GRAIN-SIZE EVOLUTION IN SUSPENDED SEDIMENT AND DEPOSITS FROM THE 2004 AND 2008 CONTROLLED-FLOOD EXPERIMENTS IN MARBLE AND GRAND CANYONS, ARIZONA

Amy E. Draut[1], David J. Topping[2], David M. Rubin[1], Scott A. Wright[3], John C. Schmidt[4]
[1]U.S. Geological Survey, 400 Natural Bridges Drive, Santa Cruz, CA 95060
[2]USGS Grand Canyon Monitoring and Research Center, Flagstaff, AZ 86001
[3]U.S. Geological Survey, Sacramento, CA 95819
[4]Dept. of Watershed Sciences, Utah State University, Logan, UT 84322

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 (Topping et al., 2000). Regulation of river discharge by dam operations has important implications for the storage and redistribution of fine sediment in the Colorado River corridor. In the absence of natural floods, suspendible sand and finer material is not deposited at elevations that regularly received sediment before dam closure. Owing to the large decrease in sediment supply and reduction in the magnitude and frequency of floods, 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 occasional higher flows such as occurred in 1983–1985 and the controlled-flood experiments discussed here, and by sediment input from 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, partially enclose eddy backwaters that form aquatic habitat sometimes used by fish, provide a source for aeolian sand that protects some archaeological sites, and are used as campsites by thousands of backcountry recreationists annually (Rubin et al., 1990; Kearsley et al., 1994; Wright et al., 2005; Draut and Rubin, 2008).

In an effort to rebuild sandbars through the Marble and Grand Canyon reaches of the Colorado River (Fig. 1), controlled-flood experiments (CFEs) 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 m^3/s experimental controlled-flood dam release in March-April 1996, sand that was newly deposited on sandbars had been eroded primarily from the lower-elevation parts of upstream bars, not from the main channel bed. This finding, coupled with rapid decreases in suspended-sediment concentrations during the 1996 CFE indicating a limited suspendible sediment supply, demonstrated that future controlled floods released from Glen Canyon Dam would require substantially more sediment in order to rebuild sandbars effectively; without sufficient tributary sediment inputs, a mainstem controlled flood would cause net sandbar erosion rather than deposition (Rubin et al., 2002; Topping et al., 2006). The second CFE occurred in November 2004 after substantial inputs of tributary sand were followed by two months of relatively low, daily fluctuating dam releases (<280 m^3/s, but still unsteady) intended to retain sand in the main channel before the high flow. Substantial increases in sandbar area and volume from the 60-hour 1,160 m^3/s 2004 CFE release 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 CFE, Topping et al. (2006) concluded that still more sand would be required in future CFEs in order to enlarge sandbars along a greater length of the river corridor. Sandbar response during a flood depends upon the complex relationship between the area and grain size of tributary-supplied sand on the bed of the main channel, parameters that are challenging to quantify accurately over the vast area of Marble and Grand Canyons. Maximizing sandbar deposition requires antecedent supply of a sufficiently large volume of sufficiently fine sand to maintain the highest possible suspended-sand concentrations during a controlled flood (D.J. Topping, written commun.).

The third controlled-flood 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 hydrographs of the 2004 and 2008 CFEs were virtually identical; the flows differed primarily in the amount of new sediment present in the main channel, with antecedent conditions of the 2008 flow being substantially more sand-rich than in 2004. Depending on reach, the level of sand enrichment before the 2008 CFE was either greater than, less than, or similar to that before the 1996 controlled flood (D.J. Topping, written commun.). In the year before the 2008 CFE, the Paria and Little Colorado Rivers (Fig. 1) supplied 0.92 and 1.12 Tg (million metric tons) of tributary sediment, respectively, compared with 0.63 and 0.19 Tg supplied by those tributaries respectively in the year before the 2004 CFE (D.J. Topping, written commun.). Topographic surveys conducted after the 2008 CFE indicated that sandbar area and volume increased substantially as a result of the flood; sandbars were typically as large or larger after the 2008 CFE than they had been after the 2004 or 1996 CFEs (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 controlled floods. Other analyses of suspended-sediment behavior during these CFEs, including modeling of transport dynamics and suspended-sediment measurements made longitudinally with the high flow, will be discussed elsewhere (Wright et al., this volume; D.J. Topping, written commun.).

