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Generalized Sorting Profile of Alluvial Fans

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Abstract
Alluvial rivers often exhibit self-similar gravel size distributions and abrupt gravel-sand transitions. Experiments suggest that these sorting patterns are established rapidly, but how—and how fast—this convergence occurs in the field is unknown. We examine the establishment of downstream sorting patterns in a kilometer-scale alluvial fan. The sharp transition from canyon to unconfined, channelized fan provides a well-defined boundary condition. The channel changes from deep and entrenched at the fan apex to shallow and depositional over a short distance, exhibiting nonequilibrium behavior. The resulting gravel-fining profile is not self-similar; the particle size distribution narrows until approximate equal mobility is achieved. Downfan, the gravel-sand transition appears to exhibit a self-similar form; field and laboratory data collapse when downstream distance is normalized by the location of the transition. Results suggest a generalized sorting profile for alluvial fans as a consequence of the threshold of motion and nonequilibrium channels.

Keywords
sorting, selective transport, downstream fining, equal mobility, gravel-sand transition, alluvial fan

Disciplines
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Key Points:
- Gravel sorting is limited by equal mobility of the grain size distribution
- The gravel-sand transition exhibit a self-similar form
- Transient dynamics control channel geometry on fan

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Generalized sorting profile of alluvial fans

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Abstract Alluvial rivers often exhibit self-similar gravel size distributions and abrupt gravel-sand transitions. Experiments suggest that these sorting patterns are established rapidly, but how—and how fast—this convergence occurs in the field is unknown. We examine the establishment of downstream sorting patterns in a kilometer-scale alluvial fan. The sharp transition from canyon to unconfined, channelized fan provides a well-defined boundary condition. The channel changes from deep and entrenched at the fan apex to shallow and depositional over a short distance, exhibiting nonequilibrium behavior. The resulting gravel-fining profile is not self-similar; the particle size distribution narrows until approximate equal mobility is achieved. Downfan, the gravel-sand transition appears to exhibit a self-similar form; field and laboratory data collapse when downstream distance is normalized by the location of the transition. Results suggest a generalized sorting profile for alluvial fans as a consequence of the threshold of motion and nonequilibrium channels.

1. Introduction and Background

Downstream changes in particle size exert a strong control on sediment transport and alluvial channel geometry. The observed pattern of an exponential decline in downstream particle size is so ubiquitous that it has been elevated to a law [*Sternberg*, 1875; *Pizzuto*, 1995; *Rice*, 1999; *Domokos et al.*, 2014]. *Fedele and Paola* [2007] demonstrated that "Sternberg's Law" may arise from size-selective deposition and revealed an even more remarkable finding. For the case of gravel, a simplification of the transport equations predicts that the standard deviation of the grain size distribution (GSD), σ, decays at a similar exponential rate to the mean, $\bar{D}$; the coefficient of variation $C_v = \sigma/\bar{D}$ thus remains approximately constant [*Fedele and Paola*, 2007]. This pattern is borne out in data from natural rivers and flume experiments of a prograding sediment wedge. The latter suggest that the sorting profile is established early on in river profile evolution and then essentially "stretches" as the river continues to prograde. As a consequence, sorting profiles at different stages of river evolution are identical when downstream distance (x) is normalized by the length of the gravel reach (L_g), i.e., $x_* = x/L_g$. Determining whether this self-similar sorting profile is as ubiquitous as Sternberg's Law requires substantially more data. A natural question that arises from the *Fedele and Paola* [2007] results is, what determines the limit to sorting in bed load (gravel) streams? A reasonable hypothesis is that size-selective transport narrows the GSD until particles are approximately equally mobile, in terms of their threshold entrainment stress [cf. *Parker and Klingeman*, 1982; *Wiberg and Smith*, 1987] and that the constant C_v is a reflection of this state. This hypothesis has not been tested, and the equilibrium *Fedele and Paola* [2007] theory cannot be used to predict how, or how rapidly, an arbitrarily heterogeneous initial GSD would converge toward a constant value.

