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Patch dynamics and stability in steep, rough streams

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[1] The beds of steep streams are typically composed of relatively immobile boulders and more mobile patches of gravel and cobbles. Little is known about how variability in flow and sediment flux affect the area, thickness, composition, and grain mobility of sediment patches. To better understand patch dynamics, we measured flow, sediment transport, and bed properties in two steep channels. Patches close to the thalweg varied in area, thickness, and grain size, whereas those outside the thalweg did not. Local variations in transport of several orders of magnitude occurred, even on a patch with a spatially homogeneous grain size distribution. During moderate flow events, partial to selective transport dominated on the entire channel bed and all individual patches. Tracer particles moved freely between different patch classes (e.g., fine and coarse patches exchanged particles), and relatively fine sediment on all patch classes began motion at the same shear stress. Therefore, the selective transport observed for the entire bed was not a result of the preferential transport of only fine patches, but the high relative mobility of finer sediment on all patches. Our results suggest that local flow and sediment supply, and not spatial grain size variations, were the primary drivers of local bed load transport variability. The use of reach-averaged flow properties to understand local patch dynamics may not be applicable.

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1. Introduction

[2] In steep channels, mobile gravel is typically deposited into sediment patches and partially buries relatively immobile boulders (Figure 1). The gravel moves in flows at or below bankfull, whereas the boulders rarely, if ever, move [*Lenzi et al.*, 1999]. Such spatial variability in local grain size and flow conditions can significantly influence sediment transport rates [*Ferguson*, 2003; *Nelson et al.*, 2009] and may be caused by differences in flow turbulence, grain interactions, or hiding effects [*Dietrich et al.*, 2005]. Although large spatial variations in sediment flux have been documented in flume experiments and through theoretical modeling, relatively few observations of sediment movement on natural patches (in steep or lower gradient channels) exist. In particular, it is unknown if patch dynamics can be predicted using reach-averaged, patch-averaged or local flow and grain size measurements [*Lisle et al.*, 2000; *Nelson et al.*, 2009]. No general theory exists to predict the relative mobility of different sized sediment on a given patch class, or the relative mobility of a given grain size on different patch classes.

[3] Although patch scale transport is poorly understood, reach-averaged grain mobility conditions are comparably well studied. The entire bed often experiences partial or selective transport at low flows and transitions to equal mobility at higher shear stresses [e.g., *Andrews*, 1994; *Wathen et al.*, 1995; *Parker and Toro-Escobar*, 2002; *Haschenburger and Wilcock*, 2003; *Mueller et al.*, 2005] or during increased relative sediment supply [e.g., *Parker and Klingeman*, 1982; *Buffington and Montgomery*, 1999b; *Lisle et al.*, 2000]. Although other definitions of partial, selective and equal mobility transport are used, we use *Parker*'s [2008] below to simplify our discussion. Equal mobility transport occurs if all grain sizes move in proportion to their frequency in the bed [e.g., *Parker and Klingeman*, 1982; *Parker et al.*, 1982; *Andrews*, 1983; *Parker*, 2008]. Partial transport occurs when only a portion of the grain-size distribution is mobile [*Wilcock and McArdell*, 1997] and often represents the condition where fine sediment moves over coarse immobile grains. In selective transport, all grain sizes are mobile but the bed load grain-size distribution is not equal to that of the bed [*Parker*, 2008]. During low to moderate flows, partial transport for the entire bed could be driven by two different end-member mechanisms of preferentially transporting fine sediment from different patches.

[4] First, the underlying grain size distribution of the bed will influence the protrusion and friction angle of a given grain [e.g., *Kirchner et al.*, 1990]. For example, a small

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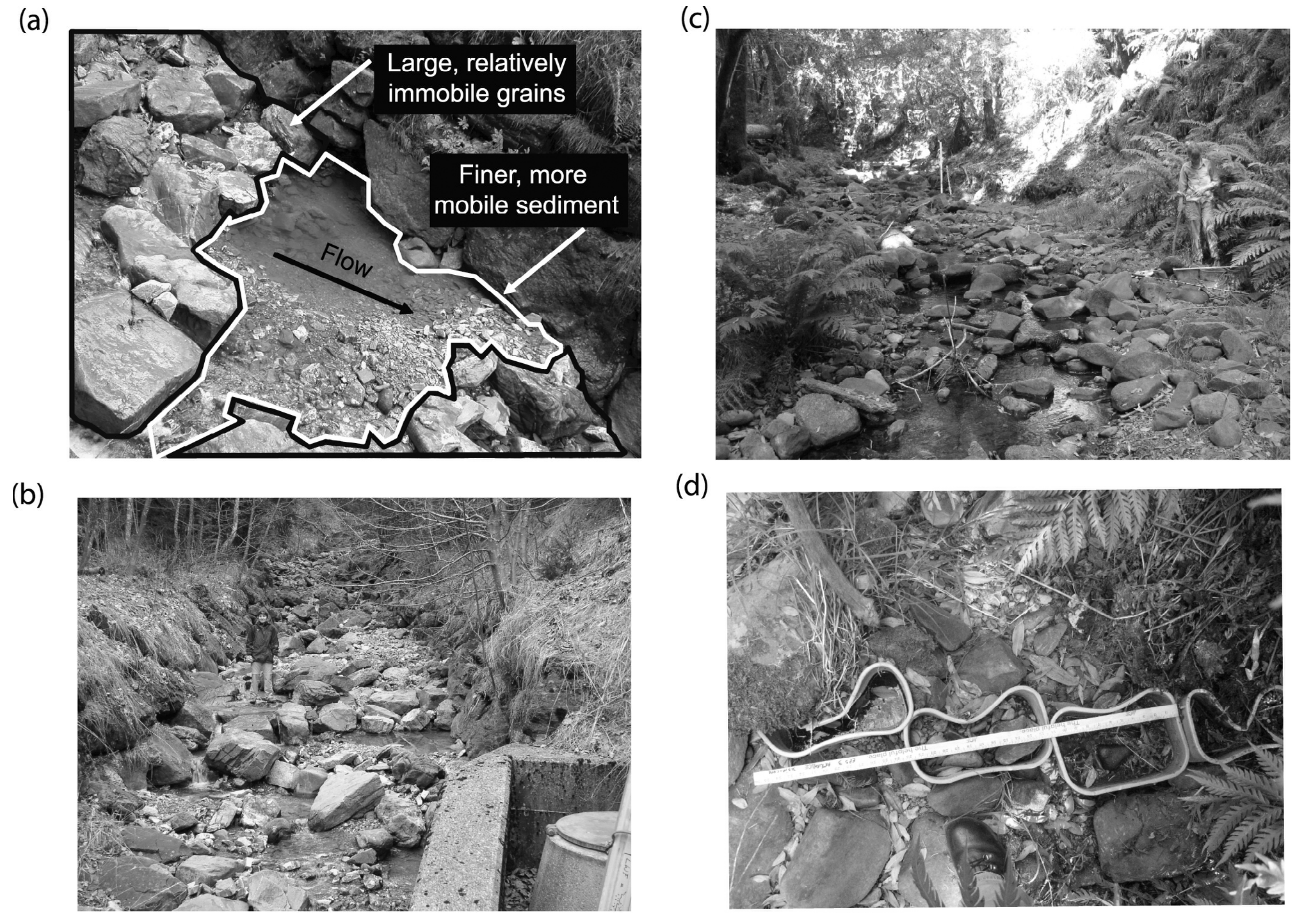

