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Experimental distributive fluvial systems: Bridging the gap between river and rock record

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Abstract

A debate has called into question as to which fluvial channel patterns are most widely represented in the stratigraphic record, with some advocating that distributive fluvial systems (DFS) predominate and others that a broad diversity of fluvial styles may become preserved. Critical to both sides is the adequate recognition of original channel planform from geological outcrops separated from their formative processes by millions or even billions of years. In this study the river and rock record are linked through experimentally created DFSs with both aggrading channel beds and floodplains. This approach allows depositing processes and deposited strata to be studied in tandem. Proximal areas comprise coarse, amalgamated channel-fills with scarce fine-grained floodplain material. The overall spread of sandbody dimensions become far more varied in medial stretches, with an overall reduction in mean width and depth. In these areas channel-fills may be sand-rich or mud-rich and, following avulsion, all channels are covered by floodplain sediment. Channels, levees and splays form discrete depositional bodies each with varying aspect ratios; a novel breadth of deposits and morphologies in aggrading experiments largely concurrent with proposed trends indicative of DFSs. The proportion of floodplain material increases distally, resulting in decreased interconnectedness of distal channel-fills. Muddy floodplain sediments significantly change DFSs behaviour and subsequent stratigraphic architecture by enhancing bank stability and reducing avulsion through the filling of floodbasins. The laboratory methods utilised here open up the possibility of controlled experimentation on the effects and mechanisms of DFSs sedimentation, which is important since the modelled stratigraphic trends are rarely so tractable in ancient geological outcrop belts.

KEYWORDS

avulsion, channels, facies criteria, floodplain, morphodynamics, stratigraphic record

1 | INTRODUCTION

Some researchers suggest distributive fluvial systems (DFS) are the dominant preserved fluvial style in the geological record (Weissmann *et al*., 2010, 2011, 2015; Hartley *et al*., 2010a, 2010b), whereas others propose that a number of system-scale planforms are well-represented (Sambrook Smith *et al*., 2010; Fielding *et al*., 2012; Latrubesse, 2015). Satellite imagery of DFS are entirely two-dimensional and therefore provide little insight regarding deposited stratigraphy. To determine the relative abundance of preserved DFS throughout geological history, it is essential that robust interpretations of original channel planform can be made from an ancient rock record that has been reworked through autogenic sedimentation (Hajek and Straub, 2017; Straub *et al*., 2020), punctuated by intervals of stasis and erosion (Tipper, 2015; Davies and Shillito, 2018) and is largely comprised of outcrops smaller than the original depositional system (Miall, 2006a; McMahon and Davies, 2018a). Riverscapes contain a wide range of planforms, a spectrum rarely reflected in interpretations of ancient alluvium. Most geological studies group successions as the product of particular end-member river types (braided, meandering) and whilst these generalizations are largely the result of a lack of traceable evidence at outcrop (Kleinhans *et al*., 2010), they have nonetheless resulted in widespread skepticism of ancient palaeochannel interpretations (Bridge, 1993; Miall, 2006b; Ethridge, 2011; Hartley *et al*., 2015, 2018; Fielding *et al*., 2018). Improved confidence in the interpretation of such channel-scale planforms is necessary to determine if any 'norm' system-scale depositional style (i.e. distributive vs tributive) extends back to the Archean Eon (Long, 2018).

In this study the gap between river and rock record is bridged by presenting insights from flume experiments where the evolving DFS and accumulating stratigraphy may be studied in tandem. The applied definition of a DFS follows that adopted by Weissmann *et al*. (2010) and clarified in Weissmann *et al*. (2015): 'the deposit of a fluvial system which in planform displays a radial distributive channel pattern' (Figure 1A). Whilst the use of this nomenclature remains a topic of debate (see Fielding *et al*., 2012; Ventra and Clarke, 2018), the methodology employed here can provide insight into the recognition of DFS in the ancient sedimentary record, and identify which intra-basinal and extra-basinal controls most profoundly influence fluvial deposits and any subsequently preserved stratigraphic architecture. Conceptual models of DFS frequently incorporate four preserved downstream trends as criteria for their recognition: (a) decreased channel size, due to bifurcation, infiltration and evapotranspiration (Horton and Decelles, 2001; Davidson *et al*., 2013; Ventra and Clarke, 2018); (b) decreased modal grain size, due to reduced discharge and increased floodplain/channel ratio (Weissmann *et al*., 2010, 2015; Owen *et al*., 2015a); (c) decreased channel confinement, due to lack of spatial restrictions (Weissmann *et al*., 2013); and (d) increased dispersal of currents, due to the radial pattern of channels away from the

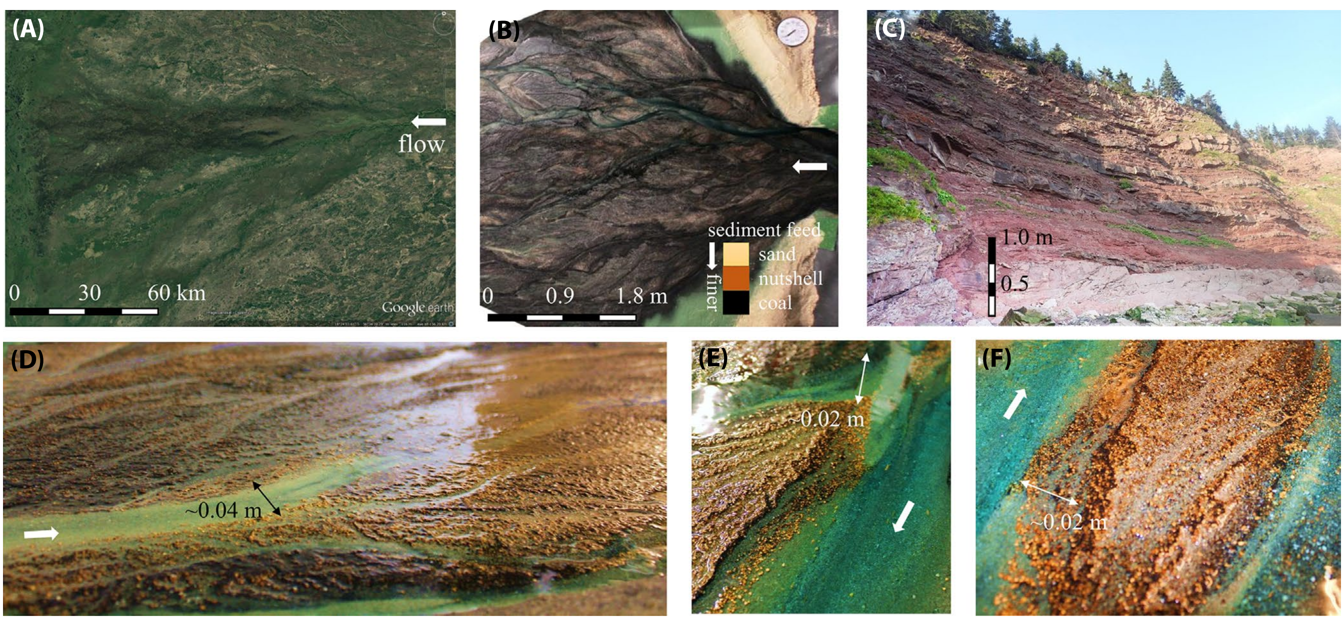

FIGURE 1 Experiments (B) designed to bridge the gap between river (A) and rock (C). (A) Satellite image of a modern DFS, Taquari River in Pantanal Basin, Brazil (Weissmann *et al*., 2010). (B) Planview image of experimental DFS. Water was dyed blue, feeder sediment is black, brown and yellow-white. The initial bed was covered with a layer of green sand. (C) Outcrop example of a Carboniferous-aged interpreted DFS, Tynemouth Creek formation, New Brunswick, Canada (Davies and Gibling, 2013). Experimental details (D through F) of morphological river elements resulting from differences in sediment mobility. (D) Top side view image of experiment with sand in the main channels, the walnut shells filling space on the floodplains as levees and coal filling space on the floodplains. (E, F) Examples of levee formation in the experiments

