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Downslope coarsening in aeolian grainflows of the Navajo Sandstone

David B. Loope [a,*], James F. Elder [b], Mark R. Sweeney [c]

[a] Department of Earth & Atmospheric Sciences, University of Nebraska, Lincoln, NE 68588-0340, United States
[b] 101 Smirle Avenue, Ottawa, Ontario, Canada KIY 0S4
[c] Department of Earth Sciences, University of South Dakota, 414 East Clark Street, Vermillion, South Dakota 57069, United States

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ABSTRACT

Downslope coarsening in grainflows has been observed on present-day dunes and generated in labs, but few previous studies have examined vertical sorting in ancient aeolian grainflows. We studied the grainflow strata of the Jurassic Navajo Sandstone in the southern Utah portion of its outcrop belt from Zion National Park (west) to Coyote Buttes and The Dive (east). At each study site, thick sets of grainflow-dominated cross-strata that were deposited by large transverse dunes comprise the bulk of the Navajo Sandstone. We studied three stratigraphic columns, one per site, composed almost exclusively of aeolian cross-strata. For each column, samples were obtained from one grainflow stratum in each consecutive set of the column, for a total of 139 samples from thirty-two sets of cross-strata. To investigate grading perpendicular to bedding within individual grainflows, we collected fourteen samples from four superimposed grainflow strata at The Dive. Samples were analyzed with a Malvern Mastersizer 2000 laser diffraction particle analyser. The median grain size of grainflow samples ranges from fine sand (164 μm) to coarse sand (617 μm). Using Folk and Ward criteria, samples are well-sorted to moderately-well-sorted. All but one of the twenty-eight sets showed at least slight downslope coarsening, but in general, downslope coarsening was not as well-developed or as consistent as that reported in laboratory subaqueous grainflows. Because coarse sand should be quickly sequestered within preserved cross-strata when bedforms climb, grain-size studies may help to test hypotheses for the stacking of sets of cross-strata.

1. Introduction

When wind crosses transverse dunes, flow separates at the dune brink and a cornice of sand accumulates high on the lee slope. Sand continues to accumulate until the angle of initial yield is exceeded, and a grainflow (sand avalanche) moves down the slope. Within the moving grainflow, the finest grains sieve downward through the coarser grains to the lower surface of the flow, perhaps lodging between grains in the underlying former surface, while the coarsest grains move to the uppermost, fastest-moving part of the flow, rolling over smaller grains (see review by Kleinhans, 2004). These processes result in inverse grading and downslope coarsening (vertical sorting); these phenomena have been observed in present-day dunes (Bagnold, 1954; Hunter, 1977; Lancaster, 1981; Sneh and Weissbrod, 1983), and have been generated in the lab (Makse et al., 1998; Kleinhans, 2004). Lab studies have shown that sieving during avalanching is especially well developed in bimodal mixtures in which the coarser grains are at least 1.5 times the diameter of the finer ones, and when there is a large difference in shape or density.

Grainflow strata in aeolian sandstones are well known for their high porosity and permeability, making them excellent reservoirs for hydrocarbons and water (Chandler et al., 1989; Howell and Mountney, 2001). There are few published studies, however, of down-slope coarsening within ancient aeolian grainflows. In their study of the Permian Cedar Mesa Sandstone of southeastern Utah, Langford and Chan (1993) observed that avalanche tongues become finer-grained and less well-defined near the tops of foresets. They also showed that the Cedar Mesa becomes increasingly fine-grained downwind, and noted that the Cedar Mesa is coarse compared to other aeolian sandstones of the Colorado Plateau region. The medium-grained grainflows in the formation are among its coarsest-grained deposits (Langford and Chan, 1993).

Aeolian sedimentary structures are more easily observed in Mesozoic sandstones of the Colorado Plateau than in active dunes or in Quaternary deposits. Although most of these ancient strata are strongly lithified, some, like those described here, are quite friable. We were therefore able to use a laser analyzer to produce grain-size data from multiple samples collected from individual Jurassic grainflows within a well-constrained stratigraphic context. There is still much to be learned about the texture of modern and ancient dunes. Interest in grain-size analysis has waned since the 1970's and 1980's (Ehrlich, 1983), but careful sampling and use of newly available instruments could yield important new insights.

