P. Delorme
IPGP

March 20, 2017

Pr. Patricia Wiberg,
Associate Editor of Esurf

Dear Editor,

We have now completed the revision of our manuscript and responded to the three reviews provided. Enclosed are the salient points raised by the reviewers and our general answers. A detailed response is provided to each review separately.

1. All reviewers point to the interest of our bimodal fan experiment.
2. All reviewers agree with our geometrical self-similar model of fan growth.
3. All reviewers agree with our main conclusions.
4. All reviewers raise concern on the use of all the experiments, or only one run (run 2), in our analysis: this misunderstanding has now been waived and we specify more clearly that all the runs performed were analyzed and used in our calculations. Run 2 was chosen only as an example, for the figures namely.
5. All reviewers ask us to be more specific with regard to the sediment transport mode and its consequences on the fan morphology. We now specify that the sediment appears to be mainly transported as bedload, and that the influence of overbank flow seems negligible, at first order.
6. R2 (Piliouras) and R3 ask us to clarify the importance of porosity in our mass balance: we have measured the porosity of our sediment and added a figure (5). We show that this porosity is essentially a constant and does not influence our mass balance.
7. R1 and R2 ask us to develop the comparison between our experimental results and natural fans. We now develop comparisons between experimental and natural fans both in the introduction and the conclusion, and wherever possible in the manuscript. We finally acknowledge that further experiments are needed in order for this first-order model to be applicable to natural fan systems.
8. Finally R3 asks us to compare our experiments with 1D experiments on granular segregation. We now include these references, and explain in more detail the mechanism we propose for the stratification we observe between the two imbricated fans.

We hope that you will find the revised version of our manuscript suitable for publication in Esurf.

Respectfully

The authors

Answer to reviewer 1

March 20, 2017

I think this is a good paper and would recommend it for publication with minor revisions.The manuscript could really use more background on field observations of alluvial fans, particularly the threshold versus transport theories of fan slope, and a discussion on how well the experiment results reflect and can be applied to real-world observations. There were a number of errors in grammar and general sentence structure. I note a few of these in the technical corrections, but the paper could use a read-through and edit by one of the native English-speaking authors.

[1] *Alluvial fans often have a single main channel, rather than many radiating from the apex. The experiments of Reitz and Jerolmack (2012) behaved similarly to real fans, with multiple channels occurring only briefly during avulsions. The experiments for this study never had fewer than 4 channels. Why is this, and how are the results applicable to real alluvial fans if they differ in this regard?*

Some alluvial fans display a radial distributive pattern where all channels are active at the same time (Hartley et al., 2010). We suspect that the spread into multiple channels is due to sediment discharge (Stebbings, 1963; Métivier et al., 2016). In the experiments of Reitz and Jerolmack (2012), channels are not active simultaneously but they define a radial distributive pattern of 4 to 5 channels. We clarified this point page 6, lines 19-21.

[2] *Stock et al (2008) report a similar distance between the proximal and distal fan, but that median grain size of gravel deposits remained constant for the upper 70% of the fan. Some discussion of this would be useful.*

In our experiments, the position of the transition, hence the change in slope, depends on the proportion of silica and coal in the mixture. This accords with the observations of Stock et al. (2008), on four alluvial fans of the Mojave Desert in California, where the slope and the gravel fraction decrease with distance from fan head. We included this observation in the conclusion on page 18, lines 9-10.

[3] *How does the 32% length for slope transition compare with real-world fans? A couple possible sources are a databases of alluvial fans: Saito and Oguchi (2005) for humid fans, and perhaps reviews by Blissenbach (1954), Anstey (1965), or Hooke (1968) for arid fans.*

The length of the transition is constant in all of our experiments. To our knowledge, only Miller et al. (2014), studied this transition in the field. They showed that it is proportional to the fan length. We edited the text to include this reference page 10, lines 20-21.

[4] *You make a few references to "run 2", and it gave me the impression that you only did your analyses for that single run. Assuming you mean to say that you are using run 2 for your figures as an example, I suggest adjusting the text to make this clear (if you did only do analyses for run 2, please explain why).*

We analyzed all the runs and used run 2 to illustrate our method and results. We clarified this throughout the revised manuscript.

[5] *Was all of the material transported as bedload, or was some portion able to transport as suspended load? Did material deposit outside of the main channel? In the distal sections (the coal only section) of the fan was flow channelized? A shift from dominantly channelized flow to dominantly overbank flow downstream might affect your assessment of fan slope being controlled by the sediment grain size. Reitz and Jerolmack (2012) report extensive overbank flow during avulsions on their experimental fans, and similar behavior has been noted for fans based on field observations (e.g. Field 2001 "Channel avulsion on alluvial fans in southern Arizona"), did your fans feature similar behavior?*

In our experiments, bedload is the dominant transport mode. Only a small amount of fine coal is transported as suspended load, and overbank flow occurs temporarily during avulsions. Neither process seems to control the fan morphology, although we cannot be positive about that. We mentioned this in the revised manuscript page 6, lines 22-24.

[6] *In the conclusion you note that you can estimate the sediment flux that fed the fan. While this may be true for your experimental fans, the grain size distribution and flux of sediment feeding alluvial fans is essentially never constant, so when examining alluvial fan surfaces we are only really understanding the depositional processes responsible for constructing the upper few meters of the fan. In addition, fan surfaces can be reworked, masking the formative process (de Haas et al, 2014). Some discussion of this and a description of how well your results can be applied to alluvial fans in the field would be very helpful.*

Multiple processes can alter the fan surface and add to the primary mechanisms that control its growth (de Haas et al., 2014). Our simple experiments concentrate on basic processes. Therefore we agree that our results cannot be transposed directly to natural systems. We clarified this page 18, lines 19-23.

[7] *The many sections of the paper seem a bit convoluted. The flow of the paper would be better sections 3-6 were merged into something like "experimental setup", "model runs", and "math analyses (or something)". As it is now the division of sections 3 and 4 (as well as 5 and 6), seem a bit arbitrary, and the lines at the end of each section offering a preview of the next section are awkward. I would also suggest adding a "Notation" section as a reference for the different variables used in your equations.*

We added a Notation section in the appendix. We also removed excessive sections (3 and 4 are now merged, as well as 5 and 6). We agree that the paper could follow the plan you propose (set-up, observations and theory). However, we prefer to introduce the hypotheses upon which the theory is built (radial symmetry, self-similarity, etc.) one after the other, when our observations support them. We have significantly edited the manuscript to clarify its structure. We hope this new version is easier to read.

Line by line comments and some technical corrections (page.line):

1.14: I think the reference here is supposed to be "Blair and McPherson (1994)-Alluvial Fan Processes and Forms". There is a new version of this book chapter from 2009 (in book "Geomorphology of Desert Environments") (the ref list has anotherBlair/McPherson paper from 1994)

Done.

2.5: "Perfect cone" is only the case for purely debris flow fed fans. See Williams et al (2006) "Aspects of alluvial fan shape. . ." (Williams et al also report that fluvially-fed alluvial fan slope-distance profiles (e.g. your figure 6b) follow an exponential fit, rather than two distinct slopes with a transition zone).

We modified the text page 2, lines 7-9, to avoid the confusion you mention.

2.6: "Possible explanations for this curvature. . ." adding into this sentence that you are talking about the "transport" and "threshold" theories fan slope would clarify other parts of the paper where you refer to threshold theory.

Done.

2.21: ". . .no clear consensus. . ." some more detail/background on this would be helpful.

We clarified this in the revised manuscript, page 3, lines 10-12.

3.14-26: this paragraph was hard to follow. See a few examples below:

3.16: rephrase sentence to "When unmixed, we find that for the same shear stress τ, the flux of coal grains is larger than that of silica grains (Fig.2)"

Done.

3.19: rephrase sentence to: "The shear stress required to move large grains in the mixture is lower than it would be in a system of only large grains, because they protrude more into the fluid."

Done.

3.21 "larges grains" change to "large grains".

Done.

3.22: ". . .different densities. . ." what about different diameter grains? Does this have an effect?

Both grain size and density affect the mobility of our sediment. We measured the critical Shields parameter, and found a higher value for silica (small grains, large density), than for coal (large grains, low density). This indicates that the density contrast exerts a primary influence on mobility. This is confirmed by experimental observations (page 5, lines 13-15, and page 6, lines 1-6).

4.4: Is the "impervious wall" vertical?

Yes it is, we added it in the revised manuscript.

4.13: See comment above. Alluvial fans typically have a single channel emanating from the apex which splits further downstream. The avulsion process appears different than the experiments of Reitz and Jerolmack (2012).

Some alluvial fans display a radial distributive pattern where all channels are active at the same time (Hartley et al., 2010). In the experiments of Reitz and Jerolmack (2012), channels are not active simultaneously but they define a radial distributive pattern of 4 to 5 channels. We clarified this point page 6, lines 19-21.

4.19: "Coal is deposited on the banks": is coal ever deposited overbank?

Overbank deposits are relatively rare, and the sediment is deposited mostly in the thalweg or on the banks. We clarified this point in the manuscript (page 6, lines 22-24).

4.26: "during run 2". Did you only examine the boundary on run 2? Or do you mean to say that Fig 3a is of run 2? If the former, why not for other runs? 4.31: Same comment as for line 26.

We analyzed all the runs and used run 2 to illustrate our method and results. We clarified this throughout the revised manuscript.

5.19: When describing similarities between profiles, do you mean all radii for a single fan, or across fans for all experiments?

We mean all radii for a single fan. We have clarified this sentence in the manuscript (page 10, line 9).

5.25: See commend above (comparing the apparent match of sediment distribution change and slope transition with observations by Stock et al (2008))

See our answer to your second comment.

7.3: the font for the variables in equations 7 and 8 is different

We checked the font of the variables.

7.20: The sentence phrasing and grammar in this paragraph could use some editing.

We did our best to improve the English of the manuscript.

7.24: Some background on the "threshold" vs "transport" theories for alluvial fan morphology would be useful.

We added a discussion on the threshold theory page 13, lines 20-22, and page 14, lines 1-2, in order to provide this background.

8.33: Do you mean to say with "sediment discharge relative to water discharge" (i.e. sediment flux)?

Both are true for a given water discharge, we have clarified this point in the manuscript (page 16, line 20).

9.20: The Conclusions section could also use some edits to grammar and sentence structure.

We edited the conclusion of the revised manuscript.

9.32: References here ("...in our experiments")

Done

9.32-33: "As a consequence, we expect that the geometry of the final deposit (location and slope of the transition and proximal and distal slopes) allows us to estimate the relative flux that built the fan." This sentence seems like a big jump. The sediment supply to alluvial fans is not constant as it was in the experiments. Perhaps you mean to say the relative flux for the most recent fan deposits?

We agree. We have changed the text in the conclusion (page 18, lines 4-11).

Figures:

Table 2: replace $g/min-1$ for sediment discharge with$Lmin-1$ (is silica fraction volume or mass...in eqn 3 it is volume) so that it uses the same units as Qw (and is easier to visualize V/V).

Done.

Fig. 3: Would it be possible to adjust contrast on photos of the fan (e.g. fig 3) so that it is easier to discern the silica against the coal?

Unfortunately, the quality of the pictures does not allow us to improve the contrast much.

Fig 6/7: I suggest using the same horizontal scale for these two figs.

We used Fig 7 to introduce the rescaling with R_c. In the revised version, we have added the physical scale accords to your suggestion.

Fig 7: Specify which run this is from (presumably run 2?)

Done.

Figure 10: this figure could probably be merged with Fig 3.

We have tried merging them, but this obscured the resulting figure.

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Williams, R. M., Zimbelman, J. R., and Johnston, A. K.: Aspects of alluvial fan shape indicative of formation process: A case study in southwestern California with application to Mojave Crater fans on Mars, Geophysical research letters, 33, 2006.

Answer to A. Pilouras

March 20, 2017

Overview: The authors report on physical experiments of alluvial fans with a bimodal grain size mixture, relating the grain size transition to a slope transition and comparing their experimental results to those predicted by threshold-channel theory. They conclude that the fans in their experiments grew in a self-similar manner, such that the fans maintained a consistent geometry and their growth could be described by a simple mass balance. However, the fan slope was significantly higher than that predicted by threshold channel theory, and the authors do not really provide a convincing argument for why this might be so. In general I find the paper to be well-written and wonderfully concise, although I do think some elaboration is required on the points outlined below. I recommend this paper for publication pending the following minor revisions.

Major comments:

The introduction is somewhat lacking. First, it would be helpful to relate the concepts discussed both in the intro and the present experiments to the natural environment and studies of natural fans. Second, the experiments need to be placed in a broader context to highlight why they are significant and how they advance our knowledge of alluvial fan dynamics and/or stratigraphy. This should also be revisited in the conclusions.

We added more references about fan morphology in the introduction (page 2, lines 11-13, and 19-20, and page 3, lines 24-25). We also discussed the applicability of our experiments in the conclusion (page 18, lines 14-23).

