Alternate bar response to sediment supply termination

J. G. Venditti,[1] P. A. Nelson,[2,3] J. T. Minear,[4,5] J. Wooster,[6,7] and W. E. Dietrich[2]

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[1] Sediment supply is widely held to be one of the primary controls on bar topography in alluvial channels, yet quantitative linkages between sediment supply and bar topography are not well developed. We explore the conditions under which alternate bars form and how they respond to the elimination of sediment supply in two linked laboratory experiments. The first set of experiments was conducted in a 28 m long, 0.86 m wide flume channel using a unimodal sand-gravel mix. The second set of experiments was conducted at field scale in a 55 m long, 2.74 m wide channel using a unimodal gravel mixture. In both experiments, alternate bars and patchy surface grain-size distributions developed under steady flow and sediment supply conditions. The cessation of the sediment supply induced a reduction in the surface grain-size heterogeneity and the bars were eliminated. In both flumes, mean boundary shear stress had declined, but were capable of moving sediments after the bars disappeared, albeit at relatively small rates compared to when the bars were present. In the smaller flume, the previously stationary bars migrated out of the flume and were not replaced with new bars. A nearly featureless bed formed with limited surface grain-size heterogeneity, a slightly coarsened surface and a slightly reduced slope. In the larger flume, the formation of alternate bars was induced by an imposed upstream flow constriction and as such, the bars did not migrate. Termination of sediment supply led to progressive erosion of bed topography and loss of the bars, coarsening of the bed surface, loss of bed texture patchiness and significant slope reduction. The original alternate bar topography redeveloped when the sediment supply was restored once sufficient deposition had occurred to reconstruct the original channel slope. This shows that the bar loss was reversible by establishing the previous conditions and highlights the importance of sediment supply for bar formation. The role of sediment supply in bar formation and stability is not often recognized in stream restoration. Our results suggest that the loss of sediment supply can significantly affect alternate bar topography and that considerable volumes of sediment may be needed restore channel bars.

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1. Introduction

[2] It is widely accepted that sediment supply is one of the primary controls on channel morphology and river channel bars [e.g., *Schumm*, 1985; *Church*, 1992, 2006]. Qualitatively, channels with higher sediment supply tend to have more complex, multiple bar morphologies [*Church*, 2006, and references therein]. Yet, how bars will respond to a change in sediment supply cannot be predicted from our current qualitative understanding. Furthermore, the quantitative relation between bar dynamics and sediment supply in alluvial channels is not well-documented in the literature. Here, we explore how a common bar form, alternate bars, respond to elimination of sediment supply. Our work is motivated by an interest in how channel topography in aquatic habitat changes in response to dam closure, which eliminates all the sediment supply to channels in near-dam reaches and can substantially reduce sediment supply to downstream reaches. An allied issue is how bar topography in channels downstream of dams will respond to the high flow releases called for in many stream restoration programs, without a sediment supply. We are also interested in the

[1]Department of Geography, Simon Fraser University, Burnaby, British Columbia, Canada.
[2]Department of Earth and Planetary Science, University of California, Berkeley, California, USA.
[3]Now at Department of Civil and Environmental Engineering, University of Genova, Genova, Italy.
[4]Department of Landscape Architecture and Environmental Planning, University of California, Berkeley, California, USA.
[5]Now at United States Geological Survey, Sacramento, California, USA.
[6]Stillwater Sciences, Berkeley, California, USA.
[7]Now at Fisheries Division, National Oceanic and Atmospheric Administration, Sacramento, California, USA.

Corresponding author: J. G. Venditti, Department of Geography, Simon Fraser University, Burnaby, BC V5A 1S6, Canada. (jeremy_venditti@sfu.ca)

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sediment supply conditions required to build bars in rivers in the context of stream restoration practices.

[3] Alternate bars are normally thought of as being 'free' bar forms (in the sense of *Seminara* [1998]) that arise spontaneously as a result of a fundamental instability. The instability is formed by perturbation of the flow and sediment transport field over topography [e.g., *Nelson and Smith*, 1989; *Nelson*, 1990]. Experimental investigations and numerical models of alternate bar formation have shown bars are initiated as shorter wavelength features that grow in size to some finite wavelength [*Ikeda*, 1983; *Fujita and Muramoto*, 1985; *Nelson and Smith*, 1989; *Nelson*, 1990]. In sand-bedded rivers, equilibrium dimensions of alternate bars are set by topographic steering effects, gravitational effects on sediment transport over a sloping bed and the production of secondary flows by streamline curvature over the bars [*Nelson*, 1990]. In gravel bedded rivers, in addition to the processes listed above, bed surface grain-size texture plays an important role in alternate bar stability. *Nelson et al.* [2010], building on earlier suggestions by *Dietrich* [1987] and *Dietrich and Whiting* [1989], demonstrated that the topographically forced divergences in the shear stress field are matched by divergences in the sediment transport field, which in turn are accommodated by changes in bed surface texture. They argued that bed surface grain-size adjusts to size-selective, cross-streambed load transport, maintaining quasi-steady state conditions without any net erosion or deposition.

[4] Bars may also be 'forced' by geometrical constraints (like channel curvature) or by non-uniform boundary conditions on bottom topography [*Seminara*, 1998]. Alternate bars have been known to form downstream of a persistent perturbation [e.g., *Lanzoni*, 2000a; *Crosato et al.*, 2011] that forms a forced bar, which triggers the formation of subsequent bars downstream by the same processes described for free bar formation by *Nelson* [1990] and *Nelson et al.* [2010]. Free migrating bars may become stationary when the width-to-depth ratio of the channel adjusts to give a resonant condition that corresponds to a natural oscillation in bed topography for a given sediment transport intensity and flow roughness [*Blondeaux and Seminara*, 1985; *Seminara and Tubino*, 1992]. This is thought to occur because the bed instability resonates with a bank instability, which may then lead to meandering planform channel morphology [*Blondeaux and Seminara*, 1985], although stationary alternate bars have also been described in the literature without resonant conditions or a persistent perturbation [*Crosato et al.*, 2011].

[5] In spite of our understanding of alternate bar formation and stability, the role that sediment supply plays in bar dynamics has not been explicitly treated. Reducing sediment supply to a gravel bedded channel causes the active transport corridor to narrow resulting in channel bed coarsening [*Dietrich et al.*, 1989; *Kinerson*, 1990; *Lisle et al.*, 2000; *Dietrich et al.*, 2005; *Nelson et al.*, 2009]. If transport capacity is well above the sediment supply, significant channel incision may also occur. This is often the case downstream of dams, where incision is commonly reported following dam closure [e.g., *Williams and Wolman*, 1984]. But when a dam is closed, the peak discharges are also typically reduced in addition to the sediment supply. The lesser discharges reduce the active channel width, often stranding bars which are then colonized by stabilizing vegetation [*Graf*, 1978; *Friedman et al.*, 1996a, 1996b; *Grams and Schmidt*, 2005]. Decoupling the effects of the reduced sediment supply and water discharge on channel topography downstream of dams is difficult. As a result, the nature of channel bar response to varying sediment supply is not well-defined.

[6] Within this context, we designed an experiment at the Richmond Field Station laboratory at the University of California, Berkeley (referred to as the Berkeley experiment) to examine how alternate bars in a gravel bedded channel respond to the elimination of sediment supply. This work was motivated by the practical question of whether habitat-forming bar topography could be rebuilt below dams by the periodic addition of gravel to the channel. The first step in our experiments was to form free alternate bars in an otherwise straight flume using gravel-sized sediment. We then eliminated the sediment supply to the channel, to simulate the effects of dam closure. We expected some incision to occur. Based on earlier experimental work by *Lisle et al.* [1993], in a channel designed to model a gravel-boulder channel with steep slopes (0.03) and flow depths that were the same as the largest particle size in the bed, we expected cessation of sediment supply would cause the active transport pathway to narrow and the channel to incise, causing the bar tops to emerge. Instead, to our surprise, the bars migrated out of the channel and disappeared. In response to this result, we modified our experimental design to create fixed bars and continued with the experiments that were eventually reported in *Cui et al.* [2008] and *Humphries et al.* [2012].

[7] The unexpected disappearance of alternate bars upon sediment supply elimination raised a number of interesting questions. Why did the bars disappear? Why did the bar tops not emerge from the flow due to vertical erosion in the thalweg as in the previous experiments of *Lisle et al.* [1993]? Do bars disappear in real rivers in response to sediment supply termination? Here, we seek answers to these questions. We begin by describing more fully the original Berkeley experiment that motivated these questions. We then report results from a field-scale laboratory experiment, conducted in the main channel at St. Anthony Falls Laboratory (SAFL experiment), with an upstream channel constriction. This constriction prevented migration of downstream bars, but upon cessation of sediment supply, the bars eroded, the bed coarsened, and slope declined. We show that by resupplying coarse sediment, the bars once again develop. We hypothesize that bar elimination is a likely outcome to sediment supply elimination if the boundary shear stress, although declining, remains sufficiently high that full bed mobility is maintained during degradation.

2. A Motivating Experiment

2.1. Experimental Methods

[8] The Berkeley experiment was undertaken in a 28 m long and 0.86 m wide flume channel at the University of California, Berkeley Richmond Field Station in Richmond, CA. A series of papers report results from other experiments conducted in this flume which record the influence of sediment supply variations over a flatbed [*Sklar et al.*, 2009; *Nelson et al.*, 2009; *Venditti et al.*, 2010a, 2010b] and over a

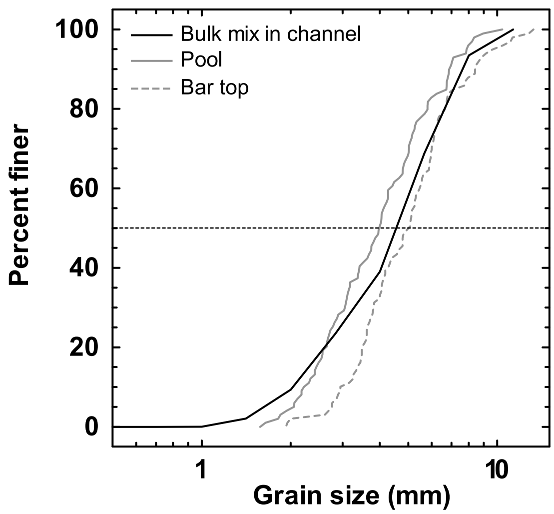

Figure 1. Grain-size distribution of the bed material placed into the channel and the sediment feed (bulk mix) in the Berkeley experiment. Also plotted are the grain-size distributions of a typical bar top and pool (measured midway along flume with fully formed alternate bars).

bed with fixed alternate bars [*Cui et al.*, 2008; *Humphries et al.*, 2012]. In this experiment, we used a unimodal gravel bed with a median grain-size D_{50} = 4.2 mm and a range between 0.8 and 11 mm (Figure 1). Water discharge was held constant at 19 ± 0.5 l/s through all stages of the experiment. The bed elevation was held constant at the downstream end of the flume by a sediment weir, over which sediment deposited into a sediment trap [see *Venditti et al.*, 2010b; *Humphries et al.*, 2012]. Water surface elevation was also held constant at the downstream end of the flume by a sharp-crested weir, several meters downstream of the sediment trap. Table 1 summarizes the hydraulic conditions in the experiment.