* Corresponding author at: 214 Bessey Hall, Earth & Atmospheric Sciences, University of Nebraska, Lincoln, NE 68588-0340, United States. Tel.: +1 402 472 2663; fax: +1 402 472 4917.
E-mail address: dloope1@unl.edu (D.B. Loope).

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2. Navajo Sandstone in the study area

We studied grainflow strata of the Navajo Sandstone at three sites in the southern portion of its outcrop belt at Zion National Park in the west, and at Coyote Buttes and The Dive to the east (Fig. 1). At each study site, thick sets of grainflow-dominated cross-strata (Fig. 2) that were deposited by large transverse dunes (Hunter, 1981; Hunter and Rubin, 1983; Loope et al., 2001; Loope and Rowe, 2003) comprise the bulk of the Navajo Sandstone. At the two eastern sites, the cross-strata in the lower part of the formation dip toward the southeast and commonly show well-developed, meter-scale depositional cycles in which darker-colored, coarser grainflow strata and lighter-colored, finer wind-ripple strata alternate along the dip direction (Hunter and Rubin, 1983; Loope et al., 2001). To explain the cycles, Hunter and Rubin (1983) made a strong case for seasonal wind shifts and an annual periodicity. Loope et al. (2001) showed that slumped cross-strata record rainfall events recurring at the same (annual) periodicity, and related both phenomena to a monsoonal climate. In the uppermost Navajo Sandstone, most cross-strata dip to the southwest (Marzolf, 1983), and generally do not show well-developed depositional cycles.

Grainflow strata intertongue downdip with wind-ripple strata (Fig. 2; Kocurek, 1991); updip, individual tongues are divided by thin, fine-grained ‘pinstripe’ layers (sensu Fryberger and Schenk, 1988). The updip pinchouts of wind-ripple tongues show that they were emplaced by subordinate winds flowing obliquely along and up the lee face. Grainflow tongues at Coyote Buttes and The Dive are typically 3–4 cm thick (Loope, 2006), and the grainflows that we sampled at Zion are on the order of 10 cm thick. In many cases, a grainflow stratum can be traced along strike for 3 to 4 m, and in some cases, for 10 m. Because most individual avalanche tongues on present-day dunes are less than 2 m wide (Breton et al., 2008), it is likely that grainflow strata wider than 2 m are lateral amalgamations of several avalanche tongues, with no visible delineation of adjacent, partially overlapping grainflow tongues. The great thickness of Jurassic grainflows relative to modern ones could be explained by vertical amalgamation of the ancient strata — pinstripes may not have been deposited on the upper surface of every grainflow. Alternatively, higher Jurassic dunes may have simply generated thicker grainflows (Kocurek and Dott, 1981).

Bounding surfaces between sets of Navajo cross-strata are typically planar to broadly concave-up (Fig. 3), but one 15-m-deep, steep-sided scour near our section at The Dive truncates four tabular sets of cross-strata. Meter-thick, silty sandstones with thin, mudcracked, silty laminae and transported mud chips are present at a few widely scattered locations (Loope and Rowe, 2003), but carbonate rocks (Eisenberg, 2003; Parrish and Falcon-Lang, 2007) are absent.

The mm-thick pinstripes that separate the preserved grainflows contain fine and very-fine sand that may represent the direct fallout of grains carried over the dune brink. However, the merging of each pinstripe at its down-dip terminus with a wind-ripple tongue (Fig. 2), suggests that many of these pinstripes may have been emplaced by upslope flow within lee eddies.

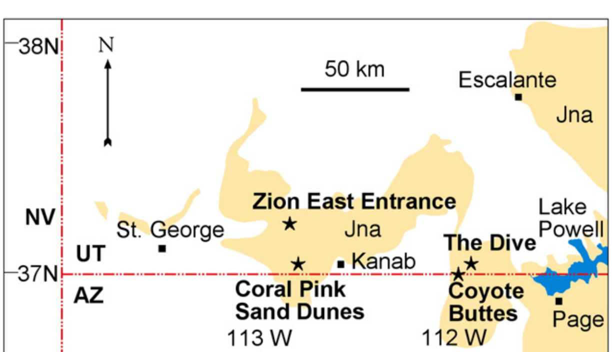

Fig. 1. Locations of study sites. Stars show locations of the four study areas and shaded areas show outcrop of Navajo Sandstone.

