Anonymous Referee #1

The manuscript submitted by Martin and Edmonds investigates the planform differences in megafans in foreland basins as a result of abandoned channels topography on avulsion pathfinding and their healing mechanisms. The study is motivated by three megafans and their channel locations and topographic features, including abandoned channels, alluvial ridges, and internal basins. A coupled 1D diffusive channel bed elevation model and 2D cell model is used to investigate both the effects of abandoned channels as attractors or repellents for avulsion pathfinding and the effects of different topographic annealing styles on modifying abandoned channel topography. Martin and Edmonds' results are very exciting and show that abandoned channels when acting as both attractors and repellents, create the characteristics topography of foreland basin megafans. Planform characteristics are also distinct between the proximal (near apex) and distal fan, which are directly related to avulsion potential and abandoned channel spacing. In their model, this spatial change in planform characteristics is only achieved if abandoned channel topography is transiently preserved and both high and low topography is diffused away over time. The megafan indefinitely progrades downstream if only the high or low topography of the abandoned channel is removed. These results provide a new and remarkable context to study the annealing of abandoned channel topography.

Below are major and minor comments and questions for the authors to consider.

- We appreciate the thoughtful and detailed review by Anonymous Referee #1. Two main themes in the review were to better support the motivation of the research by introducing a review of previous knowledge and modeling efforts earlier in the manuscript, and better supporting some modeling choices, including the decision not to vary floodplain overbank deposition rates with respect to distance from the active channel. We have changed the overall layout of the manuscript to address the first point, and we have added additional supporting justification for our modeling choices to address the second. We have also simplified some equations and added a new section on model parameter sensitivity. These suggestions, as well as all others in the review, are discussed per-item below. Overall, the reviewer is thanked for helping to improve the understandability and justifications of the manuscript and model.
- Note: line numbers referenced by the reviewer refer to the original manuscript, while (unless otherwise explicitly stated) line numbers in our responses refer to the revised manuscript with tracked changes accepted.

Major Comments

The introduction is a great summary of the motivation for this study. There is an opportunity to put the subsequent modeling efforts in context to other avulsion modeling frameworks, including those mentioned in the discussion and avulsion models related to deltas.

Besides avulsion processes, floodplain processes are the other addition to the modeling. The introduction glances over floodplain processes because not as much is known. Even with the limited knowledge about aggradation rates and their spatial trends on floodplains, the choice of spatially varying floodplain aggradation rates away from the fan apex and not away from the active channel needs to be better supported.

Lines 81-82: How does this result compare to simulations?

- Of comparable simulations (i.e., preserves abandoned channels but only routes flow through one pathway at a time), it appears that Jerolmack and Paola (2007) and Reitz et al. (2010) have results that are similar to our proximal zone (densely channelized and distributive). However, they lack the tributive distal zone. We added a line to the start of section 3.2 to make this connection (172-173).

Lines 138-139: Currently, only the avulsion location variation is plotted. What are the implications for timing?

- Avulsions become more frequent when relative superelevation (Eq. 2) is considered, compared to only the original formulation (Eq. 1). This is shown in Figure 6B. We have made this more explicit by adding the average time between avulsions to the caption for Figure 6, and to lines 519-520

Lines 213-214: Please clarify why only non-active channel cells have subsidence, especially since subsidence is accounted for in the equations of both the aggradation rates and 1D diffusive channel bed elevation model.

- Thank you for pointing out this lack of clarity. In the model, active channel cells do experience subsidence. However, it is implemented elsewhere in the routine (at the same time as the channel elevations are updated) separately from floodplain cells for logistical reasons that do not affect the outcome. As such, I have adjusted the text (260-261) to remove this unnecessary detail and make it clearer for the reader.

Lines 214-215: Please describe the motivation for varying floodplain aggradation away from the mountain front but not the active channel. Does this affect the planform result and avulsion patterns? What are the processes that distribute sediment across the floodplain in this system, especially with only one active channel (Line 84-85)?