Your results and conclusions would be stronger by including discussion of all experiments, not just Run 2. Some of your figures seem to have other experimental data in them, but since the paper never discusses anything other than Run 2, there is somewhat of a disconnect between the text and the figures.

Run 2 was used to illustrate our method and results, but we analyzed all runs. We clarified this throughout the revised manuscript.

The discussion needs a paragraph on limitations of the experiments, particularly in their applicability to natural systems. You state in the Appendix that you did experiments with laminar flow. What, if anything, does this imply for your ability to relate these experiments to nature? How might the dynamics, geometries, and/or stratigraphies of fans created with different flow conditions differ, if at all? I do not mean to imply that you need a full discussion of hydraulic scaling (you don't), but I think that a few sentences discussing your limitations and applicability will make non-experimentalists more receptive to your ideas.

We use laminar flows only to calibrate the transport laws, and measure the critical Shields parameters of silica and coal, we clarified this in the revised manuscript (page 6, lines 24-55, and page 19, lines 17-20). Nevertheless, we acknowledge that our results do not directly apply to natural systems, and we added a paragraph on limitation of the experiments in the conclusion (page 18, lines 14-23).

Regarding the lack of correlation between Qs and slope that comes out of the threshold channel theory analysis. Could this be because the flow is not always channelized and the deposit is not entirely formed by channels? You state in the first paragraph of section 6 that the deposit should have the same slope as the channels, but I'm not sure that this is true. I would guess that many alluvial fan and fan delta experiments, particularly thinking about those of Reitz and Jerolmack, are built by a combination of channelized and overbank or sheet flows. In that case, the overall deposit slope does not necessarily reflect the slope of a channelized flow, but perhaps that of some combination of processes. If your fan is partially formed by sheet flow or overbank deposits and not entirely formed by channels, which I suspect is likely true, then can you comment on the applicability of threshold *channel theory in trying to describe a deposit that is not and should not be the same as the bed of a channel? This may explain why the slope of the fan is quite a bit higher than the predicted threshold channel slope.*

When looking at our experiments, we could see the grains moving only in channels (page 6, lines 20-24). From this observation, we hypothesize that the sediment is mainly deposited within the channels or on the banks. The primary transport mode is bedload, and overbank deposition only occurs transiently during avulsions. Moreover, we do not show terraces on the DEM. Thus, although we don't know how overbank flows may affect the slope of the deposit, we suspect their effect to be minor. We clarified this page 13, lines 19-20.

Minor comments:

Page 2

Line 11: Consider adding "alluvial fans can be easily produced and boundary conditions can be easily controlled."

Done.

Line 14: Consider providing some examples of "the deposit responds by adjusting its morphology."

We added a reference to the work of Muto and Steel (2004) in the manuscript (page 2, lines 20-21) as an example of this adjustment.

Line 25: Replace "At variance" with "In contrast".

Done.

Lines 25-27: You first state that Guerit et al., 2014 proposes that Qw, Qs, and grain size act independently to influence slope, but then claim that they conclude that slope depends on Qw and grain size. These sentences are in conflict and the language either needs to be adjusted to resolve it or you need to better explain the results of their study and in what ways, specifically, Qw and grain size influence slope.

Guerit et al. (2014) used uniform sediment, and did not explore the influence of grain size but focused on the respective influence of the water and sediment discharges. They found that, for a given grain size, Q_w is the first-order control on the slope, to which Q_s adds only a perturbation. We clarified in the revised manuscript (page 3, lines 12-17).

Line 29: Omit the comma after "moderately".

Done.

Page 3

Line 10: Include more references of experimental alluvial fans.

Done.

Line 18: Omit erroneous s in "each type of grain".

Done.

Lines 19-20: "The shear stress required to move large grains in a mixture is lower than it would be in a system of uniform large grains because the grains protrude more into the fluid."

Done.

Line 21: "a higher shear stress in a bimodal mixture because they are partially shielded from the flow by neighboring large grains".

Done.

Line 27: "Below a critical shear stress".

Done.

Page 4

Line 3: Reference your experimental setup figure here.

Done.

Also consider, rearranging Section 2 to start with this information regarding your setup and procedure. This will allow you to start broader and then narrow down to the details, which will be make it read a bit more easily.

Done.

Lines 4-5: Rearrange these clauses/sentences to this order: "At the back of the tank,. . . which the fan leans. At the wall's foot, . . . concentrating along it. The three other sides . . . evacuate water."

Done.

Line 6: Does the standing water, however shallow, influence anything about the fan's growth or toe geometry?

Standing water induces the formation of a fan delta (Powell et al., 2012). Yet, as the immersed part of the fan does not represent more than 1% of the total fan volume we can neglect it in the mass balance, and therefore in our analysis. We clarified that in the revised manuscript page 4, lines 10-11, and page 5, lines 1-2.

Line 7: Is your header tank a constant head tank? If so, say so.

Yes it is a constant-head tank. We clarified the text.

Line 11: "reaches its bottom" is vague. What is "its" referring to here? The tank? Where is the bottom? Rephrase.

Its refers to the tank bottom. We rephrased it (page 6, lines 18-19).

Line 13: Why did your experiments have five or six channels at a time? This seems in contrast to many other fan experiments, particularly with those of Reitz and Jerolmack. What are the possible causes and implications of this?

Hartley et al. (2010) have shown that alluvial fans can display a radial distributive pattern where all channels are active at the same time. We suspect that the multiple channels are due to sediment discharge (Stebbings, 1963; Métivier et al., 2016). In the experiments of Reitz and Jerolmack (2012), channels are not active simultaneously but they define a radial distributive pattern of 4 to 5 channels. We clarified this point page 6, lines 20-22.

Line 19: Mustn't you also have silica deposited overbank to make the deposit shape depicted, or is silica really that narrowly deposited in the thalweg? In that case, if silica exists over much of the proximal deposit, then do the channels migrate to visit almost every point on the proximal fan in order to get that distribution or silica?

Looking at our experiments, we observe that silica is indeed deposited in the thalweg. Avulsion process, however, allows the channel to visit every point of the fan. We clarified this in the manuscript page 6, lines 22-24.

Line 24: I suggest changing the language of "eye-averaging," as it does not make your observation convincing.

Done, page 7, line 4, and page 8, line 1.

Line 28: You need an extra sentence or two here to explain your image processing methods, particularly in your rescaling/stretching and error/accuracy estimates.

We added an extra sentence to explain our image procedure (page 8, line 3-5).

Line 31: Why are you only reporting on Run 2?

We analyzed all the runs and used run 2 to illustrate our method and results. We clarified this throughout the revised manuscript.

Line 33: Again, your measurements of accuracy are unclear. Is the 19% a standard deviation? A variance? Some roughness measurement?

The 19% value corresponds to a standard deviation, we added this precision in the revised manuscript (page 8, line 10).

Page 5

Line 15: Reword to state that either your precision is better than 1mm or your error is less than 1mm.

Done.

Line 17: "This property suggests that we can compute".

Done.

Line 18: "profile of the fan with minimal error" or "with minimal loss of information".

Done.

Line 22: "We find that the slope plateaus to a value of about 0.29 near the apex and to about 0.10 near the toe."

Done.

Line 23: "transition between these slopes is smooth,"

Done.

Lines 23-24: Why are you calling this a "characteristic length?" You are only examining one experiment, or does this hold for more experiments? Please clarify.

The length of the transition is the same for all runs. We clarified it in the revised manuscript (page 10, lines 19-20).

Line 24: "55% of the fan length from the apex".

Done.

Line 26: Here you restate $R \approx 0.62$, which closely coincides with 0.55. This would be even more convincing by stating R with the error you already have $R = 0.62 \pm 0.04$. Also, do you have an error on the inflection point distance 0.55? Should be stated here, if so.

Done.

Line 28: Replace "cohesive" with "intact" to avoid confusion surrounding cohesive sediment.

Done.

Line 30: "whereas coal concentrates at the fan toe."

Done.

Line 31: Replace "smeared" with "irregular" or "gradual" or "fluctuating" etc.

Done.

Line 31: "It" is vague. Rephrase to "The transitional zone shows alternating layers".

Done

Page 6

Line 4: Insert equals signs for slope: (slope = 0.29), (slope = 0.10).

Done.

Lines 5-6: "Finally we define the transition line, which joins this intersection to the origin and passes through the alternating stratigraphic layers in the transition zone."

Done.

Lines 6-7: "more mobile sediment (coal) lying below the less mobile one (silica).

Done.

Line 7: Replace "steady climb" with "upward migration".

Done.

Equation 3: Define phi in text.

Done.

Page 7

Line 11: How and why do you "adjust" the proximal and distal slopes?

We use a linear fit to quantify the slopes of the deposit. We explained this in the revised manuscript (page 13, lines 10-11).

Line 13: Your calculated silica fraction in the deposit matches that put in during experiments. Do you account for porosity in the deposit since your input flux is likely just a mass or solids volume flux? The porosities of the coal and silica are likely different, and I would expect this to influence the overall deposit volume and volume partitioning between coal and silica.

Following your comment, we measured the porosity of our granular materials and estimated the porosity of the deposit. Within uncertainties, they are the same. We added a paragraph and Fig.(5) to explain these measurements in the revised manuscript (page 8, lines 15-29).

Line 21: Replace "type of sediment they flow onto" with "bed sediment composition".

Done.

Line 30: Replace "ramify" with "bifurcate".

Done.

Line 31: "threshold-channel theory slope predictions."

Done.

Page 8

Line 5: "cross sections per channel per measurement strip".

Done.

Line 5: "channels and their widths in each bin over the runs."

Done.

Line 6: "distance from the apex".

Done.

Line 26: "we approximate Cf with".

Done.

Equation 10: Define all variables in text.

We have carefully checked that all variables are defined in the text of our manuscript. In addition, we added a Notation section in the appendix where all variables used are defined.

Page 9

Lines 5-13: You provide a few possible explanations for departing from theory, but you need more discussion to provide a physical reasoning for why you think this is.

Guerit et al. (2014) modeled the influence of sediment discharge on the fan profile, and showed that the resulting fan slope is steeper than the threshold slope. Experiments are under way in our group to test this hypothesis. We modified the text to include this discussion page 16, lines 27-33, and page 17, lines 1-2.

Line 18: This section ends fairly abruptly.

We agree, we edited the revised manuscript (page 17, lines 8-10).

Lines 29-30: How does this straightforwardly extend to different grain size distributions?

Indeed, it might not be so straightforward. Field observations, however, are encouraging: some have shown a strong correlation between changes in slope and grain size or sand fraction (Bull, 1964; Blair, 1987; Blair and McPherson, 2009; Miller et al., 2014; Stock et al., 2008). We mentioned this in the revised manuscript (page 18, lines 4-10).

Page 10

Line 7: "both mechanisms" this is vague. Which mechanisms?

We clarified this in the revised manuscript (page 18 , lines 28-32).

Line 8: omit comma after "deposit".

Done.

Appendix A

Does threshold channel theory hold for laminar flow? Either a brief statement of affirmation or a brief discussion on any assumptions on this front is required.

Seizilles et al. (2013) have shown that the threshold theory indeed applies to laminar flows, but we only use laminar flows to measure the critical Shields parameter anyway. We clarified this in the revised manuscript (page 19, line 17-20).

Figure 1 Assign (a) and (b) to parts of figure. On your schematic, the text says there is also a trench at the downstream or rightmost edge, but it is not depicted here.

Done.

Figure 2 (a) This graph is somewhat confusing (particularly the vertical axis), as it is not the typical way that people in our community show grain size distributions, although I acknowledge it is mathematically accurate. Consider replotting as a "percent finer than."

Done.

Figure 3 (b) Label Rc, Rs.

The picture is rescaled there is no Rc and Rs but $\mathcal{R} = \frac{R_s}{R_c}$ and 1.

"The 26 pictures are each 10-minutes apart."

Done.

Figure 5 "only two sample radii 5 degrees apart".

Done.

Table 3 Are these the characteristics at the end of each run? If so, say so. Run 5 has a drastically different R than all other experiments and much higher error. Why? It is still unclear why you only discuss Run 2 in the paper.

These are characteristics at the end of each run, Run 5 has a drastically different $\mathcal{R}$ because it involves a mixture of 80% of silica. As a consequence, the silica-coal transition is more distal than in the other experiments. However, on Fig. 10, this run does not appears as an outlier. The error is due to fluctuations of the silica-coal transition. We clarified this it the revised manuscript (Table 3).

Figure 10 Consider rephrasing measurement "bins" rather than strips. Also applies to text.

Done.

Figure 11 The number of channels appears to decrease past the transition zone, but you claim that channels do not rejoin downstream. So do they just lose definition and you cannot detect them? This needs to be clarified.

Yes, they are more difficult to detect in the distal part of the fan, due to the poor contrast. We clarified this in the manuscript (page 16, lines 4-5).