[9] Starting with a bed that was raked flat (Figure 2a) with a slope of 0.0104, sediment was fed into the flume across the channel entrance uniformly at 1.33 kg/min for the first 22 h, until the bed topography reached a steady state and sediment output was approximately the same as the sediment input. Then the sediment supply was eliminated and the experiment was continued for another 80 h until the topography appeared to reach a new equilibrium. Using the predictor for the number of river bars that should develop in our channel of *Crosato and Mosselman* [2009, equation 19], we calculate a 'bar mode' of ~1, which corresponds to one bar per cross-section, suggesting that our experimental setup should produce stationary alternate bars. The non-migrating bar wavelength for these conditions, predicted using the stability theory of *Crosato et al.* [2011, equation 6], is 6.9 m.

[10] The time required to form equilibrium topography in our experiment (22 h) may seem short. However, we optimized the experimental conditions to produce alternate bars in mixed-size sediment following *Colombini et al.* [1987] and *Lanzoni* [2000b] by using a high width-to-depth ratio (~20) and a transport stage where all grain-sizes were mobile. We selected a shear stress that would produce near equal-mobility transport conditions [*Parker*, 2007] so the bed topography would develop to equilibrium quickly. Our experimental times are longer than most of those reported in *Lanzoni* [2000b], but are much shorter than the 10 weeks used in experiments by *Crosato et al.* [2011] who used suboptimal conditions (lower width-depth ratios) to demonstrate that fixed alternate bars would form without resonant conditions.

[11] We monitored the bed and water surface elevations using an ultrasonic water level sensor and an acoustic echo sounder that traversed the flume on a mechanized cart that ran along rails above the flume walls. Both of these instruments have a practical resolution (based on their calibration) of ±1 mm. Elevation data were measured along 13 alongstream profiles at 5 mm intervals. These data were used to calculate cross-stream averaged bed and water surface profiles from which mean water surface and bed slopes were calculated. Flow depth (h) was calculated from the mean difference between the cross-stream averaged bed and water surface profiles, and therefore represents a spatially averaged flow depth. Shear stress was calculated from the depth-slope product ($\tau = \rho_w g S h$ where slope, S, is taken from the cross-stream averaged water surface profile, ρ_w is the density of water, and g is gravitational acceleration). Some care needs to be taken when interpreting our calculated shear stress. Flow over topography such as channel bars is highly non-uniform [*Nelson and Smith*, 1989; *Nelson*, 1990; *Nelson et al.*, 2010] and it is the spatial variation in stress that gives rise to and maintains the bar morphology. *Nelson et al.* [2010] calculated the spatial distribution of shear stress using a 2D hydrodynamic model (FaSTMECH) for one of our experiments. Our calculated shear stress is roughly in the middle of the range calculated in the numerical model and seems to represent conditions along the thalweg quite well.

[12] We calculated the non-dimensional shear stress (Shields number) from these data as

$$\tau_* = \frac{\tau}{(\rho_s - \rho_w) g D_{50}} \quad (1)$$

where τ is the shear stress at the bed and ρ_s is the sediment density. Values of $\tau_* < 0.045$ are widely accepted as characterizing conditions below the entrainment threshold for a gravel mixture [*Miller et al.*, 1977; *Yalin and Karahan*, 1979]. It is widely known that the presence of sand may affect the mobility of gravel-sized particles [e.g., *Ikeda*,

Table 1. Hydraulic Conditions in the Berkeley Experiments

	Discharge Q (m^3/s)	Mean Velocity U (m/s)	Flow Depth h (mm)	Slope S	Shear Stress τ (Pa)	Bed Surface Grain-size $D_{50\text{-Surf}}$ (mm)	Shields Number[a] (τ_*)	Shields Ratio[b] τ_*/τ_{*c}
With bars	0.019	0.54	41	0.0108	4.2	4.4	0.061	1.33
Bars eliminated	0.019	0.45	49	0.0084	4.0	4.1	0.059	1.30

[a]Defined in equation (1).
[b]Ratio of the Shields number to its value at the threshold for sediment entrainment τ_{*c}.

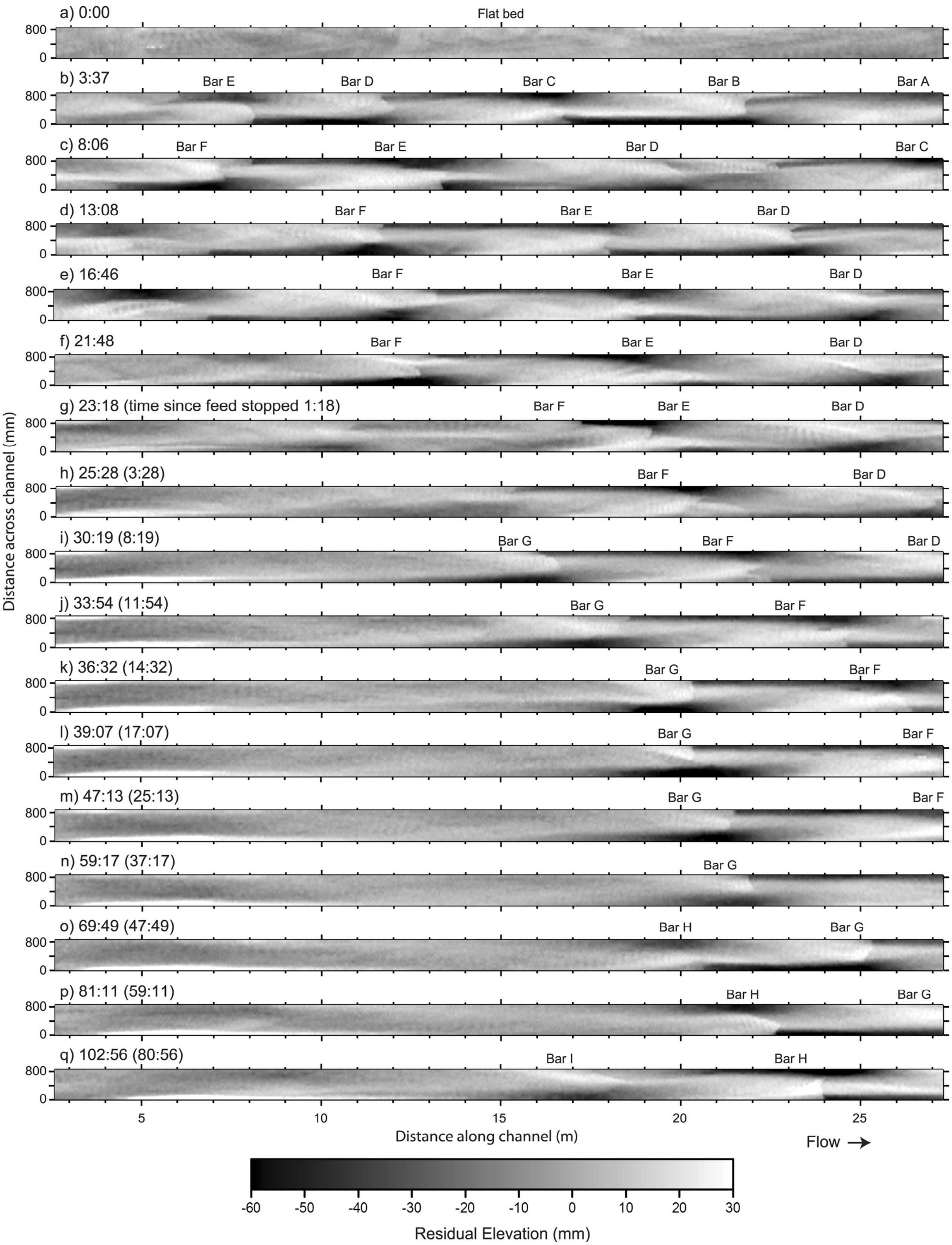

Figure 2. Residual (detrended) topographic elevation in the Berkeley experiment calculated by subtracting the channel slope from the measured topography. This highlights the bed topography otherwise obscured by the channel slope in the plots. (a) Raked flat bed. (b–f) Fully developed alternate bars with a sediment feed. The feed was eliminated at 22 h into the experiment. (g–q) Topography after the sediment feed elimination.

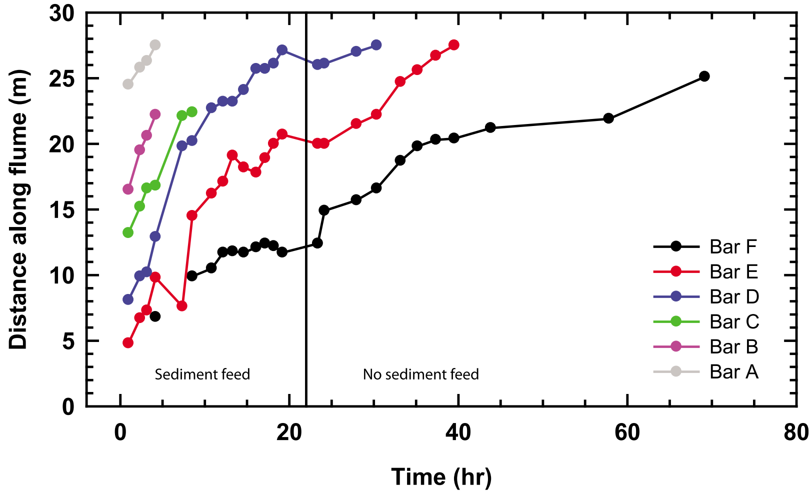

Figure 3. Position of bar heads in the flume as a function of time in the Berkeley experiment derived from hand-drawn, bar position maps. Bar A was developed first and Bar F was developed last.

1984; *Wilcock*, 1998]. In our Berkeley experiment, there was <10% sand. We tested the mobility of the mixture and found that the critical Shields number was 0.046 [*Humphries et al.*, 2012].