- Our reply regarding not varying floodplain aggradation with lateral distance from the active channel is provided in the reply to the comment on Lines 331-332. Regarding floodplain aggradation variation with respect to the mountain-front, our intuitive reasoning was that overbank deposition rate should increase with distance from the mountain-front as grain size fines and washload concentration increases. With that said, later testing showed that we still reproduced the fundamental findings of the manuscript with a base deposition rate that does not change with distance from the mountain-front. A sentence explaining as much has been added to our results (478-479) and to a new parameter sensitivity section, 6.1 (656-660).
- In the absence of spatial variations, the role of floodplain aggradation is only to counter-act subsidence. This difference is most pronounced in the proximal region where subsidence is greatest and pathfinding greatly restricts the ability for the active channel to

visit regions that are lateral to the origin and very proximal to the mountain-front. In the real world, mountain-front shedding processes or other channels should fill these topographic lows, but it is an unavoidable consequence of our decision to “ignore the impacts of other rivers or fans and of any other mountain-front processes that may advect sediment into the basin” (Lines 230-231). We have put a mention of this phenomenon in section 6.1, 654-656. Instead, our simplified model addresses this proximal “sag” by employing overbank aggradation that consists of a variable rate that increases as topographic relief (between each row’s highest levee and far-field floodplain elevation) increases. This is a somewhat simplified version of Jerolmack and Paola (2007)’s model implementation (Equation 3 at https://doi.org/10.1016/j.geomorph.2007.04.022). We do not believe that Jerolmack and Paola (2007)’s justification for this implementation is entirely unreasonable, as regions that are inundated to greater degrees should experience more aggradation. We do agree, however, that this could be presented more clearly and explicitly to the reader, and we have reworked this overbank sedimentation section of the manuscript to address any readers’ concerns that the reviewer helpfully pointed out. 383-400.

Lines 331-332: See previous comments. The motivation for floodplain aggradation changing downstream but not with distance to active channel seems counter-intuitive. Please explain how results would be affected if floodplain aggradation rates varied with distance to channel.

- By design, our model treats channels as sub grid-scale features that are small relative to the size of a cell, such that “channel-scale processes (like meandering, crevasse splays, or other lateral-distance-dependent depositional effects) are not resolved” (lines 289-290). Overbank deposition is generally modeled as decaying exponentially with increasing lateral distance to the channel (ex. Pizzuto 1987, at https://doi.org/10.1111/j.1365-3091.1987.tb00779.x0) and for a given suspended grain size (very fine sand) this should decay to a very small value within one or two cells: assuming quartz grains in water, application of Stokes’ law yields a settling velocity of ~0.005 m/s for very fine sand (75 um) and ~0.0005 m/s for silt (25 um). If we assume the flood is 1 m deep and there is an aggressive overbank velocity of 0.5 m/s, then very fine sand and silt would travel ~100 m and ~1000 m, respectively, before settling. The same exercise with clay-sized particles yields transport distances >10 km, which represents our overall floodplain deposition term. In other words, the sedimentation away from the active channel is subgrid-scale for the suspended load. If floodplain aggradation rates did vary with distance to the channel (beyond some small distance that formed local levees), we would observe broad, continuous, and uniform alluvial ridges which we do not see in our remote sensing observations (Figure 2). With that said, we think that the results could be affected in interesting ways if abandoned channel healing (via preferential deposition in topographic lows or erosion of topographic highs by overbank floods, specifically) were to vary in rates with lateral distance from the channel. We further clarified our sub grid-scale design in our floodplain processes methods. A sentence explaining this as a potential direction for future reference has been added to the discussion (6.3). Lines 708-711.

Line 335: A_fp,f is listed in Table 2 as having two different rates for proximal and distal. Please describe this variation here and share how the boundary between proximal and distal is found.

Does the boundary location change for each timestep? And how would these results differ if only one fix rate existed?

- We appreciate the reviewer identifying a possibly confusing issue for readers. As mentioned earlier in our response to the comments on lines 214-215, we intended for overbank deposition to increase downstream reflecting a supposed increase in washload concentration away from the mountain-front, with the value for each row being linearly interpolated between two end-member values. We explained this sort of interpolation between two end-member values for subsidence in our manuscript, but neglected to do the same for overbank aggradation. In other words, for the results presented in this paper, we did not establish a boundary between proximal and distal for the purposes of overbank aggradation but instead applied a linearly increasing amount per row. As mentioned in the previous reply, testing with a base rate that does not vary with distance from the mountain-front reproduced the fundamental findings of the manuscript, including reproducing the two distinct zones. This has been added to lines 656-660.

Lines 335-336: Please consider presenting the formula for A_fp,v here. Based on the description given, it's not clear if this is a positive or negative linear relationship with height difference.

- In response to the comment and in an effort to simplify our overbank deposition description, we have removed the fixed component from our Equation (12) and re-ran the models. This did not have a significant effect on our model outcomes. We have adjusted the explanation and formula to reflect this change, and also to make it clearer that our overbank deposition rate is equal to a base rate times a scaling factor that increases with increasing relief between each row’s highest levee and far-field floodplain elevation. We also ensured that we stated the directionality of this linear relationship. Line 383-400.