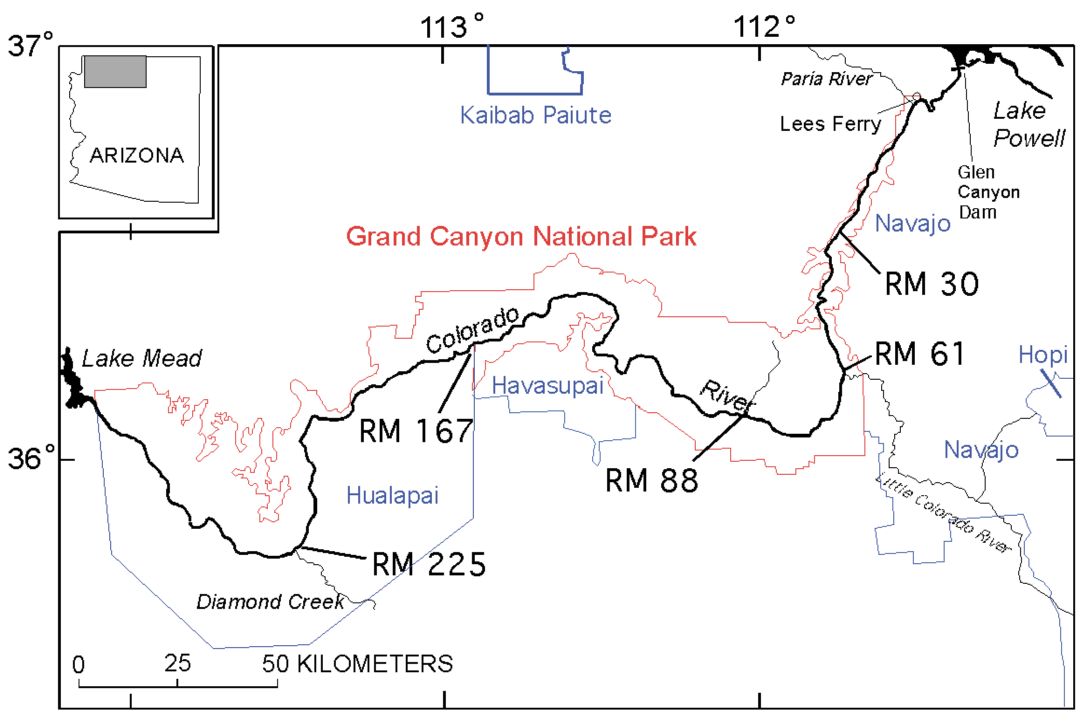

Figure 1. Location map showing the Colorado River corridor through Grand Canyon, Arizona. River miles (RM) off suspended-sediment sampling stations are shown. The reach between Lees Ferry (RM 0) and RM 30 is referred to in the text as upper Marble Canyon. The reach between RM 30 and RM 61 is referred 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 controlled-flood experiment, water samples were collected using conventional methods (Equal Width Increment and Equal Discharge Increment suspended-sediment samples collected with depth-integrating D-77 and D-96 samplers) and ISCO pump samplers[1] (Edwards and Glysson, 1999) at five locations along the Colorado River corridor through Grand Canyon (Fig. 1): river-mile (RM, as determined downstream from Lees Ferry) 30, RM 61, RM 88 (near USGS gaging station 09402500), RM 167, 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).

Several months after each of the last two CFEs, in December 2004 and March 2005, as well as May 2008 respectively, the sedimentology of sandbars deposited by the controlled floods was examined in the field; these efforts followed from the methods and sampling work of Rubin et al., (1998). Grain sizes of sediment samples collected from vertical profiles (pits and trenches) were analyzed using dry sieving in a RoTap sieve shaker at the GCMRC sediment laboratory in Flagstaff, Ariz.

RESULTS

Results presented here concern the controlled-flood experiments that occurred in 2004 and 2008 (those with identical hydrographs that can therefore be readily compared). Sandbar data from the 1996 CFE, in which the hydrograph differed substantially from that in 2004 and 2008, have been discussed elsewhere, notably by Rubin et al. (1998) and Topping et al. (2006). In sandbars formed by the 2004 and 2008 CFEs, the base of the flood 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 river stage started to rise (described following the 2004 CFE in Topping et al., 2006). 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. CFE sandbars commonly contained fluvial ripples (as in Fig. 2), and, in some sandbars, notably at river-mile 30 in deposits from both of the last two CFEs, well developed trough-cross-stratified structures interpreted to be from the migration of subaqueous dunes.