[13] Hand-drawn maps were made of the macro-scale features of the bed, including the bar head position throughout the experiment. Bed load was monitored using a continuous weighing mechanism [*Venditti et al.*, 2010b; *Humphries et al.*, 2012] that captured all sediment exiting the flume in a drum suspended in the end tank from a load cell. Herein, we present 5-min averages of the dry weight calculated by assuming a sediment density of 2650 kg m^{-3}. Bed surface grain-size distributions were obtained from photos taken from the mechanized cart. The photos were analyzed in a GIS software package using a grid-by-number technique that is similar to a Wolman count [*Bunte and Abt*, 2001; *Venditti et al.*, 2010b; *Nelson et al.*, 2009]. Values of $D_{50\text{-}Surf}$ in Table 1 are averages of 4 bed surface grain-size distributions obtained on either side of the centerline at 12 and 18 m from the entrance of the flume. The 'with bars' value is based on bed surface samples from two bar tops and two pools, while the 'bars eliminated' value is based on 4 samples from a flat bed.

2.2. Observations

[14] Bar formation began minutes after the flow was started. The bars were labeled (A-H) as they formed at the upstream end of the flume (see Figure 2). Figure 3 shows the position of the bar heads as they migrated along the flume through time. The distance between the bar heads at any given time is the bar length and the slope of each line is the bar's migration rate. Bars A, B, and C migrated downstream quite rapidly and out of the flume during the first 8.5 h of the experiment. The migration rates of the remaining bars (D, E and F) progressively slowed and the bars eventually became quasi-stationary at ~15 h (Figures 2 and 3), well before sediment supply elimination.

[15] The bed topography at the end of the sediment feed stage of the run is shown in Figure 2e and 2f. The alternate bar morphology was similar to that observed in previous investigations [c.f. *Ikeda*, 1983; *Fujita and Muramoto*, 1985]. Our bar lengths are identical to the non-migrating bar wavelength predicted using the stability theory of *Crosato et al.* [2011]. Well-developed bars formed with adjacent pools that widened and deepened in the downstream direction, eventually shoaling onto the next downstream bar. Downstream of the migrating bar heads was a large inactive zone that was formed by the pools, which had migrated with the bar heads. Very little deposition or sediment transport occurred in these inactive zones, and they were progressively covered by the upstream advancing bar head. Between the pools, flow shoaled over the downstream bar and developed a strong cross-stream component away from the bar. The amplitude of the bars was roughly equivalent to the flow depth in the pools. The surfaces of bar heads (D_{50} = 5.1 mm) were much coarser than the pools (D_{50} = 3.8 mm) (Figure 1).

[16] Sediment supply to the flume was eliminated at hour 22 and the bed immediately responded by eroding the bars, starting with the upstream-most bar and progressing downstream (Figures 2g–2q). The upstream-most bar, Bar F, underwent vertical and lateral erosion of the bar top that provided a sediment supply to bars in the lower part of the channel, and began to migrate downstream (Figures 2g and 3). One to three hours after the feed was eliminated, Bar F topography was significantly eroded and began to overtake Bar E (Figures 2g and 2h; we retain the label F to represent the bar formed by the combination of E and F). Nascent bars, formed upstream of Bar F (Figures 2d–2f), coalesced to form Bar G (Figure 2g). After ~10 h with no sediment feed, Bars D and E migrated out of the flume and the remnant topography from these features was overtaken by Bar F (Figure 2j), which grew in size as sediment was excavated from upstream. Bar F migrated out of the flume after 25 h without a sediment feed. Bar G migrated downstream until ~60 h after the feed was eliminated, when it began to exit the flume. As this process continued, the bed surface continued to scour, leaving a relatively featureless plane-bed that extended the full length of the flume upstream of the last bar.

[17] Minor bar features were generated by episodic erosion of topography at the channel walls from eroded coarse

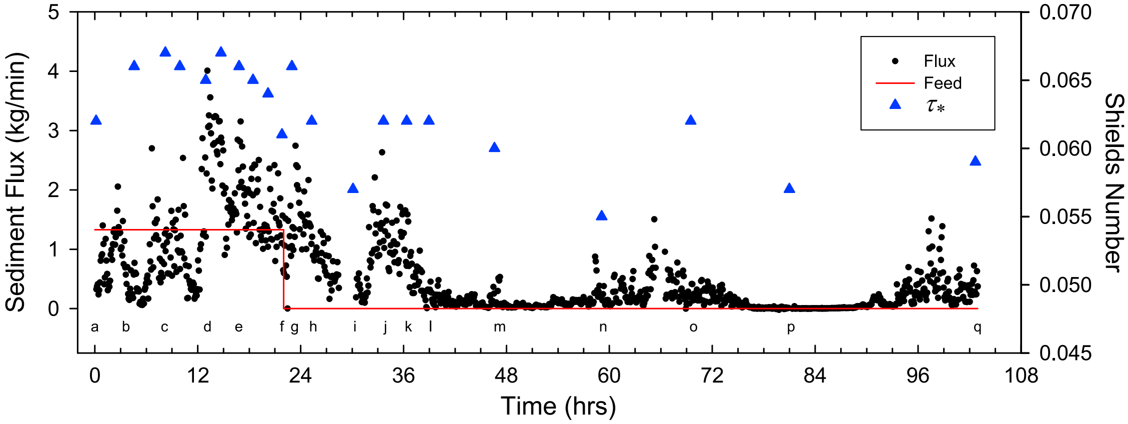

Figure 4. Measured bed load transport at the end of the flume and Shields number (τ_*) in the Berkeley experiment. Shields number is calculated using the shear stress in Figure 5c. Lower case letters correspond to Figures 2a–2q.

bar heads that had stabilized in the feed stage of the experiment. A good example of this is Bar I, developed between 10 and 15 m at 102:56 (Figure 2q), that was formed from sediment excavated from near the sidewalls (see deposit at ~10 m at 81:11; Figure 2p). New bars were not developed upstream of 15 m of the flume, suggesting that the effect of the supply elimination was to extend the distance required to form bars. Bar H, for example, formed at ~20 m from the flume inlet (Figure 2o) with no obvious erosional event upstream.

[18] We envision three possible reasons why the bars disappeared in the upstream end of the flume, but persisted in the downstream end. The first is that sediment eroded from the upstream end of the channel provided a supply to the downstream end that was sufficient to promote bar formation. The second is that flow conditions changed downstream so that shear stress was greater downstream than upstream. *Lanzoni and Tubino*'s [1999] theoretical analysis of bar instability for sediment mixtures and subsequent experiments [*Lanzoni*, 2000b] suggest that when the boundary shear stress is close to the critical value to entrain the coarse fraction of sediment, grain size heterogeneity can inhibit bar growth, but this damping effect diminishes as the shear stress increases and sediment transport becomes less size-selective. If the shear stress in the downstream portion of the flume remained essentially unchanged but the stress in the upstream end of the flume decreased to a point where this damping effect became important, it would follow that bars could have temporarily persisted downstream but not upstream. A final possible reason for bar persistence in the downstream end of the flume is that they are relict features formed when shear stress was high enough to promote bar development, but that shear stress declined in the downstream section so it was unable to erode the bars. Regardless of the change it would have to be a transient effect, because at some point, enough sediment would have been eroded from the channel to reduce the bed slope and the shear stress below the threshold for particle movement along the flume length. Without particle movement, new bars cannot form.

[19] We do not have sediment transport measurements along the flume, so it is difficult for us to assess the downstream change in transport and the supply of sediment from the upstream reach. Sediment discharge at the end of the flume (Figure 4), initially increased as bars developed, but declined as the bars stabilized, reaching the input rate (1.33 kg/min) during the steady feed period. Transport continued to vary considerably through time. When the feed was eliminated, the sediment flux approached zero about 9 h later, but there were notable periodic increases in sediment flux as individual bars migrated out of the channel (36 h, Bar D; 66 h, Bar F; 99 h, Bar G) (Figure 4). The source of these increases is not clear (they were not externally forced). Nevertheless, the increases suggest that the channel had not yet stabilized below the threshold for sediment entrainment. The periods of high sediment flux later in the experiment coincide with periods of bar rearrangement in the downstream end of the channel.

[20] Shear stresses calculated using the channel-averaged flow depth and the mean water surface slope of the whole flume show the channel was capable of transporting sediment throughout the experiment (Figure 4). There was a decline in the mean water surface slope from 0.0108, when the bars were fully formed and just before the sediment feed was eliminated, to 0.0084 at the end of the experiment (Figure 5a), an increase in the flow depth of a few millimeters (Figure 5b) and a drop in shear stress after the sediment feed was eliminated (Figure 5c). Figure 4 shows that while there was a decline in the Shields number (calculated using the shear stress in Figure 5c), it remained well above the threshold for motion after the bars had disappeared. This elevated Shields number means that sediment was continuously delivered to the lower end of the flume and presumably could be responsible for continued bar presence and migration there.

[21] We investigated the possibility of a downstream change in shear stress promoting bar persistence by calculating the flow depth, slope, shear stress and Shields number for the upstream and the downstream sections of the flume separately. We used 15 m downstream from the channel entrance as the division, except later in the experiment when there was no evidence of bars in the upstream 17.5 m of the channel. Figure 6 shows that the non-dimensional shear stress was actually higher in the bar-free upstream end of the flume than in the downstream end of the flume and

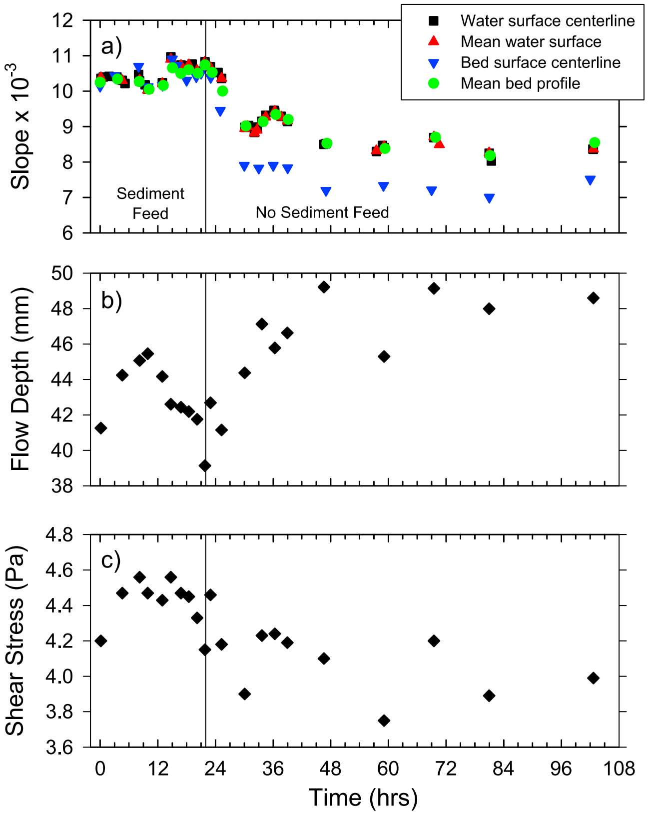

Figure 5. Channel-averaged (a) slope (S), (b) depth (h) and (c) shear stress (τ) in the Berkeley experiment.

that τ_* was less than 0.046, the observed threshold for sediment movement, for some periods. When the upstream end of the flume was bar-free, the flow depth there was a few millimeters less than downstream and the slope was much greater (Figure 6a) hence the lower end of the channel had lower shear stress. When there was a sediment feed, the channel slope was approximately the same in the upstream and downstream portions of the flume. When the sediment feed was removed, the channel slope declined, but the slope declined more in the downstream end than in the upstream end of the flume (Figure 6b). The slope in the downstream end increased from the sediment supplied by upstream erosion twice, at ~66 h and ~99 h. This resulted in an increase in τ_* above 0.046 and increased the sediment flux (Figure 4), rearranged the remaining bars (Figure 2). The reason why the slope declined more in the downstream end of the flume is not clear from our data, but it was probably because the elevation of the downstream end of the sediment bed was controlled by a 15 cm high gate. There was no erosion below the gate level, but this may have exerted a base level control on the bed. Regardless, this suggests that the bars in the downstream end of the flume were not eroded because the shear stress was below the critical value for entrainment.