Another common grain size pattern in rivers is the gravel-sand transition. This transition is remarkable for several reasons: (1) it implies that river sediments have a bimodal distribution, regardless of lithology or geologic setting [*Smith and Ferguson*, 1995; *Knighton*, 1999; *Ferguson*, 2003; *Jerolmack and Brzinski*, 2010], (2) transport conditions change dramatically, from a near-threshold bed load channel in the gravel reach to a suspension-dominated channel in the sandy portion [*Paola et al.*, 1992; *Parker and Cui*, 1998; *Fedele and Paola*, 2007; *Jerolmack and Brzinski*, 2010], and (3) the transition takes place over a distance that is small compared to the upstream gravel reach [*Ferguson*, 2003; *Frings*, 2011]. Despite the relative abruptness of the gravel-sand transition, it is not infinitesimal; it is marked by a systematic downstream increase in the surface sand fraction (F_s) from 0 to 1 and a concomitant decrease in slope. There are surprisingly few field data documenting grain size and channel geometry patterns across the gravel-sand transition, and a complete theory is lacking. It has been suggested that the transition is governed partly by the mutual influence of sand and gravel on the threshold entrainment stress of each population [*Wilcock and Kenworthy*, 2002; *Ferguson*, 2003]. *Wilcock and Kenworthy* [2002] used laboratory data to demonstrate that an increase in sand fraction causes a decrease in the threshold Shields stress (τ_{*c}) for both gravel and sand; this effect is encapsulated in the empirical formula

$$\tau_{*\mathrm{cg}} = \tau_{*\mathrm{cg1}} + (\tau_{*\mathrm{cg0}} - \tau_{*\mathrm{cg1}})\,\exp^{-14F_s} \qquad (1)$$

where $\tau_{*\mathrm{cg1}}$ and $\tau_{*\mathrm{cg0}}$ is the critical Shields stress for gravel with $F_s = 1$ and 0, respectively. The decrease in Shields stress for the sand fraction is greater than that of gravel, causing a segregation of the two size fractions. *Ferguson* [2003] demonstrated that inclusion of this effect in a numerical model for river profile evolution produced realistic-looking gravel-sand transitions, but model results have not been compared to field data. At present, there is no analytic theory for sorting across the gravel-sand transition to complement the self-similar sorting theory for gravel.

Alluvial fans are useful systems to study in order to address the questions raised above. Many fans are strongly depositional and short in length, enhancing the dominance of size-selective deposition and suppressing the confounding effects of abrasion [cf. *Hooke*, 1967; *Blair and McPherson*, 1994; *Parker et al.*, 1998]. The apex of an alluvial fan presents a well-defined upstream boundary condition. Because fans are typically fed by bedrock canyons, which lack deposition, they receive an initially unsorted, heterogeneous GSD. *Stock et al.* [2008] documented rapid deposition and downstream fining, and an associated rapid decrease in channel hydraulic radius, on several alluvial fans. Their observed grain size trends appear to be qualitatively similar to those seen in much larger rivers, motivating us to quantify these patterns and seek generality. In this study we examine downstream trends in grain size and channel geometry on a kilometer-scale alluvial fan and make comparisons to previously published meter-scale laboratory experiments. We find that as the channel adjusts from deep and entrenched to shallow and depositional, the gravel fining is not self-similar, and we demonstrate that gravel sorts toward an apparent limit associated with equal mobility. Data suggest that sorting across the gravel-sand transition does indeed exhibit a self-similar form, which should help to guide further theoretical development.

2. Methods

The field site for this research is the Dog Canyon alluvial fan (Figure 1a) at Oliver Lee State Park near Alamogordo, New Mexico. Dog Canyon drains the Sacramento Mountain range, which is composed primarily of Precambrian and Permian limestone and makes up the eastern boundary of the Tularosa Basin [*Herrick*, 1900]. At its exit from the mountains, the channel crosses a normal fault, which marks the transition to the alluvial fan, and continues as an alluvial channel approximately 12 m wide and 1.2 m deep at the apex of the fan, defined as $x = 0$ km. A secondary channel splits from the main channel at approximately 0.7 km from the fan apex (Figure 1a). The channel bed is predominantly rounded gravel for the first 1.7 km, and grain size and channel depth decrease systematically over this distance (Figure 1). The fan then transitions over several hundred meters to a sandy bed, at which point alluvial channels become difficult to distinguish. Images show that there is no significant shape change for gravels moving down fan, suggesting that abrasion is negligible [*Sneed and Folk*, 1958; *Adams*, 1979] over the short gravel reach. Head-cutting gullies exist in the sandy portion of the fan and have incised up to approximately the beginning of the gravel-sand transition, ~1.7 km from the fan apex. They are distinguishable on the ground by their deep and narrow geometry; their interference with the more subtle alluvial channels at the gravel-sand transition make it impossible to characterize channel geometry on the sand-influenced portion of the fan.

