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Key Points:

- The preservation of meander-belt deposits is assessed at multiple scales through numerical simulations of river migration histories
- Rates of planform growth of fluvial meander belts decay with time in a way that does not regularly follow a simple power-law relationship
- Geomorphic thresholds of meander-transformation change and bend cutoff likely account for nonlinearity in stratigraphic completeness

Supporting Information:

Supporting Information may be found in the online version of this article.

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Evaluation of Morphodynamic Controls on the Preservation of Fluvial Meander-Belt Deposits

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Abstract The way river morphodynamics influence the preservation of point-bar deposits at multiple scales is not fully understood. Employing time-lapse trajectories of natural rivers, a numerical model is used here to simulate planform evolutions of meander-belt reaches that embody different transformation behaviors and cutoff processes. Proxies for temporal durations are obtained considering the surface area over which a river migrated and channel migration rates that relate to average channel radius of curvature through constant, monotonic, and non-monotonic relationships. The preservation of meander-belt deposits over different timescales is assessed at three architectural hierarchies: (a) pairs and (b) sets of accretion packages, and (c) meander-belts. Results confirm that sediment preservation decreases in a predictable way with the accumulation time; however, accretion rates decay with time in a way that does not follow the expected power-law. This is interpreted to reflect the effect of the onset of geomorphic thresholds of channel transformation and cutoff.

Plain Language Summary Larger sediment volumes tend to record slower rates of deposition, because the likelihood of incorporating significant gaps in sedimentation increases with time. Hence, over timescales from seconds to millions of years, accumulation rates decrease as a power of time. This research determines whether this relationship holds true for channel belts produced by meandering rivers, and in particular for deposits that may develop over timescales of days (beds in point bars) to millennia (meander belts consisting of amalgams of bars and abandoned channels). To do this, a numerical model is applied to reconstruct the planform evolution of natural rivers. This way, sedimentation, erosion, and sediment preservation can be quantified, and proxies for time can be established based on the area over which a river migrated. The results show that, over this time window, the dependency of accumulation rates with time is more complex than anticipated. This is likely due, in part, to the sudden onset of changes in the style of river evolution (e.g., from meanders swinging laterally to sweeping downstream) and of bend cutoffs, which drive significant erosional reworking.

1. Introduction

Sediment accumulation rates tend to decrease with the time span over which they are determined: this phenomenon is known as the "Sadler effect" (Sadler, 1981; Sadler & Strauss, 1990). This happens because depositional processes are episodic in nature, and the average length of time gaps at any point in space tends to increase with the time window considered (Ager, 1993; Barrell, 1917; Dott, 1996; Miall, 2015). The fraction of time recorded in a stratigraphic section ("stratigraphic completeness") is therefore itself dependent on time (Sadler & Strauss, 1990). Based on analysis of natural examples and a numerical modeling output, Durkin et al. (2018) quantified the stratigraphic completeness of fluvial meander-belt deposits, demonstrating how sediment preservation follows a natural logarithmic decay with time. Yet, the preservation of channel-belt sediments is expected to vary significantly in relation to the natural variability of river morphodynamics. Fluvial meanders can evolve through multiple stages of bar growth, each of which may be dominated by different bend-transformation behaviors: lateral expansion versus downstream translation, commonly in combination with bend-apex rotation (Daniel, 1971; Hagstrom et al., 2019). Previously accumulated point-bar deposits can undergo partial erosion, leading to the formation of potentially complex mosaics of accretion patterns (Durkin et al., 2015; Johnston & Holbrook, 2019; Strick et al., 2018; Willis & Sech, 2019). The amount of intra-channel-belt erosion depends critically on meander-transformation behavior (Durkin et al., 2018; Ghinassi et al., 2016). Over longer timescales, meander cut-offs can lead to the abandonment of point-bar deposits; these can later be subject to cannibalization by the mobile river