[22] Overall, these results suggest that bar formation is critically dependent on sediment supply to the channel. When the sediment supply was eliminated, the bars began to migrate and did not reform upstream. As the supply from upstream decreased, the bar-free zone of the channel lengthened. We can explain why bars persisted in the downstream end of the flume. However, hydraulic data suggest that the bar-free zone was capable of transporting sediment, in agreement with our visual observations and our τ_* calculations (Figures 4 and 6c), even at the end of our experiments, so the reason why the bars were eliminated in this upstream section of our flume is not clear.

[23] Since we are unaware of any theoretical explanation linking bar disappearance with sediment supply elimination, we suspected that conditions particular to our experimental setup or the relatively small scale of our experiment conditioned the results and prevented a thorough interpretation. Although the scaling of our experiments exceeds the threshold criterion developed by *Knaapen et al.* [2001], below which scale effects are known to be important, the shallow flow depths and the difficulty in measuring bed texture variation in these fine gravel-coarse sand sediments made some measurements difficult. We therefore repeated the experiment at field scale, where it was easier to make reliable observations of shear stresses, sediment texture change and sediment transport.

3. A Field Scale Experiment

[24] These experiments were conducted in a 55 m long and 2.74 m wide flume at St. Anthony Falls Laboratory in Minneapolis, Minnesota (referred to here as the SAFL experiment). We used a sediment mixture with a median diameter of 11 mm and a range between 2 and 45 mm (Figure 7a). The 'bulk mix in the channel' plotted in Figure 7 is the sediment size distribution before it had been water worked and recirculated by the flume pumps. The maximum grain-size

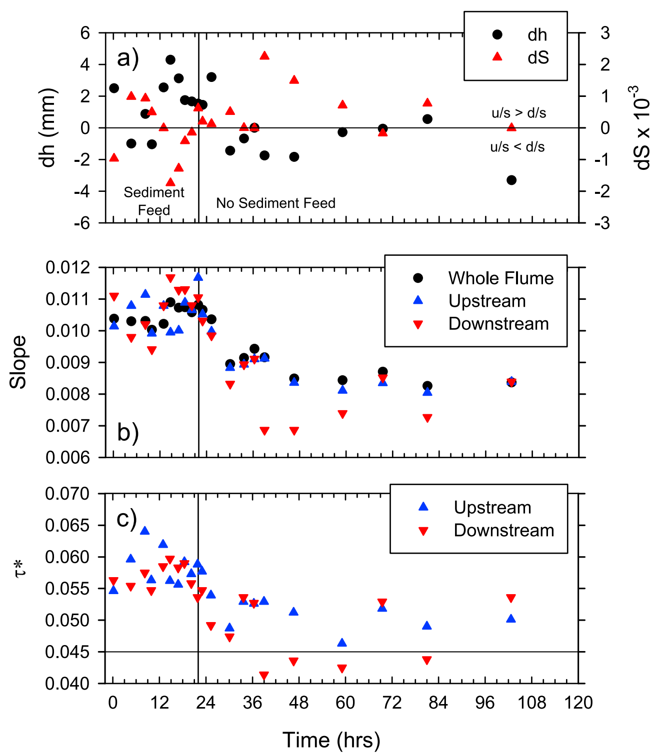

Figure 6. (a) Change in flow depth (dh), slope (dS) between the upstream and downstream sections of the flume. (b and c) Slope and Shields number (τ_*) calculated for the upstream and downstream sections in the Berkeley experiment.

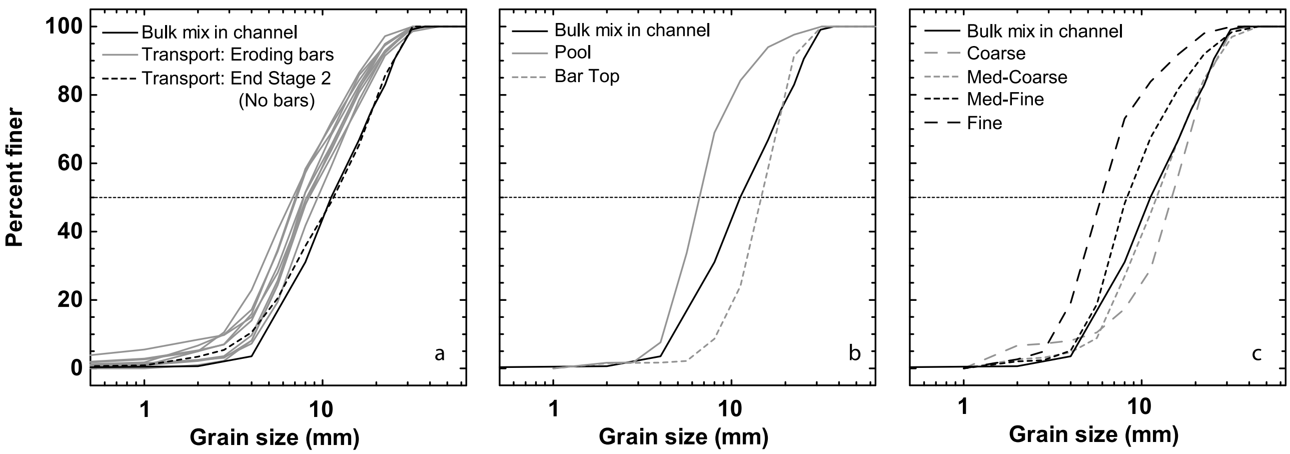

Figure 7. Grain-size distributions in the SAFL experiment. (a) The bed material placed into the channel, material in transport during bar elimination and transport at the end of the second stage of the experiment. The transport samples were taken from the recirculation pipe. (b) Surface of a bar top and pool (taken midway along flume). (c) Patch-averaged bed surface samples corresponding to mapped units in Figure 9.

observed in all our samples was 32 mm, indicating the possibility of some grain attrition. As in the Berkeley experiments, water discharge was held constant throughout the experiment, but at 400 $\pm$ 20 l/s. Table 2 summarizes the hydraulic conditions in the experiment. The flume was equipped with a recirculation system that pumped gravel and water from the downstream end of the channel to the channel head. The channel bed elevation was free to fluctuate along the whole bed length. There were no retaining structures on the downstream end of the sediment bed (unlike the Berkeley experiment). Sediment exited the flume into a sediment trap that extended across the channel width [*Marr et al.*, 2010]. The water surface elevation was held constant by a sharp-crested weir several meters downstream from the sediment trap.

[25] This experiment was conducted in four stages: 1) Alternate bar topography development with sediment recirculation and all grain-sizes mobile; 2) Elimination of the sediment recirculation, which is analogous to a sediment supply cutoff; 3) Coarse surface layer mobilization using a fine gravel feed; and 4) Addition of a coarse gravel sediment feed composed of the bed material that left the flume during the second stage (see Table 3 for a timeline). Each stage ended when we observed no net change in the bed topography except for the last stage as described below. Data from the first stage of this experiment are described in detail by *Nelson et al.* [2010]. The present manuscript focuses on the second and fourth stages of the experiment, which have not previously been reported. In particular, we report how the alternate bars and associated grain-size heterogeneity described in *Nelson et al.* [2010] changed with sediment supply elimination.

[26] In the first stage, we began with a bed that was raked flat across the channel and the right 1/3 of the flume entrance (looking downstream) was obstructed to produce a steady perturbation intended to force the formation of bars downstream [e.g., *Lanzoni*, 2000b; *Crosato et al.*, 2011]. We chose a bed slope characteristic of gravel bed rivers that could be easily accommodated in the flume (0.014) and optimized the water discharge to get a width-to-depth ratio within the range reported by *Colombini et al.* [1987] as producing stable alternate bars and to get τ_* approximately equal to $\sim$2 times the value required to entrain the bed material (τ_{*c}). *Lanzoni* [2000b] has suggested that bars will only form with full sediment mobility. *Wilcock and McArdell* [1993] demonstrated full mobility of all grain-sizes occurs when $\tau_* = 2\tau_{*c}$ for a grain-size distribution with the same range of particle sizes used in our experiment. Sediment was recirculated at a rate of 53.7 kg/min until the bed topography reached a quasi-steady state (19.4 h; see *Nelson et al.* [2010]). Our observed conditions, given in Table 2, deviated slightly from our design values due to internal dynamics of the system. We calculated the bar mode using *Crosato and Mosselman* [2009, equation 19] and found a value of $\sim$1, corresponding to one bar per cross-

Table 2. Hydraulic Conditions in the SAFL Experiments[a]

	Q (m^3/s)	U (m/s)	h (mm)	S	τ (Pa)	$D_{50\text{-Surf}}$ (mm)	(τ_*)	τ_*/τ_{*c}
With bars	0.400	1.07	137	0.0133	17.9	$\sim$10.1[b]	0.109	2.4
Bars eliminated	0.400	0.88	166	0.0073	11.9	$\sim$13.1[b]	0.056	1.3
Bars re-established	0.400	1.03	142	0.0117	16.3	$\sim$10.1[c]	0.100	2.2

[a]Variables as in Table 1.
[b]Weighted average based on data presented in Figure 9.
[c]Not measured, but assumed for the purpose of calculating τ_*.

Table 3. StreamLab06 Experiment Timeline

Stage	Event	Date	Clock Time	Cumulative Run Time (h)	Recirculation	Sediment feed (kg/min)	Feed Period (min)
1: Alternate bar development	Experiment Started	June 9	9:23	0.0	On	0	–
2: Elimination of the sediment recirculation	Supply Eliminated	June 15	17:05	19.4	Off	0	–
	Channel adjustment complete	June 19	18:26	75.5	Off	0	–
3: Fine gravel pulses	Pink Pulse Feed	June 23	13:33	75.7	Off	13.9	60.4
	Blue Pulse Feed	June 24	11:15	79.0	Off	28.7	27.1
	Red Pulse Feed	June 24	16:03	79.6	Off	29.1	35.8
4: Coarse gravel feed	Day 1 start	June 28	13:30	91.1	Off	53.7	Continuous
	Day 2 start	June 29	10:59	94.6	Off	53.0	Continuous
	Day 3[a] start	June 30	12:19	101.5	On	32.0	Continuous
	Feed end	June 30	13:16	102.4	On	0	–
	Run end[b]	June 30	15:04	104.2	–	–	–

[a]The sediment feed was reduced from ∼53 kg/min to ∼32 kg/min because ∼22 kg/min was being delivered to the top end of the flume by the sediment recirculation system.