We characterized channel geometry, particle size, and elevation along the fan. The long profile of the main channel of the alluvial fan, as well as the adjacent floodplain (i.e., fan surface), was measured using a Trimble GeoXH differential global positioning system (DGPS) with an associated lateral error of 0.1 m and a vertical error of up to 1 m. The DGPS data were smoothed using a 100 m moving-window average; the resulting profile for the main channel is seen in Figure 1a. The slope (S) above the gravel-sand transition may be approximated as constant and equal to $S = 0.04$ and rapidly decreases over a distance of 900 m to a lower constant value of $S = 0.01$ for the sand-bedded fan (Figure 1a). To allow comparison to sorting models and other river systems, downstream distance is normalized by the length of the gravel reach. We define this length as the distance from the fan apex to the gravel-sand transition, $x_* = x/L_g$, where L_g is determined as the location where channel slope has completed adjustment (i.e., where $S = 0.01$; see Figure 1a) and

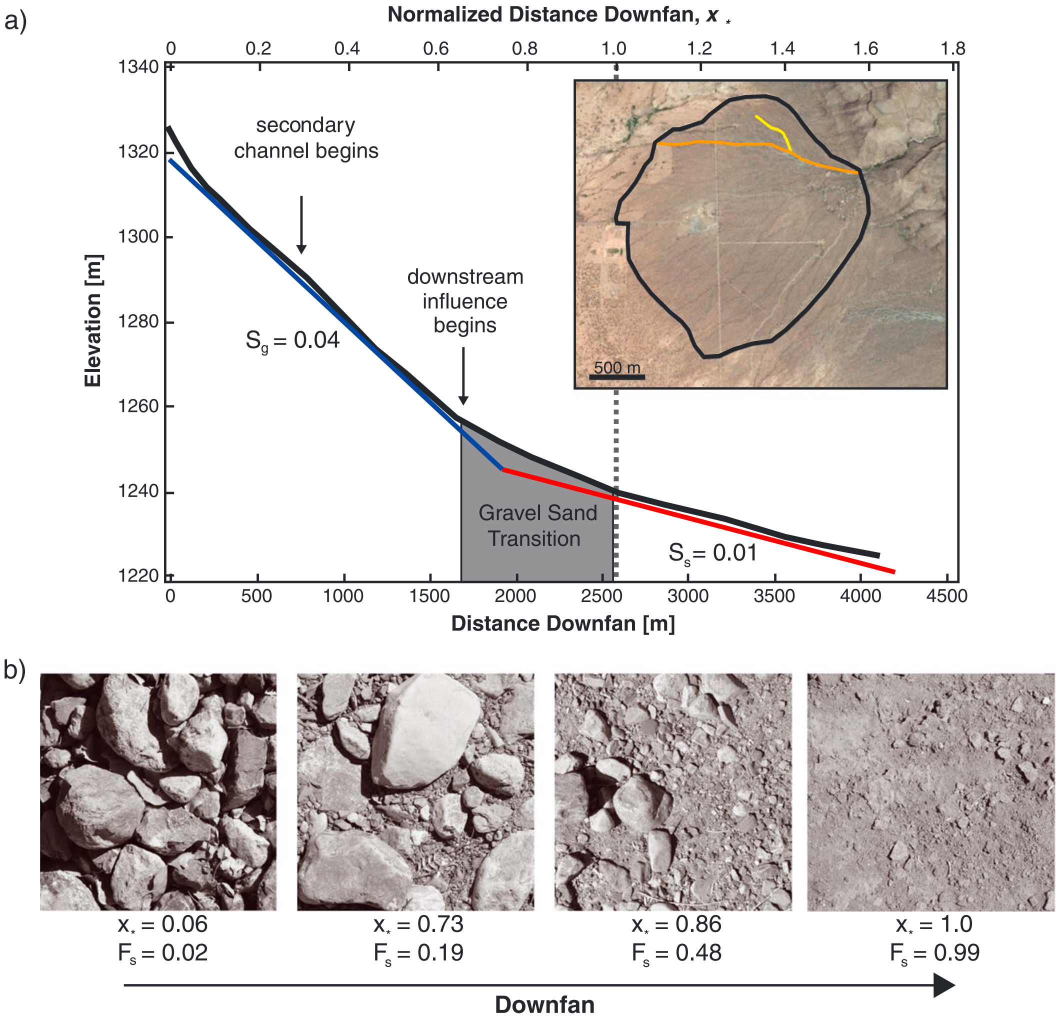

Figure 1. Dog Canyon alluvial fan. (a) Main channel profile from smoothed DGPS data. The upper gravel reach has an approximately constant slope of 0.04, which rapidly decreases to 0.01 after the gravel-sand transition. At $x_* = 0.3$ a secondary channel splits from the main channel. At $x_* = 0.63$ the gravel-sand transition begins and head-cutting gullies from downstream start to affect channel geometry. Inset shows aerial image of fan with the entire fan outlined in black, main channel denoted by the orange line, and secondary channel denoted by the yellow line. (b) Images of the channel bed illustrating increase in surface sand content.