At each station where suspended sediment was measured, during both of the last two CFEs, suspended sediment decreased in total concentration and coarsened during the 60-hour steady high-discharge 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 (D.J. Topping, written commun.). Suspended sediment generally contained higher total sand concentrations in suspension in 2008 relative to 2004; silt and clay content was generally similar during both floods except in upper Marble Canyon, where silt and clay content was greater in the 2004 CFE than in the 2008 CFE (D.J. Topping, written commun.).

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[1] Use of trade names is for descriptive purposes only, and does not imply endorsement by the U.S. Government.

Figure 2. Vertical profile through a deposit from the 2008 controlled-flood Experiment (CFE) in Grand Canyon, at river-mile 44. Dashed line marks the base of the flood deposit. Sand beneath the CFE deposit (below dashed line) includes trampled ground surface. Basal sediment of the flood deposit is planar-bedded, interpreted as likely caused by swash along the channel margin as the CFE stage 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.

Spatial and temporal trends in grain-size evolution of suspended sand and sandbar sediment from the 2004 and 2008 CFEs are illustrated in Figures 3 and 4. After the 2004 CFE, 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 strategy, few differences were apparent between the grain size of deposits formed by the 2004 CFE and those formed by the 2008 CFE; median grain size and silt and clay content of sandbars that were sampled after both the 2004 and 2008 CFEs overlap. Most deposits (21 of 22 profiles sampled) from the 2004 CFE coarsened upward (to a degree similar to coarsening of suspended sand and reduction of suspended silt and clay measured during the higher-discharge part of the flood hydrograph), with the greatest degree of upward coarsening present in the farthest-upstream sandbars (Fig. 4). Deposits from the 2008 CFE also displayed the greatest degree of upward coarsening in the farthest-upstream deposits, but a greater proportion (4 of 17 profiles sampled) in 2008 contained sand that fined upward; most fining-upward deposits occurred in downstream reaches (Fig. 4).

