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Downstream patterns of bed material grain size in a large, lowland alluvial river subject to low sediment supply

Michael Bliss Singer[1,2]

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[1] A new data set of bimodal subaqueous channel bed sediments was analyzed for longitudinal patterns in grain size. It yielded two interesting observations: (1) separate fining trends in d_{50} exist for gravel and fines that overlap for ~175 river kilometers, and (2) this overlap in fining trends results in a protracted (nonabrupt) gravel to sand transition. These suggest bed patchiness that is interpreted in the context of inherent grain size bimodality, localized hydraulic sorting due to spatially heterogeneous (and low) sediment supply, and local deviations in channel gradient. The data also show that tributaries have a minor impact on main stem downstream fining due to basin shape and tectonic history. In addition, subaqueous channel sediments were observed to be finer than nearby sediments collected from exposed bars, which may indicate a narrow active zone of transport where bars are disconnected from sediment movement. This research has implications for bed material collection and theories of downstream fining.

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1. Introduction

[2] Spatial patterns of bed material grain size in alluvial rivers are relevant in various disciplines, so much has been written on longitudinal sorting. Focus areas include the impact of tributaries on fining, rates and processes of size decline with distance downstream, and the gravel-sand transition. This paper presents a new, extensive data set, which spans the gravel-sand transition, from the riverbed of a large, lowland fluvial system subject to low sediment supply. The data exhibit several characteristics that contrast with many of the published cases of downstream fining. Hypotheses are generated about hydraulic sorting as a function of grain size bimodality, sediment supply, and channel gradient.

[3] Since early work on bed material grain size sorting posited exponential models of grain size decline with distance downstream [*Sternberg*, 1875], various authors, guided by the field observations of *Miller* [1958], recognized disruptions in grain size decline at tributary confluences [*Church and Kellerhals*, 1978] and fan contacts [*Bradley et al.*, 1972]. These lateral sediment sources, where significant, bound sedimentary links along the main stem of a river such that median grain size increases and each link has its own exponential function of grain size decline with distance downstream [*Constantine et al.*, 2003; *Knighton*, 1980; *Rice and Church*, 1998; *Rice*, 1999], although there is clearly a hierarchy of influential tributaries [*Rice*, 1998]. Others have identified a marked downstream transition in grain size from gravel to sand, which generally occurs over very short length scales [*Cui and Parker*, 1998; *Ferguson et al.*, 1996; *Ferguson*, 2003; *Gomez et al.*, 2001; *Ichim and Radoane*, 1990; *Knighton*, 1999; *Parker and Cui*, 1998; *Radoane et al.*, 2008; *Sambrook Smith and Ferguson*, 1995].

[4] Within this context, I use an extensive new data set of bed material grain size to address three questions pertaining to longitudinal sorting: (1) Are tributaries influential to downstream fining? (2) Is there monotonic grain size decline for a characteristic grain size (e.g., d_{50})? (3) Is the gravel-sand transition abrupt? A fourth methodological question emerges from the analysis: To what extent are grain size samples from bars representative of those from the adjacent bed?

2. Study Area

[5] Downstream patterns of bed material grain size were investigated along the main stem Sacramento River in northern California, USA (Figure 1). Details on the river's sediment load, drainage network, and hydrology are described elsewhere [*Singer and Dunne*, 2001, 2004a, 2004b; *Singer*, 2007], so only the factors relevant to new data collection are presented below.

[6] The Sacramento has low sediment supply, which is evident in comparisons of its sediment load near the basin outlet to those of similarly sized basins (cf. 4.3 Mt/a [*Singer and Dunne*, 2001] with loads of the Hailo, Po, Copper and Susitna Rivers, all of which exceed 15 Mt/a [*Milliman and Meade*, 1983]). This can be attributed to several factors ranging from shape and slope of the river network to anthropogenic impacts.

[7] First, the weakly meandering Sacramento River (width, ~200 m; drainage area, 68,000 km^2) is largely

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[1] School of Geography and Geosciences, University of St. Andrews, Saint Andrews, UK.

