# GRAIN-SIZE EVOLUTION IN SUSPENDED SEDIMENT AND DEPOSITS FROM THE 2004 AND 2008 HIGH-FLOW EXPERIMENTS IN THE COLORADO RIVER THROUGH GRAND CANYON, ARIZONA

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## INTRODUCTION

Since the closure of Glen Canyon Dam in 1963, the hydrology, sediment supply, and distribution and size of modern alluvial deposits in the Colorado River through Grand Canyon have changed substantially (e.g., Howard and Dolan, 1981; Johnson and Carothers, 1987; Webb et al., 1999; Rubin et al., 2002; Topping et al., 2000, 2003; Wright et al., 2005; Hazel et al., 2006). The dam has reduced the fluvial sediment supply at the upstream boundary of Grand Canyon National Park by about 95 percent. Regulation of river discharge by dam operations has important implications for the storage and redistribution of sediment in the Colorado River corridor. In the absence of natural floods, sediment is not deposited at elevations that regularly received sediment before dam closure. There has been a systemwide decrease in the size and number of subaerially exposed fluvial sand deposits since the 1960s, punctuated by episodic aggradation during the exceptional high-flow intervals in the early 1980s and by sediment input from occasional tributary floods (Beus and others, 1985; Schmidt and Graf, 1990; Kearsley et al., 1994; Schmidt et al., 2004; Wright et al., 2005; Hazel et al., 2006). Fluvial sandbars are an important component of riparian ecology that, among other functions, enclose eddy backwaters that form native-fish habitat, provide a source for eolian sand that protects some archaeological sites, and are used as campsites by thousands of river-runners annually (Rubin et al., 1990; Kearsley et al., 1994; Neal et al., 2000; Wright et al., 2005; Draut and Rubin, 2008).

In an effort to rebuild sandbars through the Marble Canyon and Grand Canyon reaches of the Colorado River (Fig. 1), high-flow experiments (HFEs) were conducted in 1996, 2004, and 2008 (Webb et al., 1999; Topping et al., 2006; U.S. Department of the Interior, 2008). During the 7-day, 1,270 m3/s HFE dam release in March 1996, sand that was newly deposited on sandbars had been eroded primarily from the lower-elevation portions of upstream bars, not from the main channel bed. This finding, coupled with rapid decreases in suspended-sediment concentrations during the 1996 HFE indicating sediment-supply limitation, demonstrated that future high flows would require substantially more sediment in order to rebuild sandbars effectively; without sufficient tributary sediment inputs, a mainstem high flow would cause net sandbar erosion rather than deposition (Rubin et al., 2002; Topping et al., 2006). The second HFE occurred in November 2004 after substantial inputs of tributary sediment were followed by two months of relatively low dam releases (<280 $m^3/s$) intended to retain sand in the main channel before the high flow. Although the 60-hour 1,160 $m^3/s$ 2004 HFE release was thus conducted under sediment conditions that were enriched relative to those of 1996, substantial increases in sandbar area and volume in 2004 occurred only in upper Marble Canyon (i.e., the first 50 km of the 400-km-long Marble and Grand Canyon reach; Fig. 1, Topping et al., 2006). Based on sandbar and suspended-sediment response to the 2004 HFE, Topping et al. (2006) concluded that still more sand would be required in future high flows in order to enlarge sandbars along a greater length of the river corridor.

The third high-flow experiment took place in March 2008—a 60-hour, 1,200 $m^3/s$ dam release that followed substantially above-average sediment inputs to Marble Canyon by the Paria River and other tributaries. The hydrograph during the 2004 and 2008 HFEs was virtually identical; the flows differed primarily in the amount of new sediment present in the main channel, with conditions for the 2008 flow being substantially more sediment-rich than in 2004. In the year before the 2008 HFE, the Paria River and Little Colorado River (Fig. 1) supplied 0.92 and 1.12 million metric tons of tributary sediment, respectively, compared with 0.63 and 0.19 million metric tons supplied by those tributaries respectively in the year before the 2004 high flow (D.J. Topping, unpublished data). Topographic surveys conducted after the 2008 high flow indicated that sandbar area and volume increased substantially as a result of the high flow; sandbars were as large or larger after the 2008 HFE than they had been after the 2004 or 1996 HFEs (Hazel et al., in review). Here, we compare trends in suspended-sediment grain size (measured at five stations) and grain size in sandbars formed by the 2004 and 2008 high flows. Other analyses of suspended-sediment behavior during these HFEs, including modeling of transport dynamics and suspended-sediment measurements made longitudinally with the high flow, will be discussed elsewhere (Wright et al., this volume; Topping et al., in prep.).

