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

N. Yan[1], L. Colombera[1], and N. P. Mountney[1]

[1]Fluvial, Eolian & Shallow-Marine Research Group, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, United Kingdom.

Corresponding author: Na Yan (n.yan@leeds.ac.uk)

Key Points:

- The preservation of meander-belt deposits is assessed at multiple scales through numerical simulations of river migration histories.
- Accretion rates 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.

Abstract

The way river morphodynamics influence the preservation of point-bar deposits at different spatio-temporal scales is hitherto unquantified. 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: (i) pairs and (ii) sets of accretion packages, and (iii) meander-belts. Results show 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: the so-called ‘Sadler effect’ (Sadler, 1981; Sadler and 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 Jr, 1996; Miall, 2015). The fraction of time recorded in a stratigraphic section (‘stratigraphic completeness’) is therefore itself dependent on time (Sadler and Strauss, 1990). Based on analysis of natural examples and numerical modeling, 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 vs. 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 and Holbrook, 2019; Strick et al., 2018; Willis and 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 (Constantine and 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 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 OSL dating, for example, can only provide spot measurements. In this work we aim to address this gap by applying a numerical model to the simulation of idealized river systems that display planform evolutions like those seen in nature.

2 Methodology

The Point-Bar Sedimentary Architecture Numerical Deduction (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). 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, 2020a, b). 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 in accretion patterns of natural analogs, visible in satellite images, LiDAR topographies or historical maps (Figure S1 in Supplementary Material). 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): (i) 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; (ii) 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 (iii) 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 Supplementary Material).