[2] Institute for Computational Earth System Science, University of California, Santa Barbara, California, USA.

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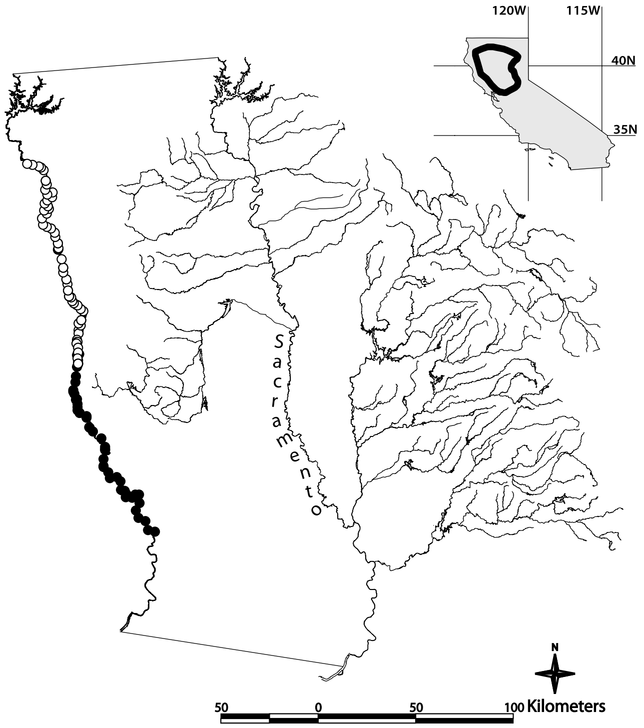

Figure 1. Map of Sacramento Valley drainage network showing major tributaries, streamflow gauges, and dams. Sampling locations are shown for Cooper Scooper (open circles) and Ponar Dredge sampler (solid circles).

located in the center of a low-gradient tectonic basin roughly 100 km wide [*Harwood and Helley*, 1987], containing >8 km of valley fill, and is thus distant from montane and hillslope sediment sources along most of its length [*Bryan*, 1923; *Gilbert*, 1917; *Singer et al.*, 2008]. Although the fine sediment load is derived from reworking of valley fills by tributaries and the trunk stream, the majority of its coarse sediment load derives from the abundant tributaries concentrated in the relatively high gradient northern reaches of the basin (Figure 1). As an illustration, prior modeling suggested ~40 kt/a of gravel passes into the study reach on the main stem (Figure 1), but there is essentially no significant tributary gravel input downstream of this point [*Singer and Dunne*, 2004a, 2006]. Given the shape and slope of the basin, the sediment loads entering the Sacramento River within the Central Valley undergo significant sorting and are thus low and relatively fine in caliber.

[8] Second, sediment remaining after the retreat of western slope Sierra Nevada glaciers was rapidly depleted from mountains and canyons, leaving only relatively small fans and terraces grading into the margins of the Sacramento Valley [*James et al.*, 2002] several tens of kilometers from the Sacramento River. Transport of remaining sediment from these sources along the basin periphery to the river is limited by the gentle gradient across the valley, as well as by a structural obstacle called the Sutter Buttes, a dormant volcano in the middle of the Sacramento Valley [*Harwood and Helley*, 1987] that forces west slope Sierran drainages into the largest tributary, Feather River, leaving a notable east-side tributary gap (Figure 1).

[9] Third, the Sacramento River has been the object of intensive management in the form of large dams (e.g., Shasta Reservoir on the main stem Sacramento has a storage capacity of 5.6×10^9 m^3) and aggregate mining operations in montane tributary basins, as well as bank protection along lowland channels, all of which have further reduced supply of sediment to the main channel enough to adversely affect salmonid spawning habitat [*California Department of Water Resources*, 1980, 1984; *Kondolf*, 1995]. Whereas hydraulic mining delivered high sediment supply to the lower Sacramento River in the late 1800s, the bed has long since adjusted its elevation [*Gilbert*, 1917; *Meade*, 1982], and therefore probably its bed grain size [*Knighton*, 1989] in part due to the self-scouring flood control design implemented in 1917 [*James and Singer*, 2008; *Singer et al.*, 2008].