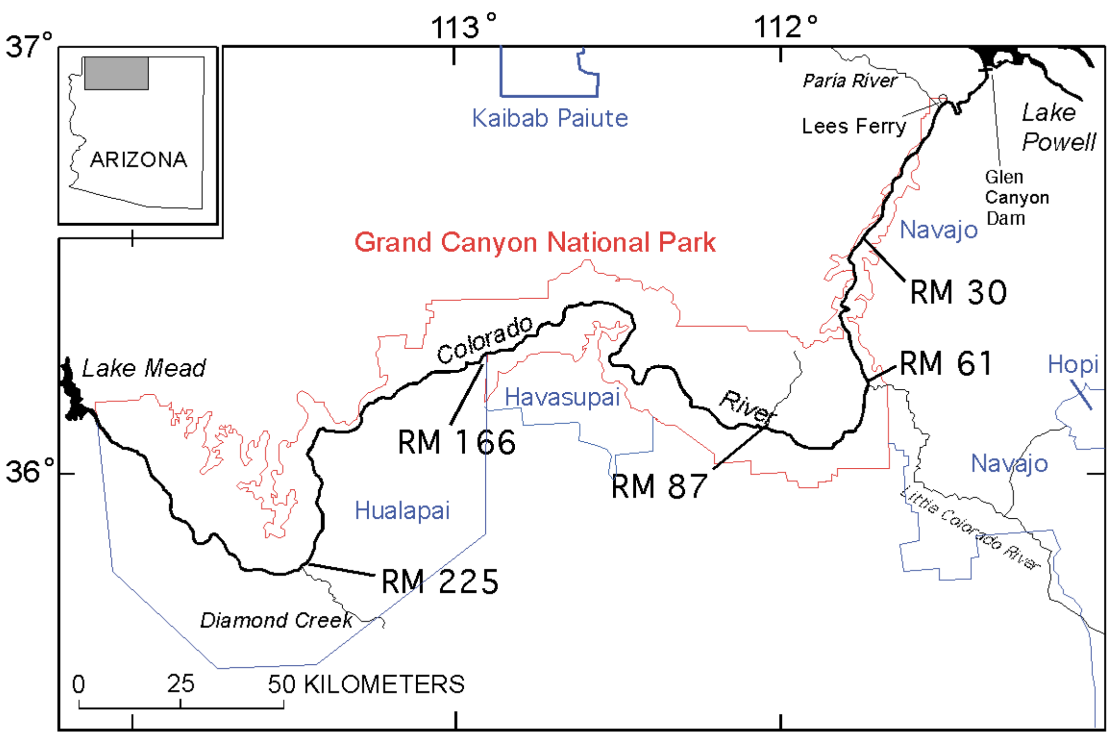


Figure 1. Location map showing the Colorado River corridor through Grand Canyon, Arizona. River miles (RM) of suspended-sediment sampling stations are shown. The reach between Lees Ferry (RM 0) and RM 30 is referred to in the text as upper Marble Canyon. The reach between RM 30 and RM 61 is referred to as lower Marble Canyon. Grand Canyon National Park boundary is outlined in red. Reservations of five Native American tribes are shown with the name of each tribe in blue.

## METHODS

During the 2008 HFE, water samples were collected using conventional methods (EWI samples collected with D-77 and D-96 samplers) and ISCO pump samplers (Edwards and Glysson, 1999) at five locations along the Colorado River corridor through Grand Canyon (Fig. 1): river-mile (RM) 30, RM 61, RM 87 (near USGS gaging station 09402500), RM 166, and RM 225. Locations in the river corridor are commonly referred to by their distance, in miles, downstream from Lees Ferry, Ariz.; this article follows that convention and uses SI units for other measurements. River miles used here are those provided by the map server operated by the USGS Grand Canyon Monitoring and Research Center (GCMRC; http://www.gcmrc.gov/products/ims/). Details of various methods used in Grand Canyon to estimate suspended-sediment concentration and grain size are discussed elsewhere (Topping et al., 2006; Topping et al., in prep.).

Several months after each HFE, in March 2005 and May 2008 respectively, the sedimentology of sandbars deposited by the high flows was examined in the field. Grain sizes of sediment samples collected from vertical profiles (pits and trenches) were analyzed using the Coulter laser particle-size analyzer at the GCMRC laboratory in Flagstaff, Ariz.

## RESULTS

In sandbars formed by both HFEs, the base of the high-flow deposit commonly contained 1–5 cm of horizontally laminated sand with grain size similar to that of the underlying pre-flood sediment (Fig. 2), possibly reflecting reworking of locally available sediment as the flow started to rise. This laminated or planar-bedded sand was overlain by finer (in some cases muddy) sediment that, at some sites, included abundant organic material presumably deposited during the rising limb of the hydrograph. HFE sandbars commonly contained fluvial ripples (as in Fig. 2), and, in some sandbars, notably at river-mile 30 in deposits from both HFEs, well developed subaqueous dune structures.