Figure 1. Photographs of (a and b) the Erlenbach and (c and d) Fox Creek. The beds of these channels are composed of large, relatively immobile boulders that are arranged into steps and patches of finer, more mobile gravel and cobbles. The sediment traps in Fox Creek are shown on the right side of the photo near the person in Figure 1c and in plan view in Figure 1d. Note that these two photos were taken many years after our measurements and the traps were flush with the streambed during our study.

diameter grain could have a lower protrusion and higher friction angle, and therefore be less mobile on coarse than fine patches [e.g., *Kirchner et al.*, 1990]. The opposite could occur for a coarse grain; it would be more mobile on fine patches than on a patch of similar sized sediment. Such changes in a grain's pocket geometry are often coupled empirically through hiding effects. If these hiding effects dominate on patches, we would expect that fine (small to medium-sized gravel) sediment would start motion on fine grained patches while remaining relatively immobile on coarse patches. Indeed, flume experiments [e.g., *Dietrich et al.*, 1989; *Lisle et al.*, 1993], field studies [e.g., *Lisle and Madej*, 1992; *Lisle*, 1995; *Garcia et al.*, 1999; *Lisle et al.*, 2000; *Vericat et al.*, 2008] and modeling work [*Paola and Seal*, 1995] show that patches of finer sediment may move at lower stages than coarser patches and could act as the major local sediment source during low to moderate flows. However, these studies do not document the movement of individual grains on patches and often infer the mobility of finer patches from bed load grain-size distributions.

[5] Another mechanism of preferential fine sediment transport is that patch-scale hiding effects are relatively unimportant and the influence of grain weight dominates; fine sediment could begin motion on all patches simultaneously. One tracer particle study has shown that finer patches transport more sediment than coarser patches, but fine and coarse patches move at similar flows [*Dietrich et al.*, 2005]. If patches significantly influence the relative motion of a given grain size, spatially variable grain size distributions may need to be incorporated into sediment transport calculations [e.g., *Ferguson*, 2003]. Conversely, if grain motion is not largely impacted by the underlying patch, spatially variable grain size distributions could be neglected through the use of one representative distribution for the entire bed. In addition to grain arrangement, the spatial variability in applied shear stress [e.g., *Ferguson*, 2003], or divergence in shear stress [e.g., *Nelson et al.*, 2010], between patches could also impact the relative mobility of a given grain. The scale(s) at which these flow variations are important and would need to be included in transport calculations is unclear.

[6] Patches can also influence local and reach-scale changes in channel morphology. It has been documented in flume experiments, over a wide range of gradients, that the

Table 1. Summary of Sediment Transport Events in the Erlenbach[a]

Event	Date	τ_{bm} (Pa)	Event Duration (min)	Integral of $\tau_{bm} - \tau_c$ (Pa s)	Transported Sediment Volume (m^3)
1	7/6/2004	271	540	7.0×10^6	1.00 ± 0.07
2	7/24/2004	226	310	3.6×10^6	N/A[b]
3	8/12/2004	187[c]	N/A[c]	N/A[c]	N/A[b]
4	8/20/2004	201	70	0.7×10^6	N/A[b]
5	8/26/2004	304	940	13×10^6	4.41 ± 0.22
6	9/24/2004	267	480	6.2×10^6	N/A

[a]Here τ_{bm} is the peak boundary shear stress, τ_c is the critical shear stress. The event duration is the total length of time when the shear stress exceeded the critical shear stress. The measured sediment volume is from surveys of the sediment retention basin where the reported errors are standard errors.

[b]No sediment transport was measured by the bed load sensors, and therefore no surveys of the sediment retention basin were performed.

[c]The τ_{bm} of event three was used to define τ_c, and the event duration is unknown.

grain size, area, and thickness of patches can vary with flow and sediment supply [*Dietrich et al.*, 1989; *Kinerson*, 1990; *Lisle and Madej*, 1992; *Lisle et al.*, 1993; *Buffington and Montgomery*, 1999b; *Dietrich et al.*, 2005; *Yager et al.*, 2007; *Nelson et al.*, 2009, 2010]. Flume experiments also show that the upstream gravel supply and spacing between boulders can strongly influence the thickness and lateral extent of gravel patches in steep streams [*Yager et al.*, 2007]. Few field observations directly show the impact of sediment supply on patch area and grain size [*Yuill et al.*, 2010]. In the field, measurements of sediment supply often require trapping and removing sediment from the flow, which will affect the downstream patches of interest. Thus, a number of studies have correlated the area, volume, and grain size of patches with the quantity and grain size of sediment leaving a reach [*Sawada et al.*, 1983, 1985; *Lisle and Hilton*, 1992, 1999; *Garcia et al.*, 1999; *Laronne et al.*, 2001; *Mueller et al.*, 2008].

