

Avulsion dynamics determine fluvial fan morphology in a cellular model

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ABSTRACT

Fluvial fans are large, low-gradient depositional systems that occur in sedimentary basins worldwide. Fluvial fans can represent much of the geologic record of foreland basins, create hazards, and record paleoclimate and tectonic signals. However, we lack an understanding of how fluvial fans grow into the variety of shapes observed around the world. We explored this aspect using a cellular model of foreland basin landscape evolution with rules for sediment transport, river avulsion, and floodplain processes. We tested the hypothesis that avulsion dynamics, namely, avulsion trigger period and abandoned channel dynamics, are a primary control on fluvial fan development. We found that shorter trigger periods lead to rounder planform fluvial fan shapes because, between avulsions, channel aggradation (and thus avulsion setup) propagates shorter distances from the upstream boundary along channel pathways. This prioritizes lateral sediment dispersion, creating shorter, rounder fans, over sediment delivery further into the basin, which would create elongated fans. Modeled fans with abandoned channel attraction (but not repulsion) generated a commonly observed abrupt fan boundary marked by a transition from distributary to tributary channel patterns. While fluvial fans are thought to be linked to climate, they can occur anywhere that rivers aggrade, lose lateral confinement, and preserve alluvial topography. Instead, fluvial fans might be more recognizable in environments that frequently trigger avulsions and preserve abandoned channels that capture future avulsions.

INTRODUCTION

Rivers that lose confinement as they exit mountain fronts create a wide variety of topographic forms until joining with other bodies of water or terminating where they lack sufficient water to maintain channels (Fig. 1 and Supplemental Material¹; Weissmann et al., 2005; Hartley et al., 2010; Moscariello, 2018). Some of these rivers form fluvial fans, which are low-relief cones that are larger than alluvial fans, lack debris flows, and radiate sediment from point sources over long time scales via fluvial processes (Ventra and Clarke, 2018). Previous work focused on understanding why only some rivers leaving mountain fronts generate fluvial fans (Leier et al., 2005; Hansford and Plink-Björklund, 2020), but comparatively little focus has been given to explaining why fluvial fans have widely differing planform appearances (Fig. 1). For example, while some fluvial fans are truncated by axial rivers or topographic

obstructions (e.g., Fig. 1D), others show a downstream transition from distributary and densely spaced to tributary and sparsely spaced abandoned channel patterns (e.g., Fig. 1B; Weissmann et al., 2013). Some fans have a round planform morphology (Figs. 1B and 1D), whereas others are elongated (Fig. 1C) or something in between (Figs. 1A and 1E). It is important to understand the mechanisms that shape fluvial fans because they are some of the largest depositional features on Earth and may represent much of the continental stratigraphic record (Weissmann et al., 2010), create substantial hazards (e.g., the Kosi river avulsion; Chakraborty et al., 2010), and record climatic and tectonic histories (Friend, 1977; Horton and DeCelles, 2001; Davidson and Hartley, 2014).

Empirical studies have related many factors to fan development and morphology, ranging from basin-focused (mountain front geometry and accommodation space; Weissmann et al., 2005; Wilkinson et al., 2006; Hartley et al., 2010) to river-focused factors (discharge, sediment flux,

and their variability; Geddes, 1960; DeCelles and Cavazza, 1999; Arzani, 2012). Basin-focused factors set the planimetric and altimetric space available for potential fans, while river-focused factors set the ways in which sediment is distributed through avulsion. Avulsion is the primary process that builds fluvial fans, and it occurs when a river that is undergoing in-channel aggradation experiences a triggering event that compromises riverbanks, allowing flow to exit channels (Mohrig et al., 2000; Slingerland and Smith, 2004). Trigger events (e.g., floods or logjams) are infrequent, difficult to predict, and are necessary (but not sufficient) for avulsion to occur. The clearest empirical relationship is that fans are most often observed in hydroclimates where discharge variability is high, suggesting that fluvial fans preferentially occur where avulsion triggers are more frequent (Horton and DeCelles, 2001; Leier et al., 2005; Davidson and Hartley, 2014; Hansford and Plink-Björklund, 2020). However, the mechanism explaining why, and how, more frequent avulsion triggers should create differences in fluvial fan formation and geometry has not been shown.