At each station where suspended sediment was measured, during both HFEs, suspended sediment decreased in concentration and coarsened during the 60-hour steady high-flow peak; coarsening was reflected both in the decreasing proportion of silt and clay and in the increasing median grain size of the suspended sand fraction (Topping et al., in prep.). Suspended sediment contained higher total sand concentrations and a lower proportion of silt and clay in suspension in 2008 relative to 2004 (Topping et al., in prep.).

Figures 3 and 4 illustrate spatial and temporal trends in grain-size evolution of suspended and sandbar sediment from the 2004 and 2008 high flows. After the 2004 HFE, sediment was sampled only from sandbars in river-miles 2 to 66 and included 15 locations, whereas in 2008 the sandbar-sampling effort included fewer sites (10) but collected data from a longer reach, river-miles 2 to 216. Although interpretations are complicated somewhat by the change in sampling schemes, few differences were apparent between the grain size of deposits formed by the 2004 HFE and those formed by the 2008 HFE; median grain size and silt and clay content of sandbars that were sampled after both the 2004 and 2008 HFEs overlap. Most deposits (21 of 22 profiles sampled) from the 2004 HFE coarsened upward (to a degree similar to coarsening of suspended sediment during the high-flow peak), with the greatest degree of upward coarsening present in the farthest-upstream sandbars (Fig. 4). Deposits from the 2008 HFE also displayed the greatest degrees of upward coarsening in the farthest-upstream deposits, but a greater proportion (4 of 17 profiles sampled) in 2008 contained sediment that fined upward (Fig. 4). During both floods, the degree of suspended-sediment coarsening throughout the high-flow peak was similar to the degree of coarsening (in upward-coarsening deposits) within nearby sandbars (shown in Fig. 3 for Upper and Lower Marble Canyon, and summarized in Fig. 4 for the Marble and Grand Canyon reaches).

Figure 2. Vertical profile through a deposit from the 2008 High-Flow Experiment (HFE) in Grand Canyon, at river-mile 44. Dashed line marks the base of the high-flow deposit. Sand beneath the HFE deposit (below dashed line) includes trampled ground surface. Basal sediment of the high-flow deposit is planar-bedded, interpreted as likely caused by swash along the channel margin as flow rose. Fluvial ripples overlie planar bedding; 1–2 cm above the base of rippled sand, deposition of finer sediment is apparent (indicated by arrow). Fluvial ripples continue in a coarsening-upward sandy deposit to a total thickness of 0.7 m at this site.

Sampling sandbar sediment from a greater longitudinal reach in 2008 relative to 2004 provided additional information about grain-size changes with distance downstream. Downstream trends in relative grain size are shown in Figures 3 and 4; downstream trends in absolute grain size (median size, $D_{50}$, of the sand fraction) and in silt and clay content are shown in Figures 5 and 6. Correlation coefficients calculated from regression lines shown in Figure 5 indicate no significant trend with distance downstream (based on F-tests and student-t tests) in the mean, lowermost, or uppermost $D_{50}$ values from sandbars or suspended sand (Figs. 5A, B, and C, respectively). Correlation coefficients calculated from regression lines shown in Figure 6 indicated significant downstream trends toward greater silt and clay content in suspended sediment (in mean value during high-flow peak, at the start of the peak, and at the end of the peak; Figs. 6A, B, C, respectively), whereas silt and clay content in sandbars showed a significant downstream increase only when just the uppermost samples of each profile were considered (Fig. 6C).