[7] Patch dynamics are particularly difficult to explain in steep streams because these channels have very wide grain-size distributions and ranges in bed mobility, limited sediment availability, and significant spatial variations in shear stress from emergent boulders. The sediment supply to these channels is primary driven by episodic landslides and debris flows, which may also influence patch grain sizes and stability. We made measurements of flow, sediment transport, and patch characteristics in two steep, rough streams to answer the following questions: (1) how do different patches influence the relative motion of a given grain size, (2) is sediment transport spatially uniform on a given patch class or between classes, (3) are reach-scaled conditions (grain size distribution, shear stress) representative of patch-scale transport and stability, and (4) what patch classes act as transient sediment sources? We discuss patches as being transient sediment sources because the exact source of sediment depends on the timescale of interest. During individual small events, upstream patches can act as sediment sources to downstream areas. However, over longer timescales (e.g., multiple events, a season, years), patches are merely areas that exchange sediment as it moves downstream from upstream hillslope sources.

[8] In our study, the transported grain-size distribution and sediment volume varied within patches to an extent that reach-averaged, or possibly even patch-averaged, flow and sediment supply conditions are unlikely to correlate with highly local patch dynamics. Coarse and fine patch classes moved at the same shear stress and although fine patches transported more sediment, coarse patches also acted as transient sediment sources.

2. Field Measurements

[9] To answer the questions listed above, we conducted field work in two steep streams, the Erlenbach torrent and Fox Creek. In the Erlenbach, we measured flow, tracer particle movements and patch changes (height, area and grain size) on a range of patch classes. We used these data to answer the four questions listed in the Introduction. In Fox Creek, we measured flow and detailed variations in bed load transport across one patch to further determine the degree of local transport variability and the applicability of reach averaged conditions to describe patch dynamics (questions 2 and 3). In both of these streams, we focus on discharges smaller than bankfull, in which we expect only a part of the bed to be mobile and patch-scale effects to be relatively important in reach-scale transport dynamics.

2.1. Erlenbach

[10] The Erlenbach is a steep (10% gradient) stream that drains 0.74 km^2 in central Switzerland and has an annual sediment yield of about 570 m^3/km^2/yr. The Erlenbach catchment is underlain by a large, valley-scale landslide, which is partially composed of flysch bedrock and gleyic soils with very low permeability [*Rickenmann and Dupasquier*, 1995]. Streamside landslides episodically deliver large amounts of poorly sorted sediment, which may include large boulders, directly to the channel [*Schuerch et al.*, 2006]. Although the catchment is steep enough for debris flow activity, there is no evidence of sediment delivery by debris flows [*Rickenmann*, 1997]. The bed of the Erlenbach is composed of large, relatively immobile boulders that form steps, and intervening finer, more mobile (gravel to cobble) sediment patches (Figure 1). The steps only move during relatively extreme events and cause significant roughness whereas the more mobile sediment moves seasonally [*Turowski et al.*, 2009].

[11] The Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL) established a stream gauging station and sediment retention basin on the Erlenbach in 1978 [*Hegg et al.*, 2006]. Bed load transport rates have been continuously measured since 1986 by Piezoelectric Bed load Impact Sensors (PBIS) or geophone-based bed load impact sensors, both hereinafter called bed load sensors, that are calibrated to yield similar signals [*Rickenmann*, 1997; *Rickenmann and McArdell*, 2007]. Snowmelt, rain-on-snow, and high-intensity summer storms cause about 20 sediment