apex (Owen *et al*., 2015a, 2015b). Whilst individually these criteria can relate to various fluvial styles (Sambrook Smith *et al*., 2010), combined they make a strong case for a depositing DFS. However, increasingly high-resolution studies of the ancient stratigraphic record of DFS recognize a greater stratigraphic complexity across the preserved fan system than previously appreciated (Cain and Mountney, 2009; Owen *et al*., 2015a; Wang and Plink-Björklund, 2019). The mechanisms facilitating some facies trends (e.g. factors that promote avulsion events, preserved as distinct channel-belt deposits) remain elusive (Wang and Plink-Björklund, 2019). Some stratigraphic studies have highlighted only weak down-DFS trends (Rittersbacher *et al*., 2014) whereas others have noted significant, apparently stochastic channel body variability (Chesley and Leier, 2018). Even the most assured facies transitions, such as an increasing fine-grained component down-DFS, caused by the downstream decrease in channel size and the increase in outward fan surficial area (Weissmann *et al*., 2010, 2015), may not be an adequate criterion for recognizing a depositing DFS in all instances (e.g. within Earth's sand-rich pre-vegetation record; Ielpi and Ghinassi, 2016).

To place a greater constraint on the links between process and product within an actively depositing DFS, physical experiments are presented with extensive floodplain formation under aggrading conditions. This methodology provides an independent test as to whether the formative conditions and processes of DFS translate to recognizable facies distributions (Figure 1A,C). The objectives of this paper are therefore to: (a) describe the novel methodology adopted for the physical scale modelling of a floodplain-dominated, aggrading DFS; (b) record and quantify depositional facies and architectures at various proximal, medial and distal reaches of a DFS; and (c) consider the necessary sedimentary outcrop dimensions required to robustly link stratigraphic architecture to the original system-scale planform. Improved links between modern process sedimentology and ancient preserved stratigraphy, through experimental design, will assist future field studies of ancient stratigraphy with the broader aim of elucidating the dominant preserved fluvial style throughout geological history, or, the 'who's who in the geological record' (Latrubesse, 2015, p. 26).

2 | EXPERIMENTAL DESIGN

The philosophy behind the experimental design resembles that of recent work aiming to reproduce sedimentary sub-environments and their depositional elements at a laboratory scale (Peakall *et al*., 1996; van Dijk *et al*., 2013a; Kleinhans *et al*., 2014). Quantifiable aspects of the sediment transport system such as slope, water discharge, flow velocity and sediment concentration, were not calculated with scaling relationships a priori, but adjusted using the combined experience from literature review and pilot experiments. This was done in order to find the experimental settings that best produced the spatiotemporal variations of sediment mobility that result in patterns of erosion and deposition most closely resembling that of natural sedimentary systems. Pilots were designed to test this for the various sediment species used here. The main purpose of supplying a range of sediments was to form a floodplain component, because this, in turn, changes the braiding pattern of uniform sand in single-thread channels with less lateral migration and more avulsion. The intricate feedbacks between sediment mobility, channel dimensions and floodplain formation make the optimal experimental conditions difficult to predict in advance. This approach is robustly underlain by scaling of sediment mobility if the transport stage of the different sediment fractions in the targeted sub-environments (e.g. fluvial channel, levee, splay, floodplain) is compared between experiment and the real world. The correspondence of the resulting landscape is closer to reality in these 'landscape experiments' (Kleinhans *et al*., 2014) than in so-called analogue models where a limited set of emergent dynamics are targeted (Peakall *et al*., 1996; Paola *et al*., 2009). Having identified the experimental settings with the most adequate behaviour, a suite of measurement techniques was applied to collect the data needed to test DFS recognition criteria.

2.1 | Experimental setup

Experiments were conducted on stream tables with various sediment feed mixtures. Initially, experiments had a flat bed of sand with an initial gradient of 0.01–0.025 (-). Water discharge was kept constant at 0.1 l s^{-1} and the total sediment discharge was set at 2.86×10^{-4} l s^{-1}. The feed channel enabled sediment aggradation at the apex and downstream, which provided accommodation. The end of the flume had an adjustable weir that allowed passage of water and sediment (suspended and bedload) and prevented incision of channels by backward eroding steps. This method of promoting alluvial aggradation by enabling uplift of the feeder channel rather than lowering of the basin floor was also used by Moreton *et al*. (2002) and Sheets *et al*. (2002). Pilot experiments (P) were performed on a small stream table of 2 × 1 m to optimize conditions and test the effects of the feed sediment composition. Aggrading DFS experiments operated on a 5.4 × 3.8 m T-shaped stream table (*T*) across a low-gradient plain (Figure 1B). Time-lapse overhead images recorded the wet surface, where blue dye in the flow and different colours of sediment were recognized. During experiments T1 and T2, flow was interrupted every 4–8 hr for draining and dry bed scanning. Surface topography was surveyed using a Faro Focus 3D laser scanner at a distance of 1.8 m, resulting in 5–100 points per 4 mm^2. Experiment T1 started with a steeper initial slope than T2 and sediment build-up was considerably lower according to the measurements of surface topography and sediment discharge over the downstream fixed weir. Surface flow over a downstream weir occurred, and the configuration implies a deep lake or river bordering the DFS. Both experiments were terminated when a single static channel remained (T1: 98 hr, T2: 209 hr) and sediment output discharge approximated the input sediment discharge.

2.2 | Sediment composition

Past experiments of fans and other fluvial systems predominantly produced bedload-dominated systems because of the technical difficulties in creating suspension-dominated systems without ossification of the channel network (Paola *et al*., 2009; Kleinhans *et al*., 2014). Minor bank cohesion in the self-formed floodplains is required to obtain sufficient channelled flow and avoid wide, braided channels, but typical overbank sediments in nature are far too cohesive for the low-energy laboratory streams. Levee formation would help to confine channels but has been particularly difficult to obtain in laboratory experiments. Channel aggradation, on the other hand, can lead to unconfined flow unless floodplain aggradation keeps pace. The experimental challenge is therefore to have relatively high rates of floodplain sedimentation, as compared to channel aggradation, without causing high cohesion that would prevent channel migration and avulsion. Other scaling targets were as in van Dijk *et al*. (2013b) and Kleinhans *et al*. (2014, 2017): the selected sand was coarse and poorly sorted enough to avoid unrealistic scours, while the slope was kept gentle enough for subcritical flow and yet have enough turbulence to hold the floodplain-forming sediments in suspension. In view of the conflicting need of high Shields mobility number and Reynolds number and low Froude number, a smaller experimental facility would not be suitable for more than exploratory pilots.