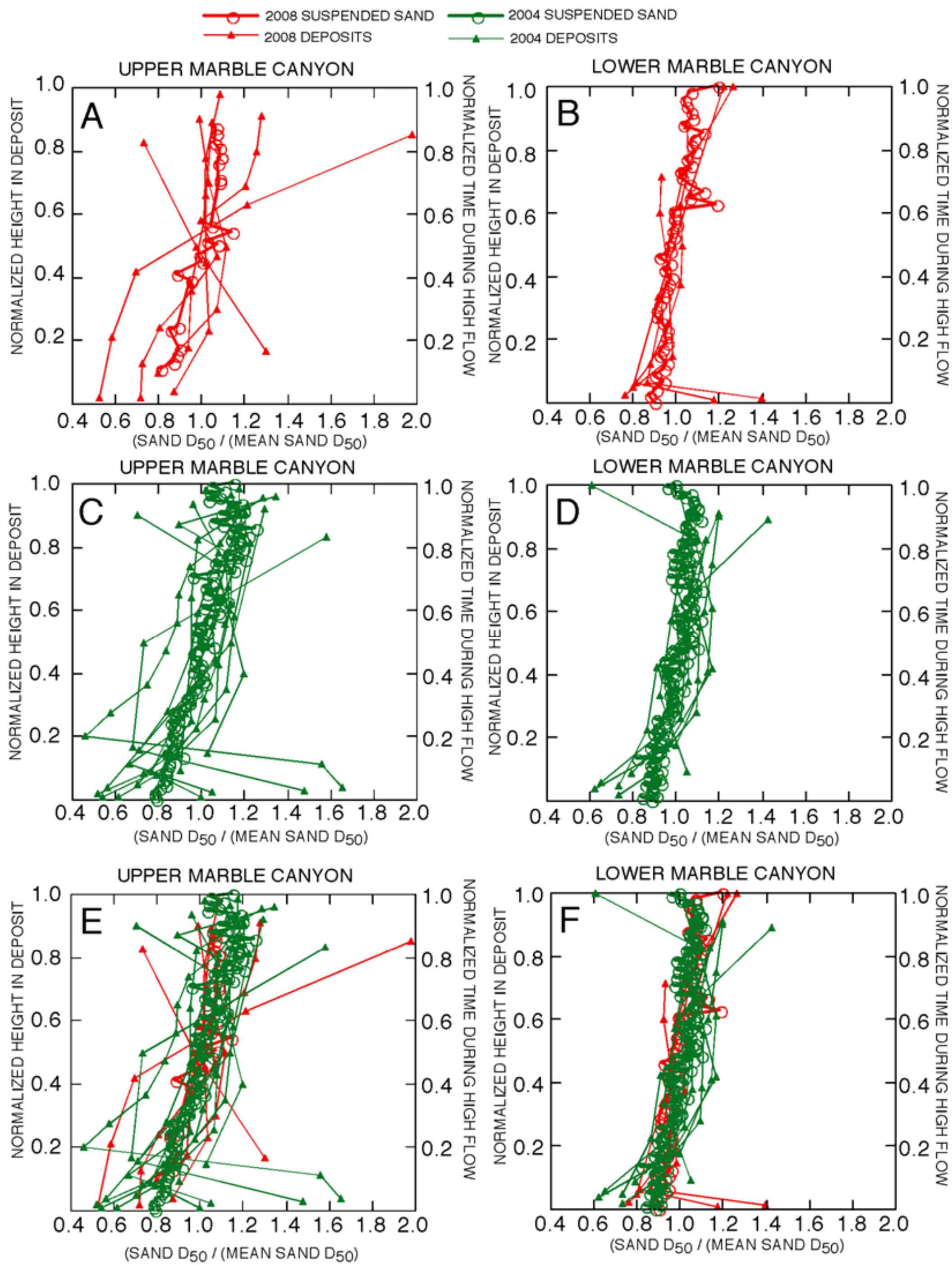

Figure 3. Relative grain-size changes of suspended sand and sandbar sediment in 2008 (A, B) and 2004 (C, D) controlled-flood experiments (CFEs) and for both floods superimposed (E, F). Data for upper Marble Canyon (A, C, E) include suspended sand sampled at river-mile 30, and sandbars sampled between 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 flood deposit for sandbar samples; right-hand vertical axis shows normalized time during high flow (time when flow exceeded 878 m^3/s) for suspended sand. 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.

Topping et al. (2006) showed that the greatest degree of coarsening (in suspension and in the sandbars) occurred in upstream reaches in Marble Canyon during the 2004 controlled flood because these reaches experienced the greatest decrease in upstream sand supply during the flood. They also showed that the degree of coarsening (in suspension and in the sandbars) was much less in downstream reaches in Marble Canyon during the 2004 controlled flood because the sand supply did not decrease as much in these reaches during the flood. Because D.J. Topping (written commun.) has shown that upstream reaches also experienced the greatest decrease in upstream sand supply during the 2008 CFE, this similarity in the relative grain-size behavior during the 2004 and 2008 CFEs is not surprising. During both the 2004 and 2008 CFEs, the degree of suspended-sand coarsening throughout the higher-discharge part of the flood hydrograph 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).

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).