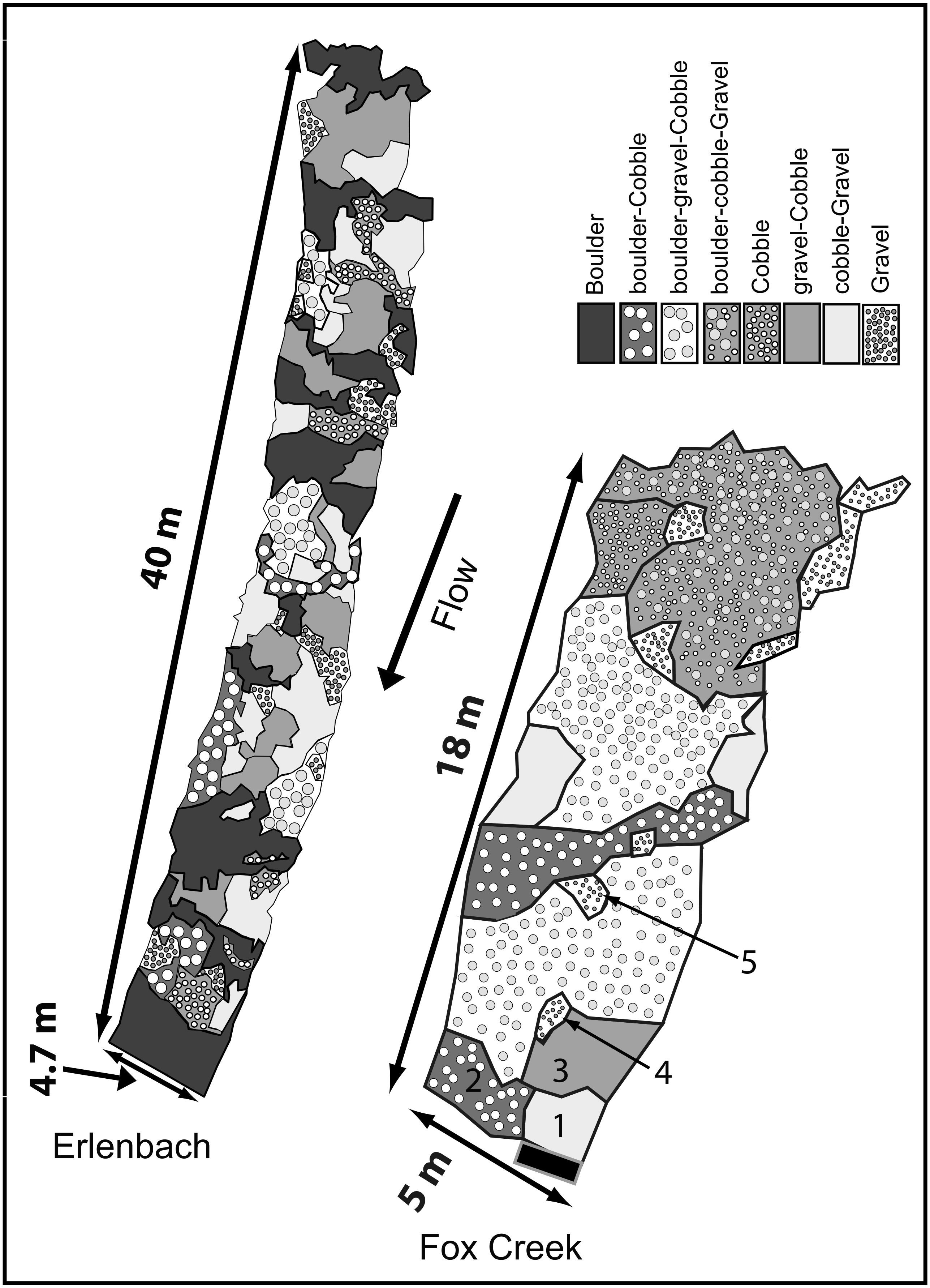
Boulder
boulder-Cobble
boulder-gravel-Cobble
boulder-cobble-Gravel
Cobble
gravel-Cobble
cobble-Gravel
Gravel
40 m
4.7 m
Erlenbach
Flow
18 m
5 m
Fox Creek
1
2
3
4
5

Figure 2

Table 2. Characteristics of Patches With Measured Grain Sizes in the Erlenbach[a]

Patch	D_{50} (mm)	D_{84} (mm)	A_p	σ	Class
17a	176	325	0.28	1.3	bC
15	110	281	0.34	1.5	bgC
34a	92	161	0.17	1.1	C
31	87	157	0.25	0.9	C
10	61	125	0.07	1.2	gC
19	69	156	0.09	1.4	gC
16	52	121	0.08	1.4	gC
21	49	114	0.10	1.5	gC
18	33	84	0.19	1.4	cG
11	25	84	0.07	1.4	cG
24	25	53	0.03	1.2	cG
29	23	44	0.05	1.1	cG
40	21	57	0.10	1.2	cG
21a	16	42	0.02	1.3	cG
18a	14	31	0.26	1.2	G
14	8	17	0.03	1.1	G

[a]D_{50} and D_{84} are the median and 84th percentile grain sizes for each patch, σ is the standard deviation of the grain-size distribution in phi units. A_p is the ratio of each patch area to the total area of its patch class. Patch classes are boulder-Cobble (bC), boulder-gravel-Cobble (bgC), Cobble (C), gravel-Cobble (gC), cobble-gravel (cG), and Gravel (G), where the dominant fraction is capitalized.

Table 3. Characteristics of Patch Classes in the Erlenbach[a]

Class	D_{50} (mm)	D_{84} (mm)	A_t
B	457	722	0.30
bC	176	325	0.08
bgC	110	281	0.09
C	88	158	0.07
gC	56	123	0.21
cG	27	70	0.19
G	12	29	0.05
Mobile	60	178	0.67
Total	146	497	1.00

[a]D_{50} and D_{84} are the median and 84th percentile grain sizes for each patch class, A_t is the ratio of the area of each patch class to the entire bed area. “Mobile” represents the bed excluding immobile steps, “Total” is the entire bed, and B are boulder patches. See Table 2 for an explanation of all other patch classes.

transport events each year [*Rickenmann*, 1997]. Our field site was a reach, 40 m long and 4.7 m wide, directly upstream of the bed load sensors and immediately downstream of a tributary junction. The only separation between our site and the retention basin was a short, steep concrete ramp designed to transport sediment over the bed load sensors without any sediment deposition. Six sediment transport events moved tracer particles during our study but only three events caused sediment fluxes that were measurable by the bed load sensors (Table 1). The bed load sensors only recorded transport if greater than 4 impacts/minute occurred [see *Rickenmann and McArdell*, 2007]. The largest sediment transport event (fifth event) had a peak discharge of 1.5 m^3/s, which has a recurrence interval of 0.6 years (determined through partial duration calculations) and was below the calculated (1.5 year recurrence interval) bankfull discharge of 2.1 m^3/s.

2.1.1. Patch Mapping and Grain Size

[12] We used the classification scheme of *Buffington and Montgomery* [1999a] to define patch classes. Each patch was named by the surface grain sizes (gravel (2–63 mm), cobble (64–256 mm), and boulder (>256 mm)) and a given size was only included in the patch name if it occupied roughly more than 5% of the total patch area. The grain sizes of each patch class were listed in order of increasing frequency in the grain-size distribution and the dominant grain size was capitalized [*Buffington and Montgomery*, 1999a]. For example, a cobble-Gravel patch was composed of mostly gravel with more than 5% cobbles. The study reach had 63 individual patches (between 0.2 and 10.7 m^2 in area) that were grouped into seven patch classes (Figure 2).