[10] All of these basin characteristics suggest low sediment supply to the Sacramento and further: (1) tributary gravel input to the Sacramento is limited to the basin periphery in the north and has declined in the last century because of human impacts; (2) naturally low sediment sources in the lowlands have declined (e.g., because of protected banks); and (3) the Sacramento River has adjusted relatively rapidly to supply changes. The Sacramento thus provides a good test case for understanding channel bed grain size patterns in a large river subject to low sediment supply.

3. Methods

[11] In order to circumvent problems with relict subaerial bars that might represent a former state of balance between sediment supply and transport, subaqueous bed material samples were collected in low-water periods between 2002 and 2004 via boat from 125 cross sections spaced ~2 km apart spanning ~380 river kilometers (RK), using the 8.2-L Ponar dredge sampler for fine beds (no gravel) and the 23.2-L Cooper Scooper drag bucket sampler for coarse beds [*Singer*, 2008] (Figure 1). There were no large floods in the intervening period, so the samples are considered as a continuous data set that establishes bed state for a particular slice of time. Samples were extracted from crossing points in straight reaches that represent the integration of sediment transport through upstream bends, in order to minimize the complicating influences of sediment sorting within meander bends. As such, these samples are more likely to represent net longitudinal transport through large river reaches instead of the dynamics of cross-stream sorting. Single samples were collected at simple, narrow cross sections (i.e., in the lower Sacramento) and up to three samples were collected across sections with variable cross-stream topography. Sediments were aggregated for drying, sieving, and weighing at each cross section. Full phi sized grain size classes ranging from 0.063 to 64 mm were used in conjunction with one bulk class < 0.063 mm in order to compute statistics presented below.

[12] The resulting data set was censored such that the largest grain in aggregated samples made up $\leq$5% of the total sample dry weight, thus satisfying the criterion of *Mosley and Tindale* [1985]. The latter standard is notably less stringent than that of *Church et al.* [1987] and small sample sizes may induce quantifiable underestimation of grain size [*Ferguson and Paola*, 1997], but it is consistent