[b]When all of the coarse sediment that exited the flume in Stage 2 was fed back into the channel, the coarse sediment feed was ceased. The flume was run for 1.8 h with the sediment recirculation system returning sediment to the top end of the flume at ∼31 kg/min.

section, which indicates our experiments should produce stationary alternate bars. The non-migrating bar wavelength for these conditions, predicted using the stability theory of *Crosato et al.* [2011, equation 6], is 23.7 m.

[27] The second stage of the experiment was designed to model a sediment supply reduction as might occur downstream of a dam following dam closure. As such, we redirected the recirculation pipe outside the flume and collected all the exiting sediment. This eliminated the upstream sediment supply. We did not decrease the water supply, as is common following a dam closure, in order to isolate the effect of sediment supply reduction. We assume that this shift from a recirculating to a non-recirculating system is equivalent to eliminating the sediment feed in the Berkeley experiment.

[28] The third stage of the experiment was designed to further test the hypothesis presented in *Venditti et al.* [2010a] that fine gravel augmentation pulses are capable of mobilizing coarser gravel bed surfaces, coarsening bed load and fining the bed surface. We use the term pulse into indicate a body of sediment introduced to the channel that can generate a sediment wave and to refer to the sediment wave itself, which may include input sediment and bed material. The fine gravel augmentations consisted of a series of 4 mm fine gravel fed to the channel (referred to as pink, blue and red, corresponding to the color that the grains were painted) to create transient sediment waves. Feed periods and rates are given in Table 3. A total of 2670 kg of painted pulse material was input to the flume. The results from this stage of the experiment are not germane to the questions addressed herein, so they are not discussed further, however, we do report their effect on bed topography, because the end of the third stage of the experiment is the initial condition for the fourth stage.

[29] This fourth stage of the experiment was designed to determine how much sediment needed to be added back into the channel to initiate the development of alternate bars. In order to accomplish this, we added the sediment that had exited the flume channel during the second stage of the experiment, by feeding it by hand uniformly across the channel width, at ∼53 kg/min which was similar to the bed load transport rate that had existed when stable bars were present (52 kg/min). In doing so, we reestablished the sediment feed to the channel that existed during initial bar development. The grain-size distribution of this sediment feed matched the material transported out of the flume in the second stage of the experiment. Toward the end of this coarse gravel feed, sediment began exiting the flume at a rate of ∼22 kg/min before the entire volume that exited the channel during the second stage was added (Table 3). In order to maintain the integrity of the recirculation system, we had to restart it, so we reduced our feed rate to 32 kg/min for 57 min of the experiment to ensure that the sediment delivered to the flume head remained at ∼53 kg/min. When the recirculation system was restarted, 92% of the material that had exited the flume channel during the second stage of the experiment had been fed. Once the sediment feed had been exhausted, we continued the experiment for another 1.8 h with the sediment recirculation running (Table 3) and no additional sediment feed until we were confident that the material fed into the flume had started to exit the channel at an increasing rate.

[30] During all stages of the experiment, we monitored the bed and water surface elevations using an ultrasonic water level sensor and an acoustic echo sounder that traversed the flume on a mechanized cart that ran along rails above the flume walls. Both of these instruments have a practical resolution (based on their calibration) of ±1 mm. Water surface and echo sounder bed measurements were obtained along 5 longitudinal profiles spaced at 0.5 m in the cross-stream direction with the middle transect located along the center of the flume. Measurements in the along-channel direction were obtained at an interval of 5 mm. The water surface elevation was measured approximately every hour with more frequent measurements later in the experiment. During the first and second stages (bar development and feed elimination stages), portions of the flow were too shallow to allow bed surface profile collection with the echo sounder. When we could use the echo sounder, bed surface measurements were obtained every 1–2 h. Bed surface elevation data were also collected with a laser distance meter mounted to the mechanized cart on a 10 × 10 mm grid when the

flume was drained at the end of each day and between experimental stages. The sediment in the channel was coarse enough that draining the flume slowly did not to disturb the topography. The laser is accurate to ±0.1 mm, which is smaller than the finest grains in the flume. Both echo sounder and laser bed elevations were used with the water surface profiles to calculate the water surface slope, flow depth and shear stress at various stages of the experiment following the method used for the Berkeley data. Slopes, depths and shear stresses calculated from the laser and echo sounder were slightly different because the laser measured the whole bed surface while the echo sounder could only measure submerged topography.

[31] Hand-drawn facies maps of the dry gravel bed were created 4 times during the second stage of the experiment, at the end of each day to record the changes in bed sediment heterogeneity. The bed was divided (by eye) into four characteristic grain-size patch types: coarse, medium-coarse, medium-fine, and fine (see *Nelson et al.* [2010] for further details on the patch mapping procedure). After the bed was mapped, bed surface samples were collected for each patch type. A 0.3 × 0.3 m square of the bed surface was painted and every painted grain was collected. The samples were sieved and the resulting area-by-weight grain-size distributions were converted to volume-by-weight distributions using the voidless cube model of *Kellerhals and Bray* [1971]. Grain-size distributions (Figure 7c) for the coarse and fine patch types are averages of three samples collected at different times. The medium-coarse and medium-fine distributions are based on single samples.

[32] Sediment transport was measured as gravel entered a floor pit with 5 side-by-side gravel collection drums each spanning 0.55 m of the channel width. Each drum was connected to a load cell with an accuracy of 55 g. The drums had three radial baffles at 120 degrees to each other. When the drum weight exceeded a user-selected weight (40 kg immersed weight), the drum rotated, dumping gravel into the recirculation system. During the first stage of the experiment (bar development), the sediment recirculation system was run continuously. During the second and third stages of the experiment, the sediment recirculation pipe was diverted to collection bins outside the flume. Sediment that exited the flume during the second stage of the experiments was stored for use in the fourth stage of the experiment. Sediment that exited the flume during the third stage of the experiments was discarded. Periodic grain-size samples were obtained from the recirculation pipe or the collection bins throughout the experiment and sieved.

4. Field Scale Experiment Results

4.1. Fixed Bar Formation

[33] Bar formation in the SAFL experiment was dominated by the flow perturbation caused by the sand bags inserted at the head of the flume. Figure 8 shows the residual bed elevation after the channel slope was subtracted from the bed elevation, which highlights the bar topography. A bar developed immediately downstream of the sand bags (upstream of the area mapped in Figure 8, which was outside the range of the instrument cart) and two more bars developed with heads at downstream distances of ~27.5 m and ~45 m (Figure 8a). The bars did not undergo any obvious migration as they developed, because the most upstream bar was anchored by the flow constriction. However, the bars did appear to stretch through time as the most upstream bar grew in size, which essentially extended the upstream flow constriction.

[34] The bed topography at the end of the alternate bar development stage is shown in Figure 8a and the grain-size heterogeneity is shown in Figure 9a. The bar morphology was similar to that observed in the Berkeley experiments and in previous work [e.g., *Ikeda*, 1983; *Fujita and Muramoto*, 1985], with distinct bar-pool morphology, fine pools that shoal downstream transitioning into coarse bar heads, and bar crossovers where flow was oriented across-channel. When fully developed, the bar amplitudes were approximately equal to the flow depth in the pool. As in the Berkeley experiments, our bar lengths are identical to the non-migrating bar wavelength predicted using the stability theory of *Crosato et al.* [2011]. The bar surfaces were considerably coarser (D_{50} = 14.7 mm) than the pools (D_{50} = 6.6 mm; see Figures 7b and 9a).

[35] Sediment flux at the flume outlet varied across the channel, recording the influence of bars. Figure 10b shows the sediment flux at the floor pit and the cross-stream elevation just upstream of the sediment collection floor pit when the bars were fully developed. Sediment transport rates were highest in the pool where the bed surface was fine-grained. Over the coarser-grained bar tops, transport rates dropped to negligible amounts. *Nelson et al.* [2010] examined flow, bed surface grain-size heterogeneity and sediment transport over these alternate bars. They found bed surface grain-size was not correlated with the local boundary shear stress. Instead, divergences in the boundary shear stress field were matched by divergences in the sediment transport field, leading to the conclusion that size-selective, cross-streambed load transport is the process responsible for maintaining the bed surface texture heterogeneity shown in Figure 9a.

4.2. Bar Response to Sediment Supply Elimination

[36] As in the Berkeley experiment, the bar topography began to disappear by erosion of the bar head and side immediately following the termination of sediment recirculation (Figure 8b). After 56 h without an upstream sediment supply, erosion had eliminated the bar topography except for a remnant of the most upstream bar (Figure 8c). This bar behaved differently than the other two downstream in that it emerged from the flow after the sediment feed was eliminated. This occurred because the sandbags at the flume entrance directed the flow along the opposite wall. The transport capacity remained the same in this part of the channel, so without the sediment feed, the pool adjacent to the bar began to deepen. This bar remnant remained emerged from the flow until it was gradually undercut by lateral erosion (Figures 8b–8h).