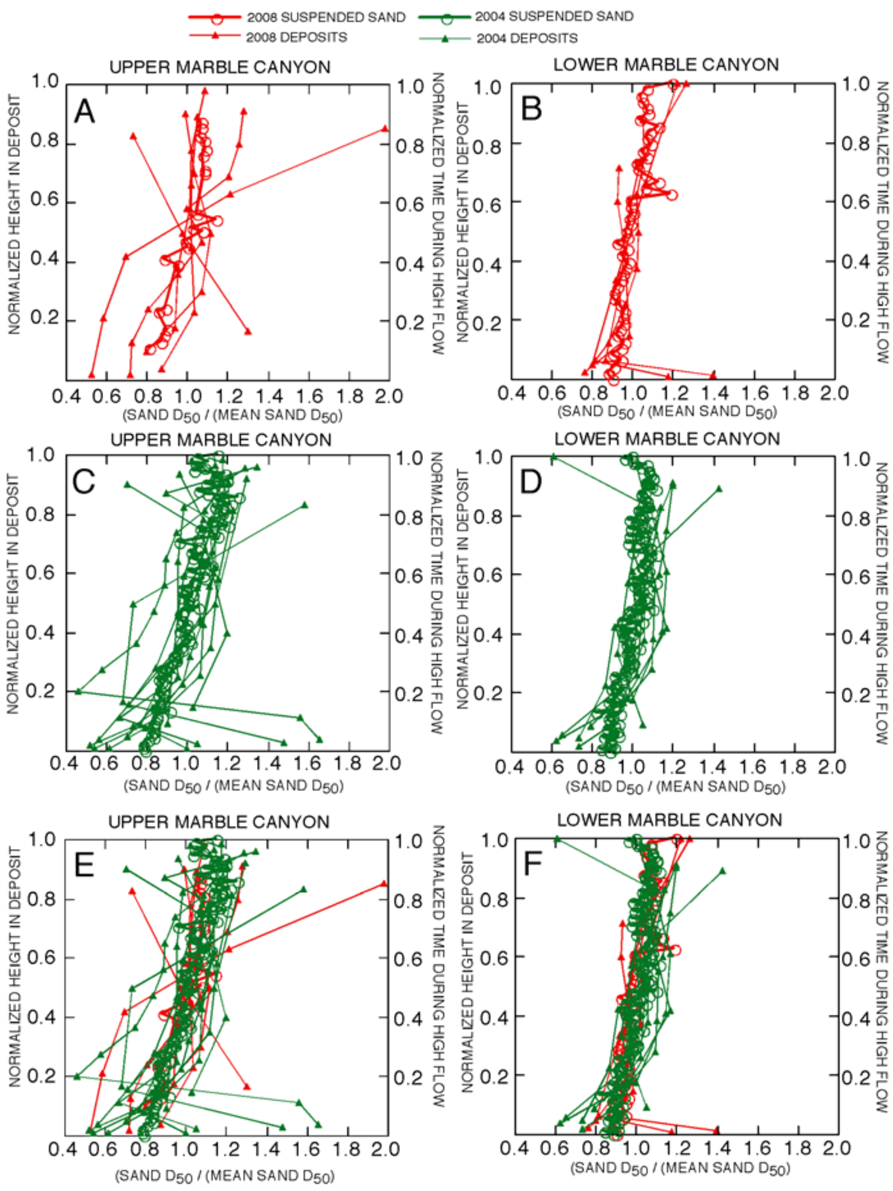


Figure 3. Relative grain-size changes of suspended and sandbar sediment in 2008 (A, B) and 2004 (C, D) high-flow experiments (HFEs) and for both high flows superimposed (E, F). Data for upper Marble Canyon (A, C, E) include suspended sand sampled at river-mile 30, and sandbars sampled between river-miles 2 and 31. Data for lower Marble Canyon (B, D, F) include suspended sand sampled at river-mile 61, and sandbars sampled between river-miles 43 and 59. In each plot, left-hand vertical axis shows normalized height within the high-flow deposit for sandbar samples; right-hand vertical axis shows normalized time during high flow (time when flow exceeded 878 $m^3/s$) for suspended sediment. Horizontal axis in all plots refers to the ratio of $D_{50}$ to the mean $D_{50}$ within each respective sandbar profile or set of suspended-sediment samples.

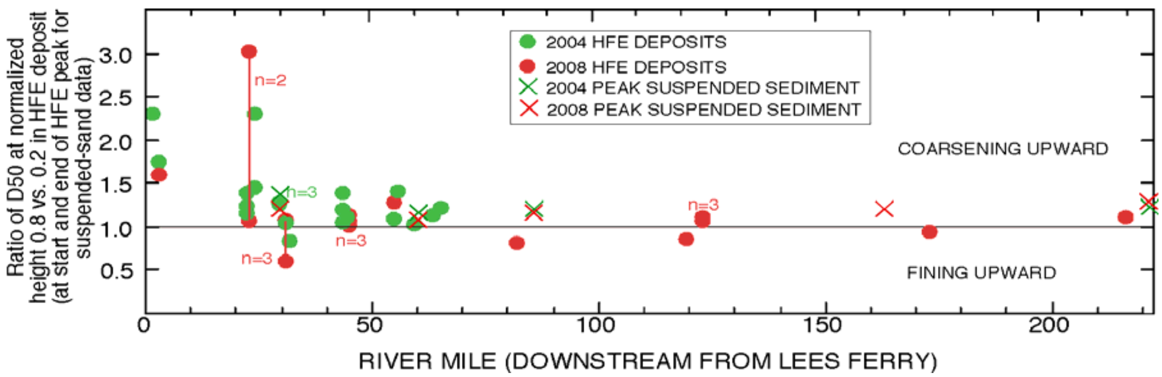


Figure 4. Relative grain-size change measured in sandbar and suspended-sediment samples from the 2004 and 2008 high-flow experiments (HFEs), with distance downstream.