the gravel fraction is zero. An image-based autocorrelation technique ("Cobble Cam") [*Rubin*, 2004; *Warrick et al.*, 2009] was used to measure the arithmetic mean grain size ($\bar{D}$) at 34 cross sections of the main channel spaced at intervals of approximately 125 m downstream. This technique also provides a measure of the variation in particle size akin to, but smaller than, the standard deviation, σ [see *Warrick et al.*, 2009]. At each cross section, ∼10 side-by-side images were taken to sample the entire width of the channel; values for $\bar{D}$ and variation from all images were averaged to produce representative values for each cross section. In order to produce estimates for σ at each cross section from images, each variation parameter was multiplied by a constant factor (1.5) that provided the overall best match with values for σ determined from pebble count data (see below). We also measured the surface sand fraction (F_s) of the bed in each image; due to a naturally occurring grain size gap, there was a clear visible distinction between sand (whose particle size could not be determined from images) and gravel (Figure 1b). Additionally, pebble counts ($n = 100$ grains) [*Wolman*, 1954] were completed at 21 cross sections of the main channel of the alluvial fan and were used to validate the image method and to examine the full GSD. Finally, channel geometry was measured at 18 locations over the first ∼1.4 km of the fan from its apex. Locations were selected at approximately constant intervals while preferentially choosing sites with well-defined channel banks. Locations for each cross-section site were recorded using the DGPS, and a laser range finder with compass attachment was used to survey the channel geometry.