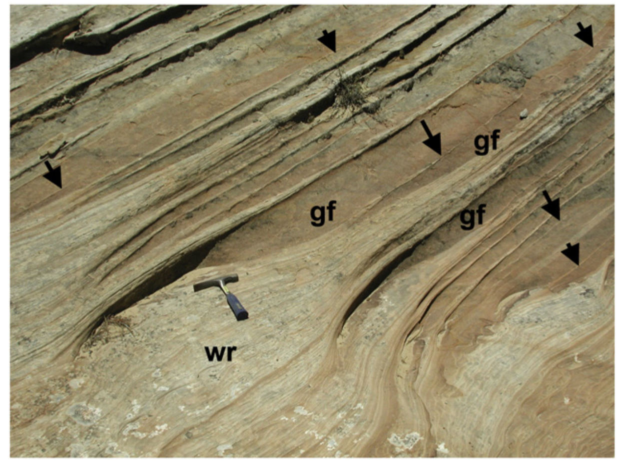

Fig. 2. Interbedded grainflow (gf) and wind-ripple (wr) bedding (Zion East Entrance). Pinstripes (arrows) merge down-dip into tips of thin wind-ripple wedges.

Two lines of evidence suggest that the water table was relatively near the surface during deposition of the dune cross-strata. Invertebrate burrows are abundant in at least three different stratigraphic intervals and thousands of vertebrate tracks are present within one interval (Loope and Rowe, 2003; Loope, 2006). Contorted bedding, likely the result of seismic shaking of shallowly buried, water-saturated sand (Doe and Dott, 1980; Horowitz, 1982; Bryant and Miall, 2010), is present within grainflow-dominated strata at many different stratigraphic levels in the study area.

Three unconformities can be recognized at Coyote Buttes on the basis of contrasting sedimentary structures (Loope and Rowe, 2003). The knife-sharp contact between cross-strata deformed by abundant insect burrows and vertebrate tracks and overlying, trace-fossil-free cross-strata near the base of our Coyote Buttes section (Fig. 4, sets 1 & 2) is both an unconformity and a signal of climate change. Other Navajo outcrops within the region also show evidence of pronounced climate change. Stromatolites up to 2 m in diameter (Eisenberg, 2003) and individual thin limestone beds displaying 15 m of depositional relief (Loope et al., 2004) that are both under- and overlain by thick aeolian cross-strata also testify to prolonged pluvial episodes within an otherwise arid sand sea.

Grainflow strata are the coarsest, best-sorted, most porous deposits of aeolian sandstones (Chandler et al., 1989; Howell and

Fig. 3. Northwestward view of large-scale, aeolian cross-strata at Coyote Buttes. Escarpment is about 75 m high. Numbered crossbed sets coincide with those on stratigraphic section of Coyote Buttes (Fig. 4).

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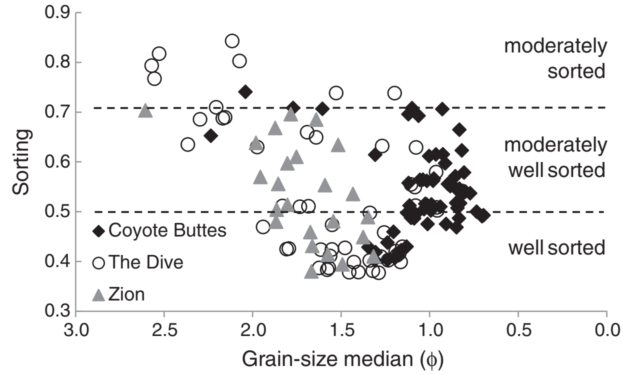

Fig. 4. Median grain size vs. sorting for all sites.

Mountney, 2001). Grainflows in our study area are coarser grained and less lithified than Navajo outcrops in other localities in southern Utah. In some portions of our eastern study areas, numerous particles within coarse, poorly lithified grainflow strata (but not wind-ripple strata) were crushed during late Mesozoic, compressional deformation (Laramide orogeny), leading to development of near-vertical compaction bands (Mollema and Antonellini, 1996; Schultz et al., 2010). The weak lithification of the grainflow-dominated rocks at the eastern study areas makes them especially vulnerable to wind erosion (Loope et al., 2008), and allows them to be easily disaggregated for grain-size analysis.

The stratigraphically lowest section (Coyote Buttes; Fig. 4) is composed of southeast-dipping cross-strata with prominent depositional cycles. The higher sections are composed of southwest-dipping cross-strata that lack obvious depositional cycles.