337-338: Does channel depth also change downstream? What are the motivations for normalizing the floodplain aggradation based on channel depth?

- It does, but the h_bar term in this equation (as defined above for Eq. 6b) refers to mean channel depth as averaged over the whole active channel, and so does not change with distance from the mountain-front. We added text to remind readers of this here (391). Our reasoning for normalizing the elevation difference between each row’s highest levee and farfield floodplain by channel depth is to create a non-dimensional scaling factor that can be applied to a base aggradation rate; it is necessary to divide this elevation difference by some value with units of meters in order to ensure dimensional homogeneity on both sides of the equation. This is the same normalization employed by Jerolmack and Paola (2007) to ensure dimensional homogeneity, and a citation has been added to reflect that (386). Our equation and text has been changed (383-400) to hopefully make this clearer, and we especially think that changing A_fp,f and A_fp,v to the single value A_fp,base should improve this section’s clarity.

Equation 12: See previous notes (and please feel free to refer to your answers there). The model presented here is a physical-based cellular model (line 13). Please describe how this formula is inspired by our communities’ understanding of floodplain aggradation processes.

- While our implementation is certainly simplified, we believe that it is not unreasonable. The updated formula employed in this revision now states that overbank aggradation increases linearly with increasing relief between the highest levee (often the active channel) and the floodplain. We added text (389-390) stating that "[w]hile simple, this scaling reflects a basic intuition that regions of the basin that are inundated to a greater depth during flooding should receive more overbank sediment." This is the same justification employed by Jerolmack and Paola (2007), but we certainly agree that this is likely a rich problem that we treat crudely, and perhaps future experiments that are more sensitive to implementation choices could be opportunities for further research.

Figure 4: In the physical-based model, how would the deposition only or erosion only healing modes affect the sediment availability in the surrounding fields since either sediment is needed or transported away in these modes. Would adding a component accounting for this in the floodplain aggradation affect the potential for equilibrium to be reached (lines 20-22)?

- The reviewer is correct to point out that a more sophisticated model would account for the mass transport from surrounding cells toward in-filling abandoned channel bases, or toward surrounding cells for abandoned channel levees. While one could perhaps argue that the sediment removed via erosion will be transported as washload and thus leave the domain without conserving mass (ex. Jerolmack and Paola (2007) in justifying channel incision rules), our motivation for not simulating these effects was ultimately due to computational efficiency; solving a 2D sediment transport equation over the whole domain once per timestep would add prohibitive time per run. We are interested in pursuing this idea for future research, however. For the purposes of this manuscript, we have updated section 5.5 to add some context about how sediment availability differs between the three modes. The reviewer does identify a key difference between the three runs, which is that they result in different amounts of floodplain mass over time, which will affect the final topography (as is evident in Figure 12) and lobe switching. Our new explanation of lobe switching (section 5.5) reflects this different in accumulated mass/topography on the floodplain, as well.

Line 357: Please be more specific of the location in the discussion, where the choice of 55,000yrs as a healing timescale is explained. How does the healing rate compare to floodplain deposition rates described previously?

- The reviewer correctly identified a mistake whereby the newest version of the manuscript did not have a matching section in the Discussion. Instead, in this revision, we have added a justification and discussion around the choice of healing timescale directly to this section. Thank you. Lines 411-424.

Section 4.1. The planform topography and feature similarity between observations and the model are striking. A short discussion on how channels bounding some of the observational fan (Fig 1 E, F) could be affecting the along-strike comparison would be helpful for context. Additionally, a short description of the 1D model validation, including the water depth of the channel, where available, would be a powerful addition to this section, especially since mean water depth dictates the healing rates (Eq 13).

- We added a mention of the lack of external topographic controls (including bounding rivers) to the end of section 5.1 (491-492). Additionally, we added a short 1D model validation component to section 5.1, including a mention of reproducing appropriate channel depths and slopes (471-473). We elected to not include a more sophisticated validation section due to the emphasis on reduced complexity modeling as opposed to reproducing all details in the environment. We believe that we have reproduced the essential topographic features and fluvial geometries necessary to investigate the roles of abandoned channels in shaping these mountain-front environments in a general sense.

Line 411: I would encourage acknowledging that some parameters were varied between the proximal and distal zone (Table 1). Therefore, it's unclear if the results are affected by the choices in parameter variations.