[13] We conducted 16 pebble counts, with at least one pebble count on each patch class except for the boulder patches (Table 2). On the boulder patches, we measured all boulders and cobbles (total of 134 grains counted) because there were less than the standard 100 grains needed on each patch for a pebble count. We repeated pebble counts on four patches (11, 14, 18a and 29) near the end of our field season. The grains in most of the pebble counts were chosen by the grid method, although a few pebble counts had grains chosen by random walks [*Wolman*, 1954; *Kellerhals and Bray*, 1971]. We chose the grid method because it eliminates user-bias in picking specific rocks and grain sizes, and it gives grain sizes comparable to those measured by bulk volume samples [*Bunte and Abt*, 2001]. The b axis of each grain was measured directly or was a minimum estimate for large, buried particles that we could not dislodge. Further details on the grain size measurements are in Appendix A.

[14] We used a total station to map the boundaries of each patch (Figure 2) and measure the topography of the bed (at an average of 14 points/m^2). Patch boundaries were identified visually as gradual or sharp gradations in grain size distributions. The grain-size distribution for each patch class (e.g., Gravel, gravel-Cobble) was the sum of the area-weighted pebble counts within that patch class (Table 3). The area weights were the individual patch areas divided by the total area with grain-size measurements for that patch class. Individual patches within the same patch class (for G, C, gC, cG classes) generally had similar grain-size distributions (Table 2). The Gravel, Cobble and Boulder patches were texturally distinct with different median grain sizes (Figures 3a and 3b). The gradational patches (gC, cG, bgC, and bC) overlapped significantly in grain size with many other patch classes, as expected.

[15] The grain-size distribution of the entire bed was the bed area-weighted sum of all pebble counts within the reach. The grain-size distribution of the relatively mobile sediment was the bed area-weighted sum of all the pebble counts on patches classified as relatively mobile sediment (excludes immobile patches). Immobile patches were defined as topographic steps composed of boulders or coarse cobbles that crossed at least half the channel width, and had a minimum pool length (10% of bankfull width) and minimum step drop

Figure 2. Maps of patches within the Erlenbach and Fox Creek study sites were made at the beginning of our field measurements. The boulder patches are large, immobile steps. Numbers on the Fox Creek patches correspond to the measured grain size distributions for individual patches in Figure 3d.

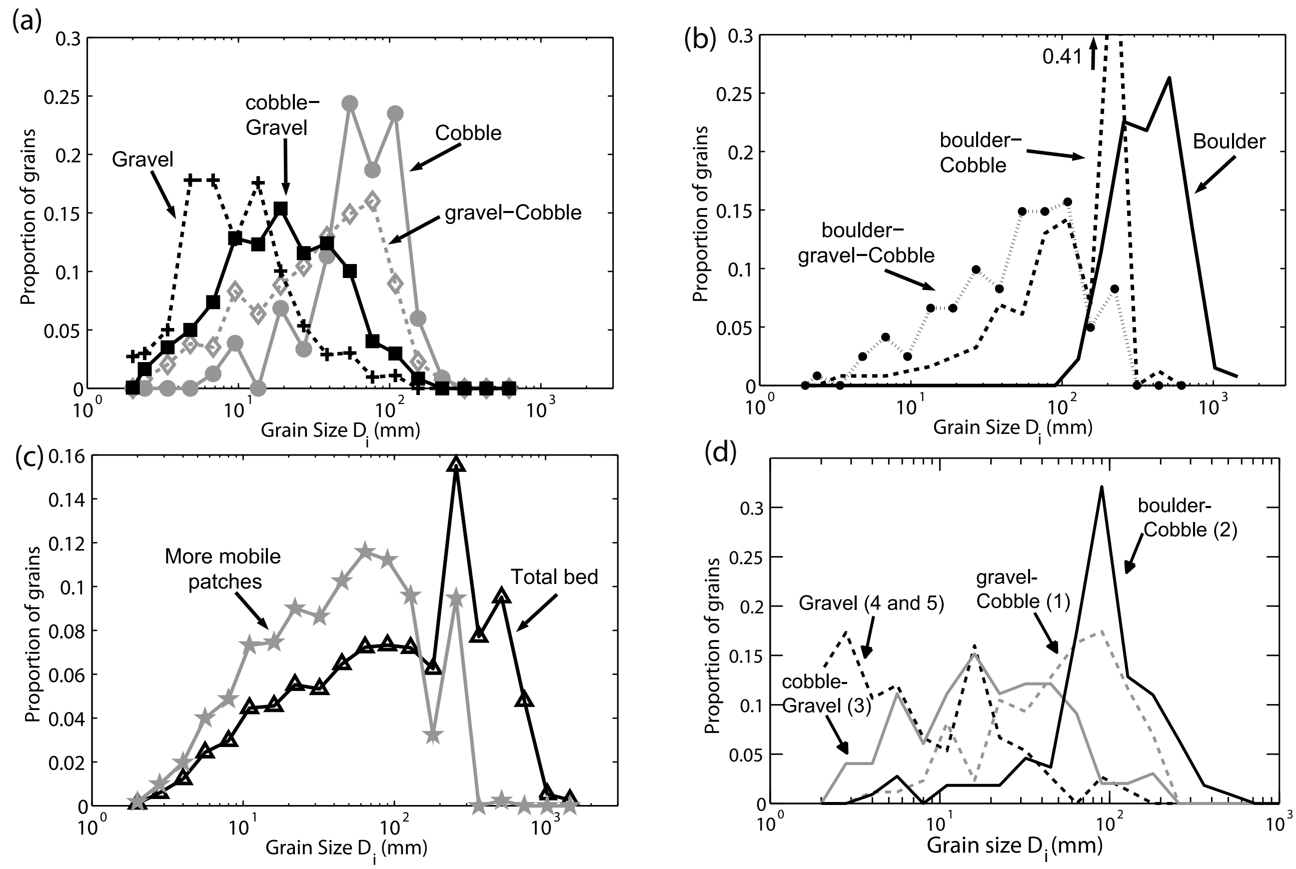

Figure 3. Grain-size distributions for each patch class in the Erlenbach are shown as (a) composite distributions for Cobble, gravel-Cobble, cobble-Gravel and Gravel patches, (b) individual distributions for boulder-gravel-Cobble, boulder-Cobble and Boulder patches, and (c) composite distributions for the relatively mobile bed (all patches except 17a and Boulder patches) and the entire bed. (d) Grain-size distributions in Fox Creek are shown for patches that are near the bed load traps or are possible fine sediment sources to the traps. The numbers following each patch name denote the individual patches identified in Figure 2. Patch 1 is immediately upstream of the traps. Each proportion is the number of grains in a size class divided by the total number of grains in all size classes.