To better understand the grainflow avalanche process, photographs and video recordings were made of avalanches on a modern seven meter transverse dune at Coral Pink Sand Dunes State Park, located approximately midway between the Coyote Buttes and Zion study sites (Fig. 1). The sand at Coral Pink is well sorted, fine to medium sand that is dominantly derived from weathering of the Navajo Sandstone.

3. Methods

Three continuous stratigraphic sections (composed exclusively of aeolian cross-strata) were measured and sampled at Coyote Buttes, The Dive, and the East Entrance to Zion National Park.

One grainflow stratum was sampled per cross-strata set. Grainflow strata were sought so that a top-to-bottom series of samples could be collected along a line parallel to dip, thus increasing the probability of sampling a single grainflow tongue. Although we were always able to find visually-undivided individual grainflow strata, in many sets there were no grainflows exposed strictly parallel to dip. Thus it was necessary to move laterally slightly going downslope, which may have resulted in sampling of sediment from adjacent avalanche tongues that had amalgamated along strike.

Samples at Coyote Buttes and Zion were collected by gently dislodging grains using the tip of a screwdriver from small (~3 cm × 3 cm) patches of friable outcrops. The surface was cleared to a depth of about 3 mm to avoid endolithic microbes. Gravity carried loosened grains from the sloping surface into a collection bag that was positioned within 1 or 2 cm of the point of detachment. Samples at The Dive came from short cores drilled with a 25 mm bit. Cores were bagged in the field. In the lab, the outermost 3 mm (possibly containing grains powdered by drilling) were removed by finger pressure, and then a sample for analysis was obtained by further rubbing. To compare the two collection methods, replicate samples were collected for one set at The Dive. The two methods produced nearly identical results.

A total of 139 samples from thirty-two sets of Navajo Sandstone cross-strata were analyzed. Particle analysis was performed by laser diffraction using Malvern Mastersizer 2000 with a Hydro 2000MU dispersion unit. Samples of approximately 5 g produced optimal obscuration; they were sonicated for 2 min (20 μm displacement) to separate any diagenetic cements or loose coatings from grains. Each sample was measured three times to produce an averaged result. Grain volume that exceeded the upper reporting range of the Mastersizer 2000 (1096 μm) were allocated to an upper bin with boundaries from 1096 to 1259 μm. We determined the median grain size and degree of sorting following Folk and Ward (1957), using four-point Bezier interpolation to calculate percentiles. Box plots were constructed to visually depict grain size distributions and changes along grain flow paths.

To measure grading perpendicular to grainflow bedding, close-spaced samples from four individual grainflows were sampled at The Dive site with a 5 mm-diameter, thin-walled steel tube.

Photographs and video recordings of avalanches on the slipface of a modern transverse dune were made during a high wind event (estimated speed of about 40 km/h), when wind was roughly perpendicular to the brink, the sand was dry, and previous conditions had shaped the dune with a near-classic transverse profile. Photographs were taken when the sun angle was nearly parallel to the slipface, greatly enhancing the visibility of surface features that are otherwise difficult to see.

4. Results

The median grain size of grainflow samples in the study area ranges from fine sand (2.61 phi; 164 μm) to coarse sand (0.70 phi; 617 μm). Using Folk and Ward (1957) criteria, all samples are well-sorted to moderately-well-sorted (Fig. 4). The grain size distributions are generally log-normal and unimodal, disregarding a distinct minor peak created by loosened diagenetic cements and dislodged coatings (which was zeroed out) (see Supplementary Data for sample analysis results).

Fig. 5 summarizes the results of grainflow sampling of consecutive cross-strata sets in three stratigraphic columns, one at each of the three study sites. Though coarsening across sets is often only slight and/or erratic, of cross-strata with two or more samples, most (all but one of the twenty-eight sets) show coarsening, in that they have a greater median grain size at the base than at the top of the crossbed set (Fig. 6). Relative median grain size (in phi units) correlates ($R^2 = 0.13$) with vertical height above the grainflow toe (Fig. 7a). The change in median size with height is statistically significant at the 95% confidence interval ($p < 0.001$). Slight correlation ($R^2 = -0.014$) was found between relative sorting and vertical height (Fig. 7b), but this correlation is not statistically significant ($p = 0.147$).