[37] The disappearance of the bar topography coincided with a reduction in the surface sediment heterogeneity after the sediment supply was eliminated (Figures 9a–9d). As the bars initially began to erode, the overall sorting pattern of coarse bar tops and fine pools reported in *Nelson et al.* [2010] gave way. Although the relative abundance of fine patches decreased (Figure 9b), the bed still exhibited substantial heterogeneity and fine patches were constrained to the center of the channel (similar to the response reported by

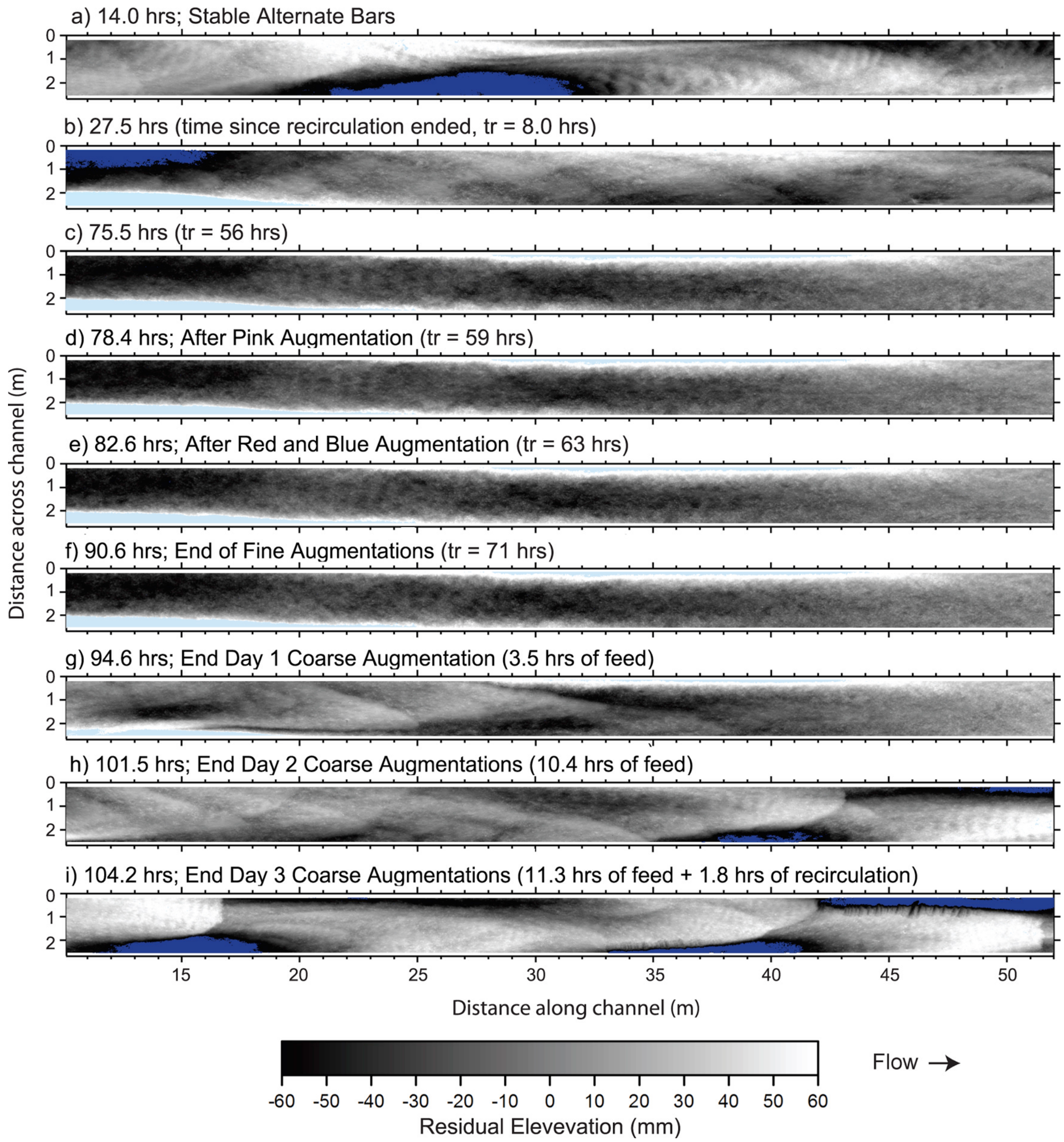

Figure 8. Residual (detrended) topographic elevation in the SAFL experiment calculated as in Figure 2 using the laser range finder data. The sand bags were upstream of the lower-left corner of the panels. The upstream sediment feed derived from the recirculation system was shut down at 19.4 h. The residual elevation scale has been constrained to highlight the bed topography. The light blue is >80 mm and the dark blue is <−80 mm. (b–h) There is a platform at the bottom right corner (light blue) that is 150–250 mm high. The depths in the dark blue pool areas are generally less than 150 mm deep. (a and i) Maximum bar amplitudes are approximately 250 mm.

Dietrich et al. [1989]). As the experiment proceeded without the sediment supply, the coarse patches expanded and the finer patches contracted, leading to an overall coarsening of the bed (Figure 9c). By the end of the second stage of the experiment, the coarse patches had expanded until the bed surface was nearly homogeneous (Figure 9d).

[38] As topography became more uniform across the channel, sediment transport did as well. Figure 10c shows sediment transport rates across the downstream end of the channel and a cross-section of the bed topography just upstream of the sediment weigh pans after the bar topography disappeared. With the bars absent, the cross-stream variation in sediment transport showed a maximum value of 1 kg/min in the center of the channel and negligible values of transport near the channel walls.

[39] This shift in the pattern of sediment transport across the channel coincided with a reduction in total flux from 52 to 1.9 kg/min over an 8 h period (Figure 11). During the second stage, 34926 kg of sediment exited the channel. The sediment that exited the flume during the second stage of the experiment was finer than the bulk mix of sediment originally put into the flume (Figure 7a). The reason for the

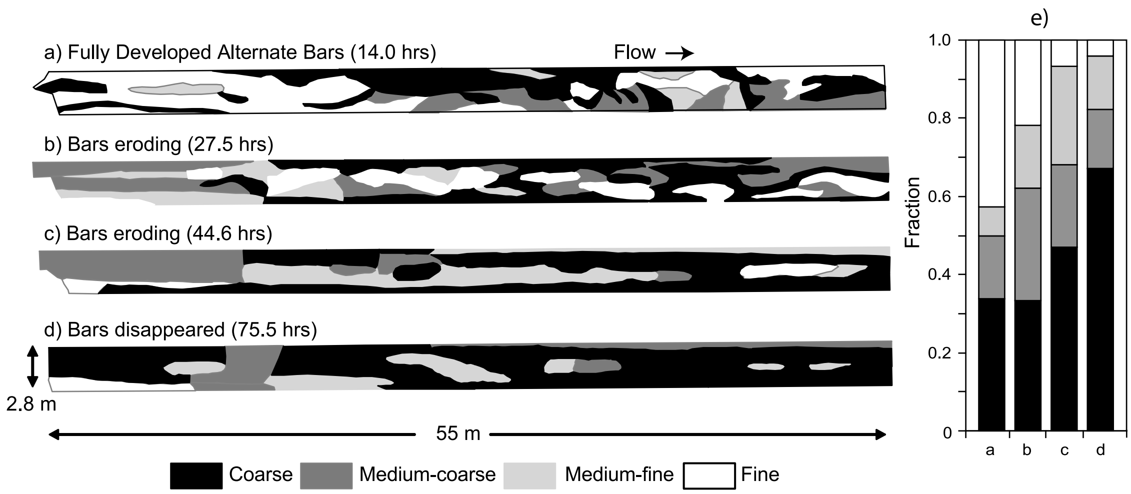

Figure 9. Facies maps of bed surface texture in the SAFL experiment drawn (a) at the end of stage 1 (alternate bar topography development), (b and c) during stage 2 after the sediment recirculation was eliminated, and (d) at the end of stage 2. (e) Fraction of the maps a-d composed of each bed texture type. Grain-size distributions corresponding to each type are given in Figure 7c. The median grain-size of each type is as follows: coarse = 14.7 mm, medium-coarse = 12.1 mm, medium-fine = 8.3 mm and fine = 5.9 mm. See *Nelson et al.* [2010] for further details on the mapping technique.

difference between the bed load transport samples is due to the deviation from equal mobility in gravel mixtures. *Nelson et al.* [2010, Figure 1b] shows that the average grain-size distribution of the material that exited the flume is the same as the distribution of the bed load predicted using the *Parker* [1990] relation if the bulk sediment grain-size distribution is used as the input bed surface size distribution. This indicates that transport was size-selective with steady state topography. We expect that the transport would become more size-selective as the bars disappeared due to declining channel slope.

[40] There were changes in the channel slope, depth and shear stress as the bars disappeared that were consistent with the changes observed in the Berkeley experiment. After the bars disappeared, the channel slope had decreased by half relative to the first stage of the experiment and there was an accompanying increase in flow depth from ~140 mm to ~170 mm (Table 2 and Figure 12). This amounted to a 33% reduction in shear stress (Table 2). The non-dimensional shear stress was above the threshold for motion of mixed size sediment ($\tau_*/\tau_{*c} \sim 1.3$ with $\tau_{*c} = 0.045$) (Figure 11), but τ_* was well below the value expected to produce full mobility of all grain-sizes ($2\tau_{*c}$) based on the work of *Wilcock and McArdell* [1993]. We found no downstream changes in flow depth, slope or shear stress.

[41] Transport increased during the third stage of the experiment due to the fine sediment pulses, but was not sustained (Figure 11). During this stage of the experiment, 2699 kg of sediment exited the flume, of which 1577 kg was painted material and 1122 kg was unpainted bed material. The unpainted material that exited the flume was composed of sediment mobilized by the pulse as well as sediment that would have left the flume whether a pulse was input or not. Our calculations show that 35% of the unpainted bed material that exited the flume was mobilized by the pulse. This means that these pulses mobilized 391 kg of sediment (equivalent to 0.6 mm of elevation change over the whole

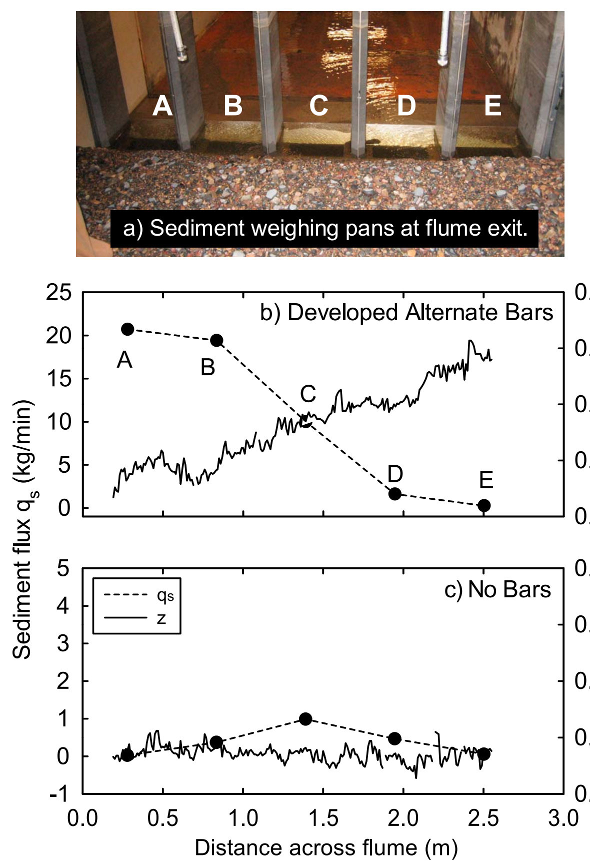

Figure 10. Sediment flux exiting the flume in the SAFL experiment. (a) Arrangement of the weighing pans at the end of the flume. Cross-stream variation in sediment flux (circles and dashed line) and elevation (solid line) at (b) 14.0 h and (c) 51.6 h. Flow is into the page.