height (3.3% of bankfull width), as defined by *Zimmermann et al.* [2008] (see *Yager et al.* [2012] for further details). In this definition, we assume that steps are immobile and significant sources of flow resistance, which resulted in all boulder patches and one boulder-Cobble patch being classified as steps. The grain-size distribution for the relatively mobile sediment was finer than the distribution for the entire bed (Figure 3c, Table 3). Grains in the 256–360 mm size class were frequent in both distributions because they were present in large quantities in boulder-Cobble patches. The steps were immobile during our observations and we use the grain-size distributions of the relatively mobile sediment or individual patches in all subsequent calculations.

2.1.2. Shear Stress and Sediment Transport Duration

[16] During each sediment transport event, we recorded the water depth at 10-min intervals from staff plates installed in three cross-sections. We used the water level in the cross-sections to calculate the reach-averaged hydraulic radius (R) for all measured points on the hydrographs of our six sediment transport events. The reach-averaged shear stress (τ_b) is given by ρgRS where ρ is the density of water, g is the acceleration due to gravity, and S is the channel slope (0.098). The maximum shear stress for each sediment transport event (τ_{bm}) was the maximum calculated τ_b. To concurrently account for the effects of shear stress and event duration, we calculated the integral of the excess shear stress (difference between applied and critical shear stresses) over the entire duration of each sediment transport event. We assumed τ_c (critical shear stress, stress needed to cause sediment motion) was the maximum τ_b during the third event, which was the smallest event for which we observed significant motion (Table 1).

2.1.3. Tracer Particle Movements

[17] To understand the variation of particle mobility with grain size, patch class, and channel location, we installed, painted (grains were not differentiated by color), and numbered tracer particles (see Table 4) with a range of sizes (11–180 mm). We placed tracer particles loosely on the bed surface and they may have been more mobile than grains that were naturally imbricated or interlocked [*Church and Hassan*, 1992; *Oldmeadow and Church*, 2006] but we supplement these data with naturally placed grains (see below). After each transport event, we added new tracer particles to the approximate original positions of tracers that moved.

Table 4. Tracer Particle Movements for Each Patch Class and Event in the Erlenbach[a]

Event	Number of Tracers	Percent Moved	Percent Photo	D_{max} Tracers	D_{max} Moved
		Entire Bed			
1	646	17	66	436	154
2	750	9	59	436	109
3	290	8	0	154	77
5	726	35	62	436	154
6	634	20	56	436	154
		boulder-Cobble patches			
1	84	4	100	436	154
2	88	1	98	436	19
3	3	67	0	19	19
5	91	23	95	436	154
6	76	12	97	436	154
		boulder-gravel-Cobble patches			
1	89	16	100	308	77
2	101	2	85	308	54.5
3	19	5	0	54.5	19
5	100	47	85	308	154
6	102	11	84	308	77
		gravel-Cobble patches			
1	112	12	62	308	54.5
2	118	19	65	308	109
3	38	8	0	154	77
5	118	39	66	308	154
6	102	25	46	308	109
		cobble-Gravel patches			
1	284	20	65	218	109
2	348	6	56	218	109
3	135	2	0	109	38.5
5	333	35	59	218	154
6	282	24	53	218	109
		Cobble patches			
1	34	41	0	77	77
2	30	33	0	77	54
3	35	23	0	154	27
5	25	48	0	154	154
6	19	21	0	154	38.5
		Gravel patches			
1	19	21	0	19	19
2	35	9	0	27	19
3	33	15	0	27	27
5	29	17	0	27	19
6	20	45	0	54.5	54.5

[a]The percent of installed painted tracers that were recovered for each event was the following, with the event number in parentheses: 57% (1), 84% (2), 89% (3), 43% (5), and 66% (6). D_{max} is in mm. "Percent photo" denotes the percent of the total number of tracers that were from photographic measurements.

This was done to ensure a significant number of tracer particles on each patch prior to every sediment transport event. After every event, the location of each tracer particle was surveyed using a compass and tape measure, to permanent benchmarks with known coordinates that were located throughout the reach. The particles were not disturbed during this process and we left them in their natural positions after each survey.

[18] Although we only painted particles, our recovery rates (43–89%) were comparable to those published for tagged tracer particles (e.g., magnets [*Ferguson et al.*, 2002]). We surveyed a number of tracer particle locations multiple times to estimate the root mean squared error (RMSE, 0.24 m) in their coordinates. Particles that moved less than 0.48 m (two times the RMSE, corresponding to a 95% confidence interval for particle position) were classified as immobile. Other tracer studies report similar uncertainties in tracer positions [e.g., *Ferguson et al.*, 2002].

[19] We supplemented our tracer particle measurements with photographic surveys of the bed, in which we could distinguish unmarked individual grains (larger than 32 mm) on patch surfaces that were exposed during low flow [*Yager*, 2008]. Photographs were taken before and after four transport events, displayed a plan view (photos parallel to the bed) of the bed, and included a horizontal scale bar (stadia rod). We were able to repeatedly identify individual grains by using their color, size, shape, location on the patch, and position relative to other grains. For a given event, the mobile tracer grains were those that could not be identified in a subsequent photograph of the same patch.