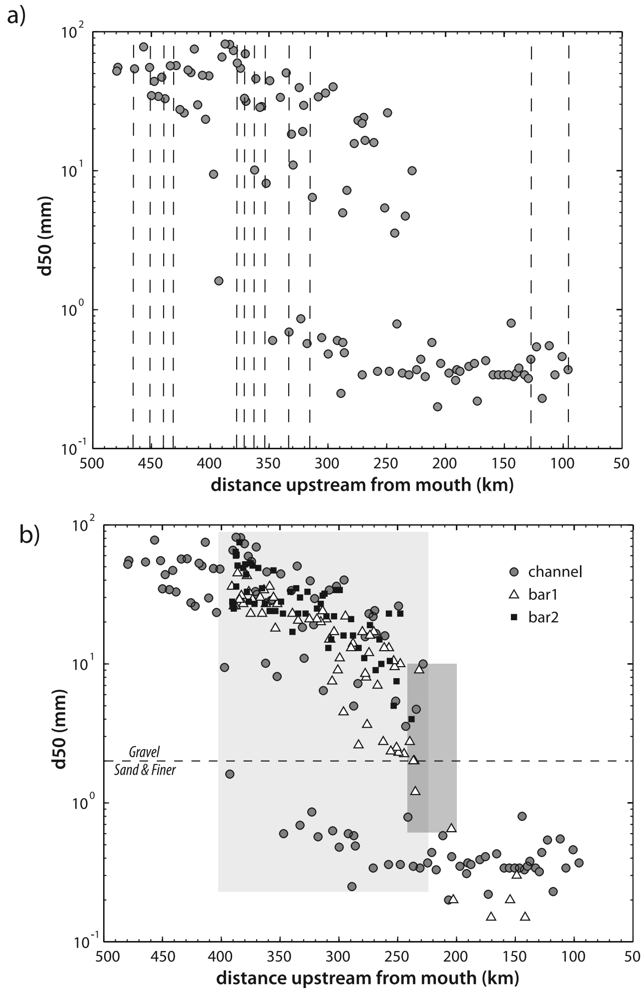

Figure 2. (a) The d_{50} of newly collected channel sediments (aggregated within cross sections) versus distance upstream from river mouth. Tributaries, shown as vertical dashed lines, have negligible influence on downstream sorting. (b) The d_{50} versus distance upstream from mouth for sediments from field campaigns of channel and bar (two separate surveys) sediments. Bar sediments exhibit a rapid transition from gravel to sand (dark gray), compared with channel sediments (light gray).

with recent criteria for bed material grain size data collection [*Haschenburger et al.*, 2007; *Singer*, 2008]. Only cross sections that satisfied this criterion (n = 109) were included in the subsequent analysis. The population from which sediments were extracted is dependent on bed state, but the sampler generally obtains bed surface sediments [*Singer*, 2008].

4. Results and Discussion

[13] Regarding question 1 (above), tributaries (of drainage area > 300 km^2) appear to have a minor influence in disrupting downstream fining in the Sacramento River, but may cause localized fining (e.g., RK 334, Figure 2a). Between RK 378 and RK 315 five tributaries enter the main stem, but they apparently do little to affect the general pattern of grain size decline (of both gravel and fines) that persists for > 100 km downstream of RK 315 within a zone of no tributaries (Figure 2a). As suggested above, the lack of significant tributary influence can be attributed to a sorting of sediment loads along the journey across the Central Valley to the main stem confluence, which results in sediment influx similar to or finer than the grain size distribution of that in the Sacramento River. This result fits with the idea that a damped tributary effect with basin size leads to a more consistent fining trend [*Gomez et al.*, 2001; *Hoey and Bluck*, 1999]. Although hydraulic mining in the late 1800s dramatically increased supply of primarily fine sediment to the lower Sacramento River, there is currently minimal influence of sediment influx from Sierra tributaries (entering at RK 128 and 96 in Figure 2a) on bed material grain size in the fine bed of this reach of the Sacramento.

[14] With respect to question 2, since tributaries do not effectively create distinct sedimentary links [*Rice*, 1999], we may investigate exponential decline over the entire data set (similar to *Gomez et al.* [2001]), assuming sediment supply is primarily from the upper (northern) reaches of the basin. There does not appear to be a monotonic pattern of grain size decline in the data set (Figure 2a). Instead, it appears as if there are two separate fining trends in the data set, a steeper one for gravel than for fines (<2 mm), although the marked difference in their slopes would dissolve if plotted in phi scale. This bimodality in fining is anticipated by prior work reporting separate fining trends for various grain sizes in distributions [*Gomez et al.*, 2001; *Knighton*, 1999; *Seal and Paola*, 1995]. However, the data presented here are all cross section–averaged d_{50}, suggesting a more distinct bimodality and segregation of gravel and fines within consecutive river reaches.

[15] As for question 3, the transition from gravel to sand is not abrupt, but instead extends for ~180 km (between RK ~400 and ~225 within the light gray box in Figure 2b), consisting of a lengthy sequence of alternating gravel and fine reaches that does not correspond to loci of tributary inputs (Figure 2a). The heterogeneous fining trends hypothesized above allows for distinct transport rates for different grain sizes [e.g., *Wilcock and Kenworthy*, 2002], but transport is probably complicated by cross-stream sorting and patchiness, which may develop in rivers with high or low sediment supply [*Dietrich et al.*, 2006; *Lisle et al.*, 1993; *Paola and Seal*, 1995]. Bimodal sediment populations mix in the transition zone (Figure 2b) and indeed may interact to affect transport rates [*Ferguson et al.*, 1989; *Paola and Seal*, 1995].