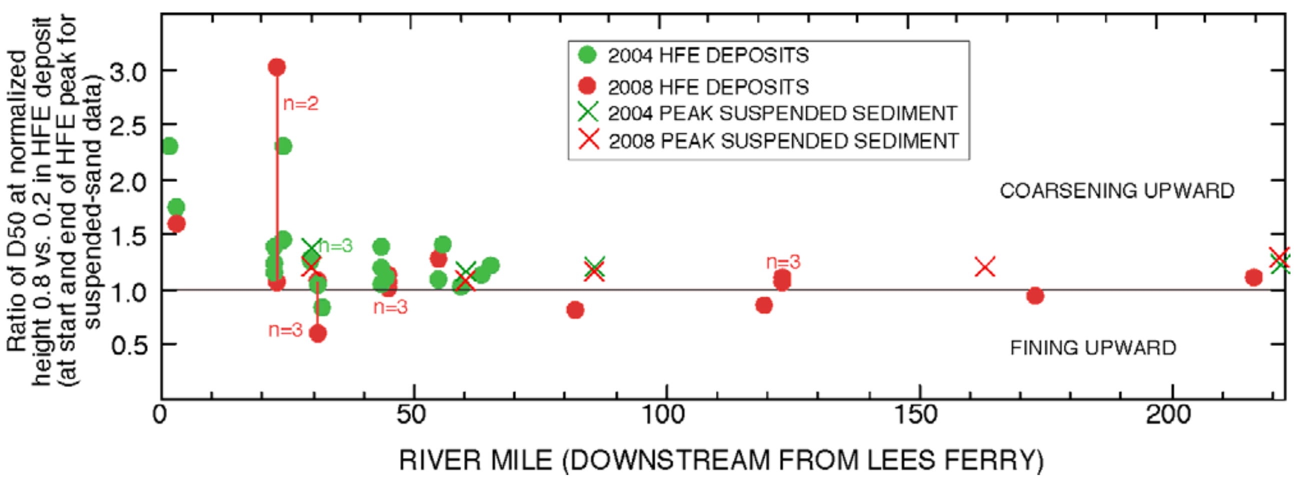

Figure 4. Relative grain-size change measured in sandbar and suspended-sand samples from the 2004 and 2008 controlled-flood experiments (CFEs), with distance downstream.