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Answer to reviewer 3

March 20, 2017

General comment:

I recommend this article for publishing if the comments are considered. The article is well-written and it is easy to read. The first two sections of the article are quite detailed, leading to sections that lack of substantial contributions to the general discussion by themselves, as they are too brief and without much analysis. Nevertheless, the article shows good results that are worthy to publish in spite the simple analysis with some flaws.

Major comments:

The analysis is focused only in some properties of the particles used and it misses other parameters that may give an important insight to the results, i.e. repose angles. Such properties of the materials could be included in the qualitative analysis, as Reitz and Jerolmack (2012) do.

We quantified the repose angle of our grains. It is presented in Table 1 in term of the friction coefficient, μ which represent the tangent of this angle. This friction coefficient appears in the definition of the threshold slope (eq. 11). We clarified it in the revised manuscript (caption of Table 1).

It is mentioned that the exposure/hiding effects are negligible because of the density difference between the particles. This is only if the sample is well-graded. There is insufficient information provided in order to neglect, or not, such effects. Also, mobility is accounted separately, for each material, so it seems irrelevant if in the final experiments are mixed, since the mobility may be affected by the other material sizes, not only by density. Even if you are able to provide evidence that it is in fact negligible, a re-writing of the paragraph could be helpful.

We agree, there exist no universal transport law accounting for the hiding/exposure effect. However, to estimate, at least qualitatively, the differential mobility of our grain we use transport laws of each species and neglect the exposure and hiding effect. We re-wrote the paragraph (page 6, lines 9-17).

There is a chapter called "Mass Balance". If you look at the equations, they are all in terms of volume. What about the packing conditions of the fan? And the packing conditions of the inlet? Why would those be the same? Is there a way to quantify the void between particles? I think that at least some assumptions should be made and explained.

Following your comment, we measured the porosity of our granular materials, and estimated the porosity of the deposit. We found that the porosity is constant, and, therefore, does not impact the mass balance. We added a paragraph and figure 5, to explain this in the revised manuscript (page 8, lines 15-29).

I found interesting the geometrical self-similarity shown in the article, but a quite more complex self-similar behavior is there. Certainly, with the results something else could be done.

We agree that this preliminary work only focuses on the first-order geometry of the deposit. To further the analysis of this self-similarity, we need to understand the physical origin of the fan's slope. For this, we need to improve the geometry of the feeding channel. An experiment is under way in our laboratory. We clarified this in the conclusion, page 18, lines 19-21.

A similar pattern to the one you show when cutting the fan radially, has been obtained by other authors in a 'quasi-two-dimensional' cell, e.g. Makse et al. (1997). It could be interesting to say something about that.

Makse et al. (1997) obtained stratification when the large particles' angle of repose was larger than the small one's. That is verified for Fig. 7, but what about the rest? Its quite interesting that the vertical cross section is not only segregated, but stratified. Could this be found in natural fans? If so, under which conditions? Since you performed experiments with silica volume concentrations ranging from 25% to 80%, maybe stratification depends of this parameter.

The cross section of figure 7 shows segregated deposits separated by a mixing zone with alternating layers of silica and coal. The extent of this mixing zone (30 % of the fan length) seems to be independent of the composition of the sediment mixture. Similar stratigraphic patterns are observed in natural fan deposits, and they are interpreted as a consequence of fluctuating water and sediment discharges (Paola et al., 1992; Clevis et al., 2003; Charreau et al., 2009; Whittaker et al., 2011; Dubille and Lavé, 2015). We were not aware of the experiments and model of Makse et al. (1997b,a), that indeed exhibit a similar pattern. We refer to them in the revised manuscript (page 10, lines 7-11).

The above leads me to another comment. It seems that you only analyzed experiment 2. What about the rest?

We analyzed all the runs and used run 2 to illustrate our method and results. We clarified this throughout the revised manuscript.

In general for a roughly 10 pages article, 6 sections is too much I think. If some sections are merged or taken as subsections it would give more significance to each section. As it is, seems that each section has nothing much to say, e.g. sections 4 and 5.

Following your comment, we merged sections 3 and 4, and sections 5 and 6.

Minor comments:

p3.line1: It it confusing the way you say that large grains are in the upper part and small ones deposit near its toe, as figure 2 shows the opposite. The system inverses the gradation?

The sentence you refer to describes the experiment of Reitz and Jerolmack (2012). In their experiments the mobility difference is driven by different grain size. In our study the mobility difference is controlled essentially by the density contrast. We clarified this in the revised manuscript (page 5, lines 14-15, and page 6, lines 1-6).

p3.line10: Routine seems something tedious, ordinary and repetitive, that has nothing special, therefore irrelevant. Another word could be better to start the chapter.

We changed routine to common.

p4.line1: Again the density. If the density difference prevails over grain size, then how is explained that mobility has nothing to do with density? If so, which difference is more relevant? Could be there an equilibrium?

We quantify the grain mobility in term of the critical Shields parameter. This parameter depends on shear stress, grain size, and density. Coal grains are larger and lighter than the silica grains. The value of the critical Shield parameter is lower for coal, which suggests that the density difference prevails over the grain size difference. Experimental observations confirm this (page 5, lines 14-15, and page 6, lines 1-6).

p4.line13: The number of channels is different from the number reported by Reitz and Jerolmack (2012). Is there a reason?

We suspect that, in our experiment, the presence of multiple channels is due to the sediment discharge (Stebbings, 1963; Métivier et al., 2016). In the experiments of Reitz and Jerolmack (2012), channels are not active simultaneously but they define a comparable, radial, distributive pattern of 4 to 5 channels. We clarified this point page 6, lines 20-22.

p4.line20: Silica proportion is introduced, is it of volume or weight? If such variable is introduced, maybe you could use a formula.

Silica proportion is introduced by volume. Following your comment, we added formulas to clarify this (page 8, lines 12-22).

p4.line24: To put explicitly eye-average, indicates subjectivity as results may change by repeating the analysis. The error by this process is considered?

We modified the sentence to avoid misinterpretation (page 7, line 4, and page 8, line 1).

p5.line5: "The observations confirm the scaling, thus..." Instead.

Done.

p5.line24: 32% and 55% of the fan length, Which fan length? Is is the average of all the experiments? Of each experiment?

We mean the percentage of the total fan length, from apex to toe. These values are for run 2. Values for the other runs are presented in Table 3. The value of the transition length is similar for all runs. We clarified the manuscript to be more specific about this (page 10, lines 17-21).

p5.line34: You say that the variability of sand-coal transition in the stratigraphy is because of channel avulsion. If you follow one of the major comments, then it is not because of that.

There are two main differences between our experiments and the experiments of Makse et al. (1997b). First, the slope of the deposit is much smaller than the angle of repose due to fluid entrainment. Second our experiment is three-dimensional whereas the experiment of Makse et al. (1997b) is two-dimensional. Furthermore figure 3 shows that the limit between the two fans is strongly dissected. Because sediments are deposited mostly within channels, we believe this pattern is the result of channel avulsion. We added a discussion in the revised manuscript page 11, lines 7-11.

p6.line9: The interpretation in the context of self-similar growth should be in the self-similar growth section.

Following your comment, we restructured our manuscript.

p8.line26: Why Chézy and that value? I understand that it is for simplicity, but still.

The Chézy coefficient is the simplest possible coefficient use in fluvial experiments to quantify fluid friction (Métivier et al., 2016). Its value depends on the channel shape and grain size. We chose the value of C_f according to Chow (1959).

p8.line27: The reference is wrong, it should be (Chow, 1959).

We corrected it.

p9.line20: Independently you consider the stratification analysis, you should say if deposits show stratification.

We added a sentence about stratification in the revised manuscript (page 17, lines 16-17).

p9.line21: If you make reference to your sediments in terms of mobility it is tricky as it is true all the time and it could include both silica and coal particles. Too obvious.

We clarified this in the revised paper.

p9.line30: It is not clear that it is possible to extend to a continuous size distribution. You did not say anything about the sample, where they well-graded?

We do not know whether the segregation mechanism could be extend to a continuous size distribution. But field observations are encouraging: some have shown a strong correlation between changes in slope and grain size or sand fraction (Bull, 1964; Blair, 1987; Blair and McPherson, 2009; Miller et al., 2014; Stock et al., 2008). As a consequence, although this should be tested experimentally, we expect that the segregation occurs similarly for a continuous grain size distribution. We mention this in the revised manuscript (page 18, lines 4-11). Our sample are not well-graded, but they have distinct mobilities.

p10.line2-3: The discussion about the most challenging problem is not fair enough. You lack of evidence or references to sustain that.

We re-wrote the conclusion to clarify.

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Self-similar growth of a bimodal laboratory fan

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Abstract. Using laboratory experiments, we investigate the growth of an alluvial fan fed with two distinct granular materials. Throughout the growth of the fan, its surface maintains a radial segregation, with the less mobile sediment concentrated near the apex. Scanning the fan surface with a laser, we find that the transition between the proximal and distal deposits coincides with a distinct slope break. A radial [..[1]]cross section reveals that the stratigraphy [..[2]]records the signal of this segregation. To interpret these observations, we conceptualize the fan as a radially symmetric structure that maintains its geometry as it grows. When combined with slope measurements, this model proves consistent with the sediment mass balance and successfully predicts the slope of the proximal-distal transition as preserved in the fan stratigraphy. [..[3]]While the threshold channel theory provides an order-of-magnitude estimate of the fan [..[4]]slopes, driven by the relatively high sediment [..[5]]discharge in our experimental system, the actual observed slopes are 3-5 times higher than those predicted [..[6]]by this theory.

1 Introduction

When [..[9]]a river leaves a mountain range to enter lowlands, [..[10]]it hits shallow slopes and loses valley confinement. This abrupt change causes it to deposit its sedimentary load into an alluvial fan [..[11]](Bull, 1977; Rachocki and Church, 1990; Blair and McPherson, 1994; Harvey et al., 2005; Blair and McPherson, 2009). As the river builds this sedimentary structure, its bed rises above the surrounding land, and its channel becomes unstable. At this point, either the river erodes its banks to migrate laterally, or[..[12]], during a large flood event, [..[13]]it overflows, and in a process referred to as "avulsion"[..[14]], establishes a new course for its channel (Field, 2001; Slingerland and Smith, 2004; Sinha, 2009). In both cases, the river

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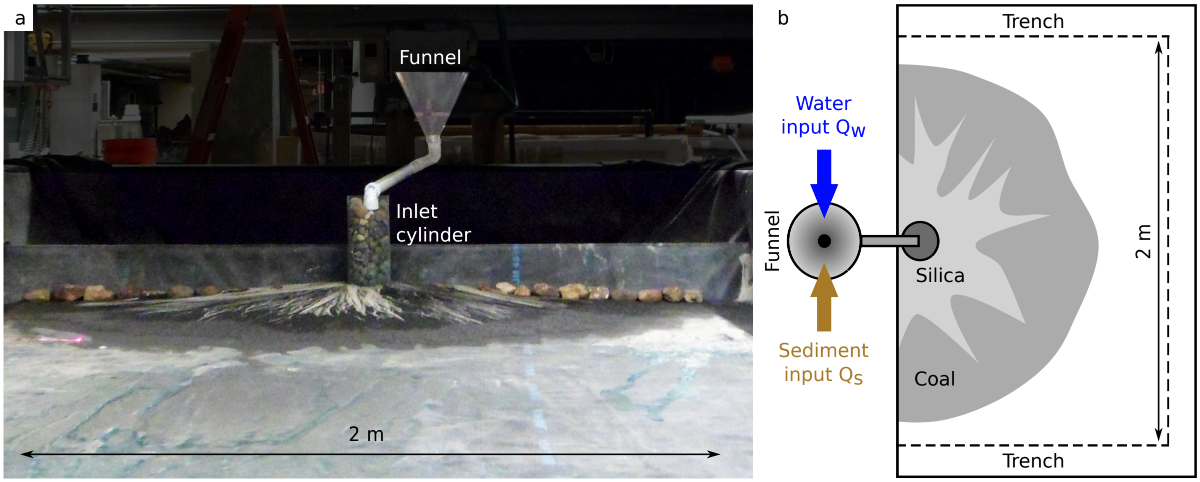

Figure 1. Experimental set-up. [..[7]](a) Front-view picture. [..[8]](b) Top-view representation.

constantly explores new paths to fill up hollows in the deposit surface and preserve its radial symmetry. The resulting deposit acquires the conical shape which characterizes alluvial fans.

As the first sedimentary archive along the river's course, an alluvial fan records the history of its catchment (Hinderer, 2012). Indeed, the geometrical reconstruction of a fan provides an estimate of its volume which, through mass balance, yields the average denudation rate of the catchment (Kiefer et al., 1997; Jayko, 2005; Jolivet et al., 2014; Guerit et al., 2016). Furthermore, when the river transports multiple grain sizes, it usually deposits the coarser sediment (gravel) near the fan apex, and the finer sediment (sand) at its toe. This segregation produces a [..[15]]gravel-sand transition front which moves forward and backward as the fan adjusts to external forcing. In radial [..[16]]cross section, this series of progradations and retrogradations appears as a boundary between lithostratigraphic units, a pattern often interpreted as the signature of tectonic or climatic events (Paola et al., 1992a; Clevis et al., 2003; Charreau et al., 2009; Whittaker et al., 2011; Dubille and Lavé, 2015).