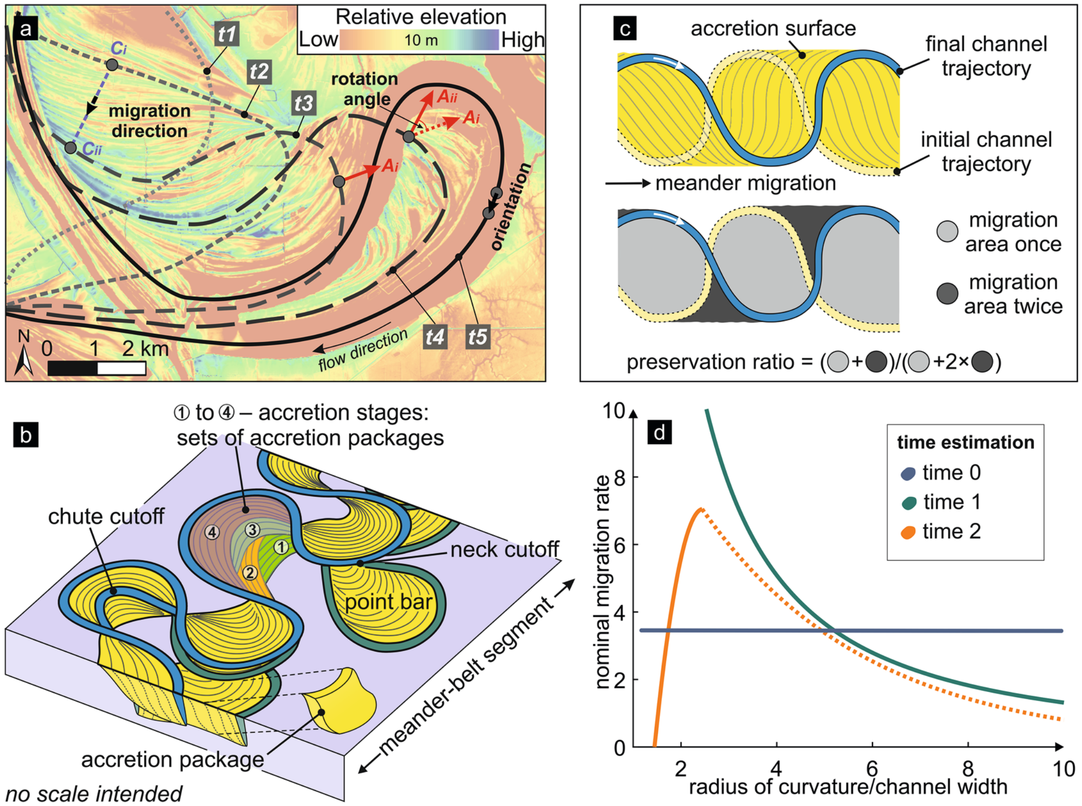

Figure 1. Illustration of methods. (a) Example input trajectories digitized over a LiDAR topography; t_1 to t_5 denote chronological order. "*C*" and "*A*"denote a control point and a meander apex, respectively. (b) Hierarchies of sedimentary architecture considered here: accretion packages, accretion stages and meander-belt segments. (c) Definition of sediment preservation ratio. (d) Relationships between reach-averaged channel migration rate (y axis) and channel radius of curvature normalized by channel width (x axis), employed to estimate time of river migration, based on three different assumptions: (i) constant migration rates for any value of channel radius of curvature ("time 0"); (ii) inverse monotonic relationship between migration rates and radius of curvature ("time 1"); and (iii) channel migration rates increasing as the ratio of radius of curvature to channel width decreases toward 2.44, then decreasing for tighter bends ("time 2"). The "time 1" and "time 2" relationships are based on nominal channel migration rates by Howard and Knutson (1984). Migration rates are on arbitrary scale.