[16] In general terms, the observed protracted gravel-sand transition probably indicates extensive patchiness in the Sacramento, an intrinsic tendency in heterogeneous (bimodal) sediments [*Dietrich et al.*, 2006]. It incorporates two interrelated effects, termed 'catch and mobilize' [*Dietrich et al.*, 1989; *Ikeda and Iseya*, 1987; *Whiting et al.*, 1988]: (1) relatively fine and more mobile sediment from upstream is transported in coherent patches that are "caught" by less mobile gravel patches, thus increasing local variance in grain size; and (2) infilling of fine sediment increases mobility of gravel patches [*Ferguson et al.*, 1989], enabling their coherent transport farther downstream. These two effects combined likely extend the gravel-sand transition upstream (with the addition of fine patches to formerly coarse beds) and downstream (with the presence of gravels transported downstream across sequences of fined surface

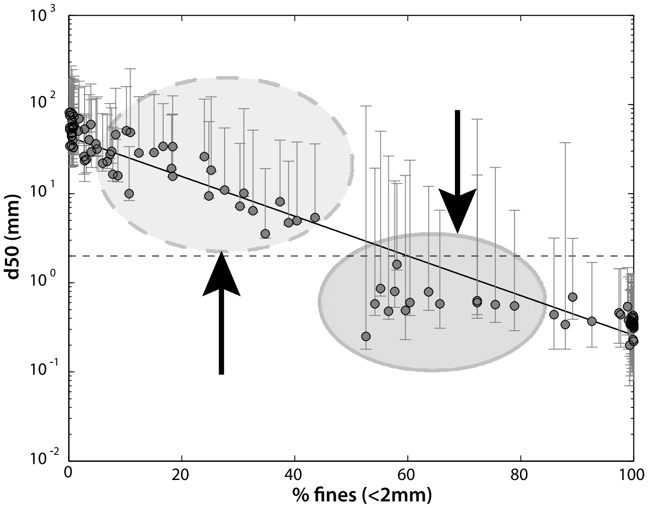

Figure 3. Channel d_{50} versus percentage of fines. Error bars are d_{90} (upper) and d_{10} (lower) for each sample. The horizontal dashed line is the gravel-sand boundary, and the solid line is the linear regression. Ovals indicate regions that are hypothesized to have undergone changes associated with low supply (arrows indicate direction of change). The populations within them overlap in space to form the gravel transition.

patches). The upstream extension of this transition would depend on the presence of local deviations in bed slope [e.g., *Ferguson and Ashworth*, 1991] that could promote transport of fines from steep sections to less steep ones and on heterogeneous supply of fine sediment upriver in sufficient quantities to create fine patches in gravel beds, but not high enough to overwhelm the gravel in an entire reach. Cursory inspection of thalweg depths between RK 350 and RK 90 from a 0.6 m U.S. Army Corps of Engineers bathymetric DEM (1997) peaks and troughs of order 5 m prevail for most of this length, which may provide deposition zones for fine material. However, the bathymetry does not reveal any abrupt inflections in the longitudinal profile that may induce patchiness in this region (RK 350–RK 225) compared with other parts of the river, so inherent bimodality and heterogeneous supply of fine material are likely to be the primary controls on patchiness in this region of river and on upstream extension of the gravel-sand transition. The downstream extension of it would depend more strongly on slope controls, as gravel sources are generally lost in the downstream direction.

[17] Indeed, the new data suggest the gravel-sand transition is complete by RK 225 (Figure 2b), consistent with the location of the largest structural control in the river basin, the Colusa Dome (opposite the Sutter Buttes), which causes a major deflection in river alignment, a break in slope (average reach gradient declines from 2.27 to 0.95 × 10^{-4}), a large backwater, and deposition of sediments [*Harwood and Helley*, 1987; *Singer and Dunne*, 2001, 2004a; *Singer et al.*, 2008]. Downstream of this point very little, if any, fining occurs. It is likely that this structural/slope control prevents the downstream transport of relatively coarse sediments, and thereby limits the downstream extension of the gravel-sand transition zone that was hypothesized above.