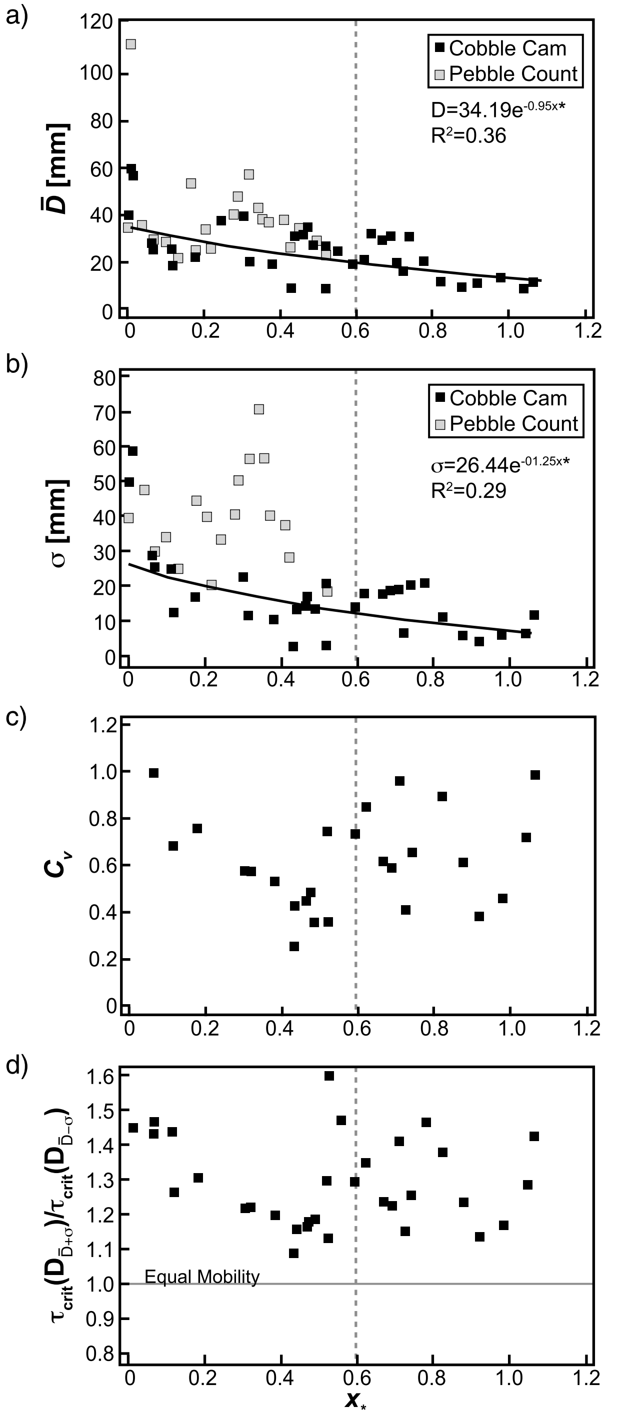

Figure 2. Gravel grain size sorting. Dashed line denotes location where channel bed transitions from gravel to sand matrix. (a) Grain size profile from both pebble count and image data shows a decrease downstream. (b) Standard deviation of grain size decreases downstream. Exponential fits in Figures 2a and 2b are to image data. (c) Coefficient of variation of grain size shows systematic decline in gravel region and then fluctuates when sand dominates channel. (d) Ratio of threshold Shields stress for grain size one standard deviation above and below mean. Plot shows that grain size distribution approaches a state of equal mobility.

3. Sorting and Channel Patterns Over the Gravel Reach

Mean grain size (> 2 mm) ($\bar{D}$), measured by both images and pebble counts, shows a distinct downstream fining pattern (Figure 2a). While trends from the two methods generally agree, pebble count data show larger variability. Inspection of the pebble count data reveals that the mean grain size does not converge to a stable value at 100 counts. Since the image analysis method averages over thousands of grains, we believe that these results are more reliable. The standard deviation of the grain size (σ) likewise shows a downstream decline for both methods (Figure 2b), with the image technique exhibiting a smoother trend. In contrast to the findings of *Fedele and Paola* [2007], C_v is not a constant value. The coefficient of variation instead declines steadily downstream to $x_* = 0.5$ and then begins to fluctuate. In other words, over the first half of the gravel reach, the standard deviation of grain size decreases faster than the mean, indicating a transient downstream sorting adjustment. Upstream of the location $x_* = 0.5$, sand makes up only a small portion of the substrate ($F_s < 0.1$), while F_s begins to rapidly increase downstream of this location (Figure 3a). We suspect that the gravel sorting pattern becomes disrupted by the presence of sand, because local patchiness of sand and gravel will create strong spatial variations in the threshold of motion [e.g., *Paola and Seal*, 1995]. Thus, we interpret the decrease in C_v up to $x_* = 0.5$ as the consequence of size-selective sorting of gravel by bed load transport in the (relative) absence of sand and the highly variable C_v downstream of this location as reflecting the absence of size-selective gravel sorting due to the presence of sand.

What physical meaning can be derived from the trend in C_v over the gravel portion of the fan? Our hypothesis is

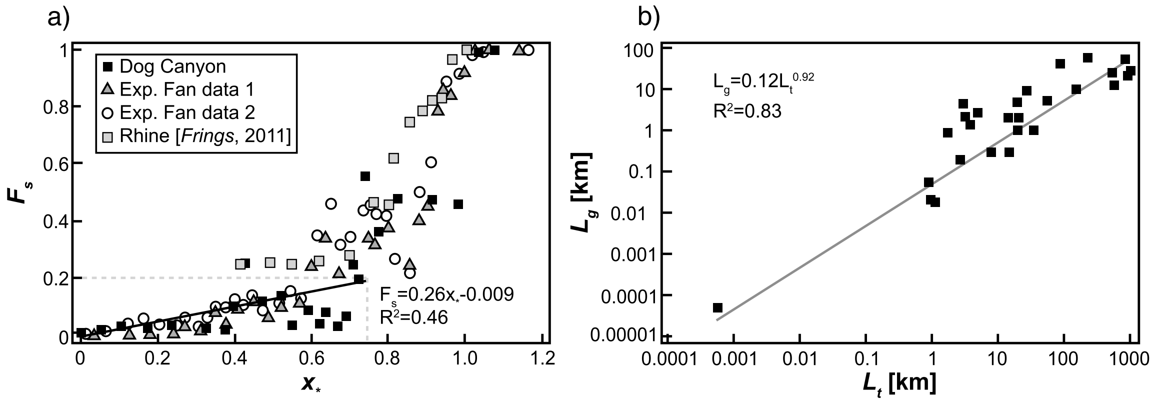

Figure 3. Gravel-sand transition. (a) Surface sand fraction profile for Dog Canyon alluvial fan, two experimental fans [*Reitz and Jerolmack*, 2012], and the Rhine river [*Frings*, 2011]. When sand fraction is plotted versus normalized downstream distance, the curves collapse indicating that the gravel-sand transition is self-similar. (b) Compilation of sizes of gravel-sand transitions from data collected by *Ferguson* [2003], Dog Canyon, and fan experiments. The best fit power law is close to linear (exponent of 0.92) indicating a self-similar "stretching" of the gravel-sand transition.