[20] The grain axes of every photographic tracer were measured using photo analysis tools in the Matlab software package. Radial distortion, camera perspective, and misidentification of stable or mobile grains may introduce errors into our estimates of the mobile grain sizes during each event. Photo distortion should be low because the photographs were level and were taken close to the bed. The photographic tracers represented the patch grain sizes fairly accurately. For example, the D_{50} of the gC patch was 58–71 mm from photographic tracers (depending on the event) and 59 mm (excluding grains finer than 32 mm to obtain an equivalent measurement to that from the photos) from pebble counts. These photographic tracers were used in combination with the installed painted particles to create Table 4 and Figures 4 and 5.

[21] We did not make any photographic tracer measurements for the third event. Photographic tracers included grains coarser than the installed painted particles and therefore the tracer particle distribution for the third event was finer than those for other events. We excluded the fourth sediment transport event from our analyses because only one particle moved during this flow. We grouped the tracer sizes into half-phi bins with median grain sizes D_i, in which i ranged from 1 to N (total number of bins, 11). We defined the proportion of the installed tracers that moved as Y_i for each D_i after *Wilcock* [1997] and *Wilcock and McArdell* [1997]. We determined which values of Y_i were statistically different (at $\alpha = 0.05$) using a Tukey-type test for multiple comparisons of proportions [*Zar*, 1999]. Further information on the tracer particles is provided in Appendix A.

2.1.4. Patch Elevation and Area

[22] Five patches (11, 14, 29, 18a, and 40), with median grain sizes between 0.8 and 25 mm (Table 2), were chosen as representative patches that could easily become mobile during many events. The elevation of each patch was measured from a level surface that was placed on a permanent benchmark of constant elevation above the patch. Patch elevations were measured to the nearest half cm at set grid points before and after each sediment transport event.

[23] The bed area occupied by each patch was measured from scaled photographs (see section 2.1.3). The proportional change in patch area was the difference between the bed area before and after each sediment transport event,

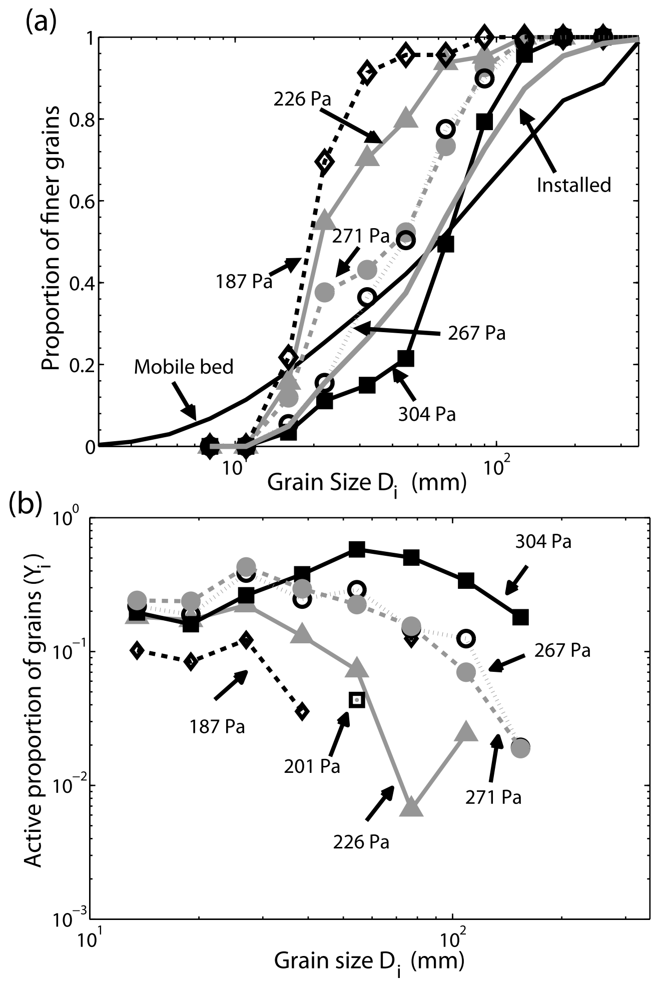

Figure 4. Data are for the Erlenbach. (a) The grain-size distributions of the original tracers (photo and installed), mobile tracers (labeled with peak boundary shear stress in Pa) and the assumed relatively mobile sediment on the bed (excludes immobile steps). (b) The mobile portion of the tracers (Y_i) for each grain size (D_i) and sediment transport event.

divided by the original patch area. We made three repeat area measurements for each patch and sediment transport event to estimate the errors in these area calculations.

2.2. Fox Creek

[24] We also measured flow, channel bed conditions, and sediment transport rates in Fox Creek, a small (drainage area of 2.8 km^2), steep (slope of 5%) tributary of the South Fork of the Eel River, Northern CA. Downstream of a cobble-Gravel patch, we installed four bed load traps that consisted of buckets (29 cm wide perpendicular to flow, 28 cm deep, 15.5 cm long in the downstream direction) buried flush with the bed surface and immediately adjacent to each other (Figures 1c and 1d). The cobble-Gravel patch (D_{50} of 22 mm, D_{84} of 60 mm and D_{max} of 190 mm) was at the outer bank of a slight and low angle bend. The traps were only partially full each time when emptied after 11 individual bed load transport events and the captured sediment in each bucket was weighed, dried and sieved to half phi intervals (Table 5). Similar traps have been previously used by a number of studies with success [e.g., *Hassan and Church*, 2001; *Sterling and Church*, 2002]. Further discussion on the trap efficiency and measured grain sizes is provided in Appendix A.

[25] We continuously recorded the flow stage using a pressure transducer installed in a surveyed cross-section upstream of the traps. The average flow depth in the cross-section, combined with about 80 concurrent velocity measurements using a dilute saline solution and conductivity probe [e.g., *Calkins and Dunne*, 1970; *Lee and Ferguson*, 2002; *Curran and Wohl*, 2003] were used to calculate the flow discharge and develop a stage-discharge relationship for a wide range of flows. The maximum measured discharge (1.3 m3/s) was approximately 75% of bankfull (1.8 m3/s), which was estimated by scaling the known drainage area and bankfull discharge of Elder Creek (a nearby tributary of the South Fork of the Eel River) to the drainage area of Fox Creek. Our discharge record in Fox Creek was not long enough to determine the 1.5 year recurrence interval flood. The maximum measured flow almost completely filled the channel banks.