[18] The region of channel upstream of the protracted transition zone in the Sacramento River indicates thorough winnowing of fines from a relatively coarse gravel bed ($d_{50} \geq 45$ mm) that is also evident in the dense pack of points near the y intercept on the left side of Figure 3. The latter plot shows a great discontinuity in d_{50} between values greater than and less than 2 mm, but a significant negative trend in these data ($p < 0.05$, $R^2 = 0.94$). What is more interesting, however, is the presence of a large number of fine bedded (>50% fines) cross sections containing gravel material (right oval in Figure 3). These poorly sorted beds overlap spatially with those contained by the left oval in Figure 3. They indicate fine patches that are largely responsible for the protracted gravel-sand transition because added fine sediment (from tributaries or winnowed from the bed upstream) has skewed the distributions (and median size) of gravelly bed sediments.

[19] These factors could result in a distortion of the curve (Figure 3) by increasing the y intercept for gravel on this plot as relatively finer materials are winnowed out of coarse beds, added to fine sediments delivered by tributaries, organized into patches, and coherently transported downstream. This would lead to a steepening of slope in Figure 3 as upstream coarse sections become coarser and downstream coarse sections shift to fine, although the intercept on the fine end of the curve would remain fixed by basin-scale comminution rates and valley-scale slope controls. As such, Figure 3 may confirm that under low sediment supply fining devolves into two separate parts. This strong heterogeneity in fining is further support for extensive patchiness, which is a natural consequence of the breakdown of equal mobility in bimodal materials that arises because of variability in local median grain size [*Paola and Seal*, 1995] coupled with the reach-scale variability in shear stress [*Lisle et al.*, 2000; *Parker and Andrews*, 1985]. Strong cross-stream heterogeneity in subsample grain size distributions [e.g., *Singer*, 2008, Figure 2b] provides additional evidence for patchiness in the Sacramento River.

[20] Last, to investigate the methodological implications of the new data, I compared the new channel data with existing data from bar head surfaces spanning ~160 km from two separate surveys [*California Department of Water Resources*, 1984; *Water Engineering and Technology*, 1990], which are generally methodologically equivalent to samples collected via Cooper Scooper in gravel riverbeds [*Singer*, 2008]. Whereas these two bar surveys are similar to each other with respect to d_{50}, they form a narrow band of downstream fining within a much wider fining range exhibited in the channel data and they contain only a single monotonic fining trend (Figure 2b). Also in contrast to the channel data, the gravel-sand transition in the "bar 1" data is very abrupt (the 'bar 2' data set did not extend across the transition). The bar data are generally coarser than the channel data such that the bar d_{50} data form a lower envelope on d_{90} data from the channel (Figure 4). On the basis of this plot, it may be surmised that the bar d_{50} is approximately equivalent to the channel d_{80}, suggesting a strong difference between bar and bed grain size populations. In unconfined fluvial systems with low sediment supply, bars are likely to be relict features in the landscape that suggest a former state of balance between sediment transport and storage [*Singer*, 2008]. Indeed, field observa-

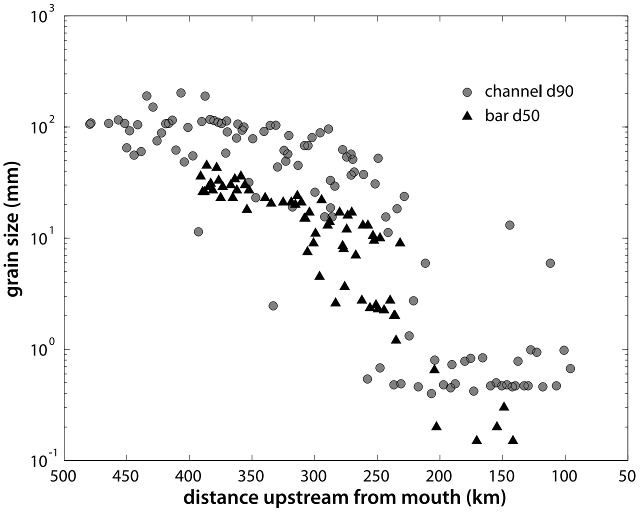

Figure 4. Channel d_{90} and bar d_{50} versus distance upstream. Median bar sediments evidently correspond to channel $\sim d_{80}$.