Fig. 8 summarizes the results of sampling perpendicular to flow within four consecutive grainflows. Three of the four individual grainflows showed no grading perpendicular to flow except near their base, where there was normal grading (downward coarsening). One grainflow showed no apparent grading throughout.

Videos of avalanching sand at Coral Pink Sand Dunes (Fig. 9) show centimeter-scale, wave-like patterns on the surface of flowing avalanche tongues. Flows are leisurely, and typically progress by two processes: 1) tumbling flow over the existing slipface surface, and 2) slumping in which downslope portions of the existing slipface become re-mobilized. The former front of the tongue commonly merges into a moving slump, and the downslope edge of the slump becomes the new leading edge of the avalanche tongue. As the moving slump becomes integrated into the flow, wave-like patterns appear on its surface. Small patches of tumbling, thin secondary avalanches often break out on the surface of the flow, usually ceasing after flowing about 10 cm. When a flow reaches the toe of the dune, back-

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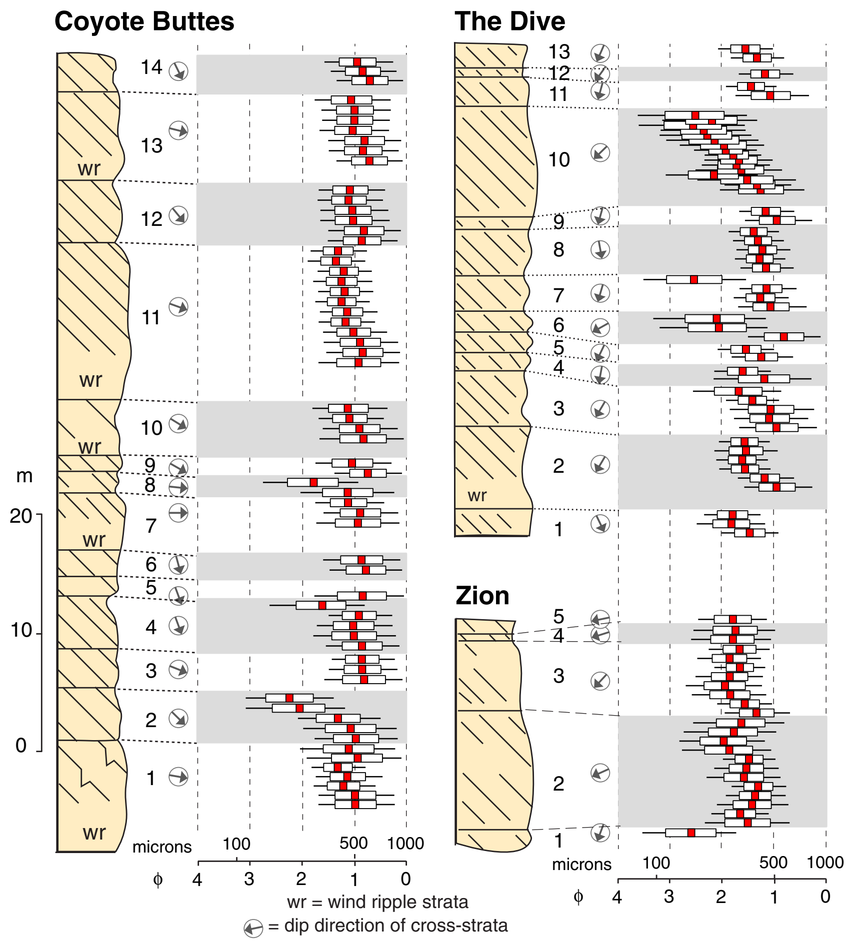

Fig. 5. Stratigraphic sections and box plots of grain size data. The box represents the 25th through the 75th percentile of the data. The middle band represents the median size (enlarged for visibility). The "whiskers" represent the 10th and 90th percentiles.

pressure propagates upward and soon the flow stops, freezing the avalanche tongue in its state at that moment.

Grainflows at Coral Pink are typically about 2 cm thick at their centers near the toe of the dune. The slipface of the dune shown in the videos was about 13 m long, on a dune about 7 m high. Angle of repose was about 32°.