- The reviewer is correct to state that certain external parameters did vary with distance to the mountain-front. Specifically, these were the overbank aggradation base rate and the subsidence rate. We added this acknowledgement to the relevant line (478). Additional modeling efforts have shown that we reproduce the same essential findings of the paper even within a basin that is subsiding uniformly or without a base aggradation rate that changes with distance from the mountain-front. A sentence reflecting these findings has been added here (478-479) and to a new section 6.1 discussing model sensitivity to non-experimental parameters (656-660).

Figure 6: Accounting for surrounding topography in T_a (Eq 1 and 2) shows a striking increase in avulsion location, especially in the proximal part of the fan. How different are the corresponding T_a distribution (Eq 1 and 2) between the red and blue line model runs?

- Because the red line (Eq. 1) in Fig 6B is normalized to the same maximum value as the blue line (Eq. 2), the red line shows that the time between avulsions is about twice as long in the red line. I have added the average time between avulsions for each case to the caption and also to lines 519-520.

Figure 7: Are the striking differences between distal and proximal related to slower healing rates and different water depth (h_avuls etc) for avulsion pathfinding?

- Abandoned channel healing rate is held constant spatially and temporally within each run, and therefore does not vary between proximal and distal domains. With our new runs that do not employ changes in base overbank deposition rates with distance from the mountain-front, we still reproduce the findings of the manuscript. With regards to channel depth, the reviewer is correct that channel depth does vary spatially because "depth [varies] as a function of local slope" (section 4.2). As slope is generally steeper on the proximal fan surface than in the distal domain, channels are generally somewhat shallower in the proximal domain than the distal (~1.2m vs ~1.8m for an example run). We hypothesize that this change in channel depth is a result of the emergence of the two domains (since one is steeper than the other), as opposed to the opposite causality. To test this hypothesis, we performed additional runs where we replaced the h_avul term with h_bar, or global mean channel depth, which does not vary spatially. Even in this case, we still generated the two distinct domains. A sentence reflecting this has been added to the new section 6.1 (656-660).

Before describing the main discussion points, a short overview of the sensitivity of the results to slight variations in floodplain aggradation and subsidence rate (Table 1) and the ratio between them would be beneficial in a section.

- Done. Added section 6.1.

Line 648-649: One set of studies that have been conducted related to channel beds and levees during and after avulsions has been led by Dr. Brandee Carlson on the Huanghe River, China. Please consider including the findings of the studies here.

- Thank you for bringing this work to our attention. While the mechanisms are not identical (as Dr. Carlson et al.'s work on the Qingshuigou Lobe primarily employs marine/tidal sediment), we can at least make reference to analogous work exploring abandoned channel annealing mechanics in another depositional setting. Added reference (703-705).

Minor

Line 10: Previous modeling work is portrayed as if they are vastly different from this study. I am not sure that's representative.

- We hope that the revisions to the manuscript that resulted in the addition of a background information section (2) early in the document will address this concern. This section explicitly frames this study as filling a research gap in the work of previous models, namely, the conscious inclusion and testing of abandoned channel dynamics.

Figure 3 is missing its caption.

- Correct. This has been fixed; thank you!

Section 3.2: Does the choice of the 1D long profile elevation model affect the profile, water depths, and sediment transport rates?

- Our 1D long profile elevation model is rather simple (diffusion) other than for the ability to transiently transport sediment instead of immediately coming to equilibrium between timesteps. This transient nature is important to include as it has effects on avulsion dynamics (Fig. 8; Fig. 9). Implementing a more sophisticated sediment transport model may refine our channel geometries, but we haven't noticed a particular sensitivity to water depths or sediment transport rates for our key findings.

It's unclear how the 1D model is used to initiate the 2D model. I would suggest including a plot of the initial 2D domain.

- Due to the length of the manuscript as-is, we have elected to add additional clarifying text to the relevant section of the methods (238-241) as opposed to adding a novel figure. We hope that this serves to clarify any confusion for readers that may have otherwise arisen.

Line 148-150: This information would be extremely helpful in the introduction.

- We agree, and have added the background information section (2) to address this.

Table 1: Please add notes to the caption that describe the motivation for the choice of parameters value. Apex elevation is missing in table 3.