To interpret the morphology and stratigraphy of an alluvial fan, we need to understand how it translates the input signal (e.g., water and sediment discharges) into its own geometry (e.g., its size, downstream slope and stratigraphy). For instance, Drew (1873) observed that the lower the water discharge Q_w, the steeper the fan slope. More recent observations point at the influence of the sediment discharges Q_s on the slope, often in the form of the ratio Q_s/Q_w[..[17]]. In general, the slope steepens when this ratio increases (Parker et al., 1998 a, b). At first sight, the shape of an alluvial fan is well approximated by a [..[18]]cone, but a closer look often reveals a steeper slope near the apex (Le Hooke and Rohrer, 1979; Blair, 1987; Blair and McPherson, 2009; Miller et al., 2014). Possible explanations for this [..[19]]include the decrease in sediment discharge caused by deposition

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[..[20]](transport hypothesis), or the downstream fining of the sediment [..[21]](threshold hypothesis) (Blissenbach, 1952; Rice, 1999; Stock et al., 2008; Miller et al., 2014). In practice, the variations of grain-size, slope and sediment discharge along a fan are correlated. When the sediment is broadly distributed in size, these variations are smooth, whereas a bimodal distribution generates a segmented fan (Bull, 1964; Williams et al., 2006).

Only seldom do field measurements allow us to separate the various parameters affecting the morphology of a fan, making it difficult to isolate their respective influence. One way around this problem is to use laboratory experiments, where small alluvial fans can be easily produced under well-controlled conditions (Schumm et al., 1987; Parker, 1999; Paola et al., 2009; Clarke, 2015). When water and sediment are injected onto the bottom of a tank, a deposit spontaneously forms around its inlet. The formation of this deposit is remarkably similar to that of natural fans[..[22]]; in particular a network of migrating and avulsing channels distributes radially the sediment across [..[23]]the fan surface. As the forcing parameters vary, the deposit responds by adjusting its morphology. Muto and Steel (2004), for example, showed that a base level fall induces upstream channel entrenchment, terrace abandonment, and fan progradation.

The sediment discharge Q_s determines the growth rate of an experimental fan. Indeed, mass balance requires that the fan volume increase in proportion to the sediment input. [..[24]]Thus, as a consequence of the symmetry, the radius of the fan increases as $(Q_s t)^{1/3}$, where t is the time elapsed since the beginning of the experiment (Powell et al., 2012; Reitz and Jerolmack, 2012). Avulsions occur more frequently as the sediment discharge increases, showing that the internal dynamics of an experimental fan adjusts to the [..[25]]forcings (Bryant et al., 1995; Ashworth et al., 2004; Clarke et al., 2010; Reitz and Jerolmack, 2012). This adjustment allows the fan to maintain its conical shape which, at first order and for a single grain size, is [..[26]]characterized by its slope only.

Even in simplified experiments (constant [..[27]]inputs, single grain size), there is no clear consensus about the mechanism by which a fan selects its own slope. [..[28]]Most investigators observed that a low water discharge, a high sediment discharge, and [..[29]]coarse grains all contribute to a steeper fan (Le Hooke and Rohrer, 1979; Clarke et al., 2010). However, the respective influence of water and sediment [..[30]]discharges on the slope [..[31]]remains debated. Whipple et al. (1998), Van Dijk et al. (2009) and Powell et al. (2012) hypothesized that the slope is a function of the dimensionless ratio Q_s/Q_w[..[32]]. In contrast, Guerit et al. (2014) propose that all three parameters act independently. In their experiment, [..[33]]a fan composed

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[28] removed: However, most investigators acknowledge that
[29] removed: large grains steepen the fan (Le Hooke and Rohrer, 1979). The
[30] removed: discharge
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[32] removed: (Whipple et al., 1998; Van Dijk et al., 2009; Powell et al., 2012). At variance with this model
[33] removed: the fan

of uniform sediment grows between two parallel plates that confine it to [..[34]]the vertical plane. [..[35]]They found that the flow maintains the deposit surface near the threshold of motion[..[36]]. As a result, a lower water discharge causes the fan to steepen. The sediment discharge perturbs the fan profile only moderately, by steepening the slope in proportion to its intensity. As the sediment [..[37]]is deposited along the fan, the slope returns to its threshold value [..[38]]as it approaches the toe; the associated curvature in this process being proportional to the sediment input.

Accordingly, the downstream curvature of an alluvial fan composed of uniform sediment can be interpreted as a signature of spatial variation in sediment transport. [..[39]]However, one can wonder what happens when the fan is composed of non-uniform sediment? When the grain size is broadly distributed, downstream fining can also affect the fan profile. This phenomenon occurs in flume experiments, where [..[40]]large grains concentrate near the inlet (Paola et al., 1992b; Smith and Ferguson, 1996). In the experiment of Reitz and Jerolmack (2012), the fan builds its upper part out of large grains, and [..[41]]deposits the smaller ones near its toe. Consequently, the proximal slope is significantly steeper than the distal one, a signal whose form is similar to the curvature induced by deposition. We should also expect that this segregation would also appear in the fan's stratigraphy, a process that, to our knowledge, has not been previously investigated in laboratory experiments.

Here, we investigate the impact of a bimodal sediment on the morphology and stratigraphy of an alluvial fan. To do so, we generate a laboratory fan fed with a mixture of two granular materials (Sect. 2). Our experiment generates a segregated deposit, similar to the laboratory fan of Reitz and Jerolmack (2012). We first analyze its morphology, describing the growth of each part of the deposit independently [..[42]]. We then relate the spatial distribution of the sediment to the proximal and distal slopes (Sect.[..[43]] 3). Based on these observations, and appealing to the threshold-channel theory, we propose a geometrical model to describe the fan deposit (Sect. 4). [..[44]]

2 Experimental set-up

Producing experimental alluvial fans has become [..[45]]common in geomorphology (Schumm et al., 1987; Bryant et al., 1995; Whipple et al., 1998; Ashworth et al., 2004; Van Dijk et al., 2009; Clarke et al., 2010; Powell et al., 2012; Reitz and Jerolmack, 2012; Clarke, 2015). Here we use a setup similar to that of, for example, Whipple et al. (1998) to generate

[34] removed: a

[35] removed: Its slope depends essentially on the water discharge and grain size. This observation accords quantitatively with the hypothesis

[36] removed: (Glover and Florey, 1951; Parker, 1978; Devauchelle et al., 2011; Seizilles et al., 2013). As for the sediment discharge, it

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[44] removed: Finally, we interpret our observations in the light of the threshold-channel theory (Sect. **??**).

[45] removed: routine in geomorphology (Schumm et al., 1987; Clarke, 2015)

Table 1. Physical characteristics of the sediment. [..[47]]The measurement method is presented in Appendix A. The friction coefficient μ is the tangent of the angle of repose.

	Density	Grain size	
	ρ_s (kg m^{-3})	d_{50} (μm)	d_{90} (μm)
Silica	2650 ± 50	130	200
Coal	1500 ± 50	400	800

	Critical Shields	Friction coefficient
	θ_c	μ
Silica	0.25 ± 0.02	0.42 ± 0.04
Coal	0.19 ± 0.008	0.58 ± 0.04

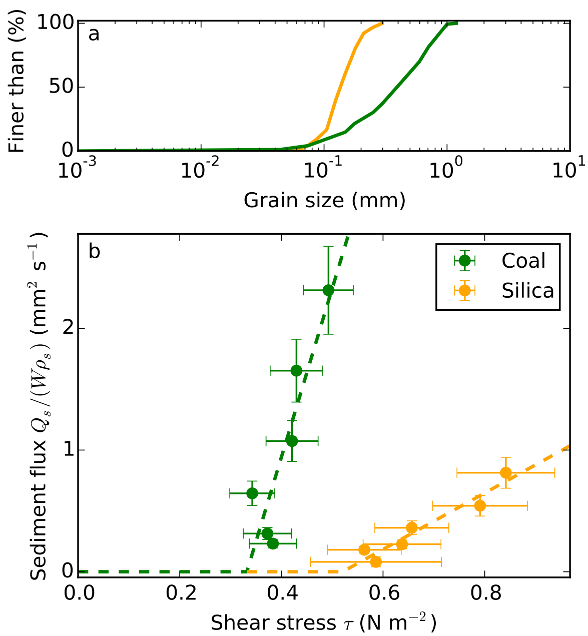

Figure 2. (a) [..[48]]Cumulative density function of the grain size. Orange: silica, green: coal. (b) Transport laws. Volumetric flux per unit width, as a function of dimensional shear stress. Dashed lines correspond to Eq. (A3) fitted to the data (method in Appendix A, coefficients in Table 1).

a radially symmetric fan over a horizontal basal surface (Fig. 1). In our experiments, however, a bimodal sediment mixture allows the fan to [..[46]]form a segregated deposit, visualized by color.

[46] removed: a form

Table 2. Experimental parameters for the five runs.

Run	Water discharge Q_w ($\mathrm{L\,min^{-1}}$)	Sediment discharge Q_s ([..[49]]$\mathrm{L\,min^{-1}}$)	Silica fraction ϕ
1	2.6 ± 0.1	[..[50]]0.019 ± [..[51]]0.001	0.5±0.05
2	2.6 ± 0.1	[..[52]]0.045 ± [..[53]]0.001	0.5±0.05
3	2.6 ± 0.5	[..[54]]0.027 ± [..[55]]0.001	0.25±0.02
4	2.4 ± 0.1	[..[56]]0.027 ± [..[57]]0.001	0.25±0.02
5	2.6 ± 0.1	[..[58]]0.020 ± [..[59]]0.001	0.8±0.08

[..[60]]The tank we use to produce alluvial fans is 2 m-wide, and more than 5 m-long. Its bottom is covered with a black rubber tarpaulin. At the back of the tank, a 30 cm-high, vertical wall simulates the mountain front against which the fan leans. To prevent flow concentrations, large pebbles ($\sim$ 5 cm) are placed along the base of this back-wall. The three other sides are bounded by trenches to evacuate water (Fig. 1). It is noted that, even with these trenches, the surface tension maintains a 0.5 cm-deep sheet of water over the base of the tank. Assuming that this standing water affects only the base of the fan, we find that it represents less than 1% of its volume. Based on this simple calculation, we hereafter neglect its influence in our analysis and interpretation.

To ensure constant inputs of water and sediment into the experiment, we use a constant-head tank to supply the water, and an Archimedes screw to supply the grains. The fluxes of water and sediment merge in a funnel, which directs them toward the tank. Before reaching the fan, water and sediment flow through a 10 cm-wide, [..[61]]wire-mesh cylinder filled with pebbles. This device reduces the water velocity and homogenizes the mixture (Fig. 1).

The mixture we used is composed of black coal and white silica grains, the colors of which are easily distinguished. The coal grains are larger and lighter than the silica grains (Table 1). To quantify the mobility of these grains, we measure their respective transport laws in independent experiments (Appendix A). We find that both transport laws, for pure coal and pure silica, [..[62]]exhibit an unambiguous threshold, below which there is no transport (Fig. 2). [..[63]]This threshold is about $0.34\,\mathrm{N\,m^{-2}}$ for coal, and $0.52\,\mathrm{N\,m^{-2}}$ for silica. Beyond this threshold, the sediment flux appears proportional to the

[60]removed: To produce a bimodal sediment

[61]removed: we mix

[62]removed: when unmixed, the coal grains are more mobile than the silicagrains: For the same shear stress τ, the flux of coal grains is larger than that of silica grains

[63]removed: When different grains are mixed, however, the shear stress exerted on each type of grains depends on their relative concentration on the bed surface (Wilcock and Crowe, 2003; Houssais and Lajeunesse, 2012). The shear stress required to move large grains is lower than it would in a system of only large grain, because they protrude more into the fluid. Conversely, small grains require a higher shear stress because they are partially shielded from the flow by neighboring larges grains (Einstein, 1950). When the mixture is composed of grains with different densities the exposure/hiding effect is negligible (Viparelli et al., 2015)

distance to threshold, with a proportionality constant of $2.4\,10^{-5}$ m^2 s^{-1} for coal and $4.8\,10^{-6}$ m^2 s^{-1} for silica. As a [..[64]]result, the same shear stress [..[65]]

[..[66]]

[..[67]]τ induces a larger flux of coal than silica, at least when the two species are unmixed. In other words, despite their larger size, the [..[68]]coal grains are more mobile than the silica ones. This, of course, is due the first being lighter than the latter. To formalize this density-induced reversal of mobility, we need to introduce the Shields parameter θ, which is the ratio of the [..[69]]shear stress over the grain's weight (Shields, 1936):

$$\theta[..^{70}] = [..^{71}]\frac{\tau}{(\rho_\mathsf{s} - \rho)\mathsf{g}\mathsf{d}_\mathsf{s}}, \tag{1}$$

where ρ is the density of water, ρ_s is the density of sediment, g is the acceleration of gravity, and we approximate the grain size d_s with its median value d_{50}. For our sediments, the denominator in Eq. (1) is larger for silica than for coal, indicating that the density difference prevails over grain size to govern the mobility of our grains. [..[72]]This is in contrast to the experiments of Reitz and Jerolmack (2012), where the mobility difference is driven by grain size. When expressing the threshold for transport in terms of the Shields parameter, we find $\theta_c = 0.19$ for coal, and [..[73]]$\theta_c = 0.25$ for silica (Table 1)[..[74]]. These values reinforce the mobility contrast induced by density.