(Constantine & Dunne, 2008). The stratigraphic completeness of meander-belt deposits is related to all these processes. However, whether these mechanisms lead to a classic Sadler effect, whereby a power-law relationship exists between planform accretion rates and measurement intervals (Sadler, 1981), has yet to be determined. This is rendered difficult by the limited availability of meander-belt examples for which a detailed temporal framework exists, since historical maps and radiocarbon or optically stimulated luminescence dating, for example, can only provide spot measurements. In this work we examine the potential timescale dependency in the rates of planform growth of meander belts, and determine the impact of morphodynamic controls on the preservation of fluvial meander-belt deposits. This is done by applying a numerical model, the Point-Bar Sedimentary Architecture Numerical Deduction model (PB-SAND; Yan et al., 2017), to simulate idealized scale-free rivers informed by observations of scroll-bar patterns identified in natural systems.

2. Methodology

The PB-SAND (Yan et al., 2017) is a numerical model that simulates the planform evolution of meander belts based on input consisting of centerlines representing the river course at selected time steps (Figure 1a; Yan et al., 2017). In PB-SAND, channel evolution and resulting channel-belt accretion and erosion are modeled by linear interpolation between input river trajectories (Yan et al., 2017, 2020, 2021). Thirty-four idealized meander-belt reaches that vary in bend-transformation styles and number of channel cut-off events are modeled based on planform evolutions documented by scroll-bar patterns of natural analogs, visible in satellite images, LiDAR topographies or geomorphological maps (Figure S1). The idealized river planforms are normalized such that the formative-channel width is the same across all examples. The tempo of point-bar accretion is dictated by the chosen spacing of accretion surfaces to mimic scroll-bar morphologies observed in nature. In the model outputs, three depositional hierarchies are considered for analysis (Figure 1b): (a) pairs of accretion packages, wherein each package is contained between two consecutive accretion surfaces; individual accretion packages are not considered because erosion within them is not simulated; (b) sets of accretion packages (here termed “accretion stages”) bounded by two consecutive input trajectories, representing phases of point-bar growth with a given style of meander transformation; and (c) meander-belt segments that are composed of multiple sets of accretion packages, each of which may be dominated by different styles of meander transformation. Accretion packages can be regarded as analogous to flood-interflood units. Due to their generation by linear interpolation between input trajectories, accretion packages in each stage exhibit similar amounts of accretion (see Supporting Information).

The “preservation ratio” is the fraction of meander-belt deposits that are preserved over a given timescale, quantified as the ratio between the planform area covered by deposits accumulated over a certain time that are preserved (area of net deposition) and the area over which the river has wandered over the same time (area of river migration) (Figure 1c). In this quantification, erosion and deposition of channel-belt deposits are only considered for accretion packages generated during the time interval in question; erosion of older packages is ignored; hence, preservation as a function of time is not expressed as a cumulative quantity (cf. “survivability curves” sensu Durkin et al., 2018, for a different approach, and see Figure S6 for data in a format comparable to that of Durkin et al., 2018). The time recorded in each accretion package is determined by the ratio between channel migration distance and channel migration rate. The channel migration distance is determined by the ratio between the surface area subtended by two centerlines and their average length. Values of average channel migration rate over each depositional package (i.e., between two consecutive channel centerlines) are determined separately based on three different assumptions of its relationship with the average channel radius of curvature: (a) constant channel migration rate for any value of channel radius of curvature; (b) migration rate decreasing monotonically as the channel radius of curvature increases (i.e., channel curvature decreases; cf. Furbish, 1988; Howard & Knutson, 1984; Sylvester et al., 2019); (c) migration rate increasing as the ratio of radius of curvature to channel width increases toward a value of 2.44 (Howard & Knutson, 1984), and then decreasing as the radius of curvature increases further. The latter non-monotonic behavior is seen in nature for migration rates measured at locations where meander bends undertake lateral shifts fastest (Finotello et al., 2019; Hudson & Kesel, 2000; Nanson & Hickin, 1983), but the implications of a non-monotonic relationship can sensibly be explored for reach-averaged values too (cf. Crosato, 2009). The second and third alternatives are determined based on relationships between channel radius of curvature and nominal migration rates that return realistic relationships between average actual channel migration rates and channel curvature in models by Howard and Knutson (1984). For these relationships (Figure 1d), the dimensionless arbitrary scale of Howard and Knutson (1984) is maintained. The dimensionless accretion time is determined by the ratio of migration distance to average migration rate. The two proxies for time length associated with the second and third alternatives (“time 1” and “time 2” hereafter) are also employed to compute meander-belt accretion rates, the ratio between accretion distance and dimensionless time.