Here, we focused on understanding fluvial fan development from the perspective of a single, aggrading, avulsive river entering a basin without lateral confinement. We present cellular model results demonstrating that by parameterizing only a few, simple avulsion mechanics (trigger period, abandoned channel repulsion and attraction), we can reproduce a wide variety of fluvial forms in alluvial basins. We show that trigger period (i.e., the average time between avulsion-triggering events) and abandoned channels exert first-order controls on fluvial fan morphology by limiting the rate at which avulsion setup propagates into basins.

CELLULAR MODEL

We modified a cellular model that relates alluvial topography to avulsion dynamics over

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¹Supplemental Material. Figure S1, describing the method used to calculate domain tributary index values for the natural fluvial fans shown in Figure 1. Please visit <https://doi.org/10.1130/G51138.1> to access the supplemental material, and contact editing@geosociety.org with any questions.

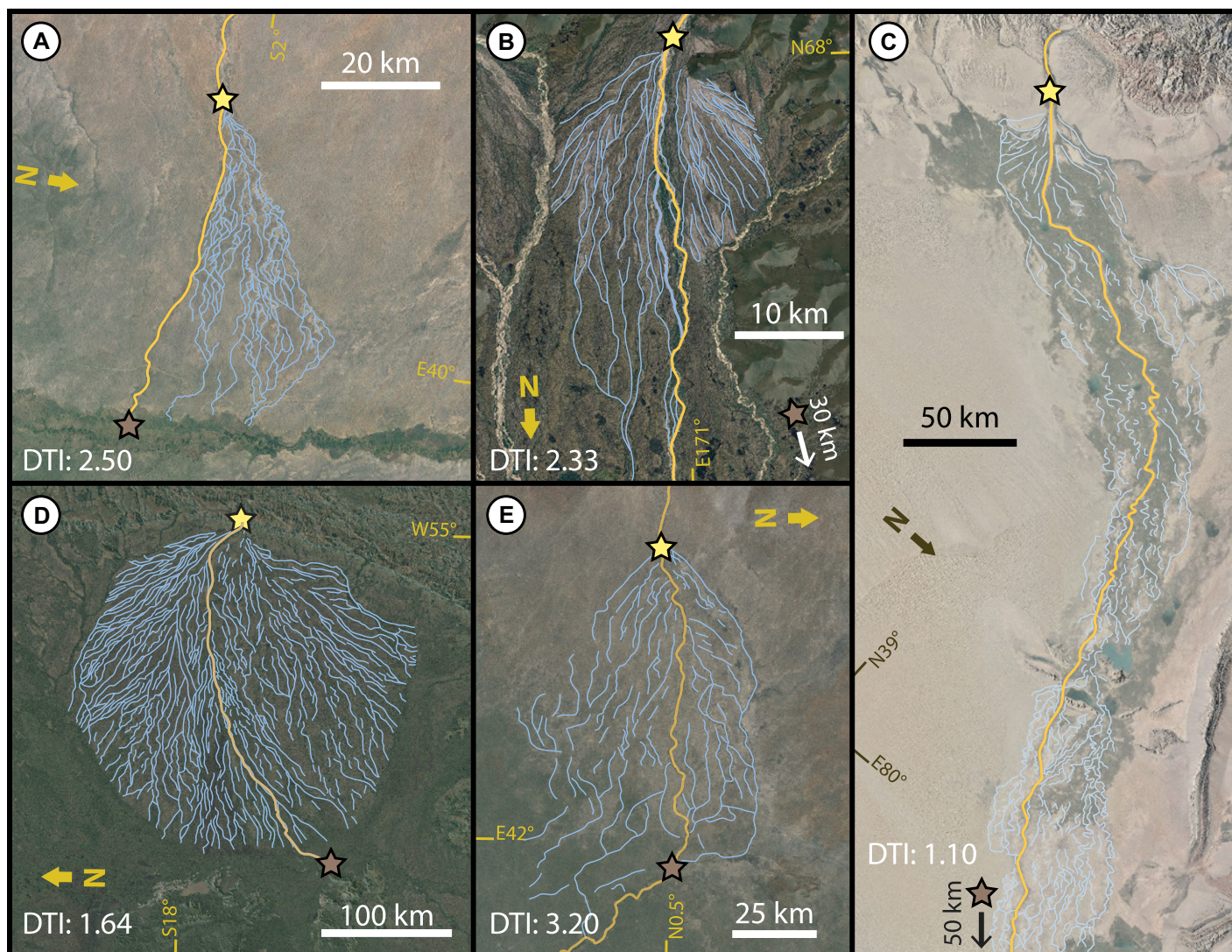


Figure 1. Variety of forms that rivers leaving mountain fronts in foreland basins can generate. Gold and blue lines mark active and abandoned channels, respectively. Apices and toes from Hartley et al. (2010) are marked by yellow and brown stars. Flow is down. See Supplemental Material for domain tributary index (DTI) calculations (text footnote 1).

large spatial (>100 km) and temporal (10^6 yr) scales. Each model run lasted 500 k.y. and introduced an equal amount of bed-load sediment. This section provides a model overview and explains changes to the previous model. See Martin and Edmonds (2022) for a more detailed description, including values of other model parameters.

In our model, active and abandoned channels are sub-grid scale (i.e., not directly resolved), and they track a high (levee or alluvial ridge crest) and a low (channel-bed) elevation. Active channel beds adjust by transiently diffusing elevation downstream (Paola et al., 1992). Avulsion setup requires both superelevation (channel-bed elevation is equal to or greater than at least one neighboring cell, including abandoned channels, in the five down-domain or lateral directions) and a gradient advantage (first step along the avulsion path is steeper than the next step along the existing path). At each time step, a trigger can occur with a