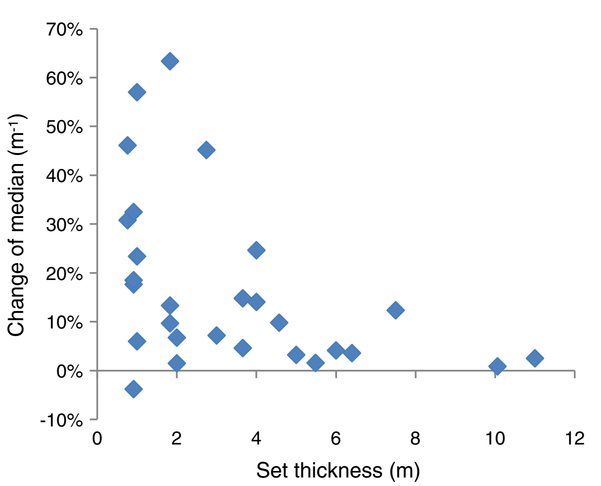

Fig. 6. Change per meter downslope of median grain size vs set thickness, for each set, where the overall change is the difference between the median grain size of the base sample and the topmost sample. Positive values indicate coarsening. Most sets (all but one of twenty-eight) showed downslope coarsening, but as shown in Fig. 4, it was not well-developed or consistent along many grainflows.

5. Discussion

5.1. Grading within grainflows

Kinetic sieving ought to result in inverse grading, yet three of four of the grainflows, each about 5 cm-thick, were found to have normal grading near their bases, with no significant grading found otherwise (Fig. 8). The videos of modern avalanches at Coral Pink Sand Dunes suggest a complex, perhaps chaotic internal structure, which could conceivably complicate grading generated by kinetic sieving. This appeal to randomness, however, is undermined by three of the four ancient grainflows showing the same (normal-graded) pattern.

Hunter (1977) reported coarser grains at both the upper and lower surfaces of grainflows in the lower slipface. Coarser grains at the upper surface are expected via the process of kinetic sieving. Coarser grains at the lower surface (shown by our intra-grainflow sampling), perhaps could have been the leading-edge, coarser grains of tumbling avalanche tongues that were overrun and buried by the flow. In this scenario, only the upper portion of an avalanche is flowing (or flowing faster than underlying layers), and it flows to the tip which gets buried. Surface flow continually replenishes the tip. Kinetic sieving is likely always occurring, proportional to movement, but lower portions of the flow may have little movement once buried. This mechanism may help explain how grainflow deposits can reach thicknesses of many centimeters.

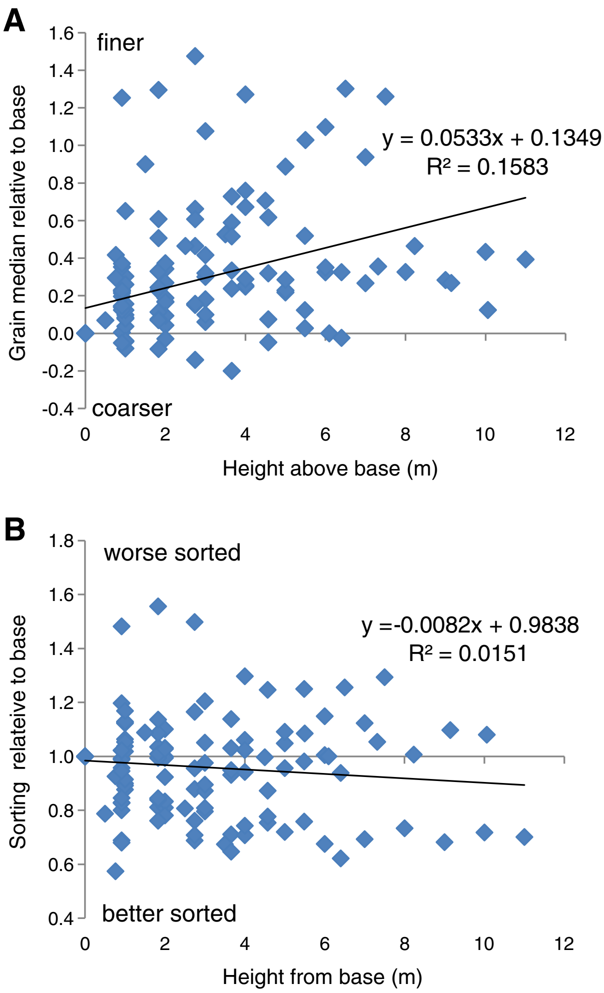

Fig. 7. Grain-size distribution parameters vs height above base. (A) Grain-size median (ϕ_i^*) relative to base sample vs. height, for each sample, given by $\phi_i - \phi_{base}$ on a per set basis. (B) Sorting (σ_i^*) relative to base sample vs. height, for each sample, given by σ_i/σ_{base} on a per set basis.

