Forum Reply

https://doi.org/10.1130/G47882Y.1

Why do large, deep rivers have low-angle dune beds?

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We thank Best et al. (2020) for taking a keen interest in our research (Kostaschuk and Venditti, 2019, 2020) on the processes that cause low-lee-angle dunes (LADs). Best et al. provide four main critiques:

First, Best et al. claim that our theory does not explain why LADs dominantly occur in flows >2.5 m; this observation is based on an earlier, and larger, data compilation by Bradley and Venditti (2017). We argue that over small dunes, wedge failures at the brinkpoint cause avalanches dominated by grain-to-grain collisions that come to rest at a steep, dynamic angle of repose (~30°), forming high-angle dunes (HADs). Over large dunes, correspondingly larger and looser depositional wedges liquefy upon failure due to high pore water pressures that occur as fluid tries to escape. At no point is our explanation linked to flow depth, but we do imply the low-lee-angle morphology is only possible for large dunes. Best et al. also argue that the occasional presence of HADs in a LAD dune field disproves the liquefaction theory, but HAD morphology may arise due to local bedload-dominated conditions within the field.

Best et al. appeal to Cisneros et al. (2020) to support their arguments. We attempted to explore how well the algorithm used by Cisneros et al. characterized dune morphology, but a request from our research group for the code was met with the response that the code was being "de-bugged". There is a data archive for Cisneros et al.; text files with spatial coordinates and measured properties. We discovered that the Cisneros et al. data are not 265,000 independent measurements (~5% of them are not unique), but rather samples from just a few hundred dunes in nine rivers, repeatedly sampled. Samples are immediately adjacent to one another, leading to a high degree of spatial interrelatedness that requires spatial averaging. We examined the spatial variation in Cisneros et al.'s "mean lee-side angle" measurements and crosschecked the variability against the same Parana dune maps used in the Cisneros et al. analysis. We found high levels of variation in immediately adjacent samples that could not be linked to physical characteristics of the dunes. It is not clear what the Cisneros et al. data tell us about liquefied avalanches that control LAD morphology, but the data are mischaracterized by Best et al., and the mean and range in Best et al.'s figure 1 are not meaningful measures.

Second, Best et al. state that bedform superposition on dunes shows that liquefied avalanches cannot occur. We recognize that bedform superposition is common on dunes, regardless of lee-side slope. Best et al. claims that the Cisneros et al. (2020) data show bedform superposition is nearly ubiquitous (~85%) on LAD stoss slopes. Cisneros et al. did not measure superimposed dunes on LADs, but rather measured all topographic variations, then applied a threshold to separate "large" from "small" dunes, but they provided no evidence that the small dunes are indeed superimposed. Superimposed stoss dunes are obvious in the Parana and Amazon River data sets but not in other data sets and, critically, Nittrouer et al. (2008) state that there is no evidence for superimposed dunes in the same Mississippi data used by Cisneros et al. Observations from the Fraser River, where LADs were first documented, are also devoid of superimposed dunes, unless the LADs are decaying.

Best et al. reason that the presence of lee-side dunes in the Amazon River precludes liquefied avalanches. The Amazon data were collected on the waning limb of the annual hydrograph. Dunes decay during a decrease in flow by stagnation of the existing bedforms and development of small, superimposed dunes that gradually cannibalize and flatten the larger bedforms (see summary in Leary and Ganti, 2020). The presence of superimposed dunes on Amazon LAD lee sides indicates that smaller dunes are consuming the LADs, and the processes that dominated LAD formation may no longer be active. Nevertheless, lee-side dunes can coexist with liquefied avalanches. We argue that downslope currents can form dunes on the lee side while the wedge develops, then get washed out by liquefied avalanches upon failure and reform.

Third, Best et al. states that dune lee-side shape is complex so continuous liquefied avalanches are not possible. Best et al. support this claim of complex lee-side shape with Cisneros et al.'s (2020) observations of the "maximum lee-side angle", arguing that their data show preferential locations of these slopes near the top or bottom of the lee side. Yet Cisneros et al. show a unimodal distribution of the maximum lee-side slope position that peaks where the avalanche slope should occur, contradicting this claim. We examined profiles extracted from Cisneros et al.'s Parana data and we cannot identify the complex lee-side slopes they describe. Instead, we observe single, straight segments, located in the middle of the lee-side profile that corresponds to the avalanche slope we describe. It is tempting to interpret Cisneros et al.'s maximum lee slope as the avalanche slope, but their metric will also identify the position of the wedge or the steep downslope faces of avalanche lobes; so, without constraints, it not a useful measure. We admit that the Amazon dunes in Best et al.'s figure 1 do have a complex shape, but it is because they are decaying after peak flow.

Fourth, Best et al. claim that we misinterpreted a LAD observed in ancient fluvial sandstone. Røe (1987) interpreted 1-m-high cross-sets inclined at 10–20° as being dunes transitioning to upper plane beds. Flows capable of producing a 1-m-high dune do not have Froude numbers >0.2 (Bradley and Venditti, 2017). The original interpretation of Røe's cross-sets as transcritical was perfectly reasonable at the time, because the existence of LADs was almost unknown. But in light of >40 years of research on LADs and the processes that dominate their formation, it is reasonable to revisit the original interpretation. Nevertheless, our conclusions are not critically dependent on this one ancient fluvial sandstone interpretation.

Best et al. end their critique with the speculation that turbulence modulation, among other processes, is somehow important for LAD formation. To date, it has been impossible to produce LADs in natural sand in small-scale experiments. LADs are characteristically large dunes that only appear in deep flows. If turbulence modulation were important, this scale effect would not exist. The only theory that accounts for this scale effect is liquefied avalanches.

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