- The specific values are not critical to the operation of our model nor our findings; we now discuss the sensitivity briefly in section 6.1. Nonetheless, we have added text (242-243, 471-472) explaining that our intention was not to simulate any specific river on earth, but rather to choose reasonable values to recreate reasonably representative rivers and megafans in a broad sense. This is in line with the philosophy of reduced complexity modeling. Apex elevation should have read “initialization length”; thank you for the catch.

Line 201: Will subsidence affect surface slope in the model?

- Yes, but not to an appreciable degree within reasonable ranges, unless it is significantly greater than aggradation. In that scenario, such effects can arise over millions of years of simulation time. This was added to section 6.1 (654-656). Otherwise, aggradation due to the channel is the principal determinant of surface slope on the fan.

Table 2: Please add notes to the caption for the motivation of the parameters. Especially sediment discharge, incoming sediment supply, and basin width.

- We hope that the newly updated caption on Table 1 will service as a disclaimer for readers, and does not require duplication for the caption on Table 2. (See response to “Table 1” above).

Line 232: It’s not clear how Table 2 relates to solving h_chan. It would be interesting to include a description of how h_chan is found.

- While we agree that such an inclusion would be interesting, in the interest of length, we decided not to include an explicit step-by-step but instead to refer readers (line 278-279) to Paola et al. (1992), whose methodology we employ. Readers interested in our specific code implementation may find interest in reviewing our publicly available (and commented) code.

Line 262: Please include where the formula for healing rate is found in the manuscript here.

- We have ensured that this section refers to section 4.2.2, which contains Equation 13.

Lines 268-270: I am confused by this statement. Could floodplain aggradation allow for the elevations of these cells to increase?

- Floodplain aggradation can increase the elevation of these cells, but cannot increase the relief between abandoned channel highs and lows.

Lines 289-290: Please clarify to which cells this applies Are floodplain and abandoned channel cells equally likely to be a site for avulsion triggers?

- Clarified (336-338) that we calculate this over the first step into surrounding cells (agnostic of the identity of what that first step could be, provided it is not the parent river from which the avulsion originates).

298-299: Please specify why 30 years was selected here. How does this compare to results from equation 2 for model runs?

- Added a brief explanation for 30 years (346-347). Added a mention of the mean time between avulsions for Eq (1) and (2) to the caption/figure of Fig 6, and to the text in lines 519-520.

Line 310: Please describe how is h_avul is calculated.

- We describe how h_avul is calculated on the lines (362-363) immediately following the equation. Essentially, we assume the avulsing flow is channelized, and calculate its depth as we would an active channel cell.

Line 341: I think this should read equation 12.

- Correct, fixed.

Figure 5, 6, 10, etc. A more complete description in the caption of the planform elevation model results would be useful, including a color bar scale and a description of what is plotted – I am assuming it’s all cells that have been channels at one point in the modeling.

- We mention that the output is detrended high elevations. The colorbar does, in fact, have a scale. We have added elaboration on the colorbar into the caption, however (498-499).

Lines 433-434: Please clarify this statement. Currently, (b) doesn’t appear to have a vertical scale.

- By “vertical axis scale for (b) is the same as (a)”, we meant to say that the y-axis on panel b uses the same tickmarks and units as panel a, i.e., distance from the mountain-front in km. We have added a duplicate label to Figure 6b to avoid confusion.

Lines 507-510: This downstream shift in sediment conveyance because of internally drained floodplains is an exciting result and makes a lot of sense physically.

- We agree, and it’s nice to have some intuitive results come out of the model!

Lines 535-537: I wonder if one of the implications for this result is that more sediment will exit the domain at the downstream extent. Does this make sense with the physical-based framework set up here?

- We would agree with that implication. We believe that this does make physical sense. A river at equilibrium would have an amount of sediment extracted from it that exactly keeps up with subsidence. A river flowing into an underfed basin may, instead, have all of its sediment extracted from it before exiting the basin. As the number of possible pathways increases, the same quantity of sediment is being “spread over” multiple pathways, keeping them further from equilibrium and sequestering more sediment proximally, as evidenced by further propagation of superelevation resulting in the avulsions further into the basin seen in these more repulsive runs.

Lines 581-592: This paragraph would be a great context for the introduction.

- Agreed, and moved to the background information section (2).

Lines 596-597: This is super interesting, especially since it’s in agreement with previous findings.

- We agree! It’s exciting to imagine that different pathfinding rules apply at different distances from the mountain-front.

Lines 611-625: This paragraph would be a great context to motivate the study and results.

- Agreed, and moved to the background information section (2).

Lines 649-650: The sentence is currently not complete.

- Fixed, thank you.