probability set by the average trigger period, initiating an avulsion from a cell randomly selected from all cells meeting avulsion criteria. If no cells meet the criteria, then no avulsion occurs; avulsion periods can thus be longer than trigger periods.

Once triggered, the pathfinding avulsion follows a slope-weighted random walk until reaching the bottom of the domain or intersecting an abandoned channel. Nondimensional parameters describe how abandoned channels can repel or attract pathfinding avulsions: Repulsion occurs if abandoned channel levee heights above the adjacent floodplain are larger than some multiple (likely greater than one; α_R) of the pathfinding flow depth, and attraction occurs if an abandoned channel's remnant relief is larger than some fraction (likely less than one; α_A) of mean flow depth (Martin and Edmonds, 2022). If captured, the river follows the steepest descent using channel-bed elevations until it exits the domain or until the abandoned channel becomes

too shallow to contain the flow, and the avulsion resumes a slope-weighted random walk.

Floodplain processes gradually anneal abandoned channels by raising channel bases and lowering levees by an equal fraction of a mean channel depth per time step until remnant relief is zero. Assuming levees and abandoned channels have similar volumes, this healing approximately conserves mass within cells. Subsidence rates decrease and partially-depth-dependent floodplain deposition rates increase distally.

We tested how avulsion trigger periods affect fluvial fan development using a series of runs with periods spanning 10–10,000 yr; while natural trigger periods are challenging to measure, they can only be as long as avulsion periods, which range from decades to millennia (Jerolmack and Mohrig, 2007; Edmonds et al., 2022).