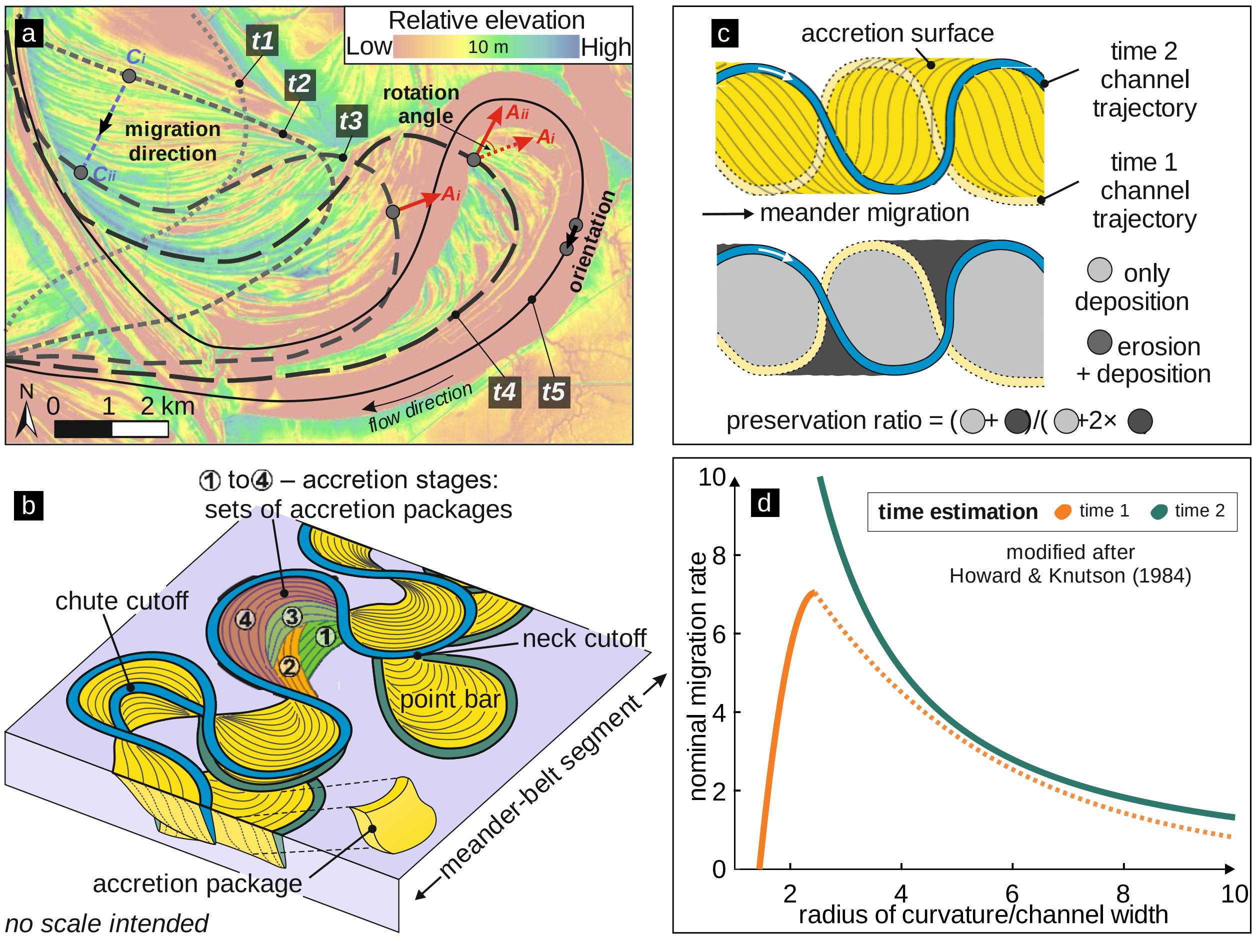

Figure 1. Illustration of methods. (a) Example input trajectories digitized over a LiDAR topography; t_1 to t_5 denote chronological order. '*C*' and '*A*' denote a control point and a meander apex, respectively. (b) hierarchies of sedimentary architecture considered here: accretion packages, accretion stages and meander-belt segments. (c) Definition of sediment preservation ratio. (d) Relationships between nominal channel migration rate and channel radius of curvature normalized by channel width (Howard and Knutson, 1984), used to estimate times of channel migration; migration rates are on arbitrary scale.

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) (Durkin et al., 2018) (Figure 1c). 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 channel radius of curvature (Howard and Knutson, 1984; Hudson and Kesel, 2000; Nanson and Hickin, 1983; Sylvester et al., 2019): (i) constant channel migration rate for any value of channel radius of curvature; (ii) migration rate increasing monotonically as the channel radius of curvature decreases (i.e. channel curvature increases);

(iii) migration rate increasing as the ratio of radius of curvature to channel width decreases towards a value of 2.44 (Howard and Knutson, 1984), and then decreasing as the radii of curvature decrease further. The second and third alternatives are determined based on relationships between channel radius of curvature and nominal migration rates that return realistic relationships between 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). 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). The degree of rotation for each meander belt is the average across all meanders. A more detailed description of the methods is provided in the Supplementary Material.

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 & b). 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. 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).