A mixture of non-cohesive and weakly cohesive materials that are sufficiently suspended compared to the sand supplied as bed load was supplied to achieve this. Various overbank-forming sediments were tested and the outcome compared with a control experiment using only sand. The sediment used comprised poorly sorted sand containing <2.8 mm diameter granules, and a median diameter of 0.5 mm (van Dijk *et al*., 2013a; Kleinhans *et al*., 2017). Overbank-forming sediment comprised crushed walnut shells and coal with a low density (1,100–1,300 kg/m^3) relative to sand (2,650 kg/m^3). These materials were found to be successful mud substitutes in previous physical experiments (Sheets *et al*., 2002; van de Lageweg *et al*., 2016). The addition of walnut to sand (experiment 6 in Figure 2) resulted in increased sinuosity of relatively wide channels, increased channel flow and decreased floodplain flow. The addition of coal (experiment 7 in Figure 2) reduced channel width and length, as well as the extent to which channels migrated laterally. The input of coal additionally resulted in increased avulsion processes including the formation of splays. A mixture of coal and walnut with sand (experiment 8 in Figure 2) formed a channel system with a distributive character. The system developed laterally migrating channels and distinct channel-belt and floodplain components.

The pilot experiments demonstrated that large low-weight grains promote levee formation, while small low-weight grains preferentially accumulate on the surrounding floodplain (Figure 1D through F and Figure 2). The experiments with a mixture of sand, coal and crushed walnut shell produced repeated downstream channel cutting, terminal bifurcation and splay formation, in addition to backward filling processes followed by renewed avulsion. Image processing was allowed by colour contrasts: coal was distributed distally on the floodplain

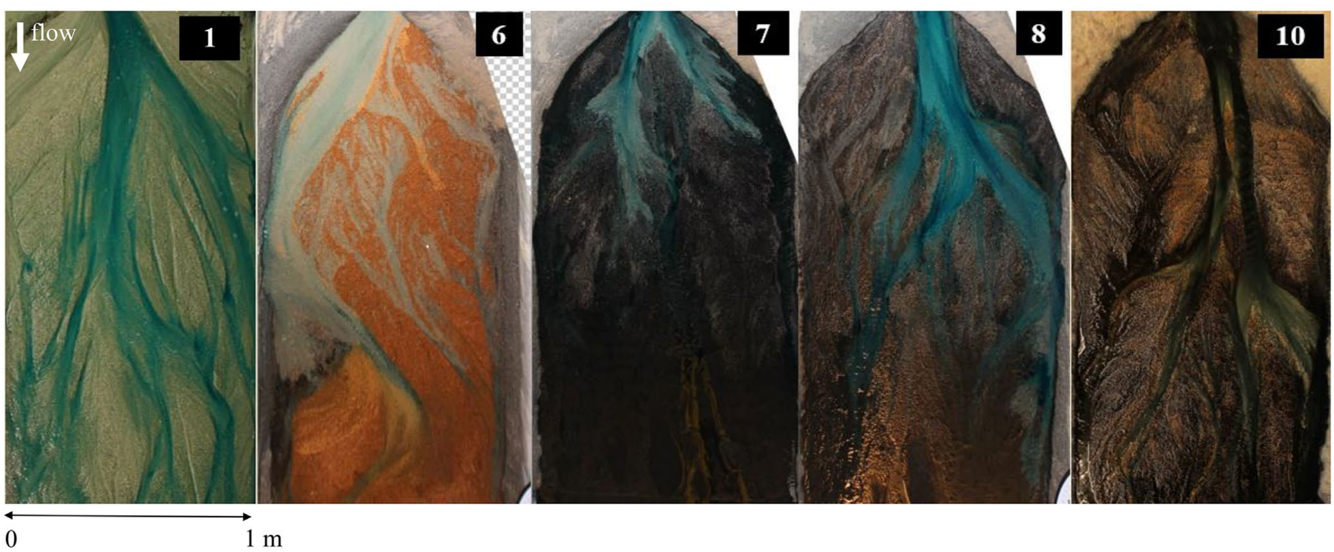

FIGURE 2 Planform of experiments P1, P6, P7, P8, P10 (Table 1) with different sediment compositions on a stream table of 2 x 1 m

TABLE 1 Experimental conditions with water discharge (Q_w) in l/s, sediment discharge (Q_s) in l/s, and description of sediment compositions as a fraction of Q_s

Experiment name	Q_w (L/s)	Q_s (L/s)	Initial slope (–)	Sand (poorly sorted) (–)	Walnut shell (mix) (–)	Walnut shell (1.3–1.7 mm) (–)	Coal (mix) (–)	Coal (powder) (–)
P1	0.1	0.0003	0.014	1	—	—	—	—
P5	0.1	0.00029	0.018	1/3	—	1/3	—	1/3
P6	0.1	0.00034	0.014	1/3	—	2/3	—	—
P7	0.1	0.0003	0.014	1/3	—	—	—	2/3
P8	0.1	0.0003	0.014	1/3	1/3	—	—	1/3
P9	0.1	0.0003	0.014	1/3	1/3	—	1/3	—
P10	0.1 & 0.15	0.00032	0.014	1/5	2/5	—	2/5	—
T1	0.1	0.00029	0.025	1/3	1/3	—	1/3	—
T2	0.1	0.0003	0.01	1/3	1/3	—	1/3	—

and deposited preferentially on top of the crushed walnut shell, meaning that the overhead image colour enabled the recognition of the floodplain filling stage. Properties of crushed walnut shells, coal and poorly sorted sand are complementary and provide evident sorting patterns. Two sets of experiments were done: (a) pilot experiments to choose a sediment composition and concentration that best produced a natural system, with more sustained channel flow than typically observed on fans without floodplains (Sheets *et al*., 2002; van Dijk *et al*., 2012) and (b) DFS experiments to record and quantify depositional facies and architectures at various proximal, medial and distal reaches of a DFS. For previously reported DFS experiments, aggradation tended to unchannelled flow events and braiding, while incision led to single-thread quasi-meandering (Kleinhans *et al*., 2014). The sediment mixture used for the DFS promotes erodible floodplain sedimentation and avoids a large number of the adverse scaling effects which have hampered past models (Kleinhans *et al*., 2014, 2017).

2.3 | Data processing

The evolving channel planform was monitored using time-lapse photography with a Canon Eos D600. Water was dyed blue and the feeder sediment had a number of distinctive colours, including yellow-white for sand, black for coal, and brown for the crushed walnut shell. Two approaches based on colour recognition in the images were used to measure evolving channel planform in eight cross-sections drawn at equal spacing down the depositing DFS: (a) an algorithm which determined the location of active channels ('cumulative channel activity') and by means of stacking the temporal evolution is shown (Figure 3B) and (b) an algorithm detecting channel change over time from an abrupt temporal change in colour (see caption of Figure 3C). The algorithm is based on transformation of the red, green and blue colours (RGB) to the 'LAB' colour space of luminosity and two colour axes *A* and *B*. Thresholds for luminosity and colour were empirically determined to distinguish channels, while colour information was used for interpretation. Timestacks of colour through time were plotted for specific cross-sections spaced 0.45 m apart from proximal to distal locations on the fan in order to capture the system dynamics. The best results were acquired for the proximal and medial region because water appears bluer there, while in the distal region the floodplains were dark with low contrast.

After each experiment, the deposit was cut and photographed at matching cross-sectional transects, after which a colour threshold algorithm was applied to indicate channel deposits. The depositional bodies thus recognized in the images were manually digitalized.

Surface topography was surveyed using a high-resolution laser scanner. The resulting elevation models are continuous raster arrays with a horizontal resolution of 8 mm and median elevation values calculated from >25 scan points per grid cell, providing quantitative data on bed thickness (Figure 3E; van de Lageweg *et al*., 2013). The series of elevation models were processed for specific proximal to distal cross-sections to obtain deposit age and erosional set boundaries in the same manner as van de Lageweg *et al*. (2013). Performance of the scanner on areas covered with dark particles was poorer so that digitization of bed load deposits was done manually from photographs.