Then, for a given period, we simulated 54 pairings of α_R and α_A to explore how abandoned channels affected fluvial fan form. To quantify

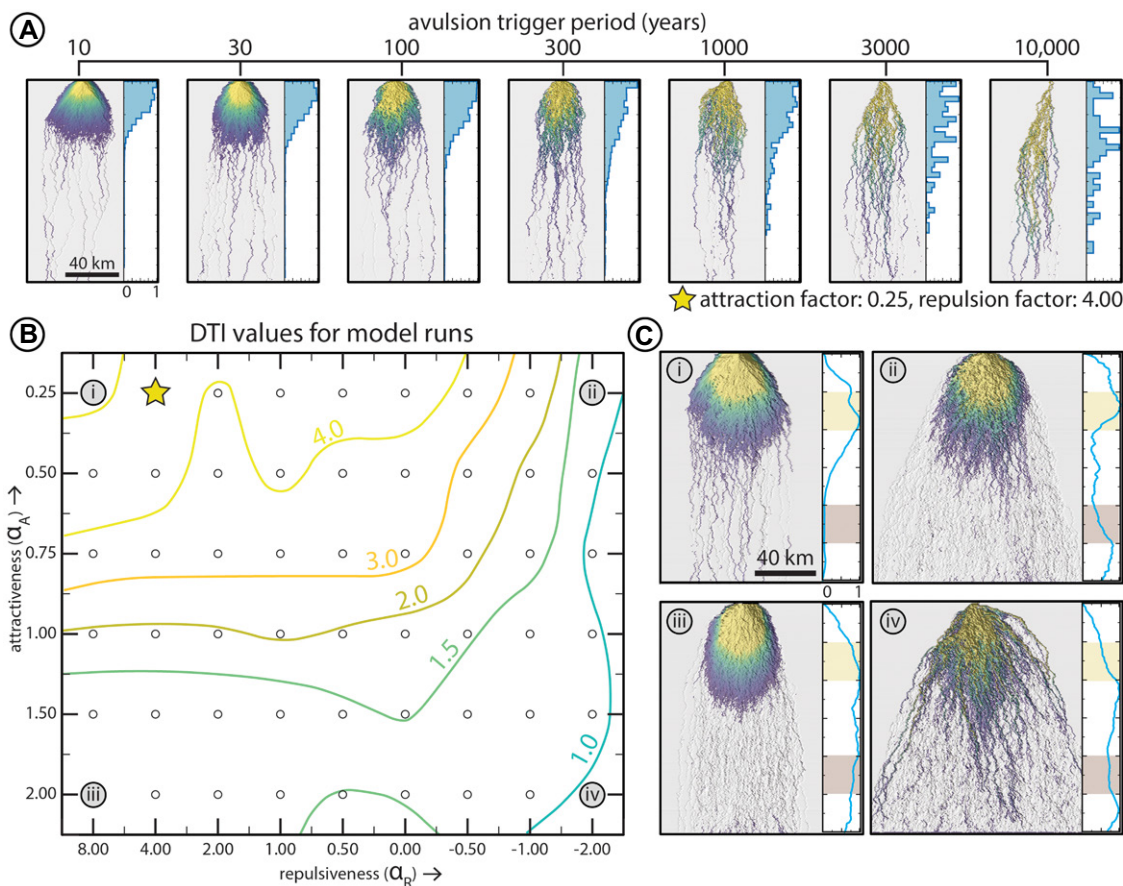


Figure 2. (A) Fluvial fan morphology is significantly affected by avulsion trigger period. Star in B marks location of these runs in abandoned channel parameter space. See Figure 4 for color bar. Histograms show normalized distributions (x axis: 0–1) of avulsion location (6.25 km bins) with distance from mountain front (y axis is same as planform topography). (B) Down-domain tributary index (DTI) values for 54 pairings of α_R and α_A with 30 yr avulsion trigger period. Lower values of α_R and α_A are more repulsive and more attractive, respectively. (C) Example end-member planform appearances. Blue lines show distribution of unhealed abandoned channels present on floodplain per row. Yellow and red highlights in bar at right show proximal and distal zones for Equation 1.

fan morphology, we defined a down-domain tributary index (DTI) as the ratio between the median number of unhealed abandoned channels per row in proximal ($N_{A,P}$; 25–50 km down-domain) and distal ($N_{A,D}$; 100–125 km) reaches (Fig. 2C):

$$DTI = \frac{N_{A,P}}{N_{A,D}}. \quad (1)$$

This equation quantifies the transition from distributary to tributary forms down-domain as flow pathways coalesce (Leeder, 1977; Heller and Paola, 1996). Because the model contains stochastic elements, each pairing's DTI was averaged across five runs.