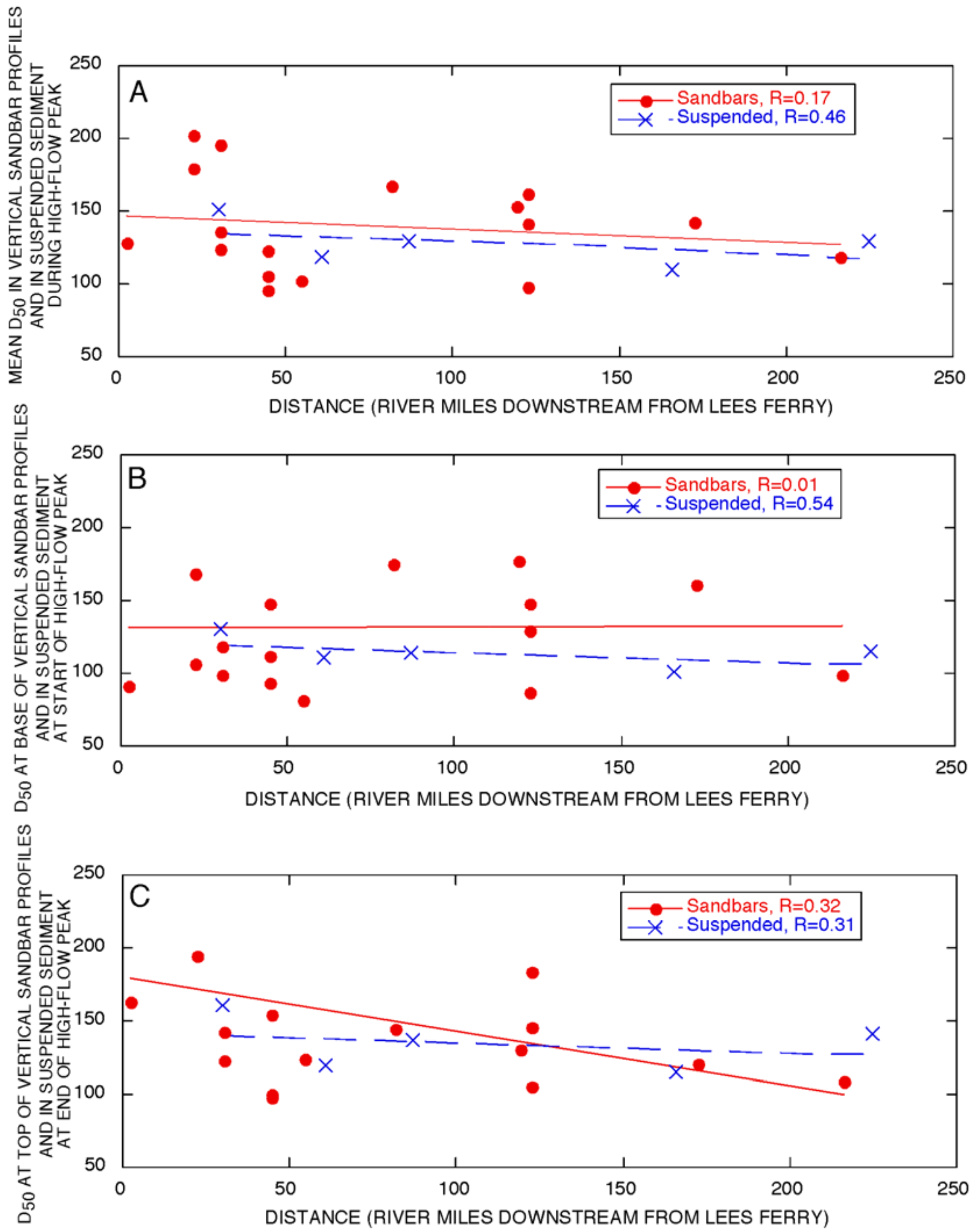

Figure 5. Downstream progression of D_{50} of the sand fraction in sandbars sampled after the flood (red circles, with red regression lines) and suspended sediment sampled during the flood (blue crosses, with blue dashed regression lines) from the 2008 controlled-flood experiment (CFE). A, mean sand-fraction D_{50} in vertical sandbar profiles and in suspended sediment during the 60-hour CFE peak. Neither sandbars (p=0.528) nor suspended sand (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 CFE peak. Neither sandbars (p=0.980) nor suspended sand (p=0.352) show significant trends. C, sand-fraction D_{50} at the top of vertical sandbar profiles and in suspended sand at the end of the 60-hour CFE peak. Neither sandbars (p=0.212) nor suspended sand (p=0.615) show significant trends.