[..[75]]

[..[76]]When different grains are mixed, the shear stress exerted on each species depends on the mixture composition (Wilcock and Crowe, 2003; Houssais and Lajeunesse, 2012). The shear stress required to move the larger grains in a mixture is lower than for large grains alone, because the smaller ones cause them to protrude into the fluid. Conversely, small grains in a mixture require a higher shear stress because they are shielded from the flow by neighboring large

[64] removed: consequence, we now consider that the flow exerts

[65] removed: on coal and silicawhen they are mixed. Accordingly, we use Fig. 2 as a first-order approximation for the differential transport of a mixture of coal and silica . If this interpretation is correct, the experimental river could transport coal while depositing silica, thus segregating the sediments based on their mobility.

[66] removed: Top-view pictures of an experimental fan (run 2). (a) Time evolution. Green dashed line indicates fan toe, R_c. (b) Average of rescaled pictures. The 26 pictures are 10-minutes apart. Dashed lines indicate silica-coal transition (orange) and fan toe (green). After rescaling, the fan length is one. Transition between silica and coal occurs at dimensionless distance $\mathcal{R}$ from apex.

[67] removed: Our experimental transport laws feature unambiguous thresholds. Below this critical shear stress τ_c, no sediment is transported. This widespread observation is often interpreted in terms of

[68] removed: critical Shields parameter θ_c, which represents

[69] removed: flow-induced shear stress to gravity (Shields, 1936):

[72] removed: In addition, we find the threshold Shields parameter to be about 0.19

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[75] removed: The tank we use to produce alluvial fans is 2 m-wide, and more than 5 m-long. Its bottom is covered with a black rubber tarpaulin. At the back of the tank, a 30 cm-high, impervious wall simulates the mountain front against which the fan leans; the three other sides are bounded by trenches to evacuate water. At the wall's foot, 5 cm-rocks prevent the flow from concentrating along it. Despite the trenches, surface tension maintains a 0.5 cm-deep sheet of water over the tank bottom.

[76] removed: To ensure constant inputs of water and sediment into the experiment, we use a header tank to supply the water, and an Archimedes screw to supply the grains. The fluxes of water and sediment merge in a funnel, which directs them toward the tank.Before reaching the fan, water and sediment flow through a 10 cm-wide, wire-mesh cylinder filled with pebbles. This device reduces the water velocity and homogenizes the mixture (Fig.1)

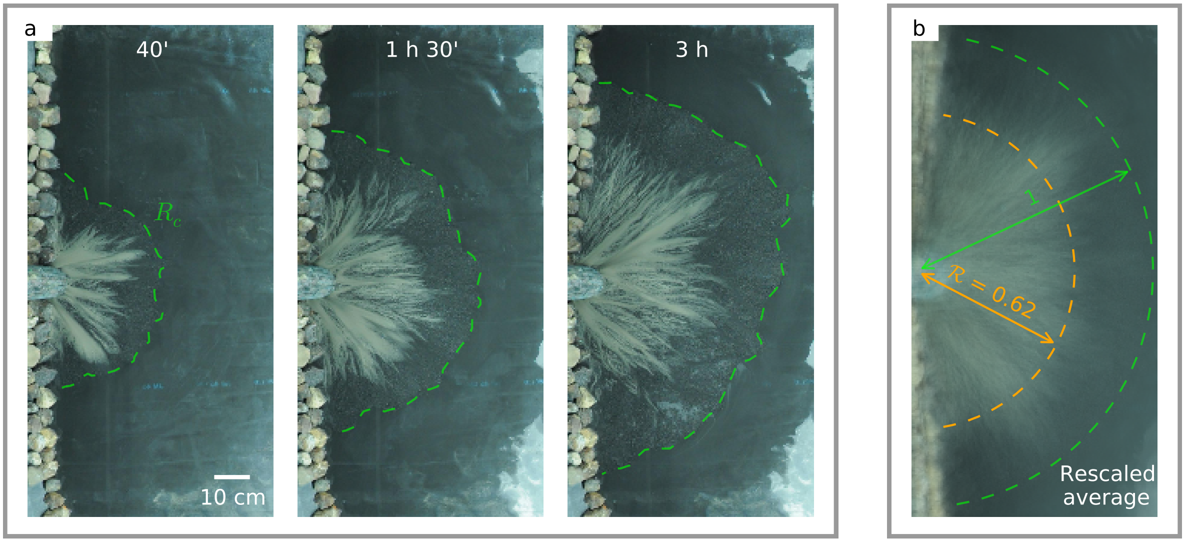

Figure 3. Top-view pictures of an experimental fan (run 2). (a) Time evolution. Green dashed line indicates fan toe, R_c. (b) Average of rescaled pictures. The 26 pictures are each 10-minutes apart. Dashed lines indicate silica-coal transition (orange) and fan toe (green). After rescaling, the fan length is one. Transition between silica and coal occurs at dimensionless distance $\mathcal{R}$ from apex.

grains (Einstein, 1950). For grains of different densities but uniform size, exposure and hiding are negligible (Viparelli et al., 2015). There exist no universal transport law accounting for all these phenomena, and deriving an empirical one for our mixture would be a daunting task. We thus use the transport laws of Fig. 2 to account for differential transport and estimate the mobility of our grains, although this is certainly a rough approximation. If it holds, at least qualitatively, we expect the rivers that build our experimental fans to segregate the sediment based on grain mobility, by depositing silica while transporting coal further downstream.

An experimental run begins with an empty tank. When the mixture of water and sediment reaches [..[77]]the horizontal bottom of the tank, it forms a half-cone deposit. Initially, a sheet flow spreads [..[78]]uniformly over this sediment body. After a few minutes, the flow confines itself into distinct, radial, channels (typically five or six)[..[79]]. All these channels appear to transport sediment simultaneously. The experiment of Reitz and Jerolmack (2012) also produced about 5 channels, although only one of them was active at a time. Both configurations occur in the field (Weissmann et al., 2002; Hartley et al., 2010). In our experiments, bedload appears as the dominant transport mode, although a small amount of fine coal is suspended, and gets deposited on the banks. The width of our channels varies between about 1 and 2 cm. Assuming they share the total water discharge evenly, the typical Reynolds number of their flow is above 500, suggesting that, most

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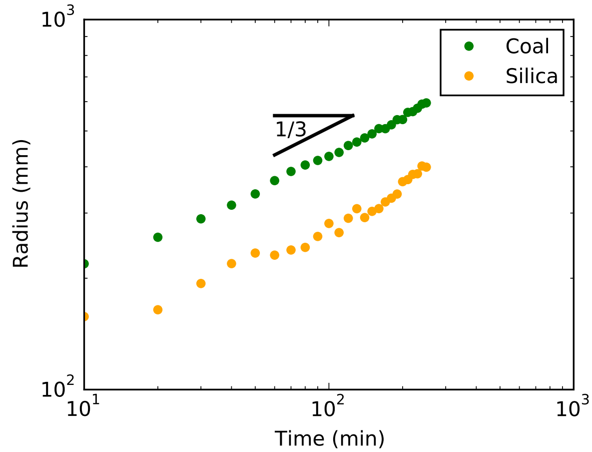

Figure 4. Evolution of the radial fronts of the silica (orange) and coal (green) [..[83]]deposits in run 2.

of the time, they are turbulent. They avulse regularly to maintain the radial symmetry of the fan[..[80]]. During an avulsion, overbank flow occurs temporarily, a phenomenon also observed by Bryant et al. (1995) and Reitz and Jerolmack (2012). [..[81]]Our experiment stops when the deposit reaches the sides of the tank, typically after 3 to 4 hours.

As it grows, the fan deposits the silica grains upstream of the coal grains. Accordingly, the apex of the fan is mostly composed of silica, whereas coal constitutes most of its toe. The boundary between the two types of sediment follows the path of channels, thus adopting a convoluted shape. [..[82]]To explore the influence of the sediment composition on the morphology of the fan, we varied ϕ, the volumetric proportion of silica in sediment mixture, from 25% to 80% over five experiments (Table 2).

3 Self-similar growth of a segmented fan

During each run, we track the evolution of the fan surface with a camera (Nikon D90 with a wide-angle lens Nikon AF DX Fisheye-Nikkor 10.5 mm f/2.8G ED) fixed above the center of the tank. We record an image every minute (Fig. 3a). The exact location of the boundary between silica and coal varies significantly during a run. [..[84]]For a run, however, [..[85]]this boundary appears at a constant location relative to the fan length. This fraction depends on the composition of the sediment mixture (Table 3). To confirm this observation, we manually locate the fan toe on 26 pictures, 10 minutes apart from each other [..[86]](Fig. 3a). From these individual measurements, we estimate the average radius R_c of the fan with an accuracy of about 6% on each picture. We then rescale each picture with [..[87]]the corresponding value of R_c, thus normalizing the size of the fan to

[80] removed: , much as in the experiments of

[81] removed: An

[82] removed: At the scale of a channel, silica grains generally concentrate around the thalweg, whereas coal is deposited on the banks.

[84] removed: Eye-averaging over its convolutions

[85] removed: suggests a constant ratio between the distance from the boundary to the apex and the total lengthof the fan

[86] removed: , during run 2

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one. Finally, we average all the normalized pictures of an experimental run (Fig. 3b). [..[88]]By construction, the average picture shows a fan of radius one. It also confirms that the fan is radially symmetric[..[89]], and reveals a somewhat blurred but localized transition between the silica and coal deposits. This observation suggests that the fan preserves the spatial distribution of coal and silica as it grows.

[..[90]]

To verify the self-similarity of the fan growth, we analyze the evolution of its geometrical properties[..[91]]. To do so, we manually locate the silica-coal transition and the fan toe (Fig. 3a). We then calculate the average distance R_s from the apex to the transition. The boundary of the silica deposit being more convoluted than the toe, the [..[92]]standard deviation of R_s is about 19%. Both distances increase in proportion to the cube root of time (Fig. 4). [..[93]]Following Powell et al. (2012) and Reitz and Jerolmack (2012), we interpret this observation as a direct consequence of mass balance[..[94]]. Indeed, the total [..[95]]mass M of the deposit increases linearly with [..[96]]time:

$$M = Q_{s,m}\, t \tag{2}$$

where $Q_{s,m}$ is the total mass flux of sediment. To express this relation in terms of volumes, we need to measure the packing fraction λ of our sediment mixture. In general, this quantity depends on the composition of the mixture. To estimate it, we measure the packing fraction of pure silica, of pure coal, and of a 50% silica-coal mixture (red dots, Fig. 5). The three values are similar, with a mean of $55\% \pm 1\%$. Accordingly, we approximate the packing fraction of the entire deposit with this value, regardless of the composition of the sediment mixture. This approximation introduces an error of less than 5%. We now define the volume discharge of sediment Q_s, such that

$$[..^{97}]Q_{s,m} = Q_s(1-\lambda)\left(\phi\rho_s[..^{98}]+(1-\phi)\rho_c\right) \tag{3}$$

and substitute Q_s for $Q_{s,m}$ in Eq. (2). The mass balance then reads

$$V = Q_s\, t \tag{4}$$

where V is the total volume of the deposit. In a self-similar fan, any distance scales like the cube root of the fan volume; in particular, both R_c and R_s increase in proportion to $(Q_s t)^{1/3}$. Our [..[99]]experimental fans conform to this scaling, thus supporting the hypothesis of a self-similar [..[100]]growth. A direct consequence of this self-similarity is that the relative

[88]removed: The resulting picture

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[90]removed: Topography of an experimental fan (run 2). Black lines: elevation contours 15 mm apart from each other. White dashed lines indicate the bounds used for averaging (only two radii appart from 5° are represented for clarity).

[91]removed: during run 2.