that gravels sort to a limiting GSD that reflects a state of equal mobility. To test this idea, we calculate the ratio of the threshold shear stress of the grain size one standard deviation above the mean ($\tau^c_{\bar{D}+\sigma}$) to that of the grain size one standard deviation below the mean ($\tau^c_{\bar{D}-\sigma}$), using the hiding function from *Wilcock and Crowe* [2003]:

$$\frac{\tau_i}{\tau_{50}} = \left(\frac{D_i}{D_{50}}\right)^b \tag{2}$$

where

$$b = \frac{0.67}{1 + \exp(1.5 - \frac{D_i}{D_{sm}})} \tag{3}$$

and where τ_i and τ_{50} are the critical shear stresses required to transport the *i*th and 50th percentile grain size D_i and D_{50}, respectively, and D_{sm} is the surface mean grain size. Our image technique only measures the mean, not the median, so we use $\bar{D}$ for both D_{50} and D_{sm}. Pebble count data indicate that the mean and median are typically within 20% of each other. The computed ratio of the threshold stresses, $\tau^c_{\bar{D}+\sigma}/\tau^c_{\bar{D}-\sigma}$, decreases toward unity from the apex of the fan to the location $x_* = 0.5$ (Figure 2d). We note that similar results are obtained using threshold stress values computed using the method of *Wiberg and Smith* [1987]. These calculations support the notion that gravels on the Dog Canyon fan sort toward a limit of equal mobility, at which point all gravel sizes have comparable entrainment stresses.

4. Gravel-Sand Transition

As the gravel reaches its sorting limit on Dog Canyon fan, the channel starts to rapidly transition from gravel to sand bedded. The pattern of downstream increase in F_s observed at Dog Canyon (Figure 3a) is similar to the numerical results of *Ferguson* [2003] for model runs that included the *Wilcock and Kenworthy* [2002, Figure 3] two-fraction threshold stress (1). Since *Ferguson* [2003] modeled a river profile and not an alluvial fan, this similarity suggests that the gravel-sand transition pattern is general to both systems. To test for generality, we seek self-similarity in the sand fraction profile by comparing Dog Canyon to available data from two other systems at very different scales. The first is from laboratory experiments of *Reitz and Jerolmack* [2012] on alluvial fans with a length scale $L_g \sim 10^{-3}$ km, which featured a bimodal mixture of granite chips and acrylic sand that scales to a cobble-sand mixture in the field; details of the experiment can be found in *Reitz and Jerolmack* [2012]. The second is the Rhine River, which is not an alluvial fan, with a length scale $L_g \sim 10^2$ km [*Frings*, 2011]. For all systems, the gravel-sand transition exhibits a very similar pattern of increasing F_s when distance is normalized by the length of the upstream gravel reach. Downstream changes in F_s appear to follow a sigmoidal curve (Figure 3a). On closer inspection, however, we see that the curve is not symmetric; it may be better approximated as two segments. In the first segment, sand fraction increases slowly and perhaps linearly from $F_s = 0$ at $x_* = 0$ to $F_s \approx 0.2$ at $x_* \approx 0.6$. In the second segment there is a rapid and qualitatively different pattern of increasing F_s toward a value of 1. This proposed separation occurs at a surface sand fraction of 20%, which coincides with the point that a river bed transitions from a gravel-supported to a sand-supported matrix [*Wilcock and Kenworthy*, 2002]. As a further test of self-similarity, we plot the length of the gravel-sand transition (as determined from slope changes in river profiles), L_t, against L_g for a large number of rivers using the compilation of *Ferguson* [2003] (Figure 3b). The data are best fit by a power law, which is nearly linear with an exponent of 0.92, implying that L_t is a constant fraction of L_g—of order 10^{-1}. Taken together, the collection of data over different scales leads to the tentative conclusion that the gravel-sand transition is self-similar.