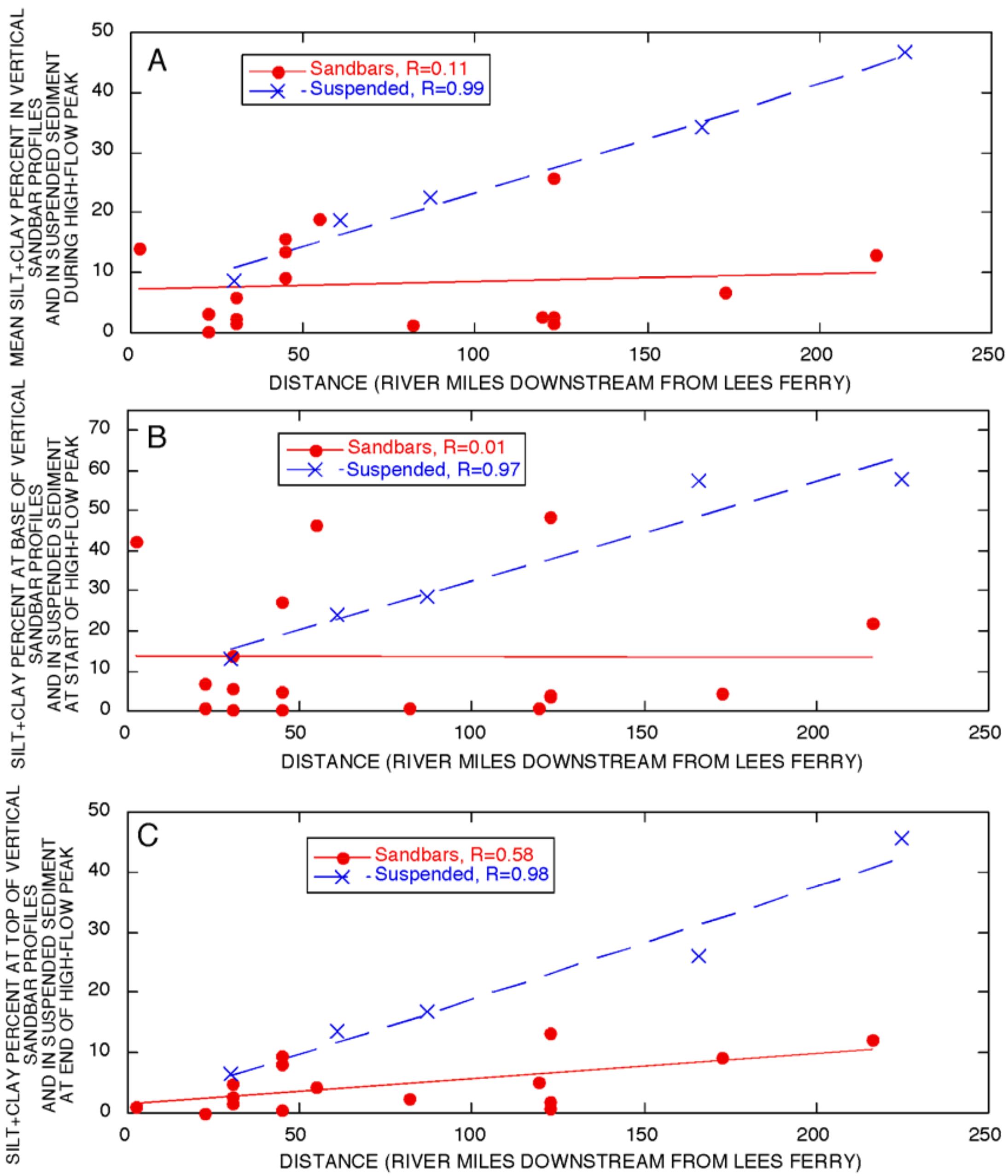

Figure 6. Downstream progression of silt and clay proportion in sandbars sampled after the flood (red circles, with red regression lines) and suspended sediment sampled during the flood (blue crosses, with blue dashed regression lines) from the 2008 controlled-flood experiment (CFE). A, mean silt and clay percent in vertical sandbar profiles and in suspended sediment during the 60-hour CFE 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 CFE 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 CFE peak. Sandbars show a significant downstream trend with p=0.015; suspended sediment shows a significant downstream trend with p=0.004.

DISCUSSION

Although the 2008 CFE occurred under enriched antecedent sediment conditions in the mainstem Colorado River (relative to conditions during the 2004 CFE; D.J. Topping, written commun.), and although sandbars were as large or larger after the 2008 CFE relative to their size after the 1996 and 2004 CFEs (Hazel et al., in review), trends of 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 CFE. 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 controlled floods combined with currently approved, diurnally fluctuating flow dam operations (Wright et al., 2008).

Sediment-supply limitation can be reflected in the composition and structure of sedimentary deposits. Many modern and Holocene fluvial deposits in Grand Canyon, including some left by the 2004 and 2008 CFEs, 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, 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, 2008). The observation that most deposits sampled from the 2004 and 2008 CFEs coarsen upward (Fig. 4) is therefore consistent with evidence of sediment-supply limitation in the suspended-sediment transport data from both CFEs (Fig. 3, and D.J. Topping, written commun.). Comparing the degree of coarsening in the sand fraction during the two floods, 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 samples through Marble Canyon in 2004 and 2008 (Fig. 3). Similar relative grain-size evolution in sandbars and in suspended-sediment transport in Marble Canyon during the 2004 and 2008 CFEs 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 CFE in 2008 was higher than in 2004, the relative increase in sand transport between upper and lower Marble Canyon was in the range of ~40% in both flows; D.J. Topping, written commun.). We infer that although there were differences in sediment supply (and, at least in upper Marble Canyon, in grain size) in the two floods, those differences apparently were not great enough to yield substantial, measurable differences in sandbar grain-size evolution—at least not in the sandbar-sampling methods that were used. It is also possible that grain size of CFE sandbars was affected by the flow regime that occurred between the major influx of tributary sediment and the start of the CFE, processes still being investigated—the magnitudes and durations of flows between tributary sediment input and CFE were substantially different in 2004 and 2008 (T.S. Melis, written commun.).

To what extent were the generally relatively sand-enriched conditions of the 2008 CFE (compared to 2004) reflected in its sedimentary deposits? Topographic surveys showed that sandbar area and volume increased substantially as a result of the 2008 controlled flood; sandbars were as large or larger after the 2008 CFE than they had been after the 2004 or 1996 CFEs (Hazel et al., 2010). Nevertheless, whereas concentration and grain size differed (at least upstream of river-mile 50) in the suspended-sediment data from the 2004 and 2008 CFEs (D.J. Topping, written commun.), sedimentary deposits sampled at the same locations after the two floods did not have substantially different absolute grain sizes (Fig. 7). This discrepancy between suspended-sediment 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 CFEs and those sites sampled in 2008 (Fig. 7) did not replicate the exact positions within individual sandbars of profiles sampled after the 2004 CFE.