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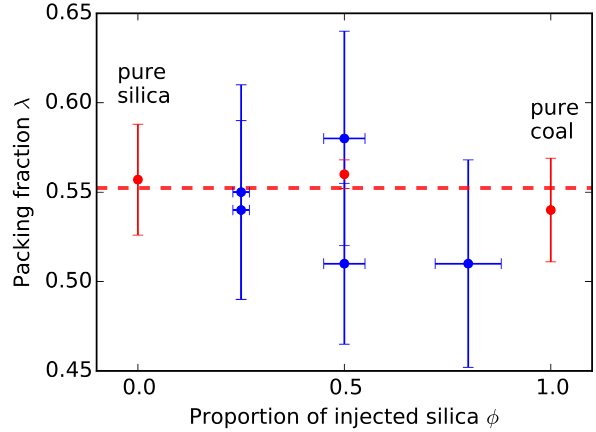

Figure 5. Packing fraction of the deposit as a function of the composition of the sediment mixture. Blue dots calculated from experiment. Red dots measured independently. The red dashed line is the mean packing fraction measured independently.

location of the transition, defined by the ratio $\mathcal{R} = R_s\,/\,R_c$, remains constant [..[101]]throughout growth ($\mathcal{R} = 0.62 \pm 0.04$ for run 2, other runs are presented in Table 3, Figs.3b and 4).

This self-similarity means that, as it grows, the fan preserves its structure, which can therefore be extrapolated from the final deposit. [..[102]]

4 [..[103]]

A few minutes after the experiment stops, all the surface water has drained away from the fan, leaving the entire deposit emergent. At this point, we scan the deposit's surface with a laser to measure its topography (OptoEngine MRL-FN-671, 1 W, 671 nm). A line generator converts the beam into a laser sheet (60° opening angle, 1 mm thick), the intersection of which with the fan surface is recorded by a camera attached to the laser, about 2 m above the tank bottom (Sick Ranger E50, 12.5 mm lens). The precision of the measurement is [..[104]]better than 1 mm in every direction.

Using the digital elevation model (DEM) of our experimental fan, we compute the final volume of our fans to check the total packing fraction of the deposit (blue dots, Fig. 5). Despite some dispersion, we find that the [..[105]]packing fraction of our deposit is about 54% $\pm$ 2%, close to the value estimated independently.

The elevation contours of the DEM are well approximated by concentric circles, another indication of radial symmetry (Fig. 6). This property suggests that we can compute the radially-averaged profile of the fan with minimal loss of information

[101] removed: during fan

[102] removed: In the next section, we describe the final deposit, through its slope and radial cross-section.

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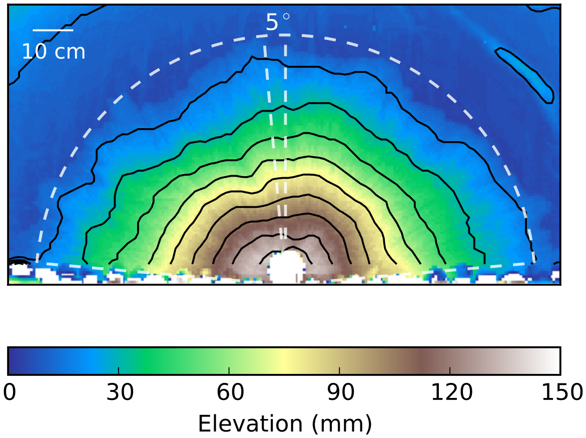

Figure 6. Digital elevation model of an experimental fan (run 2). Black lines: elevation contours 15 mm apart from each other. White dashed lines indicate the bounds used for averaging (only two sample radii 5 degree apart are represented for clarity).

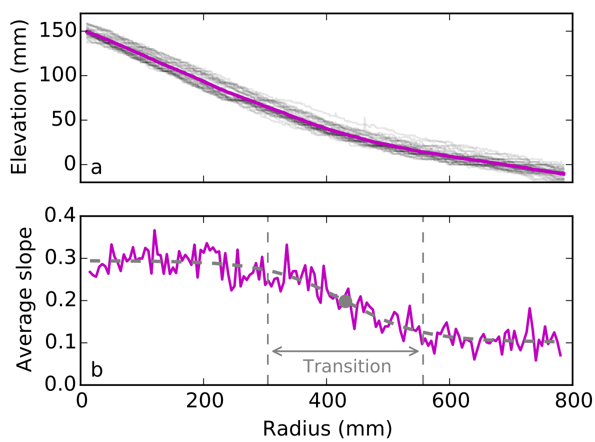

Figure 7. (a) Fan profiles at different angles (run 2). Gray: individual profiles; magenta: average profile. (b) Average downstream slope (magenta). Fitted hyperbolic tangent (dashed gray). Inflection point (gray dot) and boundary of the transition area (vertical dashed gray line).

(Reitz and Jerolmack, 2012). To do so, we interpolate the DEM along 34 radii, 5° apart from each other, [..[106]]at the end of each run (Fig. 6). [..[107]]For each run, the resulting profiles are similar to each other, and differ from the mean by less than 7% (Fig. 7a). The average fan profile is steeper near the apex than at the toe and can be approximated by two segments of uniform slope. Natural fans sometimes feature a similarly segmented profile (Bull, 1964; Blair and McPherson, 2009; Miller et al., 2014). When we plot the downstream slope of this average profile as a function of the distance to the apex, the transition appears as a decreasing sigmoid curve (Fig. 7b). To [..[108]]evaluate the location of the transition, and the extension of the transition zone, we fit a hyperbolic tangent to the slope profile [..[109]](Fig. 7b for run 2, other runs in Table 3). For run 2, we find that the slope plateaus [..[110]]to a value of about 0.29 near the apex, and [..[111]]to about 0.10 near the toe. [..[112]]We define the location of the transition [..[113]]as the inflection point of the [..[114]]sigmoid, which occurs at 55% [..[115]]± 9% of the total fan length (Fig. 7b). The slope thus breaks [..[116]]where the sediment turns to coal, suggesting that these transitions are closely [..[117]]related (Fig. 3, [..[118]]$\mathcal{R} \approx 0.62 \pm 0.04$). The location of the transition depends on the mixture composition (Table 3). We now define the extension of the transition zone as the characteristic length of the sigmoid. For run 2, we find that the transition between the two segments of the fan occurs over a length of 32% of the total fan length. This value is almost independent of the sediment mixture (about 30% ± 3% on average for all runs). Miller et al. (2014) found a comparable value (about 22%) for natural and laboratory fans.

To [..[119]]investigate the relation between the slope break and the silica-coal transition, we now turn our attention to the internal structure of the deposit. After the water and sediment supplies have been switched off, the fan remains [..[120]]intact, and we can cut it radially to reveal a vertical cross section (Fig. 8). Silica and coal appear segregated, in accordance with the top-view pictures of the fan (Fig. 3), and with the experiments of Reitz and Jerolmack (2012). Silica concentrates near the apex, in the upper part of the deposit, whereas coal [..[121]]concentrates at the fan toe. The [..[122]]location of the silica-coal transition fluctuates, and generate an intricate stratigraphy that combines segregation at the fan scale, and stratification near the transition. The transition zone shows alternating layers of silica and coal, which extend over about one third of the cross-section area. [..[123]]In natural fans, such stratifications result from fluctuations of the sediment and water discharges,

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[123] removed: We interpret the variability in the sand-coal transition in the stratigraphy as the result of channel avulsion

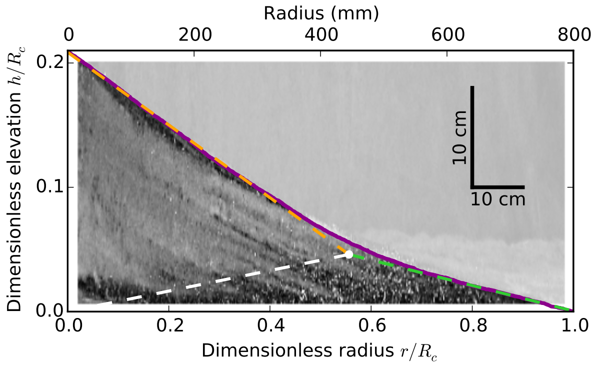

Figure 8. Average radial profile (magenta line), superimposed on radial cross section[..[124]], for run 2. Dashed lines: slope of the silica (orange) and coal (green) deposits. White dashed line indicates silica-coal transition. Scale is for the picture. h and r are respectively the fan elevation and the distance to the apex.

but this mechanism cannot be invoked in our experiments (Paola et al., 1992a; Clevis et al., 2003; Whittaker et al., 2011). Dry granular flows can also generate a similar pattern (Makse et al., 1997b, a). In our case, the succession of channel avulsions is another possible mechanism. Our observations do not allow us test these hypotheses.

The surface of the [..[125]]cross section resembles the average profile of Fig. 7a. Indeed, when superimposed, the two lines become virtually indistinguishable, with the slope break occurring near the transition between silica and coal (Fig. 8). Neglecting the span of the transition, we may approximate the average profile by fitting two straight lines to it. The proximal line joins the apex to the transition (slope = 0.29), and the distal line joins the transition to the toe (slope = 0.10). The two lines intersect at 56% of the deposit length. Finally [..[126]]we define the transition line, which joins this intersection to the origin [..[127]]and passes through the [..[128]]alternating stratigraphic layers in the transition zone. The transition line thus divides the deposit into two imbricated wedges, with the more mobile sediment (coal) lying below the less mobile one [..[129]](silica). The upward migration of the sand-coal transition in the deposit section reflects the outward growth of the transition accompanied by net deposition. In the next section, we formalize this interpretation in the context of self-similar growth, and combine it with mass balance to understand how the fan builds its deposit.

4 Mass balance

Based on our laboratory observations, we propose a first-order geometrical model of an alluvial fan fed with a bimodal mixture of sediments. We consider a radially symmetric structure, which grows by expanding itself without changing its geometry.

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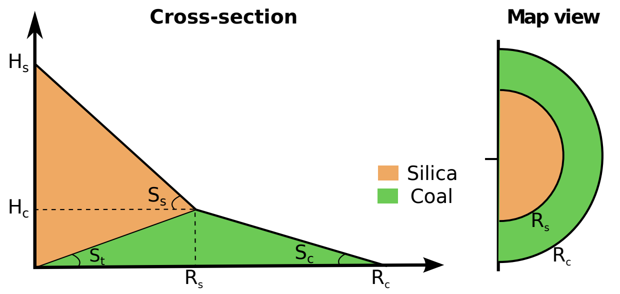

Figure 9. Representation of an alluvial fan (template). Silica: orange; coal : green.

Table 3. Geometrical characteristics of the experimental fans, measured at the end of each run. The errors on $\mathcal{R}$ are due to fluctuations of the silica-coal transition.

Run	Slope ratio $\mathcal{S}$	Transition location $\mathcal{R}$	S_t/S_s $\mathcal{S}_t$
1	3 ± 0.3	0.56 ± 0.07	0.37 ± 0.08
2	2.9 ± 0.1	0.55 ± 0.09	0.36 ± 0.08
3	4 ± 0.6	0.41 ± 0.1	0.57 ± 0.12
4	4.6 ± 0.6	0.39 ± 0.1	0.61 ± 0.13
5	3.3 ± 0.3	0.83 ± 0.2	0.12 ± 0.03

A consequence of these assumptions is that the geometry of the fan, at any time, is entirely determined by a fixed, two-dimensional template of its cross section (Fig. 9). The simplest possible template consists of two triangles with a common side. The proximal triangle defines the geometry of the silica deposit, and the distal one represents the coal deposit. Three dimensionless parameters define this template: the proximal slope S_s, the distal slope S_c and the relative location of the transition $\mathcal{R} = R_s/R_c$.

The geometry of the template sets the proportion of silica and coal in the deposit. As a consequence, mass balance relates the three parameters that define the fan template to the composition of the sediment mixture injected in the experiment, ϕ. Indeed, since the sediment discharge is constant, and assuming the deposit is fully segregated and the packing fraction is constant, we should have

$$\frac{V_s}{V_s + V_c} = \phi\,, \tag{5}$$

where V_s is the volume of silica in the deposit, and V_c that of coal. For a self-similar fan, this relationship holds at any time.

The silica deposit is composed of two half-cones sharing their base. Its volume reads

$$V_s = \frac{\pi}{6} R_s^2 H_s\,, \tag{6}$$

where H_s is the elevation of the fan apex. To calculate the volume of coal in the deposit, we first evaluate that of a truncated half cone with slope S_c, radius R_c, and height H_c (the elevation of the transition). We then withdraw the volume of the lower cone of the silica deposit. The resulting volume reads

$$V_c = \frac{\pi}{6}\left(R_c^2 + R_c R_s\right) H_c \,. \tag{7}$$

The proximal and distal slopes are simply those of the corresponding right triangles:

$$S_s = \frac{H_s - H_c}{R_s} \quad \text{and} \quad S_c = \frac{H_c}{R_c - R_s}. \tag{8}$$

Using the four above equations, we finally relate the composition of the sediment mixture to the geometry of the fan, as a function of the slope ratio and the transition location:

$$\phi = \frac{(1-\mathcal{S})\mathcal{R}^4 - \mathcal{S}\mathcal{R}^3 - \mathcal{R}^2}{(\mathcal{R}+1)\left((1-\mathcal{S})\mathcal{R}^3 - 1\right)}\,, \tag{9}$$

where we have defined the ratio of proximal slope to distal slope $\mathcal{S} = S_s/S_c$. Equivalently we may express the composition of the sediment mixture as a function of the slope ratio and the slope of the transition:

$$\phi = \frac{1-\mathcal{S}_t}{1+\mathcal{S}_t\left((\mathcal{S}\mathcal{S}_t)^2 + 3\mathcal{S}\mathcal{S}_t + 2\right)}\,, \tag{10}$$

where we have defined the ratio of transition slope to proximal slope $\mathcal{S}_t = S_t/S_s$.