Planform characteristics of each architectural hierarchy are characterized in terms of average circular variance of channel centerlines, meander-apex rotation, and accretion style (Figure 1a). The circular variance of channel orientation is computed along the downstream direction for pairs of consecutive control points (centerlines vector nodes); this is an indirect measure of channel sinuosity. A quantity called “migration angle” is defined for each accretion package as the absolute angle between the direction of channel migration, approximated by the direction of shift of corresponding control points across two consecutive trajectories, and the circular mean of downstream channel direction, which approximates the channel-belt orientation (Figure 1a). Point bars of expansional meanders are expected to return average migration angles close to 90°, whereas downstream-translating point bars are expected to return migration angles smaller than 45° (Yan et al., 2021). The degree of rotation of meanders is defined as the change of direction of the meander apex, itself identified as the point of local maximum curvature between two channel inflection points, across consecutive accretion packages (Figure 1a). For each meander belt, the amount of rotation is quantified as the average across all meanders. A more detailed description of the methods is provided in the supporting information.

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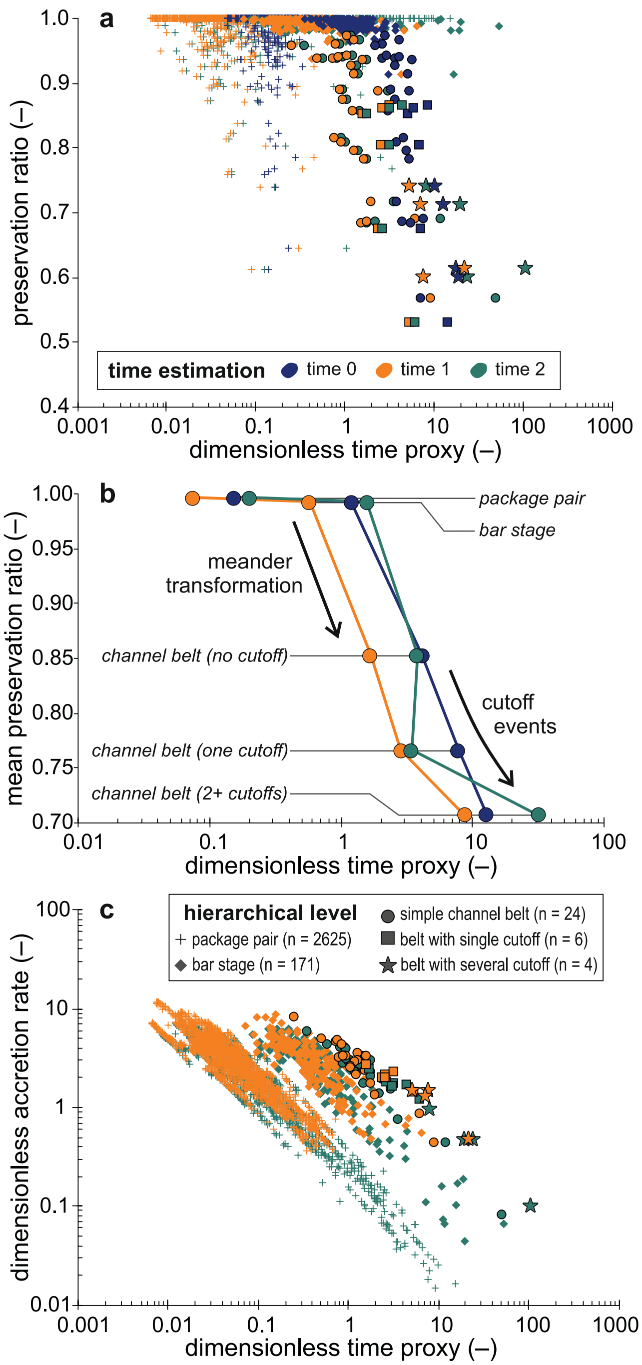

Figure 2. Scatterplots of preservation ratio (a), mean preservation ratio (b), and accretion rate (c) versus time span, for the different architectural hierarchies and approaches to time estimation. Preservation ratio is defined as in Figure 1c.

