize that the apparent connection between H/W and planform may indicate that bank cohesion is a critical determinant of planform (Ielpi and Lapôtre, 2019b; Lapôtre et al., 2019; Dunne and Jerolmack, 2020; Ielpi and Lapôtre, 2020) as opposed to channel slope.

Further, while our data showed that S/Fr could not discriminate between single- and multithread rivers, S/Fr could discriminate multithread planform style. In multithread rivers, new threads may have multiple origins, including avulsion in anastomosing rivers and bifurcation in braided rivers (Jerolmack and Mohrig, 2007; Kleinhans et al., 2013; Carling et al., 2014). Our data suggest that S/Fr may capture a process transition, where multithread rivers are likely to be anastomosing when $S/\mathrm{Fr} < 0.003$ (shallower slopes) and braided when $S/\mathrm{Fr} > 0.003$ (steeper slopes) (Fig. 3B). These thresholds are easy to apply to geologic data, where paleoslope can be reconstructed (e.g., Trampush et al., 2014), and they are a better fit to modern and stratigraphic observations of multithread rivers.

While estimates of H from geologic outcrops are robust (e.g., Lyster et al., 2021), estimating W remains difficult because it requires preservation of channel architecture and/or channel fill (Toonen et al., 2012; Ielpi and Ghinassi, 2014) and knowledge of the number of active threads. Paleo-planform prediction therefore remains limited by uncertainties in H/W, and we advise that our criteria should be implemented for a range of plausible widths. Moreover, while our criteria resolve inconsistencies between facies interpretations and planform predictors, it is important to couple these approaches. For Blackhawk and Castlegate channels, reconstructed planforms are broadly similar (Fig. 2), but their stratigraphic architectures are distinct. Consequently, understanding the kinematic and stratigraphic controls on the geologic preservation of planforms, as opposed to their geomorphic equivalents, is now a pressing research need.

Where hydraulic geometries can be reconstructed from fluvial strata, our new criteria provide a simple and effective way to predict paleo-planform. The results are important given ongoing discussions regarding the limited preservation potential of planform in the rock record (Fielding et al., 2018; Best and Fielding, 2019), and they are particularly useful where outcrop is limited or facies interpretations are equivocal, such as unvegetated fluvial systems of early

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Earth and Mars. Our criteria will improve the fidelity of water, sediment, and biogeochemical flux reconstructions from fluvial strata, which are crucial to decipher river responses to tectonic and climatic forcing (e.g., Lyster et al., 2021), and they will provide new insights into channel-forming processes and channel stability. Together, these constraints will help to build a more complete picture of fluvial landscape evolution in the geologic past.

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