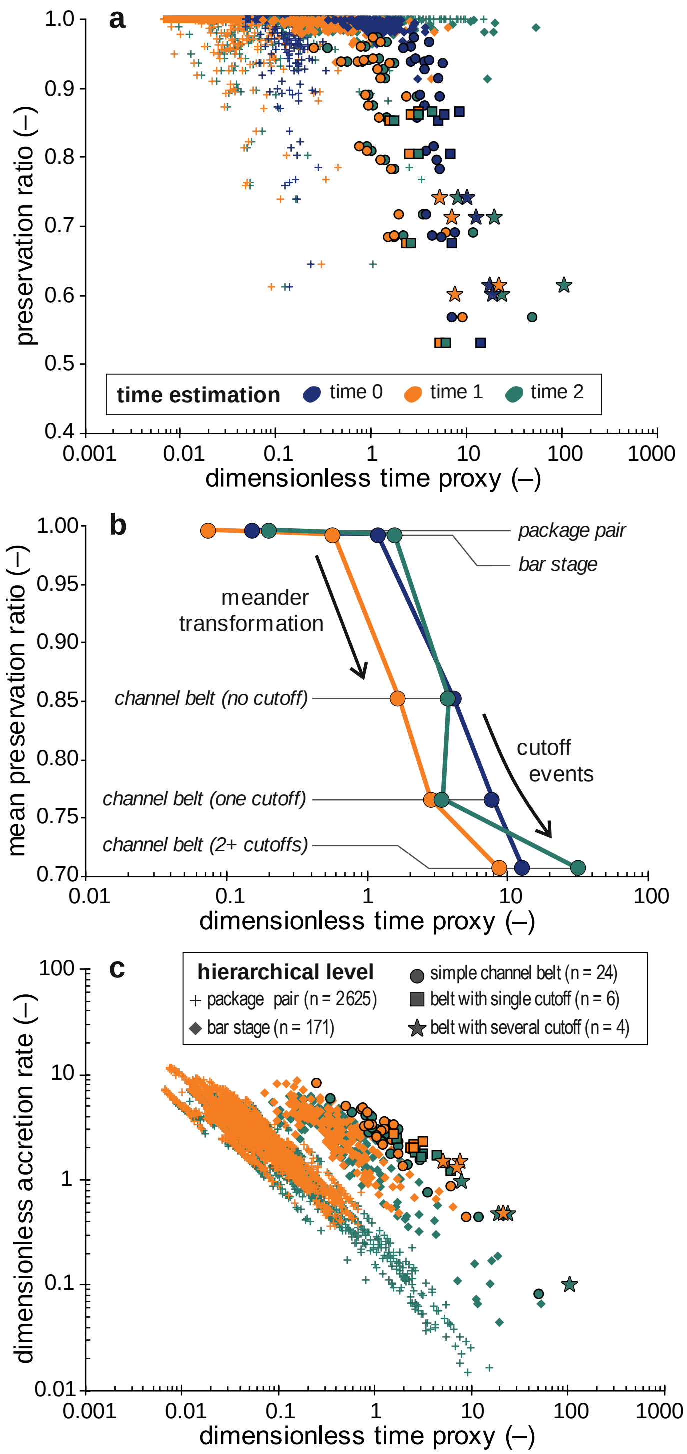

Figure 2. Scatterplots of preservation ratio (a), mean preservation ratio (b) and accretion rate (c) vs time span, for the different architectural hierarchies and approaches to time estimation.

Negative power-laws emerge between accretion rates and both 'time 1' and 'time 2', with coefficients of determination (R2) of 0.56 and 0.71, and with exponents of -0.44 and -0.60, respectively. These exponents differ markedly from the value of -0.75 documented by Sadler (1981; Pelletier and Turcotte, 1997) (Figure 2c). Stronger power-laws can also be fitted to each architectural hierarchy for both computed times, with R2 varying between 0.73 and 0.93, and exponents ranging from -0.61 to -0.80.

Sediment preservation ratios tend to covary with meander-belt planform characteristics (Figure 3). Meander belts with lower average centerline circular variance tend to have lower preservation ratio (Figure 3a). This may reflect (i) 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 (ii) 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 (Figure 3b), possibly because this quantity can fail to capture the type of bend transformation (Yan et al., 2020b), 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 (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. Modest correlation exists between the standard deviation of migration angles across accretion stages and the preservation ratio (Figure 3d). This may reflect the effect of toggling between expansion and translation on intra-point bar erosion (cf. Johnston and Holbrook, 2019).