It is unlikely that the entire thickness of a many-centimeters-thick grainflow was ever in motion at once, and thus ever had a chance to undergo kinetic sieving across its full vertical cross-section. More likely, as sand drained downward from an eroding cornice, it initially flowed over the former slipface and, if there was back-pressure, flowed over or around the just-laid deposit, tumbling over it and/or entraining or pushing layers of it in slumps. Building up the grainflow thickness continues until the cornice is finally exhausted. Kinetic sieving would only be active in surficial layers (probably about one or two centimeters thick) as they flow and/or slump. If the volume of sand in the cornice was large, the result of these mechanisms was a many-centimeter-thick flow with complex internal textual structure, including shear planes and partial-height grading.

Despite normal grading or localized complexity within a grainflow, the overall trend downslope is for grain size to coarsen, which implies that kinetic sieving is dominating even if there are other mechanisms that oppose it.

5.2. Downslope coarsening in grainflows

Our sampling of grainflows at one meter intervals did not show continuous and monotonic downslope coarsening. Deviations in grain size along the length of a single grainflow may be attributed to: 1) inadvertent sampling of superimposed, amalgamated grainflows, 2) incorporation of sand from older flows during transport downslope, or 3) inadvertent sampling of lateral margins of flows. If grainflows have complex internal structures, as implied by videos and our measurements of grading, then it is also possible that downslope variations in measured grain size are due to variations in the location within a grainflow (with respect to the base of the stratum) where a sample was obtained. Our samples were obtained from the exposed surface of the eroded grainflow, with no regard to controlling for perpendicular height from the base of the flow.

5.3. Sorting of grainflows

The sampled grainflows generally showed erratic and little net sorting downslope (Fig. 7b), whereas studies of subaqueous slipfaces (e.g., Kleinhans, 2005) find that sorting increases downslope. A possible explanation for the lack of a strong trend in downslope sorting is that the much longer and thicker deposits of the study area accreted in a more complex and drawn-out process, in time and space, than the shorter, thinner flows typical in laboratory flumes. Unmeasured textural parameters, such as grain shape, also may have confounded the results.

The great thickness of many grainflow strata at the study sites (Figs. 2, 8) suggests that the dunes were typically quite high. It is possible that most of the coarsening occurred high on the slipface, and by the time the sand reached the lower (preserved) part of the dune, it

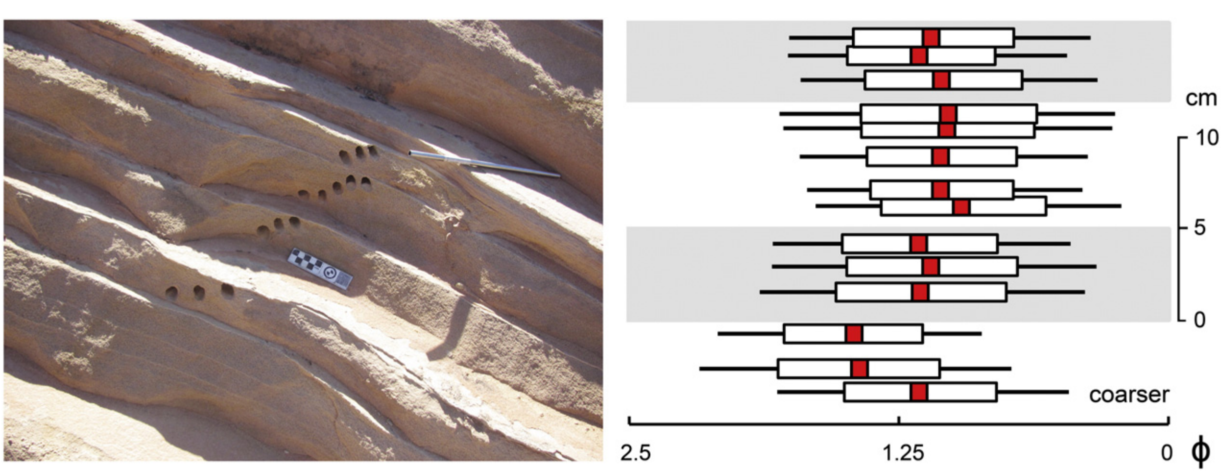

Fig. 8. Grading within individual grainflows. Although aeolian grainflows often develop inverse grading, subsampling of four Navajo grainflow tongues at The Dive found normal grading perpendicular to stratification. Stratification in the photo is made evident mostly due to the presence of distinct, preferentially cemented pinstripes that constitute a tiny proportion of the rock.