In the following sections, the images made from the stratigraphic sections are described and discussed together with the time-lapse images and elevation models taken during the experiment.

3 | RESULTS AND DISCUSSION

3.1 | Recognising ancient DFSs: Facies criteria

Modern DFS develop in aggradational settings such as actively subsiding basins (Hartley *et al*., 2010a) and therefore

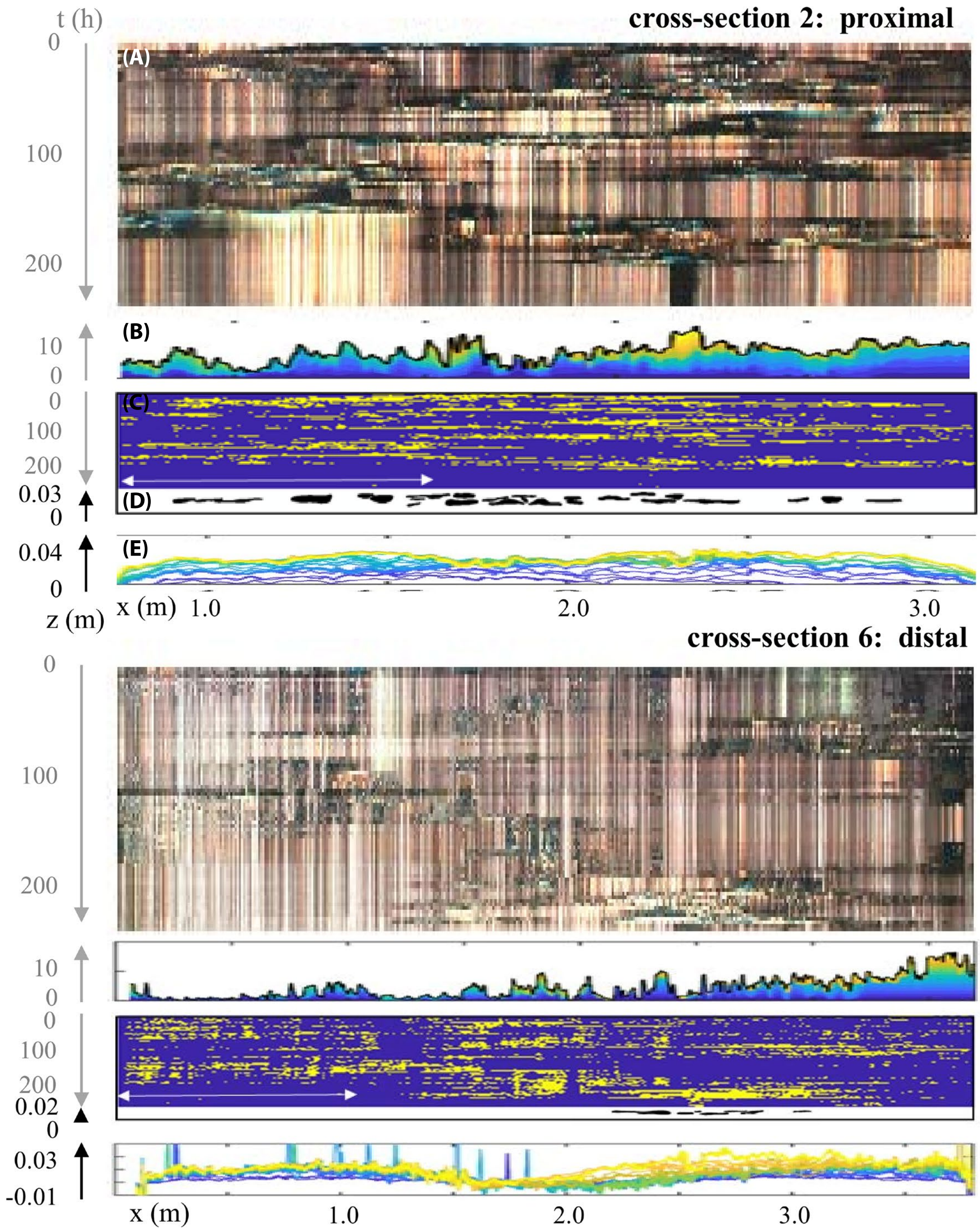

FIGURE 3 (A) Stacked images of cross-section showing the location of the active channels in the timestack along the cross-section in blue (bright blue—dark blue). (B) Cumulative channel activity (hr) based on cross-sections. Colour shade represents the temporal evolution from $t = 39$ hr (blue) to $t = 209$ hr (yellow) in 15 intervals. (C) Time-stack that labels changes in time in the image. If there is no change, floodplain remains floodplain (blue), if there is change the channel is reworking the area (yellow). (D) Interpretation of channel bodies based on photographed cross-sections (see Supplemental material). Set thickness decreases from proximal to distal. (E) Build-up of the system from 41 bed elevation measurements from $t = 0$ hr to $t = 225$ hr

undoubtedly form a considerable part of the alluvial rock record. Such aggradational conditions were enforced in the experimental runs. DFSs have decreasing discharge downflow and generally transition from proximal, channelled flow to distal, unconfined flow where terminal splays form (consistent with the online movie provided as supporting material on https://doi.org/10.17608/k6.auckland.12046449.v7; Nichols and Fisher, 2007; Cain and Mountney, 2009). The experimental systems were built up from one or more avulsing channels. Bedload sediment was confined to channels and floodplain sediment sourced by overbank flow. Crevasse and terminal splays predominantly developed in medial and distal zones as a by-product of avulsion or channel unconfinement.

The cross-sections demonstrate multiple processes: (a) temporally alternating episodes of increased channel migration (Figure 3A,B); (b) levee formation along major channels (e.g. Figure 1D through F, in yellow at $x = 2.2$ and $x = 2.5$ of Figure 3E; Figure 4 inset); (c) decreased channel activity and bed aggradation downstream (compare the two timestacks of Figure 3 where the many more 'vertical lines' in the distal cross-section indicate a lack of large channels and channel migration); and (d) significant autogenic reworking (see lateral migration of channels in blue in the proximal cross-section in Figure 3A). It is increasingly understood that sedimentary archives record mundane, sub-annual deposition as opposed to extreme events (Paola *et al*., 2018; Davies *et al*., 2019; Holbrook and Miall, 2020), such that the conducted experiments can be appropriately linked to the four most widely followed down-DFS facies criteria: (a) decreased channel size; (b) decreased grain size; (c) decreased channel confinement; and (d) increased dispersal of currents (Horton and Decelles, 2001; Weissmann *et al*., 2010, 2013, 2015; Davidson *et al*., 2013; Owen *et al*., 2015a, 2015b; Ventra and Clarke, 2018).

3.1.1 | Decreased channel size

Downstream losses in discharge, through factors including bifurcation, infiltration and evapotranspiration, were tested experimentally to determine if they resulted in decreased channel dimensions down-DFS (Horton and Decelles, 2001; Cain and Mountney, 2009; Weissmann *et al*., 2013, 2015). Groundwater was observed to have exfiltrated everywhere on the downstream boundary, showing that there was significant downstream loss in discharge during the experiment.