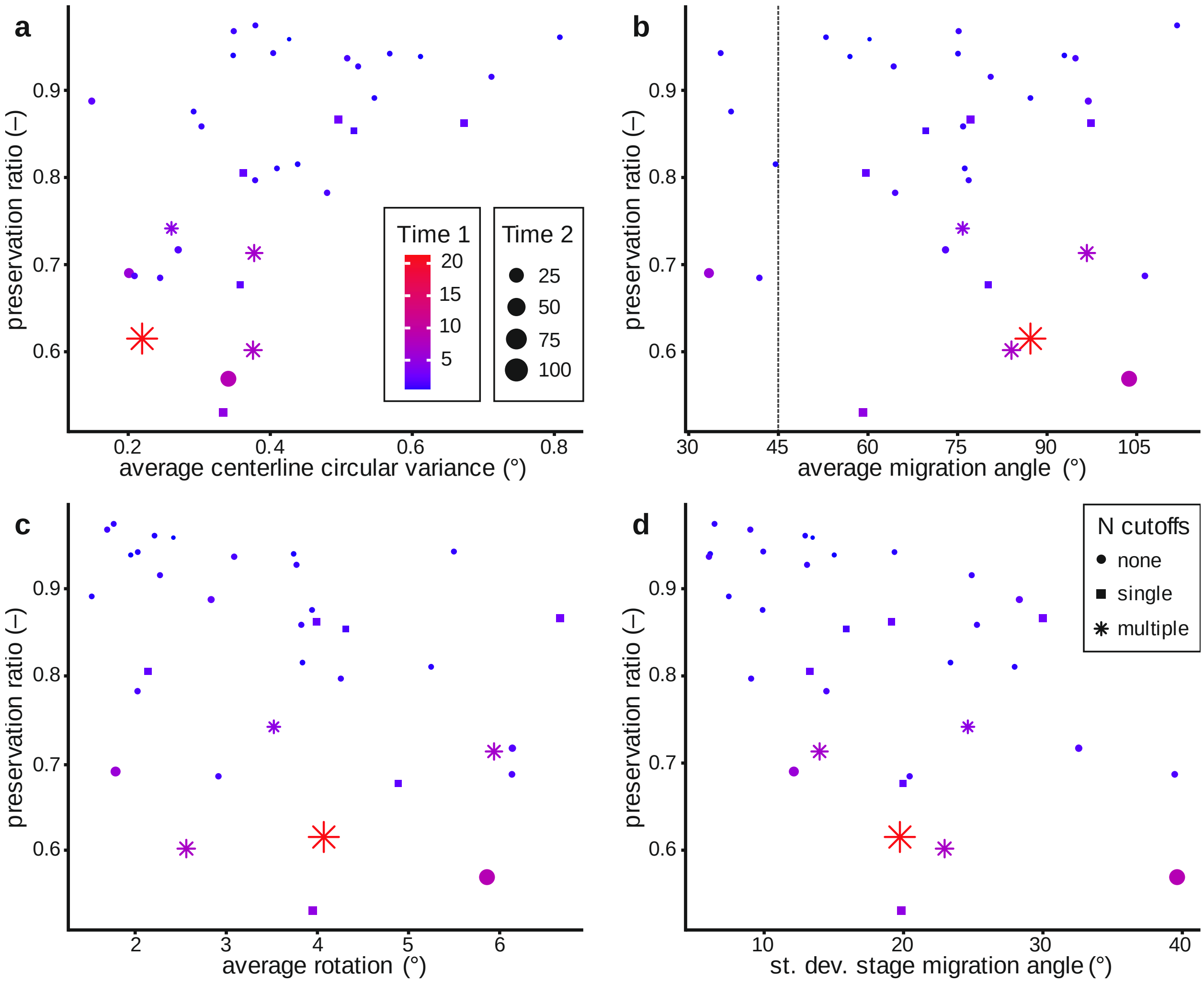

Figure 3. Scatterplots of preservation ratio vs metrics describing planform characteristics of meander belts, for two different approaches to time estimation.

4 Discussion

The adopted numerical modeling approach allows simulation of meander-belt evolutions that are inherently realistic, being based on natural examples. 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. It therefore becomes possible to determine whether and where the so-called ‘Sadler effect’ – the dependency of sediment accumulation rate on timescale (Bailey and Smith, 2005; Durkin et al., 2018; Holbrook and Miall, 2020; Miall, 2015; Plotnick, 1986; Sadler, 1981, 1999) – persists or breaks down in meander-belt successions, when considered 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 and Turcotte, 1997; Sadler, 1981) does not emerge. Instead, the three architectural hierarchies, associated with different timescales, appear to yield different power-law relationships. Important overlap exists in the preservation ratio and the accretion rate 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 and 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 and 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., 2020b). 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 and Foufoula-Georgiou, 2016).

The modelling approach taken in this work is subject to limitations (see Supplementary Material). The assessment of sediment preservation of meander belts was undertaken considering planform areas as proxies for sediment volumes (Durkin et al., 2018), therefore disregarding changes in meander-belt thickness and aggradation on preserved volumes. The influence of autogenic dynamics (e.g., bend cutoff; Schwenk and 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-year or 100-year floods, for example, 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 and 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.

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.

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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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