tions of rapid bar colonization and inspection of high-resolution aerial photographs reveals a preponderance of vegetated bars [*U.S. Army Corps of Engineers*, 1991]. Grain size distributions on bars, therefore, may be expected to differ from those in the riverbed, especially given the spatial heterogeneity of grain size sorting on bars. Such differences between the bed and bars are exaggerated by the fact that bars are products of a sorting process that is more refined than that in the channel, wherein bars are composed of a censored population of sediments in transit along the riverbed [*Church and Jones*, 1982; *Julien and Anthony*, 2002].

5. Conclusion

[21] The data presented show separate fining trends for gravel and fines, a protracted gravel-sand transition, and patchiness in the bed of this large, alluvial river subject to low sediment supply. The interpretations provided are consistent with prior work describing the controls of sediment supply, as well as basin size and shape on fining patterns. In particular, basin shape and slope of the Sacramento Valley limits sediment influx to the main channel [*Rice*, 2007], thereby minimizing the influence of tributaries on fining and affecting bed state [*Dietrich et al.*, 1989; *Lisle et al.*, 1993; *Robinson and Slingerland*, 1998]. Augmenting the effect of inherently low supply, anthropogenic supply reduction has occurred suddenly in the Sacramento Valley with the installation of seven large dams (each with capacity $> 1 \times 10^8$ m^3) in 26 years [*Singer*, 2007], and with extensive aggregate mining [*Kondolf*, 1995] and bank protection measures. Sediment supply reduction may result in coarsening at the edges of the channel, a relatively finer "ribbon" of active sediment transport, a stranding of bars [*Dietrich et al.*, 1989; *Lisle et al.*, 1993] and bed patchiness [e.g., *Dietrich et al.*, 2006, 2007; *Gran et al.*, 2006; *Meade et al.*, 1981], all of which would influence longitudinal patterns of downstream fining.

[22] Over a longer time scales, the longitudinal profile of the Sacramento River would be expected to smoothly adjust (e.g., by lowering) to these supply reductions with a concomitant adjustment in longitudinal sorting [*Hoey and Ferguson*, 1997]. However, the pattern of transient adjustment to sudden, dramatic supply reduction is likely to be one of upstream winnowing [*Little and Mayer*, 1976; *Parker*, 1990; *Shen and Lu*, 1983] (Figure 3), localized scour into former materials [*Hoey and Bluck*, 1999], and increasing influence of fine sediment loads delivered by lowland tributaries (Figure 2a). These would give rise to bimodality in transport and fining, narrowing of the band of active transport, and bed patchiness. Such characteristics, in turn, could manifest in the observed fluctuations in median grain size with distance downstream, dual fining trends, an extension of the gravel-sand transition over a much greater distance than anticipated by prior studies (Figure 2), and strong differences between bar and bed sediments (Figure 4). These physical characteristics probably arise in large fluvial systems with primarily upstream sediment sources (and minimal sedimentary influence of tributaries), inherently heterogeneous sediments, and strong tendencies for cross-stream and reach-scale sorting (e.g., due to a sawtooth long profile). Caution should be exercised in characterizing bed material grain size in such systems, as bar material is likely to be distinct from bed material [*Singer*, 2008].

[23] Further work is necessary to clarify the spatial patterns in bed state and elevation in response to sediment supply and the impact of altered flood regimes [*Singer*, 2007], but the concomitant effects of hydrologic alteration and sediment deficit on grain size patterns are not easily anticipated [*Hassan et al.*, 2006; *Lisle and Madej*, 1992; *Pitlick et al.*, 2008].

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M. B. Singer, School of Geography and Geosciences, University of St. Andrews, Irvine Building, North Street, Saint Andrews KY16 9AL, UK. (bliss@icess.ucsb.edu)