3. Results

For each architectural hierarchy, the sediment preservation ratio decreases overall as the time span of sedimentation increases, in a similar manner across the three approaches used to estimate time (Figures 2a and 2b). The variability in preservation ratio is limited for package pairs (st. dev. = 0.019, mean = 0.997) and accretion stages (st. dev. = 0.010, mean = 0.993) (Figure S5), but more significant for meander-belt segments (st. dev. = 0.128, mean = 0.816). A systematic decrease in preservation with channel-belt maturity (Figure 2b) reflects the combined effect of intra-point-bar erosion between accretion stages and point-bar cannibalization following bend cut-offs (Durkin et al., 2018). The average preservation ratio is 0.84, 0.77, and 0.67, for meander belts that respectively record no cut-off ($N = 24$), a single cut-off ($N = 6$), and multiple cut-off events ($N = 4$).

Negative power-laws fitted to accretion rates and variables "time 1" and "time 2," have coefficients of determination (R^2) of 0.56 and 0.71, and exponents of −0.44 and −0.60, respectively. These exponents differ markedly from the value of −0.75 documented by Sadler for vertical accumulation rates of fluvial strata (Pelletier & Turcotte, 1997; Sadler, 1981) (Figure 2c). Stronger power-laws can also be fitted to each architectural hierarchy for both computed times, with R^2 varying between 0.73 and 0.93, and exponents ranging from −0.61 to −0.80. Similarity in the results relating to "time 1" and "time 2" can be related to the limited number of modeling steps for which values of average normalized channel radius of curvature fall below 2.44 (Figure S3b).

Sediment preservation ratios tend to covary with certain meander-belt planform characteristics (Figure 3). Meander belts with lower average centerline circular variance tend to have lower preservation ratio (Pearson's $R = 0.516$, $p = 0.002$, Figure 3a). This may reflect (a) how downstream bend translation tends to maintain channel sinuosity while driving point-bar erosion by sweeping meanders, at a shorter timescale (Ghinassi et al., 2016), and (b) how periodic cutoffs reduce channel sinuosity while causing point-bar cannibalization, at a longer timescale (Camporeale et al., 2008). The average migration angle does not show correlation with the preservation ratio ($R = 0.063$, $p = 0.737$, Figure 3b), possibly because this quantity can fail to capture the type of bend transformation (Yan et al., 2021), but also because of a lack of examples that record long-term channel evolutions dominated by bend translation. The average bend rotation correlates weakly with the preservation ratio for cases of comparable timescales ($R = 0.381$, $p = 0.026$, Figure 3b). However, the data suggest that the effect of rotation as a mechanism of intra-point bar erosion on sediment preservation may be subordinate. The standard deviation of migration angles across accretion stages quantifies variability in modes of meander-belt accretion through the modeled timescale: modest correlation exists between this quantity and the preservation ratio ($R = 0.434$, $p = 0.010$, Figure 3d). This may reflect the effect of toggling between expansion and translation on intra-point bar erosion (cf. Johnston & Holbrook, 2019), for example, as seen in Case 18 (Figure S1).