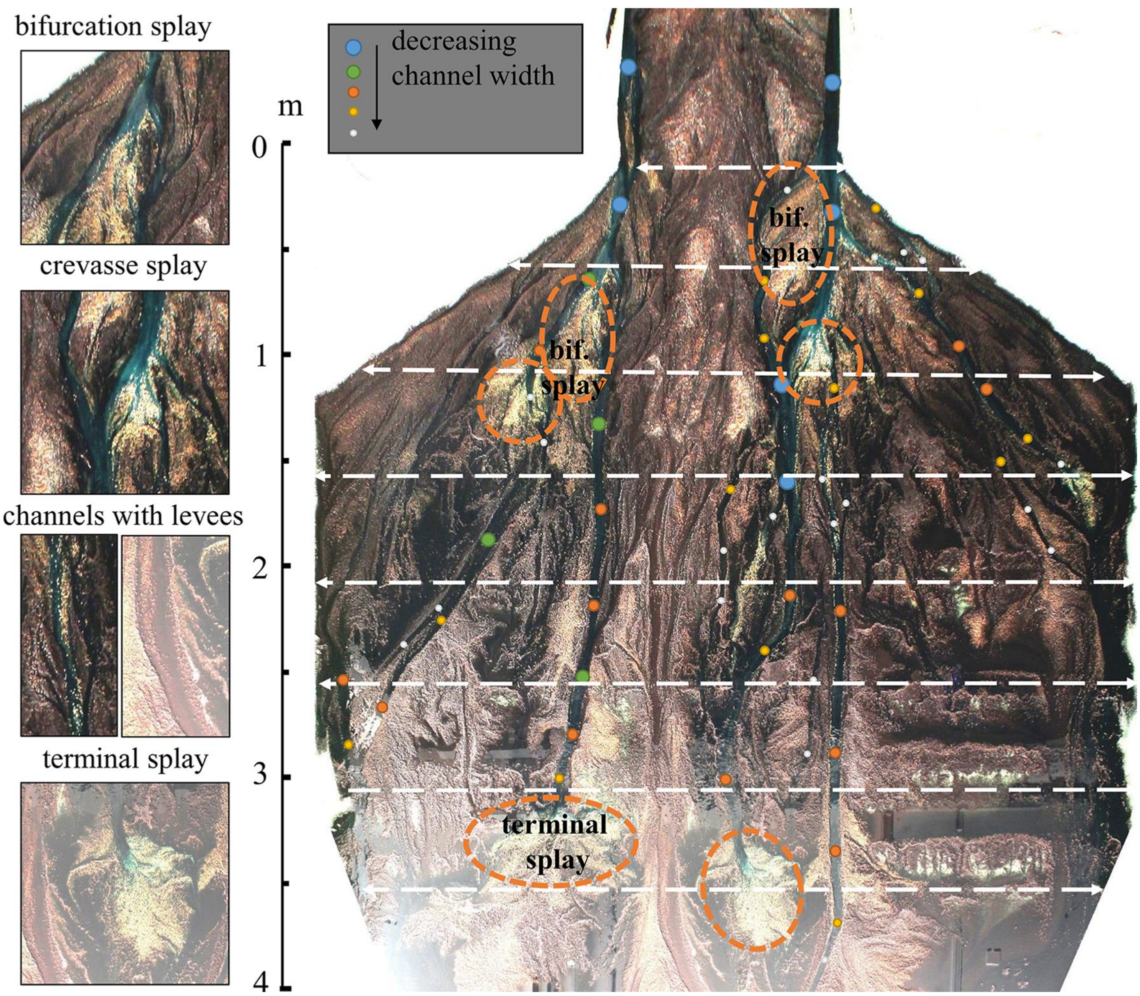

FIGURE 4 Example of channel planform with decreasing channel width from the proximal to distal reaches of the main channel and of bifurcating channels. Three types of splays were observed: (1) a bifurcation (bif.) splay where a channel splits into two or more channels and the in-channel flow capacity decreases. Sediment deposits predominantly in the lee of the bifurcating channel and on the levees. (2) A terminal splay where a channel becomes unconfined and spreads onto the floodplain (e.g. downstream of a bend). It typically migrates laterally as the feeder channel migrates or moves upstream as the flow in the feeder channel reduces. (3) Crevasse splays related to levee breaches

Dimensions of active channels highlight that any disparity most commonly arises following bifurcation, with the main trunk channels splitting to form multiple smaller channels (Figure 4). Thus, two mechanisms caused a downstream decrease in channel dimensions in the experiments: loss of discharge to groundwater and channel bifurcation as part of the systems avulsion dynamics.

This model largely concurs with the supposed trend of decreasing channel size down-DFS (Figure 5A). Channel-body dimension decreases from proximal to medial areas, although significant variation in channel size is evident in medial and distal stretches. This disparity, recognized in each analysed depositional-strike section, contradicts the suggestion that ancient DFS successions have a narrow range of channel dimensions without outsized channel bodies (Fielding *et al*., 2012). Comparisons between Figure 3A,D show that small-sized channels were related to bifurcation and terminal splays (see clear examples of splays in Figure 4). Also, the final deposits in distal regions are wider than the original depositing channels (Figure 3), with the ultimate aspect ratio dictated by the lateral extent of multiple autogenically reworking channels, and not the cumulative activity and width of an individual channel. Channel-fills contain increased fine-grained sediment down-DFS (Figure 3D), suggesting a transition from bedload to mixed-load deposition consistent with a downstream reduction of discharge.

3.1.2 | Decreased grain size

The coarsest deposits occur within the main channels in the proximal and medial zones of the system, with median grain-size decreasing down-DFS, indicated by darker coloured sand bodies down-DFS (Figure 5C). As channel size decreases downstream and because DFS cover an increasingly large area, the spacing between channel-fill deposits increases within medial and distal areas (Weissmann *et al*., 2013). The percentage of deposits 'in-channel' was documented from measurements of 99 channel-fills at various depositional-strike transects (Figure 6). In proximal regions, 35%–45% of