## DISCUSSION

Although the 2008 HFE occurred under enriched antecedent sediment conditions in the mainstem Colorado River (relative to conditions during the 1996 and 2004 HFEs), and although sandbars were as large or larger after the 2008 HFE relative to their size after the 1996 and 2004 HFEs (Hazel et al., in review), decreasing concentration and coarsening of suspended sediment throughout the 60-hour peak, combined with the common occurrence of upward-coarsening deposits (e.g., Fig. 3), indicate that, even in the sediment-enriched 2008 scenario, this system was still limited with respect to fine-sediment supply during the 2008 HFE. Sediment-supply limitation, particularly of fine material, occurred in the Colorado River through Grand Canyon even prior to the influence of Glen Canyon Dam, because the timing of greatest sediment input (late summer-fall monsoon season) and highest discharge (spring snowmelt flood) did not coincide (Rubin et al., 1998; Topping et al., 2000). Limited availability of fine sediment remains a challenge as scientists and managers attempt to rebuild sandbars and minimize sand export from Grand Canyon using HFEs and normal dam operations (Wright et al., 2008).

Sediment-supply limitation can be reflected in the composition of sedimentary deposits. Many modern and Holocene fluvial deposits in Grand Canyon, including some left by the 2004 and 2008 HFEs, differ from most described examples of slackwater flood deposits in that they contain basal silt and clay that grades upward into coarser silt and fine to very fine sand (Draut et al., 2008; e.g., Figs 2, 5, 6). This contrasts with deposits observed in many other fluvial systems; flood deposits are commonly normally graded (fining upward) with a fine-grained, laminated ‘drape’ in the uppermost part of the deposit formed as sediment settles out of suspension (e.g., Ashley et al., 1982; Kochel and Baker, 1982, 1988; Dawson, 1989; Marriott, 1992; Waitt, 2002; Navratil et al., 2008). Normal grading can occur even in bedrock-canyon flood deposits, given a sufficient sediment supply (Benito et al., 2003). Inverse grading of many Grand Canyon sedimentary deposits is attributed to winnowing of the sediment supply during the flows that produced these strata (Rubin et al., 1998; Topping et al., 2000, 2005). The observation that most deposits sampled from the 2004 and 2008 high flows coarsen upward (Fig. 4) is therefore consistent with evidence of sediment-supply limitation in the suspended-sediment data from both flows (Fig. 3, and Topping et al., in prep.). Comparing the degree of coarsening in the sand fraction during the two high flows, the similarity of vertical grain-size changes within Marble

Canyon sandbars in 2004 and 2008 corresponds closely with similar degrees of coarsening in suspended sediment through Marble Canyon in 2004 and 2008 (Fig. 3). Similar relative grain-size evolution in sandbars and suspended sediment in Marble Canyon during the 2004 and 2008 high flows is attributed to similar proportional increase in suspended-sand export from upper to lower Marble Canyon during both floods (although absolute sediment mass exported by the HFE in 2008 was higher than in 2004, the relative increase in sand transport between upper and lower Marble Canyon was ~40% in both flows; Topping et al., in prep.). We infer that although there were differences in antecedent sediment supply in the two floods, those differences apparently were not great enough to yield substantial and measurable differences in sandbar grain-size evolution—at least not in the sandbar-sampling methods that were used.

To what extent were the relatively sand-enriched conditions of the 2008 HFE (compared to 1996 and 2004) reflected in its sedimentary deposits? Topographic surveys showed that sandbar area and volume increased substantially as a result of the high flow; sandbars were as large or larger after the 2008 HFE than they had been after the 2004 or 1996 HFEs (Hazel et al., in review). Nevertheless, whereas concentration and grain size differed in the suspended-sediment data from the 2004 and 2008 HFEs (Topping et al., in prep.), sedimentary deposits sampled at the same locations after the two high flows did not have substantially different absolute grain sizes (Fig. 7). This discrepancy between suspended and sandbar grain-size behavior may have been caused by local eddy dynamics affecting sandbar grain size more than did the suspended-sediment content of the flow as a whole. Alternatively, the sampling strategy may not have resolved real differences that were present; few sites were sampled in common after both HFEs and those sites sampled in 2008 (Fig. 7) did not replicate the exact positions within individual sandbars of profiles sampled after the 2004 HFE.