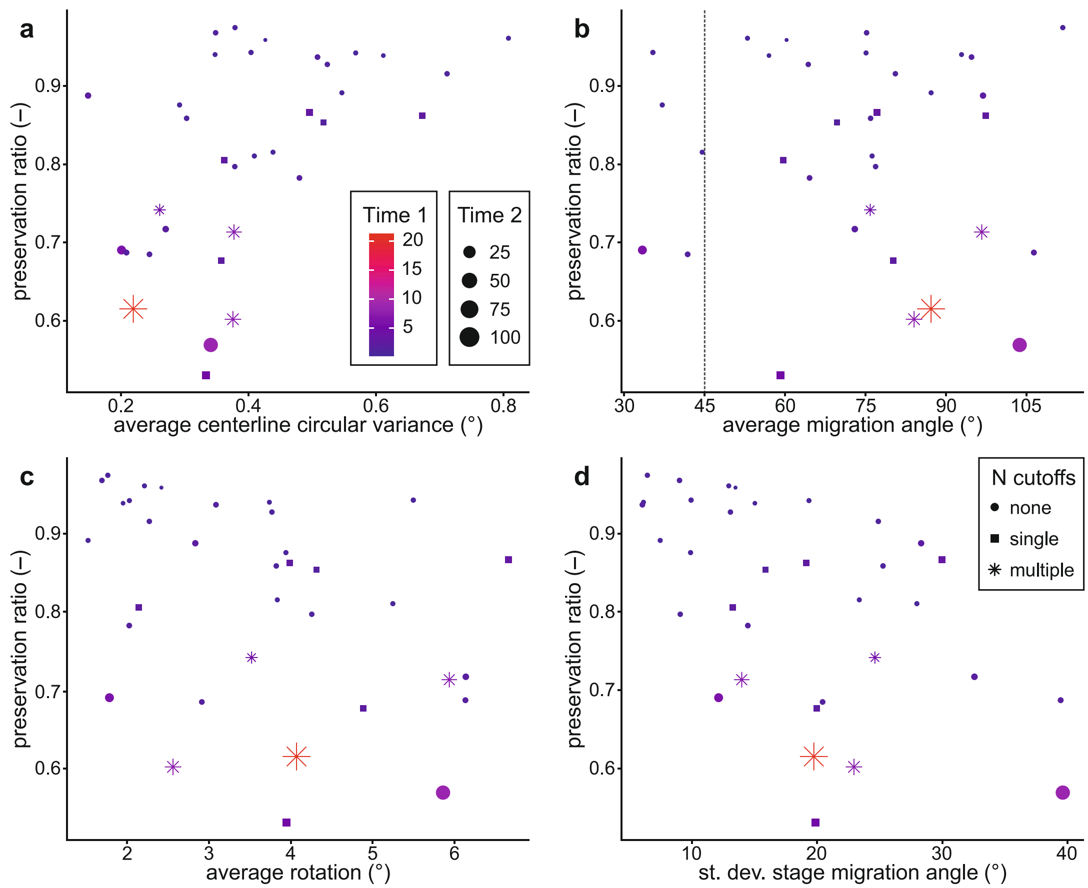

Figure 3. Scatterplots of preservation ratio versus metrics describing planform characteristics of meander belts, for two different approaches to time estimation.