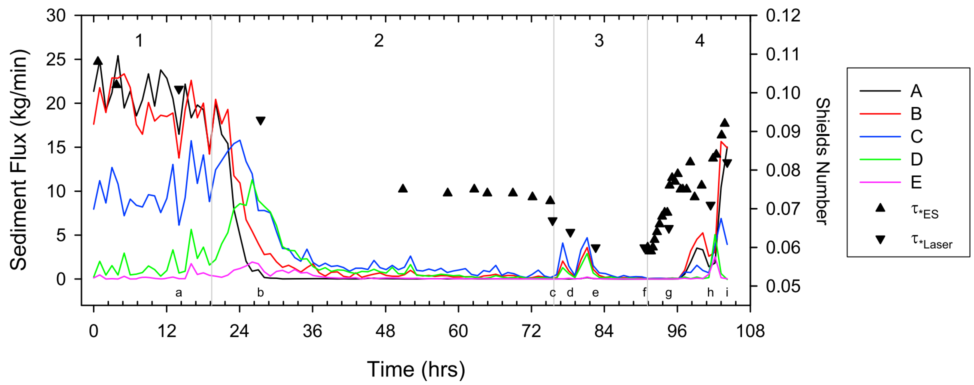

Figure 11. Hourly averaged sediment flux exiting the flume and the Shields number in the SAFL experiment. The sediment flux curves are for the individual pans (A-E) shown in Figure 10a. The total sediment flux reported in the text is the sum of all 5 curves at any given time. The Shields number is calculated using equation (1) using the bulk median grain-size (11 mm) and the shear stress shown in Figure 12c. The sediment supply was removed at 19.4 h. Lower case letters correspond to Figures 8a–8i. Numbers 1–4 indicate the experiment stage. 'ES' indicates that the bed surface data was obtained using the echo sounder. 'Laser' indicates that the bed surface data was obtained using the laser range finder.

surface area of the flume channel, assuming a porosity of 40%) and thus did not significant affect the bed topography (see Figures 8d–8f).

4.3. Bar Response to Sediment Resupply

[42] The final stage of the experiment (addition of coarse gravel) was designed to examine the amount of sediment needed to reestablish the bars. The 34926 kg of sediment that exited the channel during the second stage of the experiment was fed into the upstream end of the flume at 53 kg/min, the bed load transport rate that existed prior to the feed elimination. This sediment was finer than the sediment originally placed into the flume (Figure 7). We elected to feed the exact same sediment discharged from the flume back into the channel, despite this sediment being slightly finer, due to the cost and practicalities of handling 35 t of sediment. Our visual inspection of the sediment feed suggested that it was well-mixed and there were no obvious or systematic changes in the feed grain-size during the sediment resupply.

[43] The sediment addition took 11.3 h. Low-amplitude bars appeared in the flume when the channel bed topography was measured after 3.5 h with the coarse sediment supply (Figure 8g). The nascent bars appeared as lobes of sediment that extended halfway down the flume. When bed topography was measured after 10.4 h of feed (Figure 8h), 92% of the sediment evacuated from the flume during bar disappearance had been added. Rhomboid bars had developed along most of the flume length and well-developed alternate bars had developed near the channel exit. Previous experimental studies have documented this same evolution from rhomboid bars to alternate bars through time at constant flow and sediment feeds [e.g., *Ikeda*, 1983; *Fujita and Muramoto*, 1985]. The sediment feed did not build the channel slope uniformly, instead, slope increased in the upstream section and a weakly defined sediment wedge propagated downstream (Figure 8h). The sediment wedge began exiting the channel after 10.4 h of feed (Figure 11). The recirculation system was turned on for the final 2.7 h of the experiment because letting the sediment weigh pans fill with sediment while the recirculation system was off would have damaged the equipment. To compensate for the sediment delivered to flume entrance via the recirculation system, we reduced our feed rate to maintain sediment delivery to the channel head

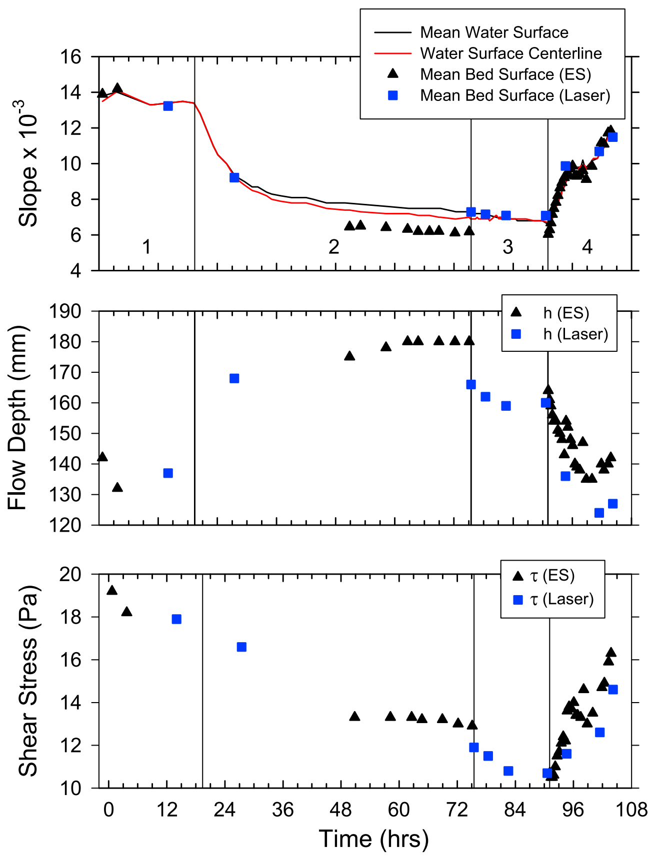

Figure 12. Channel averaged slope (S), depth (h) and shear stress (τ) in the SAFL experiment. Calculations as in Figure 5. 'ES' indicates that the bed surface data was obtained using the echo sounder. 'Laser' indicates that the bed surface data was obtained using the laser range finder.

at ∼53 kg/min for 0.9 h, after which the sediment feed from the second stage of the experiment was exhausted. The bar configuration did not change when the sediment recirculation system was started. Echo-soundings taken at 101.1 h (with sediment feed only), at 102.4 h (with sediment feed and recirculation) and at 103.4 h (with sediment recirculation only) are nearly identical, but the bar amplitudes increased. The experiment was ended when it was clear that the feed sediment was exiting the channel because the sediment flux out of the flume began to rise up toward the transport rate observed in the first stage of the experiment (Figure 11). Once this wedge of sediment was exiting the channel, the bars rearranged slightly forming the topography shown in Figure 8i. As in the first stage of the experiment, the bar amplitudes were approximately equal to the flow depth in the pool.

[44] In response to the sediment supply, the channel slope increased from to 0.0073 to 0.0117, flow depth declined from 166 mm to 142 mm, and the shear stress increased by 30% (Table 2 and Figure 12). The channel-averaged, non-dimensional shear stress began to increase as soon as the sediment feed began, and continued to increase toward the value expected to produce full mobility of all grain-sizes on the bed (Figures 8i and 11).

[45] The new pattern of bars (Figure 8i) differed from the original bars (Figure 8a) in that they were on the opposite sides of the channel. While in the first stage, the recirculated sediment was added upstream of the perturbation, the hand-fed sediment in the fourth stage was added into the constricted portion of the channel. This evidently trapped less sediment behind the flow perturbation and the first bar formed by shoaling of sediment out of the constricted channel rather than in the lee of the perturbation. The rearrangement of the bar topography observed at the end of the experiment may have been linked to this upstream shift in where sediment was added to the head of the channel.

5. Discussion

5.1. Implications for Bar Development

[46] Our observation of the reduction in bed surface sediment heterogeneity when the sediment feed was eliminated broadly agrees with previous experimental observations [*Dietrich et al.*, 1989; *Nelson et al.*, 2009] and field observations [*Kinerson*, 1990; *Lisle et al.*, 2000; *Dietrich et al.*, 2005]. Their work indicates that as sediment supply to a channel is reduced, coarse sediment patches expand as fine sediment is winnowed from finer patches, until the bed is uniformly coarse except for a narrow transport corridor. *Lisle et al.* [1993] extended the earlier work of *Dietrich et al.* [1989] in the same flume channel with a much larger width-to-depth ratio to explore how an alternate bar channel responds to reduced sediment supply. Flow depth in their experiment was the same as the largest grain-size in the sediment mixture, as is common in steep mountain channels. They found that the active channel width shrank and the coarse patches that form the bar tops expanded. *Lisle et al.* [1993] also found that alternate bars responded to sediment supply reductions primarily by deepening in the pools and by emergence of the bar tops. Our work appears to confirm that coarse patches expand as sediment supply is eliminated (Figure 9). However, we did not observe bar emergence as a result of supply reduction. Instead, bars in our experiments disappeared when the sediment supply was eliminated.

[47] In our experiments, the specific mechanism for the bar disappearance differs between the SAFL and Berkeley experiments. In the SAFL experiment, the bars were fixed in place by the upstream constriction, so they could not migrate out of the channel. Instead, they were stripped out of the channel by net erosion. As such, it is difficult to compare these results to *Lisle et al.* [1993]. Our Berkeley experiments are a more suitable comparison since the bars were formed under a sediment feed, stopped migrating prior to the feed elimination and had similar sorting patterns (coarse bar tops and fine pools). In the Berkeley experiment, the bars began migrating downstream when the feed was eliminated. New bars did not reform in the upstream end of the flume, although bars persisted in the downstream end of the channel because shear stress fell below the level required to erode them. The bars were reactivated when erosion of lag deposits at the channel walls in the upstream end of the flume increased the channel slope and shear stress.

[48] Why didn't the bars emerge in our experiments? We suspect that there were critical differences in the initial conditions between our experiments and those of *Lisle et al.* [1993]. In the earlier work, bars became fixed in place and immobile because of bed surface coarsening with 'limited incision' [*Lisle et al.*, 1993]. They argued that their bars were stabilized by coarse sediment deposition on the bar head and incision in the pools. Erosion of the bars tops was prevented by low particle submergence, high hydraulic resistance of the coarse particles, and the jammed arrangement of coarse particles, all of which increased entrainment thresholds. When the sediment feed was reduced in their experiments, there was limited flow and sediment transport over the bar heads. Yet there was a narrow active bed load transport corridor that was 61% of the water surface width, which was 80% of the flume width prior to bar emergence. This corridor was as much as 95% sand and the total boundary shear stress was well in excess of that required to move the sediment. In essence, a corridor of flow and transport had developed through their bar sequence at high feed rates because their flow depths were so small compared to the grains on the bar heads. As the feed was reduced, the channel vertically incised slightly, abandoning the bar tops, and the bed load transport corridor coarsened and narrowed further.