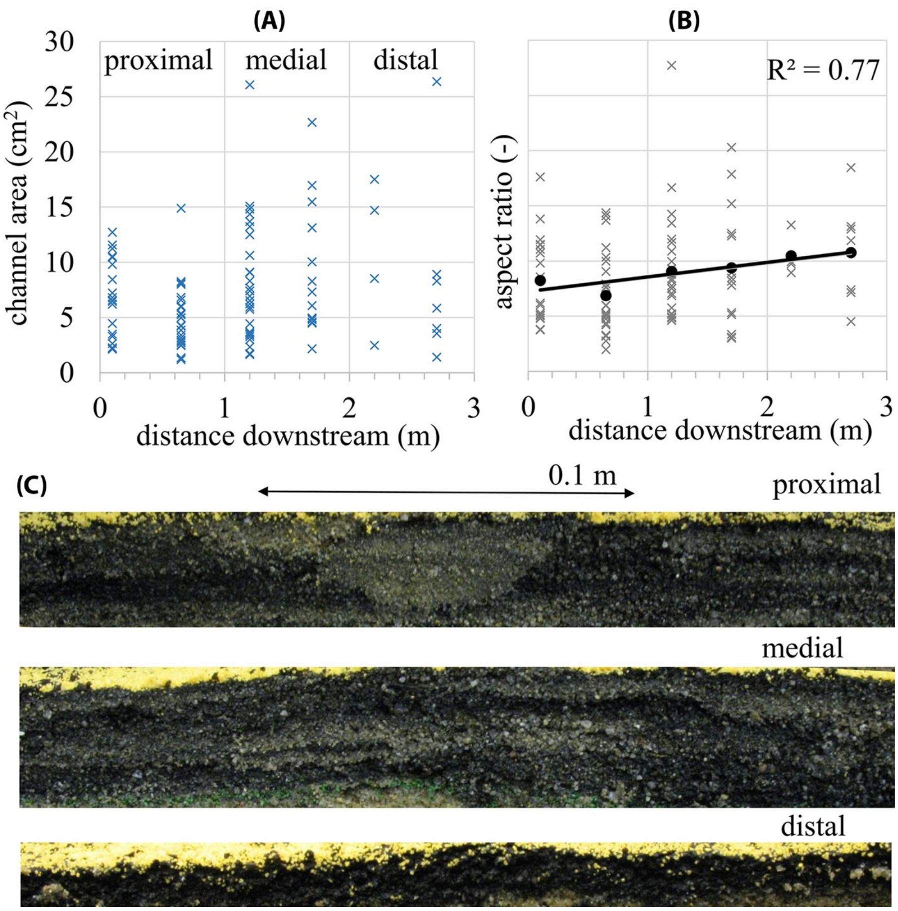

FIGURE 5 (A) Channel cross-sectional area measurements. Note proximal to medial decreases in body cross-sectional area, and highly varied body sizes in medial and distal reaches, variability that can be related to splay deposition. (B) Aspect ratio of deposited channel and splay bodies. The coefficient of determination is determined from the trendline through the means (C) photographed cross-sections with sediment colour enabling the recognition of channel and overbank facies (coal = black, sand = light gray) and decreasing thickness from proximal to distally located channel bodies

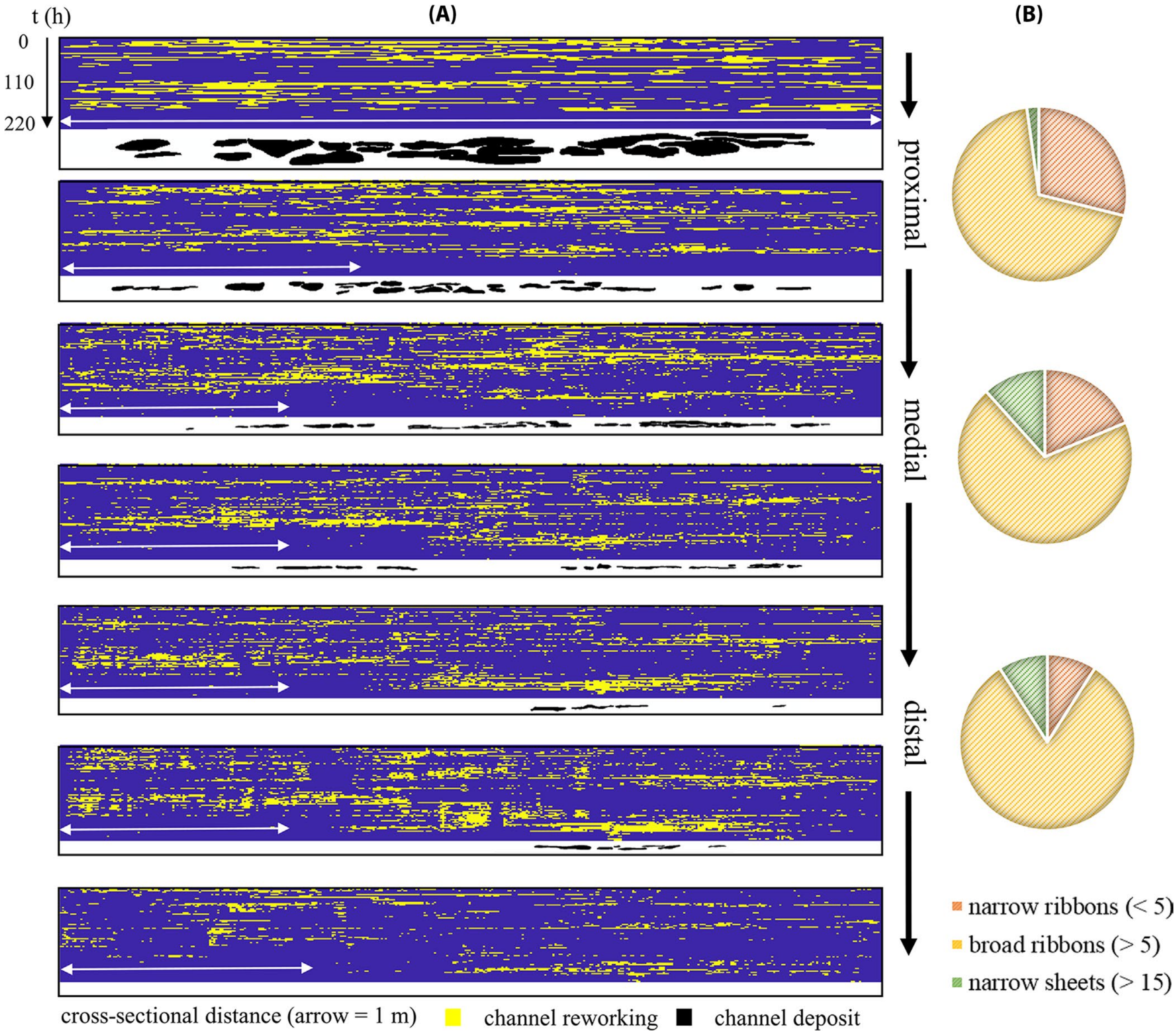

FIGURE 6 (A) Time-stack that labels colour changes in time in the image. If there is no change, floodplain remains floodplain (blue), if there is a change the channel is reworking the area (yellow). Below the time stack is the interpretation of channel bodies based on photographed cross-sections (Appendix DR3). Set thickness decreases distally. Cross-section scale: white arrow is 1 m. (B) Channel-body classification (Gibling, 2006)

the deposits resided inside channels, with this value decreasing to 10%–30% and 0%–5% in the medial and distal areas respectively (Figure 7). This trend is attributed to the greater depositional role of overbank processes and increased sparseness of deposition occurring within channels. More energetic flows in proximal reaches prevent the widespread deposition of fine material due to high rates of autogenic reorganization. In medial and distal areas channel-fills may be sand-rich or mud-rich, with overbank flow processes playing a significant role in channel filling in abandoned areas on the floodplain. This is consistent with both modern DFS characteristics (Weissmann *et al*., 2010), and those derived from the ancient stratigraphic record (Owen *et al*., 2015a). The experiments link these trends to changes in processes associated with the general widening of the DFS downstream, avulsive behaviour, and the progressive loss of discharge. Over the long time of significant aggradation this also causes the lower distal slopes and distal fining.

3.1.3 | Decreased channel confinement

Applying the channel-body geometry classification scheme set out in Gibling (2006), channel-fills are grouped as narrow ribbons (aspect ratio <5), broad ribbons (5–15) or narrow sheets (>15), with the overall ratio of narrow sheets to narrow ribbons increasing distally (Figure 6B), indicating decreased channel confinement downstream. The average aspect ratio

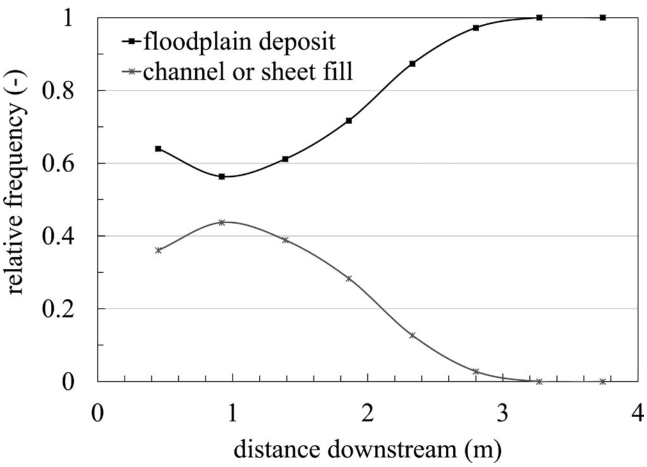

FIGURE 7 Total percentage of floodplain and channel/splay deposit of cut cross-sections at increasing distances from the DFS apex

of channel bodies increases downstream (Figure 5B; proximal average = 7.5, medial average = 9, distal average = 10.5). However, the spread around the mean is considerable and the trend in the data is weak (Figure 5B). At the same time channel bases become less deeply incised into the surrounding floodplain deposits downstream. This is because: (a) channels increasingly distribute discharge over multiple contemporaneously active channels down-DFS; and (b) channels progressively lose discharge to the floodplain down-DFS (see online movie) through surface runoff processes and by infiltration. The slope of the system decreases distally resulting in a decreased capacity to cause incision into the underlying substrate.