The trend toward increasing concentration of suspended silt and clay with distance downstream in the 2008 HFE (Fig. 6) was not readily apparent in the silt and clay percent measured in sandbar samples. Deposits left by the 2008 HFE, which were sampled over a 340-km-long reach (river-miles 2 to 216; Figs. 4–6), showed no significant correlation between distance downstream and mean $D_{50}$, and no significant correlation between distance downstream and mean silt and clay percent. A significant correlation ($p$=0.015) was found between distance downstream and the silt and clay percent measured at the top of the 2008 HFE deposits (Fig. 6C), but its significance relies on the downstream-most two sandbars sampled (deposits at river-miles 173 and 216); had those two profiles not been sampled, the remaining sandbar data would have R=0.31, $p$=0.270, and the correlation would not have been significant. This suggests that sampling more deposits from a longer reach, especially downstream of river-mile 66 (which was limited after both HFEs by logistical challenges of scheduling field work in this remote setting), could provide valuable information in studies of future HFEs.

## CONCLUSIONS

Understanding suspended-sediment and sandbar response to the 2004 and 2008 high-flow experiments on the Colorado River through Marble and Grand Canyons can help inform future management decisions regarding the timing and magnitude of "sandbar-building" flows relative to tributary sediment influx downstream of Glen Canyon Dam. Replication of the hydrograph between the two HFEs allows for a comparison of the effects of antecedent sediment conditions;

compared to the 2004 HFE, the 2008 high flow contained more, and (downstream of river-mile 30) finer, suspended sand. Topographic surveys indicated that sandbar area and volume increased substantially as a result of the 2008 high flow; sandbars were as large or larger after the 2008 HFE than they had been after the 2004 or 1996 HFEs.