5. Channel Geometry

At its exit from the canyon, the Dog Canyon channel is entrenched relative to the fan surface; the channel at the apex of the fan is relatively deep and narrow. At $x = 550$ m, the channel and fan-surface profiles converge (Figure 4a). Over this region, the measured channel depth (h) rapidly decreases and channel geometry shifts from being single-threaded with well-defined banks to a braided channel with indistinguishable boundaries (Figure 4b). For a self-formed gravel river at equilibrium, theory predicts that the

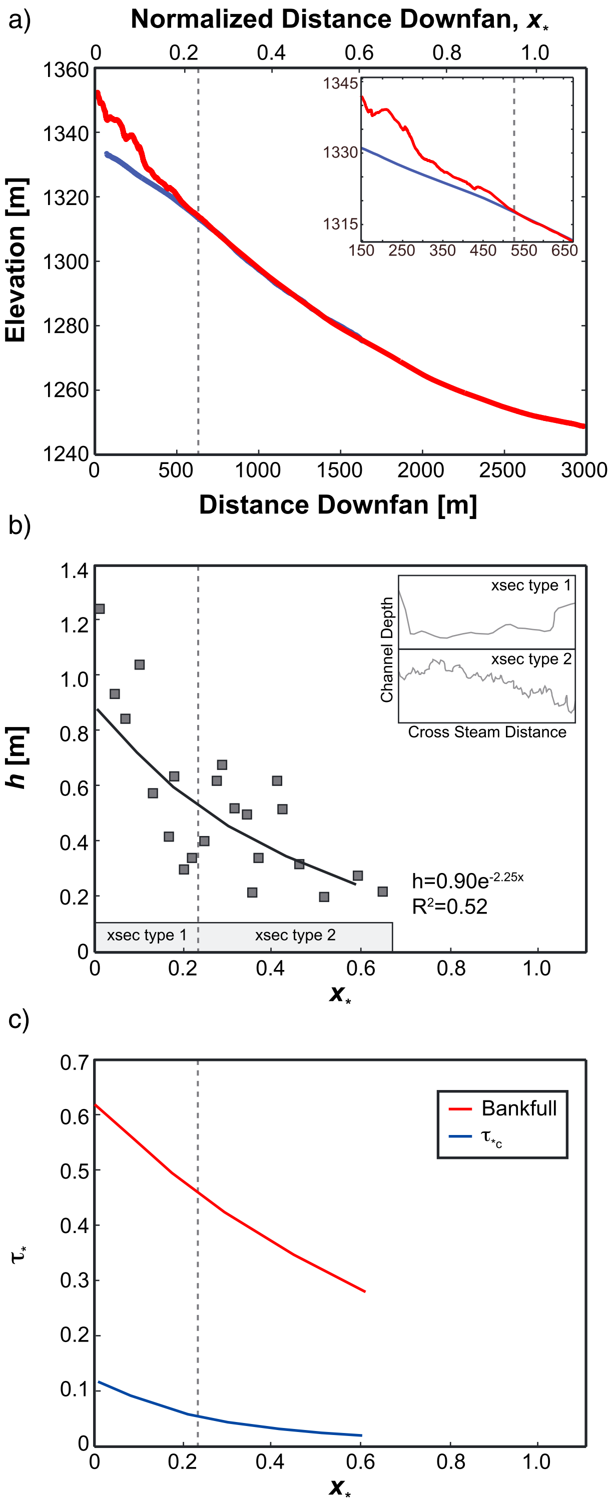

Figure 4. Channel geometry. Dashed line denotes location where the channel is no longer entrenched. (a) Comparison of fan profile (red) to channel profile (blue) from smoothed DGPS data. Channel is entrenched for the first $x = 550$ m. (b) Plot of measured average channel depths downstream. Where the channel is not entrenched, the depth is measured as twice the standard deviation of the cross-stream elevation profile. Inset shows the difference in channel geometry in the two regions as the channel transitions from well-defined banks to braided. (c) Plot showing estimated bankfull Shields stress (red) and calculated threshold Shields stress.