The aspect ratio of the channel-fill deposits in the Miocene Huesca system substantially decreased downstream, suggesting distal flows had a reduced ability to erode channel banks due to lower discharge (Hirst, 1991). In distal reaches the flow increasingly spreads over tributaries and floodplain lows, restricting the overall flow strength and the ability of channels to migrate laterally. Ultimately, less energetic flows and increasingly cohesive floodplains reduce the extent of autogenic reworking. The experiments presented here show this reduced ability to erode channel banks distally, favouring increased confinement, but the channel-fills are mud-rich and do not form recognizable sand bodies. On the other hand, terminal splays are not constrained with channel banks and these deposits are coarser and form broad ribbons and narrow sheets.

3.1.4 | Increased dispersal of channels

The recognition of increasingly dispersed palaeocurrent measurements distally is an evident signature of an ancient DFS requiring no testing through experimental models (Weissmann *et al*., 2010). The terminal splays in Figure 4 nicely illustrate fanning current directions. Within ancient sedimentary outcrops, once a dispersal in palaeocurrents has been identified, quantified analyses of azimuths (for which statistical computations already exist; Owen *et al*., 2015b) can provide insight on the position of the original DFS apex. This information is invaluable for palaeogeographic reconstructions and basin-scale facies predictions, but critical to this process is adequate in-situ measurement taken from outcrops of sufficient scale (see Section 3.3).

3.2 | Channel dynamics in relation to floodplain processes

In the experiments, coarse suspended grains promote levee formation, while fine mobile grains accumulate on floodplains. The presence of coarse and fine mobile grains also gives rise to an important geomorphic feedback: backwards sedimentation up the fan. Both terminal splays and bifurcation splays show this morphodynamic mechanism (Figure 8, also see online movie).

The steeper experiment (T1) frequently showed avulsion of channels by reoccupation of former channels and by the carving of new channel segments into the floodplain, sometimes with diverging channels and deposits reflecting avulsion splays. The avulsion dynamics are related to erosion and sedimentation in the various channels, but how precisely was hard to observe in detail. The combinations of complex floodplain relief and frequent flooding made the avulsion unpredictably irregular. These avulsion styles (reoccupation and carving new channel segments in the network) are often found in barely aggrading fluvial plains (Stouthamer, 2005, Kleinhans *et al*. 2013). The former channels lost discharge due to increased flow through the new channel, but also silted up with coarse floodplain sediment in the upstream direction.

The aggrading gentler-sloped experiment (T2), however, more frequently showed avulsion followed by terminal splays. These rarely developed further into complete avulsion (as in Smith *et al*. 1989; Buehler *et al*. 2011). More often, the flow divergence on the splays triggered sedimentation that led to backward channel filling in the upstream direction, reduction of discharge and eventual abandonment and filling, first by coarse floodplain sediment and later by fines (dark tones). This quasi-cyclic avulsion process of backfilling, renewed avulsion and splay formation is most often associated with deltas. Indeed, this avulsion style documented in the aggrading, gentler-sloped fan experiment is reminiscent of the first delta experiments with cohesive sediments, performed by Hoyal and Sheets (2009), who found that channel cutting after avulsion was repeatedly followed by downstream divergence into a splay, which caused backfilling of the channel and ultimately led to new avulsion. This style of quasi-cyclic avulsion behaviour has also been observed in fluvial fan experiments (van Dijk *et al*., 2012), where terminal crevasses disperse currents. The backward sedimentation up the fan is

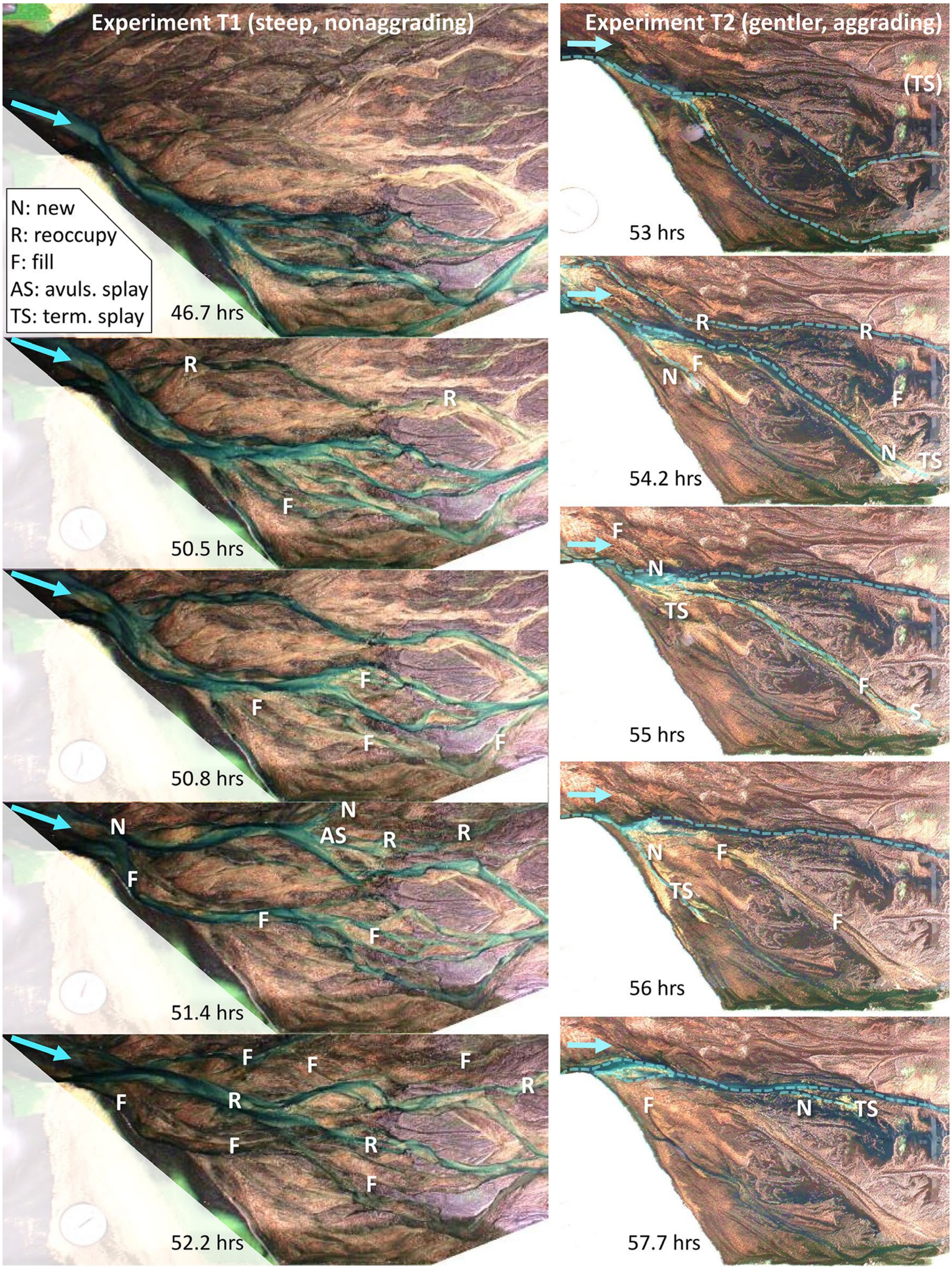

FIGURE 8 Examples of observed avulsions in experiments T1 and T2. The images were enhanced in colour depth as a whole. Main channels are indicated in the T2 images (right), which had less colour contrast between channels and floodplain than in T1