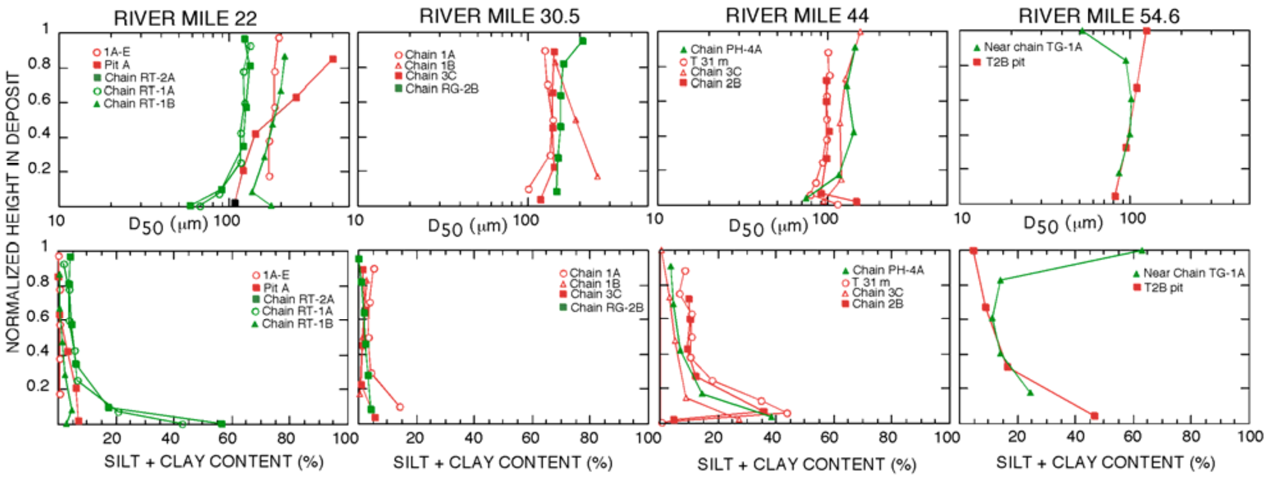

Figure 7. Absolute grain size (D_{50} of the sand fraction, in upper plots, and silt and clay percent, in lower plots) with normalized height in vertical profiles through sandbar deposits at river-miles 22, 30.5, 44, and 54.6—the four areas sampled after both the 2004 (green) and 2008 (red) controlled-flood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

The trend toward increasing concentration of suspended silt and clay with distance downstream in the 2008 CFE (Fig. 6) was not readily apparent in the silt and clay percent measured in sandbar samples. Deposits left by the 2008 CFE, which were sampled over a 340-km-long reach (RM 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 CFE deposits (Fig. 6C), but its significance relies on the downstream-most two sandbars sampled (deposits at RM 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 CFEs by logistical challenges of scheduling field work in this remote setting), could provide valuable information in studies of future controlled floods.

CONCLUSIONS

Understanding sandbar response to the 2004 and 2008 controlled-flood 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 CFEs allows for a comparison of the effects of different antecedent sediment conditions; compared to the 2004 CFE, the 2008 flood contained more suspended sand. In the 2008 controlled flood, upper Marble Canyon contained coarser suspended sand than in 2004; below river-mile 30, suspended sand in the 2008 CFE did not have substantially different grain size than in 2004. Topographic surveys indicated that sandbar area and volume increased substantially as a result of the 2008 controlled flood; sandbars were as large or larger after the 2008 CFE than they had been after the 2004 (and 1996) CFEs.

The different antecedent sediment conditions in 2008 compared with 2004, and generally greater sandbar enlargement, did not translate in a straightforward way into grain-size differences of the resulting sandbars. Many of the deposits from both controlled floods coarsened upward, consistent with coarsening suspended sediment (inferred progressive sediment-supply depletion); the upstream-most deposits from both CFEs 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 CFE 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 CFEs. 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 controlled floods.

ACKNOWLEDGMENTS

Controlled floods involved substantial effort and time contributed by personnel from the USGS and Humphrey Summit Support of Flagstaff, Ariz. In addition to the authors, sediment data were collected in the field by C. Crouch, S. Erwin, R. Griffiths, N. Hornewer, K. Killoy, T. Sabol, D. Topping, R. Tusso, K. Vanaman, N. Voichick, and K. Welhouse. D. Hanes and T. Melis provided helpful reviews.

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