[49] In our Berkeley experiments the active bed load transport zone extended across the entire channel as bars developed. We observed much higher transport per unit width in the pools than over the bar heads, but the bar heads had not been abandoned. Further, our mean flow depth was ∼4 times the diameter of the largest particles in the bed, and there was flow and periodic erosion and deposition of large particles even over the bar heads. Well-defined inactive zones with limited flow and sediment transport such as those reported by *Lisle et al.* [1993] did not occur in our experiments (except in the pool just downstream of the bar head). Consequently, vertical and lateral incision were active in our flumes and this was conducive to stripping the bar topography out of the channel. Another reason for the different behavior between our experiments and those of *Lisle et al.* [1993] may have been the presence of sand. In the Lisle experiments, 76% of the feed was sand and the surface of the

active transport corridor was over 95% sand. *Wilcock and Crowe* [2003] demonstrated that the critical Shields number of a bed is dependent on the fraction of sand. The cross-channel variation in the critical Shields stress and the transport capacity would be much greater with a sandy thalweg and gravel bar tops, leading to relatively more rapid incision in the thalweg than lateral bar erosion. In our Berkeley experiments, <10% of the mixture was sand (there was no sand in our SAFL experiments) and the bar tops were only slightly coarser than the thalweg. This should be conducive to a gradual lateral and vertical erosion of the bars, which is what we observed.

[50] The bar response in the SAFL experiment and the work of *Nelson et al.* [2010] on the linkage between the flow, grain-size heterogeneity, sediment transport, and topography provide insight into why the bars disappeared. *Dietrich* [1987] and *Dietrich and Whiting* [1989] argued that in gravel bedded meanders with low excess boundary shear stress and low sediment supply, shear stress divergences might be balanced by divergences in sediment transport achieved primarily through bed grain size adjustment, rather than primarily through topographic adjustments that affect stress and gravitational vectors. *Nelson et al.* [2010] showed that this was true and that bed surface patchiness develops to moderate local bed mobility such that the divergences of stress and sediment flux are in balance. The quasi-steady topography at the end of the alternate bar stage of the experiment was maintained through size-selective cross-stream sediment transport, which was responsible for the observed coarse bar tops and fine pools, despite large stress divergences. We hypothesize that the static bars eroded in place because the reduction in sediment supply caused a downstream propagating imbalance between the stress divergence field and sediment transport field. Progressive imbalances in local sediment delivery in the bed, reduced the local bed level, reducing the stress divergence, and with overall stress reduction the bed coarsened and shifted toward size selective transport and a relatively planar bed. Thus, the chain of reactions initiated by removal of the upstream sediment supply ultimately led to the development of a bar-free, coarse bed.

5.2. Do Bars Disappear in Response to Dam Closure of Rivers?

[51] From a qualitative perspective, our results are entirely consistent with the conceptual linkage between sediment supply and channel morphology highlighted in channel classifications [*Mollard*, 1973; *Schumm*, 1985; *Church*, 1992, 2006]. Low sediment supply channels are described as being straight and without bars. However, these classifications lack any quantitative basis. So the question remains as to which behavior bars in an alluvial channel will adopt in response to sediment supply reductions or elimination. Will the channel incise, stranding the bar tops or will the bars erode, leaving a planar bed? Both behaviors have been observed following dam closure.

[52] Channel incision, often assessed by examining changes in hydrometric gauging station cross-sections, is commonly reported downstream of dams [e.g., *Williams and Wolman*, 1984]. Incision tends to be more pronounced near the dam site and decrease in the downstream direction as bank erosion and tributaries contribute increasingly to the sediment supply. Some authors have also reported channel aggradation following dam closure because tributary sediment is deposited under the new dam-controlled hydrologic regime [*Knighton*, 1988; *Everitt*, 1993; *Grams and Schmidt*, 2005]. In the Green River downstream of Flaming Gorge dam, *Grams and Schmidt* [2005] demonstrated that reaches previously thought to be incising are in fact stable or aggrading.

[53] We can scale the time it took to remove the bars in our SAFL experiment to larger scales using the sediment removal rate per unit channel width. When bars are eroding, the slope declined by $\sim$0.0053 over the first 16 h following the sediment feed termination (Figure 12), during which the sediment removal rate was 0.3 m^2/s. In order to get the same reduction in bed slope over 5 km downstream of a dam, it would take $\sim$25 years at the same non-dimensional shear stress. This time is within the range of times to reach maximum incision reported in *Williams and Wolman* [1984], suggesting that our incision rates are not atypical.

[54] A number of studies have documented channel narrowing and simplification following dam closure [e.g., *Andrews*, 1986; *Allred and Schmidt*, 1999; *Merritt and Cooper*, 2000; *Grams and Schmidt*, 2002], but this is because the hydrologic regime is also altered, typically by reducing or eliminating peak flows. Reduced discharges reduce the active channel width, often stranding bars and secondary channels [*Allred and Schmidt*, 1999; *Grams and Schmidt*, 2005], which are subsequently colonized by stabilizing vegetation [*Graf*, 1978; *Knighton*, 1988; *Friedman et al.*, 1996a, 1996b; *Grams and Schmidt*, 2005]. In the end, it is difficult to know from these studies how bar topography would change in an alluvial channel if the sediment supply was reduced and peak flows were maintained.

[55] There are a few well documented cases of bar erosion in bedrock canyons due to reduced sediment supply by dams. Sandbars in the Grand Canyon are well-known to have begun eroding shortly after closure of the Glen Canyon Dam [*Dolan et al.*, 1974; *Howard and Dolan*, 1981; *Beus et al.*, 1985; *Schmidt and Graf*, 1990; *Bauer and Schmidt*, 1993]. Recent work has highlighted that the erosion of the sandbars occurred due to a deficit of sediment in the canyon [*Wright et al.*, 2005; *Grams et al.*, 2007]. While bar erosion is well-documented, the bars are normally associated with tributary debris fans that partially block the channel and are formed by eddy recirculation cells [*Schmidt*, 1990; *Rubin et al.*, 1990], forcing their position. As such, these are not perfect field examples of our laboratory observations. Nevertheless, there is an obvious similarity in that the recirculation bars are eroding due to a sediment deficit.

[56] Ultimately, whether bars will erode in response to sediment supply conditions or be stranded as the active corridor of sediment transport incises may depend on local conditions. In natural channels bar development is normally forced by channel curvature or some lateral perturbation (e.g., wood, boulders or debris flow fans), so bars are not likely to disappear in the same manner as we observed following sediment supply reduction or elimination. Downstream of dams, the reduction in flows capable of transporting sediment may have a greater influence on how the channel responds. Had we reduced flow rates along with the sediment supply in our experiments, we may have found a different result. Nevertheless, the fact that bars formed with a sediment supply in our experiments and then disappeared when the

sediment supply was removed suggests that bars are not stable at the flows that form them without a sediment supply. Without sufficient sediment supply, flows that form bars may also degrade them once available sediment sources have been exhausted.

5.3. Implications for Stream Restoration

[57] In our experiments, we found that the original bar topography redeveloped when the sediment supply was restored to the channel. This rebuilt the channel slope, increased the shear stress and returned the channel to a condition with active transport of all bed surface sizes. This result has implications for the way stream restoration strategies are designed. One of the oft-stated goals of stream restoration in sediment-deprived channels is the restoration of geomorphic processes [e.g., *Sear*, 1994; *Kondolf*, 2000; *Tompkins and Kondolf*, 2003]. Reactivation of geomorphic processes in these channels requires replacing the upstream coarse sediment supply in some form, typically with gravel augmentation. Despite the large expense involved and the 30+ yearlong history of gravel augmentation projects in the United States and abroad, very few augmentation projects have been conducted with reference to the transport capacity of the stream [*Kondolf*, 1997]. However, projects have been reported that have successfully prevented incision when augmentation rates are matched to transport capacity (e.g., *Kuhl* [1992], referenced in *Kondolf* [1997].

[58] It is common for restoration plans to call for increased flows to reinvigorate channel bars in an attempt to increase topographic diversity. Without a sustained upstream sediment supply, high flows and exposed bar surfaces may have effects exactly opposite those intended. Bars that are not fixed in place may erode, decreasing desired topographic diversity. Similarly, the restoration practice of creating sinuous stream planforms with bar and pool topography, without regard to restoration of upstream sediment supply, is not a sustainable practice and will likely result in bars eroding or disappearing and degradation of the restored stream morphology. Ultimately, channel-scale restoration of geomorphic processes and topographic diversity appears to require the restoration of the necessary flow conditions *and* sediment supply necessary to actively form and maintain bars.

6. Conclusions

[59] We explored how alternate bars respond to decreased sediment supply in two linked laboratory experiments modeling a gravel bedded river. In our experiments, bars disappeared in response to the sediment supply reduction rather than emerging from the flow. Coarse patches of sediment expanded at the expense of fine patches to produce a nearly uniformly coarse, gravel bed in both experiments. The mechanism for bar disappearance differed in our two experiments. In the smaller flume, the bars began migrating downstream when the feed was eliminated. New bars did not reform in the upstream end of the flume but new bars did form in the lower end. In the larger flume, the bars were fixed in place by a channel constriction, so they could not migrate downstream. Instead they were stripped out of the flume by net erosion. A corresponding reduction in sediment heterogeneity of the bed surface (coarsening) followed.

[60] We hypothesize that the static bars eroded in place because the reduction in sediment supply caused a downstream propagating imbalance between the stress divergence field and sediment transport field. Hence, progressive imbalances in local sediment delivery in the bed, reduced local bed level, reducing the stress divergence, and with overall stress reduction the bed coarsened and shifted toward size selective transport and a relatively planar bed. A similar final outcome was found in the upstream reach of the Berkeley flume. In the downstream reach, however, the stress divergence and sediment transport fields continued to produce migrating downstream bars, but the reduction in sediment load led to a reduction in the overall boundary shear stress and episodic slowing of the bars. We propose that if we had run the Berkeley flume significantly longer, eventually the shear stress would drop below critical shear stress, but by then the residual bar forms would have been smoothed out.

[61] The reason bars were eliminated in our experiments rather than emerged (as found in previous work by *Lisle et al.* [1993]) appears to be related to different initial conditions. High flow resistance over the bar tops relative to the thalweg and the presence of a sandy thalweg through gravel bar tops appears to have led to some vertical incision and bed coarsening in the previous work. In contrast, lower relative flow resistance between the bar tops and thalweg as well as a lesser differential between the grain-size on the bar tops and in the thalweg in our experiments led to both vertical and lateral erosion of the bars. The bar topography was restored in the larger-scale experiment when we fed enough sediment to rebuild the channel slope and increased the mobility the bed material so all grain-sizes were mobile. Our results further suggest that a sediment supply must be maintained in order to maintain bar topography at formative flows. Stream restoration projects that seek to build topographic diversity in channels through increased water discharge or channel design must include a long-term sediment supply to be successful.

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