triggered by gradually reducing discharge of the feeder channel induced by the upstream-directed backwater effect due to the flow friction on the splay, and by substantial local deposition upstream of the splay. In the experiments with near-critical flow, the backwater effect is negligible, but is also not a necessary condition. Backward sedimentation is now known to drive avulsion even on submarine fans dominated by supercritical turbidity currents (Hamilton *et al*. 2017) and on single-phase debris flow fans (de Haas *et al*. 2016), showing this to be a ubiquitous mechanism that probably operates on DFS, as well as a diverse range of other distributive sedimentary systems.

The channels, levees and splays all form depositional bodies; a so far novel breadth of deposits and morphologies in aggrading experiments. The size of the splay elements relates to the discharge of channels at the splay apex. They therefore occupy nearly half of the fan width in proximal reaches, which are dominated by the large channels of the fan apex. A more diverse range of channel sizes occupies the medial fan over time (Figure 4, see also Section 3.1.1), as avulsion cycles mature. Splay sizes are similarly more diverse in medial stretches, and occupy a smaller fraction of the total fan width due to the radial fan geometry (1/6th to 1/20th of fan width). In the distal reaches, channel sizes are mostly small and terminal splays are broadly of a single size (Figures 4 and 6). These results emphasize that the morphological processes increase local variability in grain size and channel size on the DFS, especially in the medial reaches of the fan. This is potentially an aspect of DFS architecture that can be tested in the field (Wang and Björklund, 2019).

The fine-grained floodplain material dramatically altered the behaviour and appearance of the experimental DFS compared to experiments with simpler mixtures of sediment (Sheets *et al*., 2002) and with bedload only (van Dijk *et al*., 2012). It is important to consider the prodigious muddying of Earth's continents following the evolution of land plants (McMahon and Davies, 2018b) when assessing whether or not DFS deposition represent the normal preserved fluvial style right back to the Archean Eon (Long, 2018). Only a limited number of sandstone-dominant 'pre-vegetation' DFS have been described from the alluvial rock record (Williams, 2001; Ielpi and Ghinassi, 2016), with many of these claims contested (Krabbendam *et al*., 2008; Went and McMahon, 2018). As the availability of mud-rich sediment has not been uniform over geological time, it is not possible to assume that Earth's riverscapes have behaved constantly (Davies and Gibling, 2010; Gibling *et al*., 2014; Kleinhans *et al*., 2018). Future experimental DFS should further elucidate the perhaps fundamental role of ecosystem-engineering species with live plants (Jones *et al*., 1994; Van Dijk *et al*., 2013b; Lokhorst *et al*., 2019).

3.3 | Outcrop scale and orientation versus experimental data

The downsizing of an actively depositing DFS to the scale of these experiments enables study of complete proximal to distal stratigraphic trends, at a resolution rarely rivalled by natural geological outcrop belts. In the analysis of modern DFS, the vast majority of DFS have apex-toe lengths exceeding 30 km, with some systems having lengths exceeding 700 km (Hartley *et al*., 2010a). Refined interpretations of downstream changes to fluvial style at this scale may become challenging at the dimensions of 'normal' sedimentary outcrop belts. A tenable DFS interpretation requires detailed observations from multiple depositional-strike exposures variably spread along a source-to-sink transect. Interconnecting depositional-dip exposures are desirable to help prove a matching source, with outcrop orientation biases having the potential to influence sedimentological interpretations. These enforced limitations do not detract from previous ancient DFS identifications made from extensive outcrops where interpretations of evolving fluvial system planform were attainable (Friend and Moody-Stuart, 1972; Friend, 1978; Nichols and Fisher, 2007; Cain and Mountney, 2009; Weissmann *et al*., 2013; Owen *et al*., 2015b, 2017; Wang and Björklund, 2019). They do serve to promote caution when interpreting the ancient geological record, and the need for a richer experimentally-derived set of possible DFS element assemblages for pre-vegetation and syn-vegetation systems. While the presented experiments are not the first to include some form of floodplain sedimentation, they are the first to simulate DFS, inputting a greater floodplain-channel sediment ratio than used elsewhere, and thus pushing the high priority experimental frontier of suspension-dominated fluvial systems identified by Paola *et al*. (2009).

3.4 | Using experiments to bridge the gap between river and rock record

Analysis of modern aggrading continental basins suggests that active sedimentation patterns on the continents are dominated by DFSs (Weissmann *et al*., 2010, 2011, 2015; Hartley *et al*., 2010a, 2010b). Demonstrating if this 'normal' depositional style extends back throughout geological history requires a thorough understanding of the deposited stratigraphic architecture archived by a depositing DFS. This is imperative if we are to determine whether or not many widely adopted facies schemes based on tributive channel patterns are fit for purpose. These experiments, active under aggrading bed conditions, provide a mechanism linking active sedimentary processes typical of a terminal DFS to the more ancient stratigraphic record.

The results in this study favour an ancient depositing DFS if preserved outcrop belts host evidence of a number of distinct proximal to distal trends including: (a) a decrease in average grain size (Figures 5C and 7); (b) a decrease in the proportion of amalgamated channel-belt deposits (Figure 3); (c) a decrease in average channel thickness (Figures 4 through 6); and (d) increasingly dispersed palaeoflow azimuths. Significant changes in deposit architecture should accompany these trends, with proximal transects more probably to be dominated by vertically stacked successions of amalgamated channels, whereas distal deposits are more regularly typified by sheet and ribbon sandstones (Gibling, 2006) interspersed with thick accumulations of floodplain muds (Figures 5 through 7). Channel deposits in these more distal stretches show little amalgamation.

Future studies of sedimentary outcrop belts should aim to quantify facies variations across a number of distinct depositional dip and strike sections, in an effort to derive robust assessments of system-scale planform. A database of quantified facies assessments for formations dating from the Archean-Recent times (e.g. downstream changes to grain size, spatial relationships, sandbody geometry; Colombera *et al*., 2013) will help elucidate any prevalent channel patterns over the course of geological history.

4 | CONCLUSIONS

A depositing DFS was created in order to test experimentally widely followed criteria for recognizing such systems in the ancient stratigraphic record. Proximal areas comprise coarse, amalgamated channel-fills with grain-size fining in medial and distal zones. Avulsion sequences, migrating channels and upstream migrating splays vary the dimensions of channel deposits, such that simple downstream decreases in channel dimensions cannot always be relied upon. Muddy floodplain sediments significantly alter DFS behaviour and their subsequently deposited strata, with ramifications for recognizing DFS in Earth's mud-poor Precambrian record. The experimental approach followed here reduces the need to depend upon ancient planform recognition, and informs the widespread debate on which fluvial channel patterns are most abundantly preserved in the terrestrial alluvial rock record.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are provided on figshare https://doi.org/10.17608/k6.auckland.12046449.v7.

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