If the template is a reasonable representation of the fan geometry, the location and the slope of the transition and the two surface slopes of the deposit should adjust to the composition of the sediment input, according to Eqs. (9, 10). To evaluate this model, we measure the geometry of the fan at the end of every experimental run (Table 3). Using the radially averaged profile [..[130]]we first fit, using a linear regression, the proximal and distal slopes and calculate their ratio. Then, we estimate the location of the transition using the position of the inflection point (Sect. [..[131]]3). We find that, for all runs, the proportion of silica in the deposit, as deduced from our measurements through Eqs. (9, 10), matches the composition of the sediment mixture (Fig. 10).

[..[132]]

At first order, we can thus represent our experimental fan as a radially symmetric, fully segregated structure which preserves its shape as it grows. These features determine the dynamics of the fan, and the geometry of its deposit. This model, however, involves two free parameters: the proximal and distal slopes. These are selected by the fan itself, by a mechanism that remains to be understood. [..[133]]

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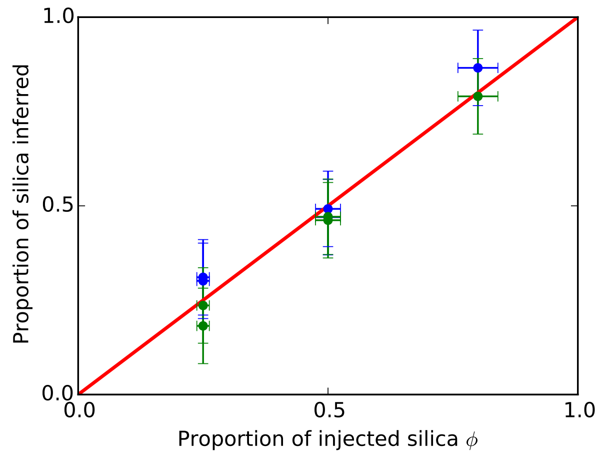

Figure 10. Proportion of silica inferred from the geometry of the deposit, after Eq. (9) (blue) and after Eq. (10) (green), as a function of the composition of the sediment input. Red line: perfect agreement.

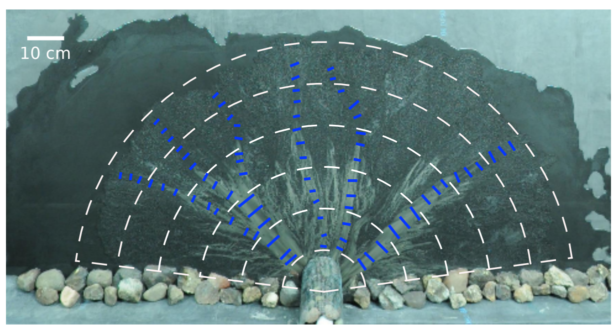

Figure 11. Top-view of an experimental fan superimposed with measurement bins (white), and channels cross sections (blue).

[..[135]]

[..[136]]Each deposit is built by a collection of channels, which select their own slope according to the [..[137]]composition of the bed, and to their sediment and water discharges. [..[138]]On the DEM of our experimental fans, the channels are virtually invisible, showing that their downstream slope is that of the fan (Fig. 6). It is thus reasonable to assume that the deposit inherits the slope of the channels that build it.

The way a river selects its morphology is still a matter of debate, but it has been recently pointed out that most laboratory rivers, including those flowing over an experimental fan, [..[139]]remain near the threshold for sediment transport (Reitz

[135]removed: Top-view of an experimental fan superimposed with measurement strips (white), and channels cross-sections (blue).
[136]removed: Two imbricated deposits make up our experimental fan.
[137]removed: type of sediment they flow onto
[138]removed: The deposit then
[139]removed: compare well with the threshold-channel theory

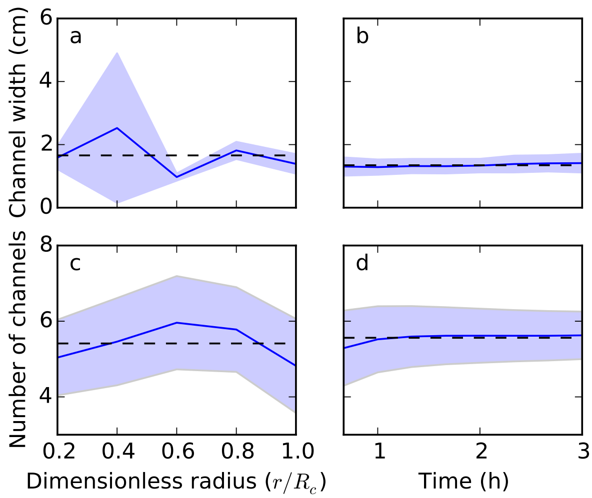

Figure 12. Evolution of active channels for all the runs. Channel width as a function of the dimensionless radius (a) and time (b). Number of channels as a function of dimensionless radius (c) and time (d). Black dashed line: average. Shaded area: variability over experimental runs.

and Jerolmack, 2012; Seizilles et al., 2013; Reitz et al., 2014; Métivier et al., 2016b). [..[140]]Assuming a channel is exactly at threshold yields a theoretical relationship between its water discharge and its slope (Glover and Florey, 1951; Henderson, 1961). Could this theory inform us about the slope of our fans?

Returning to our experimental fans, we find them enmeshed in a collection of channels flowing radially (Fig. 11). These channels sometimes [..[141]]bifurcate downstream, but do not recombine as they would in a braided river. [..[142]]We would like to compare their slope to the prediction of the threshold-channel theory. Unfortunately, our experimental setup does not allow us to measure [..[143]]the water discharge of individual channels. If the [..[144]]flow distributes itself evenly among the channels, though, we can approximate their individual discharges to a fraction of the total discharge.

To evaluate this approximation, we now analyze top-view pictures of our developing fans (about 15 pictures per run). We first divide the surface of each fan into five concentric [..[145]]bins, where we count the active channels and measure their widths (at least two cross sections per channel and per bin, Fig. 11). We then average the number of channels, and their width[..[146]], over experimental runs. The resulting quantities depend on the time of their measurement, and on the distance [..[147]]from the

[140] removed: The experiments of Stebbings (1963) suggest that sediment discharge causes a channel to widen, until it becomes unstable and breaks into a braid (Métivier et al., 2016b). The individual threads of a braid, in their turn, behave as threshold channels, both in laboratory flumes and in natural rivers (Reitz et al., 2014; Gaurav et al., 2015; Métivier et al., 2016a).

[141] removed: ramify

[142] removed: However, following the above contributions, we

[143] removed: their individual water discharges

[144] removed: water

[145] removed: strips

[146] removed: over

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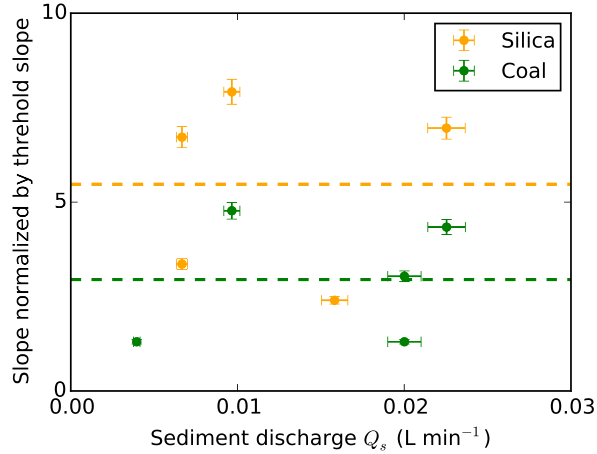

Figure 13. Slope normalized by the threshold slope, calculated with Eq. (11), as a function of the sediment discharge. Dashed lines: average slopes.

apex, r. Further averaging over time yields radius-dependent quantities, whereas averaging over distance yields time-dependent quantities (Fig. 12).

When plotted as a function of radius, the width of the channels varies between about 1 and 2.5 cm, with no clear trend (Fig. 12a). The [..[148]]variability of the width is much larger in the proximal part of the fan than in its distal part. When plotted as a function of time, we find that the width is more consistent, with a relative variability of about 10% around a mean value of 1.3 cm (Fig. 12b). Overall, the channels appear reasonably homogeneous in size, suggesting that they share the total water discharge evenly.

The number of channels n_c varies between 5 and 6 across the fan (Fig. 12c). As expected for a radially oriented structure, we count fewer channels near the apex. We also find fewer channels near the toe, although the poor color contrast of the coal-dominated areas [..[149]]probably bias our count. This variability compares with the disparity we observe between runs. The number of channels is nearly constant over time (Fig. 12d). Hereafter, we choose $n_c = 5.5$, and divide the total water discharge accordingly.

We now wish to compare the slope of our experimental fans with the threshold theory, applied to the characteristic channel defined above. This theory assumes that the combination of gravity and flow-induced shear stress maintains the channel bed at the threshold of motion (Glover and Florey, 1951; Henderson, 1961; Seizilles et al., 2013). As a result, the width, depth and slope of the channel are set by its water discharge. In particular, according to the simplest version of this theory (Devauchelle

[148] removed: width variability

[149] removed: could

et al., 2011; Gaurav et al., 2015; Métivier et al., 2016b), the equilibrium slope reads

$$S_H = \left(g\,\mu^3 \left(\frac{\theta_c}{\mu} \, \frac{\rho_s - \rho}{\rho} \, d_s \right)^5 \right)^{1/4} \sqrt{\frac{2^{3/2}\,\mathcal{K}(1/2) n_c}{3\,C_f\,Q_w}}, \tag{11}$$

where μ is Coulomb's coefficient of friction (Table 1), $\nu = 10^{-6}$ m^{2}s^{-1} is the kinematic viscosity of water, $\mathcal{K}(1/2) \approx 1.85$ is the elliptic integral of the first kind, and C_f is Chézy's coefficient of fluid friction. The Chézy coefficient C_f depends on the bed roughness and the flow Reynolds number. For simplicity, we approximate [..[150]]C_f with a constant value of 0.02 (Moody, 1944; Chow, 1959). [..[151]]

[..[152]][..[153]]

[..[154]]Since we imposed the same water discharge during all experimental runs, and found the number of channels n_c to be relatively constant, the slope corresponding to the threshold theory depends on the sediment only. We find $S_{Hs} \approx 0.042$ for silica, and $S_{Hc} \approx 0.023$ for coal, using Eq. (11).

Intuitively, we expect that, all things being equal, the fan slope [..[155]]increases with sediment discharge. Previous observations support this intuition, but there is no consensus yet about its physical origin, which involves the response of a single channel to sediment transport and its destabilization into multiple threads (Whipple et al., 1998; Ashworth et al., 2004). We do not find any correlation between sediment discharge and slope in our experiment [..[156]](Fig. 13). Even after normalizing our measurements according to the threshold theory, the data points appear segregated according to the sediment species: the mean slope [..[157]]of the silica deposit is about $S_s/S_{Hs} = 5.6 \pm 2.0$, whereas we find $S_c/S_{Hc} = 2.9 \pm 1.5$ for coal ([..[158]]$S_s \approx 0.23$ and $S_c \approx 0.068$). The [..[159]]surface slopes of the two fan segments are thus significantly higher than predicted by the threshold theory. [..[160]]

A possible cause for this departure from the threshold channel could be the bimodal mixture we use. To assess this hypothesis, we have produced an experimental fan with pure silica [..[161]]($Q_s \approx 0.014$ L min^{-1}, $Q_w \approx 2.6$ L min^{-1}). We found that, like its bimodal counterparts, its slope was approximately five times higher than [..[162]]predicted by the threshold-channel theory ($S_s = 0.2$). [..[163]]Another possible explanation is the infiltration of surface water into the [..[164]

[150]removed: it

[151]removed: Finally, $\mathcal{L}$ is a characteristic length:

[154]removed: In our experiment, $\mathcal{L}$ is about 130 μm for silica and 65 μm for coal.

[155]removed: to increase

[156]removed: , despite considerable dispersion

[157]removed: ratio

[158]removed: this corresponds to

[159]removed: silica deposit is steeper than the coal deposit, to a higher degree

[160]removed: We have made

[161]removed: and the same water discharge to certify thatthe bimodal mixture does not cause the departure from threshold. The slope of this fan is also

[162]removed: the threshold slope

[163]removed: This is a common feature in experimental channels, as well as in natural rivers, although its origin is debated (Métivier et al., 2016a, b). A

[164]removed: sediment

]deposit. Indeed, based on Eq. (11), a [..[165]]lower water discharge induces a steeper channel. [..[166]]Measuring this leakage would be experimentally challenging. Finally, the breakdown of the threshold-channel theory could result from sediment transport, [..[167]]since active channels must be above threshold (Whipple et al., 1998; Guerit et al., 2014). [..[168]]In their one-dimensional experiment, Guerit et al. (2014) have shown that the higher the sediment input in their experiment, the more slope departs from its threshold value. Again, we cannot evaluate quantitatively this hypothesis in our experiments.