Finally, because abandoned channels can shortcut avulsion setup by providing adjacent low elevations (Martin and Edmonds, 2022), we explored how abandoned channels may affect avulsion period on fluvial fans. For each cell in each run, we measured the time that an abandoned channel cell would be immediately superelevated over a neighboring cell if reoccupied. For this definition, a cell's low elevation must be greater than that of at least two neighboring downstream or lateral cells; these cells, if reoccupied, would route flow through one such neighbor and remain superelevated over the other. We divided this time by the total time that cell contained an abandoned channel.

RESULTS

Our simplified cellular model showed that avulsion trigger period has two key effects on fluvial fan formation. First, shorter trigger periods create rounder fluvial fans and concentrate avulsions proximally (Fig. 2A) by limiting the distance that channel aggradation (and thus avulsion setup) propagates downstream from the mountain front along channel pathways. Rounder fans result when avulsions are concentrated over a small part of the domain, forcing pathfinding to disperse sediment laterally near the location where rivers lose lateral confinement (Brooke et al., 2022). With longer avulsion

trigger periods, rivers deliver sediment farther downstream between avulsions, creating more elongated fans with a longer range of avulsion locations and less lateral dispersion (Fig. 2A).

Second, shorter avulsion trigger periods create a spatial memory of avulsions, defined as the tendency of the next avulsion to preferentially occur close to the previous one. We measured this by calculating the distance between successive avulsions for individual runs and comparing these distributions to a randomized model that removed any temporal signal by shuffling the order in which avulsions occurred (Fig. 3). With short trigger periods, avulsions exhibited spatial memory;

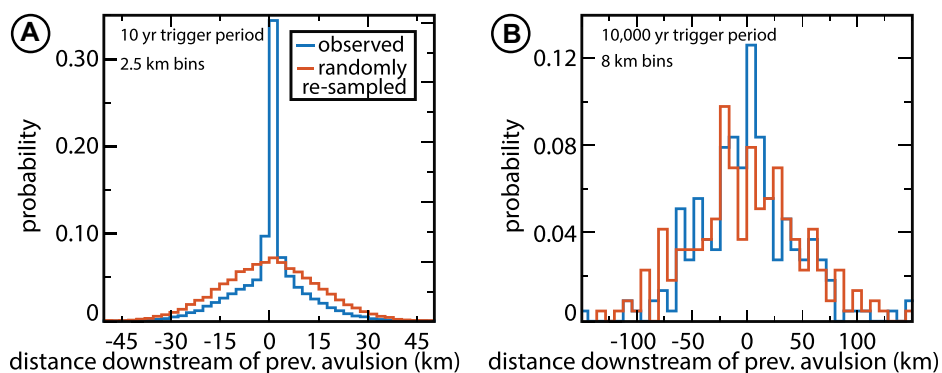


Figure 3. (A, B) Distribution of distance between successive avulsions for two avulsion trigger periods. Negative x-axis distances are upstream. (B) Because each run had fewer avulsions, this plot aggregates data from five identical runs. Note different y axes.

43.1% of avulsions occurred within 2.5 km of the previous one, which is 3.1 times greater than the randomized model (Fig. 3). Spatial memory can occur because, after avulsion, upstream cells can remain superelevated, and downstream cells can rapidly aggrade from transient diffusion (Martin and Edmonds, 2022). At longer avulsion periods, the measured and randomized model showed similar distributions because transient adjustment occurred relatively rapidly, and spatial memory was lost. Spatial avulsion memory reinforces lateral sediment dispersion by concentrating avulsions upstream, interrupting downstream transport.