4. Discussion

The adopted numerical modeling approach allows simulation of meander-belt evolutions that are inherently realistic, being based on natural examples, overcoming limitations of numerical models of meandering channels (see Frascati & Lanzoni, 2009, and references therein). Yet it also permits a systematic evaluation of sediment preservation over a range of timescales and at a resolution that would not be achievable using datasets from rivers for which chronometric constraints are available. Results from the numerical models elucidate how sediment preservation is determined by morphodynamic processes that operate at different spatial and temporal scales, and that affect depositional units of variable hierarchies (Figure 2b). It therefore becomes possible to determine whether and where the so-called "Sadler effect" — the dependency of vertical sediment accumulation rate on timescale (Bailey & Smith, 2005; Durkin et al., 2018; Holbrook & Miall, 2020; Miall, 2015; Plotnick, 1986; Sadler, 1981, 1999) — persists or breaks down in meander-belt successions, when considered for rates of planform growth, and for datasets with suitable continuity and granularity in the record of processes and products. It is significant that a single power-law relationship between time and point-bar accretion rate that would align with the power law observed for fluvial deposits tout court (Pelletier & Turcotte, 1997; Sadler, 1981) does not emerge. Instead, the three architectural hierarchies, associated with different timescales, appear to yield distinct power-law relationships. A primary reason why a simple power law is lacking can be found in the important overlap in preservation ratios and accretion rates of package pairs and stages (Figure 2c). This likely reflects how the rate of erosion of developing point bars remains relatively steady in time under conditions of constant style of meander transformation; this situation may be best depicted by meanders undergoing progressive bend tightening. When changes of meander transformation styles occur, instead, more significant intra-point-bar erosion commonly takes place (Durkin et al., 2018; Hagstrom et al., 2019; Johnston & Holbrook, 2019). Significant erosion can occur when formerly expansional meanders commence a trajectory of downstream migration, for example, where channel banks encounter less erodible substrates, such as valley walls or abandoned channel fills (Ghinassi et al., 2016). Meander rotation is also a driver of point-bar erosion, especially in the vicinity of the outer banks of rotating apices (Ielpi & Ghinassi, 2014; Strick et al., 2018). Yet, the role of steady meander rotation in generating intra-point-bar erosion may be secondary relative to threshold changes from one meander transformation style to another (Figure 3), since such erosion tends to be localized (Yan et al., 2021). The influence of neck or chute cutoff events on the long-term preservation of channel-belt deposits only becomes important for channel belts that have reached a certain maturity. Cutoffs serve as a geomorphic threshold that drives the systematic obliteration of older reaches (Camporeale et al., 2008; Schumm, 1973) and that potentially triggers further cutoff and ensuing channel-belt erosion (Schwenk & Foufoula-Georgiou, 2016).

The modeling approach taken in this work is subject to several limitations (see Supporting Information). The modeled time windows are limited to lengths of time over which the temporal evolution of the rivers can be reconstructed with confidence; none of the considered examples span lengths of time bracketed by river avulsions. The assessment of sediment preservation of meander belts was undertaken considering planform areas as proxies for sediment volumes (cf. Durkin et al., 2018). It therefore disregards how preserved volumes are affected by (a) changes in meander-belt thickness in relation to streamwise variations in channel bathymetry (e.g., across meander pools and riffle zones, Yan et al., 2021) and (b) streambed aggradation. This is a reasonable simplification for freely meandering rivers in which rates of lateral migration are much larger than rates of aggradation. The influence of autogenic dynamics (e.g., bend cutoff; Schwenk & Foufoula-Georgiou, 2016) on accretion rates, and hence recorded time, is also not considered. The time embodied by accretion packages was calculated based on trajectories that are linearly interpolated, effectively assuming that point-bar accretion in each stage takes place in regular pulses (meaning that 10-years or 100-years floods, e.g., are assumed to have comparable impacts), and that hiatuses of variable magnitude associated with accretion surfaces do not exist. In reality, the amount of erosion recorded between and within individual accretion packages can be considerable (cf. Moody & Meade, 2014), but the fragmentary nature of point-bar bedsets is not simulated through the chosen approach. This is likely to explain, at least in part, the limited variability in preservation between accretion-package pairs and stages. Also, the considered scroll-bar morphologies may not accurately mirror the patterns of point-bar accretion, particularly where scroll bars are partly sculpted by erosional processes (cf. Mason & Mohrig, 2019).

5. Conclusions

Detailed reconstructions of meander-belt evolutions have revealed the role of different morphodynamic processes in controlling point-bar sediment preservation over a range of timescales. In the channel belts of meandering river systems, relationships between time, preservation and accretion rates appear to be rendered complicated by threshold processes of meander transformation change and bend cutoff. Yet, nonlinearity in point-bar accretion cannot be captured by a simple power law between sedimentation rate and time. This has implications for the inference of the temporal significance of depositional units of variable hierarchy.

Data Availability Statement

Data of this study are available from the data repository of the University of Leeds at https://doi.org/10.5518/970.

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