channel is adjusted such that the Shields stress at bankfull is slightly in excess of the threshold value for the median grain size [*Parker*, 1978]; the average value from field observations is $\tau_* = 1.4\tau_{*c}$ [*Paola et al.*, 1992; *Dade and Friend*, 1998; *Parker and Cui*, 1998; *Parker et al.*, 2007]. There is reason to believe, however, that this prediction should not hold on the Dog Canyon fan or alluvial fans generally. In laboratory alluvial fan experiments, *Reitz and Jerolmack* [2012] observed an avulsion (channel switching) cycle of channel cutting, progradation, and backfilling; for most of the avulsion cycle, the channel was entrenched at the fan apex and transitioned downstream to a shallower, depositional form. This pattern is common on alluvial fans and is observed at Dog Canyon (Figure 4a), which exhibits fan-head entrenchment and evidence of avulsion and formation of a secondary channel (Figure 1a). *Reitz and Jerolmack* [2012] proposed that alluvial fan channels are in a perennial state of disequilibrium due to the progradation-avulsion cycle and that channelization in this setting is a transient phenomenon. To understand controls on transport and channel organization on the Dog Canyon fan, we estimated the bankfull Shields stress profile, $\tau_*(x) = (h(x)S_g)/(R\bar{D}(x))$, from best fit equations to downstream trends in h and $\bar{D}$. We compare the calculated bankfull Shields stress with the expected threshold value using the two-fraction threshold model (1) with a best fit linear relation for F_s over the gravel region of the fan (Figure 3a); we computed $\tau_{*cg0} = 0.1082$ by applying the slope correction from *Mueller et al.* [2005] and assume a lower value of $\tau_{*cg1} = 0.01$ in accordance with *Wilcock and Kenworthy* [2002] (Figure 4b). Both Shields stress and critical Shields stress decrease exponentially downstream at approximately the same rate, making the ratio almost constant; however, the computed value $\tau_* \approx 6\tau_{*c}$ implies transport that is far above threshold. Moreover, "bankfull" at the entrenched fan apex is likely not related to any formative flood, as the transient channel is likely incising. Therefore, it is not clear that the estimated Shields stress profile is representative of any actual transport conditions. Based on the entrenched channel head and its transition to a shallow depositional channel downstream, we infer that the Dog Canyon fan is not in equilibrium and likely exhibits strongly nonuniform transport conditions downstream. It is possible that this transition drives the transient response in grain size sorting along the gravel-dominated portion of the fan.

6. Discussion and Conclusions

Field and laboratory data indicate that sand deposits gradually downstream in a gravel bed alluvial fan (or river), until it reaches a critical fraction ($F_s \approx 0.2$) that is sufficient to disrupt the gravel matrix. Three things happen at this point on the Dog Canyon fan: (1) the surface sand fraction increases rapidly, (2) channels quickly decay in depth and disappear, and (3) channel slope begins to decrease. We separate the discussion, therefore, into distinct problems associated with distinct patterns: sorting and channel adjustment in the gravel-dominated upstream segment of the fan and sorting across the gravel-sand transition.

Gravel sorting at Dog Canyon produces a downstream decrease in C_v, in apparent contradiction to the prediction and empirical findings of *Fedele and Paola* [2007]. However, this is not wholly unexpected. Downstream channel geometry indicates nonequilibrium and strongly nonuniform conditions, likely a result of transient channel adjustments due to the cycle of progradation and avulsion. The *Fedele and Paola* [2007] model does not treat mixed gravel-sand transport; it assumes a constant Shields stress and assumes equilibrium channel conditions. Transient channel dynamics may be causally related to the gravel-fining trend on Dog Canyon, and this may be a common feature of alluvial fans generally, but more work is needed. It is intriguing that gravel seems to sort to an equal mobility condition in a zone where aggradation is occurring (Figure 2d). This suggests that the channel downstream aggrades without sorting rather than reaching a bypass condition. Once a state of equal mobility is achieved, sand deposition increases rapidly and the gravel sorting pattern is destroyed. There may be a limiting C_v that reflects the limiting hydraulic sensitivity of size-selective entrainment [cf. *Fedele and Paola*, 2007]. *Jerolmack et al.* [2011] observed saturation of sorting effects after several kilometers in an aeolian dune field, at the point where the GSD achieved an empirical limit related to modes of grain transport. Future research should explicitly explore and test this idea.

Considering the gravel-sand transition, there is evidence that sorting across the transition follows a self-similar form (Figure 3). The collapse of data from systems spanning 6 orders of magnitude in spatial scale suggests that the dynamics controlling sand deposition are insensitive to local details of hydraulics, topography, and particle size. What is common to all systems is a bimodal GSD, in which the coarse particles deposit first to form a steeper portion of the channel while the finer particles travel in suspension. It appears that the gravel-sand sorting profile emerges rapidly and then is stretched as rivers lengthen—analogous to proposed self-similar gravel sorting patterns of *Fedele and Paola* [2007]. Our observations offer a tentative generalized profile for alluvial fans and rivers (Figure 3a) that may serve as a useful target for future modeling efforts.

Three concepts—size-selective sorting, equal mobility, and transient channel dynamics [*Parker and Klingeman*, 1982; *Wiberg and Smith*, 1987; *Fedele and Paola*, 2007; *Reitz and Jerolmack*, 2012]—have been used to explain the first-order trends in grain size and channel geometry observed on the Dog Canyon fan. Given the generality of these concepts, our conclusions may be critically tested by examining grain size trends on other alluvial fans.

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