Finally, a change in the way in which avulsions interact with abandoned channels also

changes fluvial fan planform shape. Observations commonly show a downstream transition from distributary and densely spaced to tributary and sparsely spaced abandoned channel patterns (Fig. 1). In our model, this transition emerged only in runs with more attractive and less repulsive abandoned channels (Figs. 2B and 2C, part i). In contrast, runs with more repulsive abandoned channels (Figs. 2B and 2C, parts ii and iv) had distributary zones that extended farther from the mountain front. Sufficiently repulsive runs never formed tributary domains. Finally, runs with no attraction and no repulsion (Figs. 2B and 2C, part iii) also formed distributary domains entirely to the exit of the

domain because forming tributary domains would require flow capture.

DISCUSSION

Our model of an avulsing river in a subsiding basin reproduced a wide variety of fan morphologies by varying only a few, basic avulsion processes. Previous empirical work suggested that fluvial fans preferentially form in climates with higher fluvial discharge variability because these areas should have more frequent avulsions due to more frequent triggers (Leier et al., 2005; Hansford and Plink-Björklund, 2020). Our work shows that classic, well-rounded fluvial fans with sharp downstream boundaries at the transition from distributary to tributary channel patterns only emerge when avulsion trigger periods are short, and abandoned channels capture, and do not repel, pathfinding flows. However, that does not mean rivers with long trigger periods do not produce fans; in fact, no matter the trigger period, our model created some kind of distributary fan-like deposit (Fig. 2A). The model predicted that all aggrading rivers that can avulse radially and preserve abandoned channels on floodplains will eventually form fans, broadly defined, albeit with different shapes (North and Warwick, 2007; Hartley et al., 2010). The simplest way to prevent a mountain front river from forming a fan is to remove its ability to avulse (e.g., due to external confinement or insufficient sediment supply); otherwise, it should form a fluvial fan. Our results show that the downstream decrease in channel forms on fans can vary, from abrupt to gradual to minimal (Fig. 2). Stratigraphic studies often cite a downstream decrease in channel number as an important indicator of fan deposition (e.g., Owen et al., 2015; Wang and Plink-Björklund, 2019; dos Reis et al., 2022), but assuming that our modeled *DTI* is representative of the stratigraphic record, then fans without attractive abandoned channels may not exhibit this downstream decrease (Figs. 2B and 2C, iii and iv).

Our results also showed that trigger periods alter the avulsion process to create different fan morphologies. This raises the question of why fans are sensitive to trigger periods, considering that previous work suggested that avulsion setup via channel bed aggradation is the more relevant parameter for avulsion period (e.g., Jerolmack and Mohrig, 2007). Instead, fans in our model were trigger-limited: Shortening the trigger period also shortened the avulsion period without changing sediment supply, super-elevation criteria, or channel depths. This arose because our fans had pervasive superelevation (Fig. 4) due to unhealed abandoned channels that provided topographic lows adjacent to active channels, and transiently adjusting local channel beds that rapidly aggraded downstream postavulsion (Martin and Edmonds, 2022). This contrasts with setup-limited environments like coastal rivers (e.g., Chatanantavet et al., 2012),