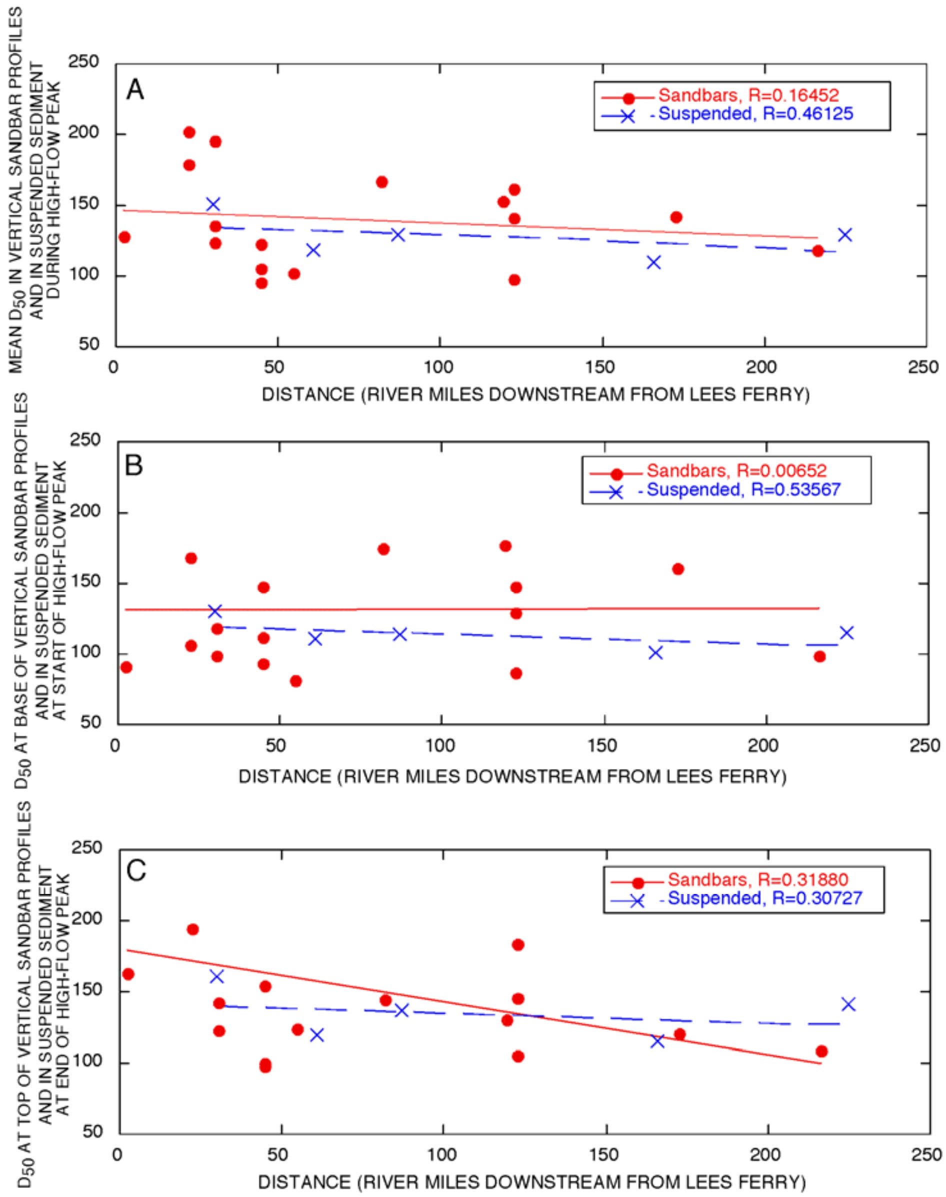


Figure 5. Downstream progression of $D_{50}$ of the sand fraction in sandbar samples (red circles, with red regression lines) and suspended-sediment samples (blue crosses, with blue dashed regression lines) from the 2008 high-flow experiment (HFE). A, mean sand-fraction $D_{50}$ in vertical sandbar profiles and in suspended sediment during the 60-hour HFE peak. Neither sandbars ($p$=0.528) nor suspended sediment ($p$=0.434) show significant trends using F-tests or student-t tests. B, sand-fraction $D_{50}$ at the base of vertical sandbar profiles and in suspended sediment at the start of the 60-hour HFE peak. Neither sandbars ($p$=0.980) nor suspended sediment ($p$=0.352) show significant trends. C, sand-fraction $D_{50}$ at the top of vertical sandbar profiles and in suspended sediment at the end of the 60-hour HFE peak. Neither sandbars ($p$=0.212) nor suspended sediment ($p$=0.615) show significant trends.