The [..[169]]proximal and distal slopes seem independent from sediment discharge (Fig. 13). [..[170]]For lack of a physical interpretation, we now treat this observation as an empirical fact, and attribute a fixed value to the [..[171]]ratio of proximal slope to distal slope: $\mathcal{S} = S_s/S_c = 3.4 \pm 1.0$. Substituting this value in Eqs. (9, 10), the mass balance [..[172]]relates, without any additional parameters, the composition of the sediment mixture to the location and the slope of the transition (Fig. 14). Despite significant uncertainties, which probably reflect the rudimentary mass balance we used, our observations agree with this semi-empirical relationship. [..[173]]

In principle, one could use Fig. 13 to infer the composition of the sediment input from the geometry of the deposit. This method, however, relies on the value of the slope ratio $\mathcal{S}$, which we have fitted on our observations. A more comprehensive theory should explain how a bimodal fan spontaneously selects the value of this ratio.

5 Conclusion

Using a laboratory experiment, we generated alluvial fans fed with a bimodal sediment. [..[174]]Five or six active channels deposit their sediment load to form a radially-symmetric fan. The heavier sediment (silica) concentrates around the apex, [..[175]]whereas the lighter one (coal) get deposited near the toe. [..[176]]The location of silica-coal transition fluctuates over about 30% of the total fan length. A radial cross section of the deposit [..[177]]reveals a similar segregation: two superimposed triangles make up the stratigraphy of the fan. The lowest triangle is mostly coal, whereas the upper one, located near the apex, is mostly silica. The transition [..[178]]between the two parts of the fan fluctuates to produce strata,

[165] removed: reduced

[166] removed: We were not able to measure the total water discharge near the fan toe, and therefore could not account for this leakage . Another likely cause for the channel steepening is

[167] removed: which induces departure from

[168] removed: Although we could not measure sediment discharge in the channels on our experimental fans, from visual observation it was clear that the sediment was in vigorous motion in the channels

[169] removed: slope ratio appears to be independent from the composition of the sediment mixture

[170] removed: We can

[171] removed: slope ratio

[172] removed: of Sect. 4

[173] removed: These uncertainties probably reflect the rudimentary mass balance we used

[174] removed: The deposit they produce is segregated, with the less mobile sediment concentrated near

[175] removed: and the more mobile one

[176] removed: This segregation also appears in the radial cross-section

[177] removed: in the form of a front that rises at a constant angle

[178] removed: from the proximal deposit to the distal one occurs over about

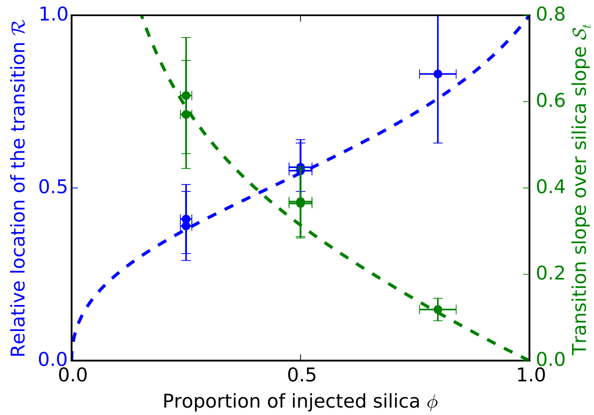

Figure 14. Relative position of the transition $\mathcal{R}$ (blue) and dimensionless transition slope $\mathcal{S}_t$ (green), as a function of the composition of the sediment input. Dot: experimental measurements. Dashed line: Eqs. (9, 10) with $\mathcal{S} = 3.4$.

which extend over 30% of the total fan length[..[179]]. As a first approximation, we may represent this transition with a straight line, and treat the fan structure as two imbricated deposits. Combining this geometric model with mass balance, we find that [..[180]]the fan preserves this structure as it grows, with a precision of about 15%. This observation suggests that [..[181]]our laboratory fans act essentially as sieves, which segregates the sediment [..[182]]they are fed with. This process controls the geometry of the resulting deposit. As a consequence, we can use the final geometry of our laboratory fans to infer the composition of the sediment input. In practice, a top-view picture of the deposit suffices to do so. Alternatively, measuring the slope of the transition in the stratigraphy, even if the latter is incomplete, also suffices.

[..[183]]Natural fans often exhibits a sharp transition from gravel to sand [..[184]](Blair and McPherson, 2009; Miller et al., 2014). Like in our experiments, this front divides the fan profile into two segments. The proximal segment, composed mainly of gravel, is steeper than the distal one, composed mainly of sand. Bull (1964) and Blair (1987) found natural fans featuring three segments bounded by two successive transitions. Again, the size of the deposited sediment changes abruptly at each front. These observations suggest that the segregation mechanism at work in our experiment can repeat itself to generate nested deposits. A natural extension of our work would be to enrich the sediment mixture with additional grain sizes (or densities) to produce fans with multiple segments. We would expect these fan to sort sediment species based on their mobility, and reduce their slope downstream, as observed on the surface of many natural fans (Stock et al.,

[179] removed: , in the form of a complex stratigraphy. However, as

[180] removed: we can represent the self-similar growth of the fan

[181] removed: an alluvial fan acts essentially as a sieve

[182] removed: it is

[183] removed: We expect this interpretation to hold for a richer mixture of sediments, although this assumption should be tested experimentally. The geometrical model we propose extends straightforwardly to an arbitrary number of grain sizes, and even to a continuous distribution. However, typical coarse alluvial fans, even though supplied with a wide range of grain sizes, often show a clear

[184] removed: over a frontthat we believe behaves similarly to

2008). In other words, the structure of an alluvial fan should reflect the composition of its sediment input. For instance, in principle, one could infer the grain-size distribution of the sediment input from a DEM of the fan.

In practice, however, secondary processes such as weathering, runoff, and aeolian erosion reworks the surface of most natural fans, thus hampering our ability to infer their history from their present state (de Haas et al., 2014). To circumvent this issue, one can either reconstruct geometrically the paleosurface of the fan, or use its stratigraphy. Indeed, even partial access to the internal structure of the fan could reveal the slopes of the transitions in the stratigraphy, and thus the grain-size distribution of the input.

In our experiments, the inputs of water and sediment were constant. In general, this is not true for natural fans, and the [..[185]]interpretation we propose here does not apply in its present, oversimplified, form. The self-similar model we propose here thus cannot account for climatic and tectonic signals. However, the fundamental hypothesis upon which it relies, namely that the fan sorts the sediments based on their mobility and adjusts its own slope accordingly, might still hold when the inputs fluctuate. If so, our geometrical model might be extended to account for these fluctuations. This is the subject of present work.

Our [..[186]]experiments also suggest that the process by which an alluvial fan distributes grain sizes in its deposit, although a primary control on its structure, may not be the most puzzling component of its machinery. The way it selects its slope [..[187]]remains a challenging problem, which we have circumvented here by fitting a parameter to our observations (Le Hooke and Rohrer, 1979; Whipple et al., 1998; Stock et al., 2008; Van Dijk et al., 2009; Powell et al., 2012; Guerit et al., 2014). Indeed, the threshold theory can only provide us with a first-order estimate [..[188]]

[..[189]]

for the slope of a channel. We need to understand how a channel adjusts its slope to its sediment load. Recent investigations have shown that, [..[190]]provided the sediment discharge [..[191]]is low enough, one can produce stable active channels in laboratory experiments (Seizilles et al., 2013; Métivier et al., 2016b). If this method works for a laboratory fan as well, it might [..[192]]generate a single-channel fan. This would be a simpler experimental tool to investigate the relationship between the slope of a fan and the intensity of its sediment input.

[185] removed: simplified fronts we observed in our experiments. As a consequence, we expect that the geometry of the final deposit (location and slope of the transition and proximal and distal slopes) allows us to estimate the relative flux that built the fan

[186] removed: experiment suggests

[187] removed: is a more challenging problem

[188] removed: of a channel slope , which proved underestimated by a factor of five in our experiments. Progress requires improvement in our understanding of how a channelreacts to sediment transport.

[189] removed: At least under some circumstances, a higher sediment discharge induces a steeper channel . Sometimes, like in our experiment, it also destabilizes the river into multiple channels, which then share water and sediment. In a fan, both mechanisms alter the slope of the deposit, and therefore its structure. To assess the influence of sediment discharge on channel slope , we need to either impose or measure its value. When the flow is distributed in multiple channels, measurement is the only way. Experimentally however, it is certainly easier to impose the sediment discharge of a single, stable channel.

[190] removed: to keep a stable channel in a laboratory flume, we need to maintain

[191] removed: below a critical value

[192] removed: produce simpler analogs of alluvial fans, and thus more convenient tools to investigate their formation

Appendix A: Transport law

To calibrate the transport laws of our sediments, we use an independent set-up similar to that of Seizilles et al. (2014). The flow is confined between two Plexiglas panels separated by a 3.2 cm-wide gap in which we inject water and sediment at constant rate. Once the experiment has reached equilibrium, typically ten to twenty hours after it started, we measure the slope of the water surface S to estimate the shear stress τ. Since the Reynolds number is below 500 in our flume, we may assume that the flow is laminar. The shear stress acting on the sediment thus follows Poiseuille's law:

$$\tau = \rho (Sg)^{2/3} \left(\frac{3 Q_w \nu}{W} \right)^{1/3}, \tag{A1}$$

where W is the width of the gap, and ν the viscosity of water. We then calculate the Shields parameter, which represents the ratio of the flow-induced shear stress τ to gravity:

$$\theta = \frac{\tau}{(\rho_s - \rho) g d_s}, \tag{A2}$$

and calibrate the transport law (Fig. 2). We find that below a critical value θ_c, which correspond to a critical shear stress τ_c, the sediment flux vanishes. Above this threshold, the flux appears proportional to the departure from the critical Shields parameter:

$$\frac{Q_s}{W} = q_0 (\theta - \theta_c), \tag{A3}$$

where q_0 = [..[193]]4.8 $\pm$ [..[194]]0.9 10^{-6} $m^2\, s^{-1}$ [..[195]]and θ_c = 0.25 $\pm$ 0.02 for our silica grains, and q_0 = [..[196]]2.4 $\pm$ [..[197]]0.2 10^{-5} $m^2\, s^{-1}$ [..[198]]and θ_c = 0.19 $\pm$ 0.008 for our coal grains.

These value are measured in a laminar flow, whereas our laboratory fans are produced by (mostly) turbulent channels (Sect. 2). However, regardless of the nature of the shear-inducing flow, the grain Reynolds number $d_s^2 \dot{\gamma}/\nu$ is constant near the threshold for sediment transport ($\dot{\gamma}$ the vertical shear rate) (Andreotti et al., 2012). Accordingly, we use the above measurements to estimate the threshold slope with equation (11).

Appendix B: Notations

Acknowledgements. We thank B. Erickson, E. Steen and C. Ellis for their help in building the experimental set-up; S. Harrington and K. François-King for assistance with experiments; J-L. Grimaud for the data on sediments; L. Guerit and E. Gayer for useful discussions.

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[193] removed: 28
[194] removed: 9 g
[195] removed: m^{-1}
[196] removed: 77
[197] removed: 20 g
[198] removed: m^{-1}

Table 4. Variables used.

Symbol	Definition	Unit
Q_s	sediment discharge	L min^{-1}
$Q_{s,m}$	mass sediment discharge	g min^{-1}
Q_w	water discharge	L min^{-1}
ρ_s	sediment density	kg m^{-3}
ρ	water density	kg m^{-3}
g	acceleration of gravity	m s^{-2}
d_{50}, d_{90}	50th and 90th percentile	μm
θ	Shield number	
θ_c	critical Shield number	
μ	friction coefficient	
τ	shear stress	kg m^{-1} s^{-2}
τ_c	critical shear stress	kg m^{-1} s^{-2}
q_0	characteristic sediment flux	m^2 s^{-1}
W	width of the channel	cm
λ	packing fraction	
r	distance to the apex	m
h	elevation	m
V_c	volume of coal	m^3
V_s	volume of silica	m^3
ϕ	proportion of silica	
R_c	radius of coal	m
R_s	radius of silica	m
$\mathcal{R}$	radius ratio	
H_c	elevation of the transition	m
H_s	elevation of the fan apex	m
S_c	distal slope	
S_s	proximal slope	
S_t	slope of the transition	
$\mathcal{S}$	ratio of proximal to distal slope	
$\mathcal{S}_t$	ratio of transition to proximal slope	
S_H	threshold slope	
n_c	number of channel	
C_f	Chézy's coefficient	
$\mathcal{K}(1/2)$	elliptic integral of the first kind	

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