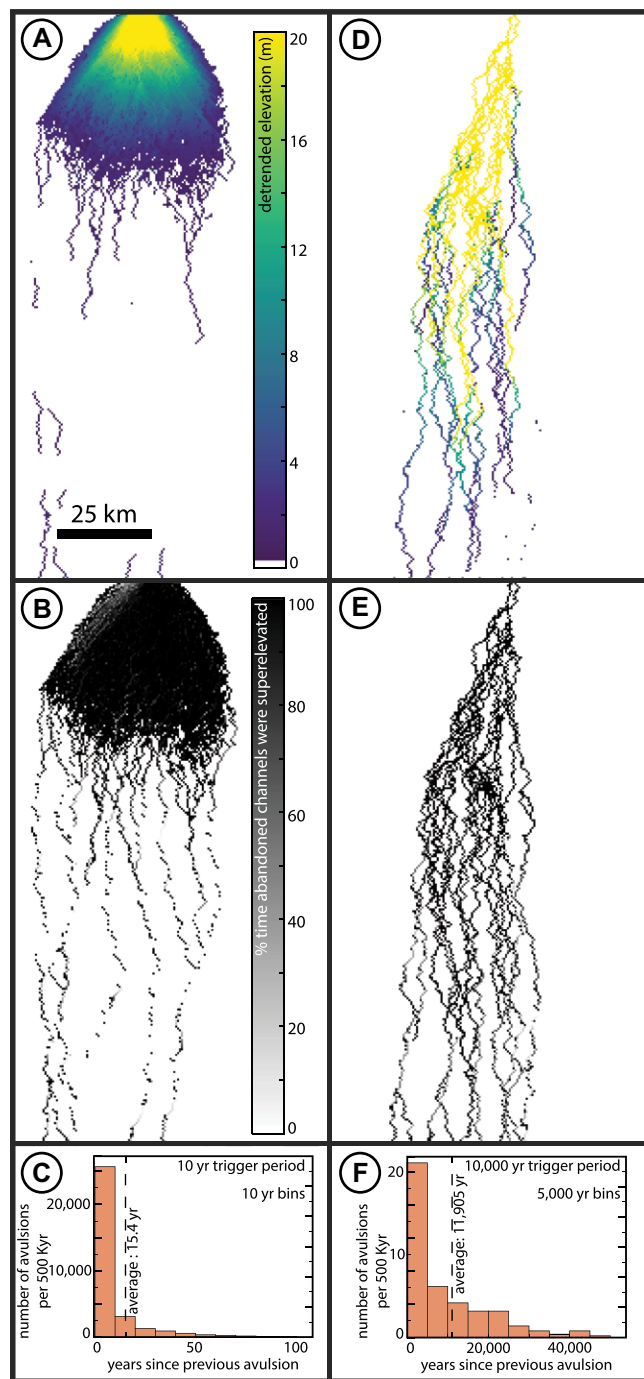


Figure 4. (A, D) Planform topographies, (B, E) super-elevation frequency maps, and (C, F) distribution of time between successive avulsions for 10 yr (A–C) and 10 k.y. (D–F) avulsion trigger period runs. Note different axes between C and F. Plot in F aggregates data from five identical runs.

where bed aggradation determines avulsion period. These different controls on avulsion period may arise because of more-rapid abandoned channel annealing on deltas (Carlson et al., 2020), forcing rivers to aggrade more to achieve superelevation.

CONCLUSIONS

We modeled fluvial fan development and morphology through the river-focused lens of avulsions. By parameterizing only a few, simple avulsion mechanics, we created a wide variety of fluvial fan forms. Rivers with shorter avulsion trigger periods created more well-rounded fans, amplified by spatial avulsion memory, as avulsions occurred closer to the mountain front and distributed sediment radially instead of farther into the basin. Abandoned channel attraction also affected fluvial fan topography, creating a well-defined transition from distributary to tributary channel patterns. Finally, fluvial fans were sensitive to changes in trigger period because abundant abandoned channels created a trigger-limited domain that required little to no aggradation between avulsions. This is a conceptual distinction from avulsion period formulations that describe setup-limited systems. By reinforcing avulsions as the fundamental mechanism of fluvial fan development, our model findings provide insight into fluvial fan formation and shape. While fluvial fans can occur anywhere that rivers aggrade, lose lateral confinement, and preserve alluvial topography, environments that provide frequent avulsion triggers and maintain floodplain topography should preferentially create well-rounded, easily recognizable fluvial fans.

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