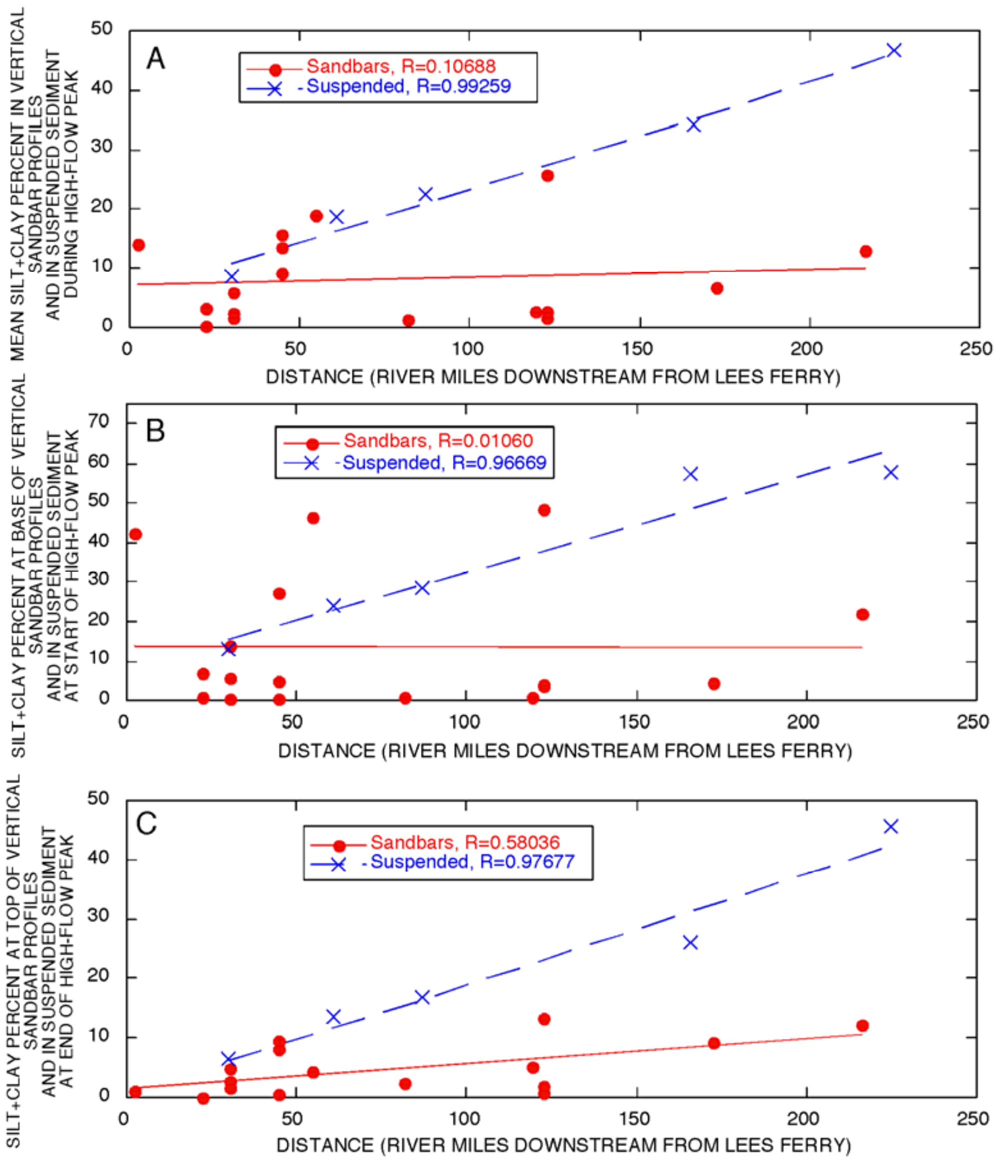


Figure 6. Downstream progression of silt and clay proportion in sandbar samples (red circles, with red regression lines) and suspended-sediment samples (blue crosses, with blue dashed regression lines) from the 2008 high-flow experiment (HFE). A, mean silt and clay percent in vertical sandbar profiles and in suspended sediment during the 60-hour HFE peak. Sandbars show no significant downstream trend ($p$=0.683), whereas suspended sediment ($p$<0.001) does show a significant downstream trend using F-tests and student-t tests. B, Silt and clay percent in samples at the base of vertical sandbar profiles and in suspended sediment at the start of the 60-hour HFE peak. Sandbars show no significant downstream trend ($p$=0.968), whereas suspended sediment ($p$=0.007) does show a significant downstream trend. C, Silt and clay percent in samples at the top of vertical sandbar profiles and in suspended sediment at the end of the 60-hour HFE peak. Sandbars show a significant downstream trend with $p$=0.015; suspended sediment shows a significant downstream trend with $p$=0.004.

Greater sand abundance and finer grain size in the 2008 HFE than in 2004, and greater sandbar enlargement, did not translate in a straightforward way into grain-size differences of the resulting sandbars. Many of the deposits from both HFEs coarsened upward, consistent with coarsening suspended sediment (inferred sediment-supply limitation); the upstream-most deposits from both HFEs showed the greatest degree of relative coarsening, and, in general, deposits and suspended sand in Marble Canyon coarsened to a similar degree throughout the 2004 and 2008 high flows. Similarity in absolute grain size between 2004 and 2008 HFE sandbars in Marble Canyon may reflect a sandbar-sampling strategy that was not sufficiently dense and did not replicate the 2004 profile locations precisely in 2008; or, this could reflect hydrodynamic controls on deposition rates that prevailed over sediment-supply differences between the two HFEs. Trends toward higher concentrations of silt and clay in suspended sediment with distance downstream were not readily apparent in the silt and clay percent measured in 2008, although more intensive sampling especially in the downstream-most part of the study reach might better resolve this relationship in studies of future HFEs.

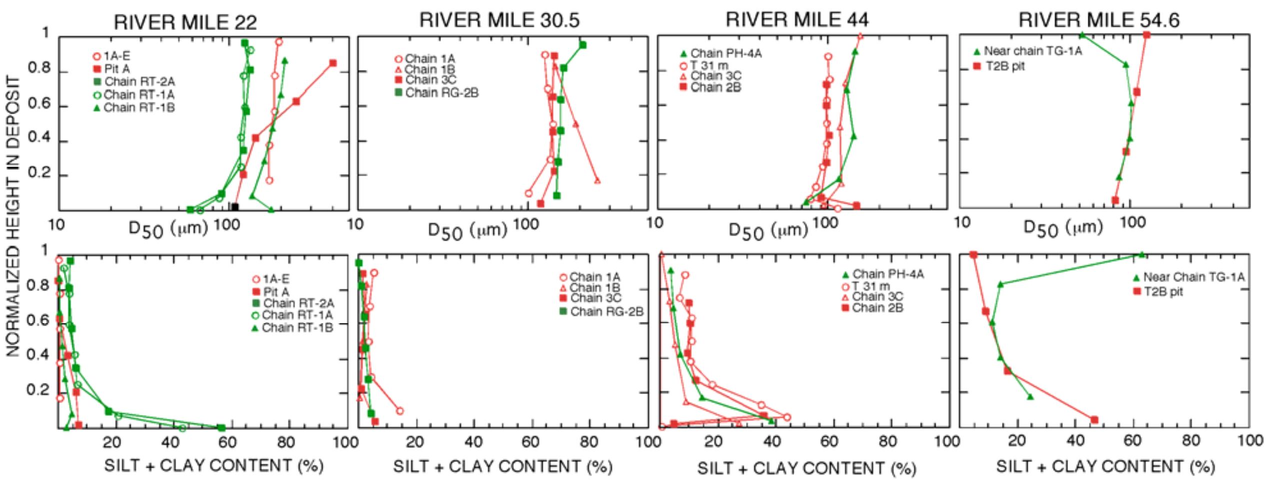


Figure 7. Absolute grain size (*$D_{50}$* of the sand fraction, in upper plots, and silt and clay percent, in lower plots) with normalized height in vertical profiles through sandbar deposits at river-miles 22, 30.5, 44, and 54.6—the four areas sampled after both the 2004 (green) and 2008 (red) high-flow experiments (HFEs).

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