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was already as sorted as it could be (due to differences in grain shape, for example), thus accounting for the only-slight downslope coarsening found in many of the studied grainflows.

5.4. Dune height

Using their hypothesis of downwind bedform climb, and based on studies in southwestern Utah where preserved crossbed sets average 10 m, Rubin and Hunter (1982) estimated that the Navajo dunes averaged at least 33 m in height. Paola and Borgman (1991) explained the variability of set thicknesses in aggrading fluvial crossbed sets via random or chaotic scour and fill processes. Flume experiments have shown that with this model, too, the mean preserved thicknesses of crossbed sets are about one third of bedform height (Leclair, 2002).

Our study found a general trend toward downslope coarsening of grain size, although sampling 'noise' and/or unidentified dependencies complicate the trend. Perhaps a clearer 'signal' could be obtained by averaging samples from several grainflow slopes within a particular set. If a function could be found to relate grainflow textural characteristics to distance downslope, perhaps it could be inverted to find the height of the original dune, or height relative to other dunes in the same stratigraphic column.

5.5. Why so much coarse sand?

Most present-day, coastal aeolian dunes are dominantly composed of fine sand; inland dunes range from fine to medium sand (Ahlbrandt, 1982). Dunes at the downwind margin of ergs are typically finer than at upwind sites (Langford and Chan, 1993 and references therein). The major source of sand for the Navajo Sandstone (and for other aeolian sandstones on the Colorado Plateau) was the Appalachian Mountains (Dickinson and Gehrels, 2003; Rahl et al., 2003). Most of this sand was probably transported westward by rivers to a coast in present-day Nevada, possibly moved southward by longshore drift, and finally blown inland several hundred kilometers by northwesterly winds. It seems highly unlikely that the abundant coarse sand at Coyote Buttes arrived there via this long transport path. Some paleogeographic maps for the Early Jurassic (Blakey, 2008; Blakey and Ranney, 2008) show eroding highlands a few hundred kilometers south of our study sites that could have provided coarse debris to north-flowing ephemeral streams. Study of detrital zircons from Navajo samples from these localities could test this hypothesis.

5.6. Preferential trapping of coarser grains in preserved cross-strata

Vertical trends in grain size within cosets of ancient cross-strata could help to reveal the processes (Rubin and Hunter, 1982; Paola and Borgman, 1991) involved in the stacking of cross-strata. On dune stoss slopes, coarse grains lag behind fine and medium grains during saltation transport, and then race ahead during avalanching of the lee slope. If dunes are not climbing, all grains are recycled and the texture of the bedforms doesn't change. When dunes climb, the lower portions of the crossbed set are left behind. Coarse grains are therefore more likely to be sequestered within truncated cross-strata than the finer grains deposited higher on the slope. Coarser grains should therefore be lost relatively quickly from steadily climbing bedforms — fewer coarse grains are recycled, and coarse grains cannot "catch-up" with the faster moving, finer grains. Higher sets, because they have travelled further than the lower sets since climb was initiated, should be finer grained. No progressive upward loss of coarse grains is evident in our sections, so we hypothesize that preferential filling of rare, deep scours (Paola and Borgman, 1991) better explains the stacking than the climb of laterally adjacent bedforms.

6. Conclusions

Analysis of Navajo Sandstone grainflow strata found that these strata are generally coarsest at the base of each set of cross-strata, and become increasingly coarser-grained down the dip slope. This is evidence of sorting processes on the lee slopes of ancient dunes, in accordance with field and laboratory observations of dry grainflows. In contrast to the results of Kleinhans (2005), however, our samples from Navajo grainflows do not become better sorted downslope.

Perpendicular normal grading within grainflows we sampled is evidence that processes other than kinetic sieving also operated. Video recordings of present-day dunes suggest that grainflows have complex internal structures.

Further use of precise sampling and laser analysis in studies of the texture and structure of the lee-face deposits in modern dune fields would aid understanding of the deposits of ancient sand seas and the winds that moved them.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.sedgeo.2012.04.005.

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