[26] We used a total station to map the bed patches upstream of the traps and measure the channel longitudinal profile (Figure 2). We used this topographic survey to obtain patch areas and classify patches as being relatively mobile or immobile following the methodology in section 2.1.1. We conducted a pebble count on each patch class using a similar method to that discussed in section 2.1.1, although our counts in Fox Creek used the random walk technique. Examples of patch grain size distributions that were immediately upstream or proximal to the traps are shown in Figure 3d, where the numbers next to each patch class correspond to the patch numbers labeled in Figure 2.

3. Results

3.1. Erlenbach

3.1.1. Tracer Movements for the Entire Bed

[27] We combined the movements of all tracers, regardless of the patch class of origin, to better understand reach-scale sediment transport. In general, the largest transported D_i (Figure 4a, Table 4) increased with the maximum boundary shear stress (τ_{bm}). The observed increases in Y_i with τ_{bm} (between 226 and 304 Pa) were statistically significant for most grains larger than 32 mm (Figure 4b). For grains finer than 32 mm, most differences in Y_i with τ_{bm} were not statistically significant and Y_i remained constant at about 20–40% for the majority of shear stresses. Thus, coarse grain transport increased at high shear stresses, whereas the flux of finer particles was not shear stress dependent for our measured flows. For a given τ_{bm}, most of the changes in Y_i with D_i were not statistically significant. However, for every τ_{bm} except 304 Pa, the finest grains (less than 32 mm) had statistically higher Y_i than the coarsest grains (greater than 90 mm). This demonstrates that in all but the largest event, the finest particles were more mobile than the coarsest particles on the bed. The largest tracer grains (diameters larger than 180 mm) were either completely immobile or only partially mobile during the fifth and largest event. The highest Y_i for this event was 60% and most size fractions had a Y_i between 0 and 35%.

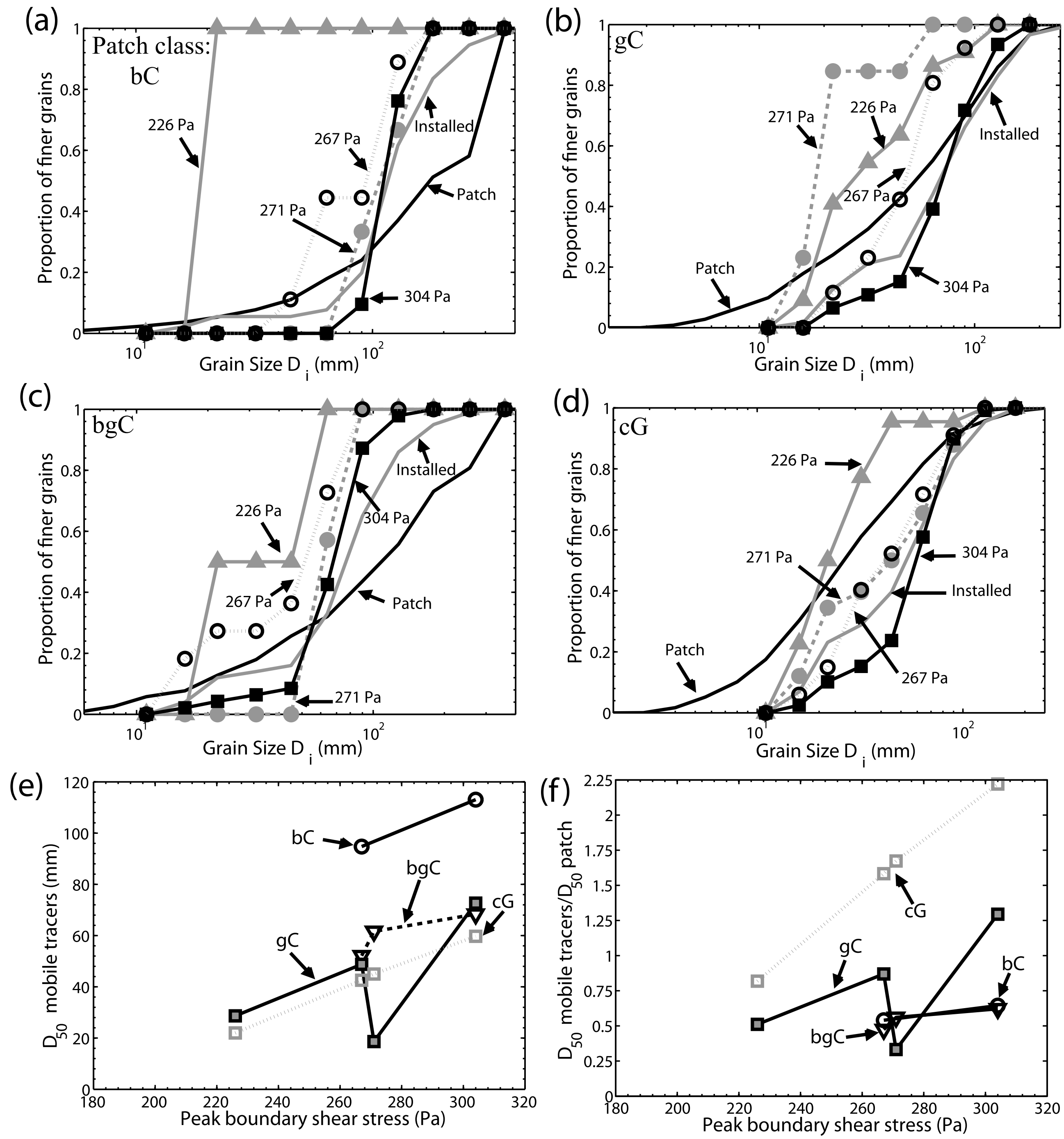

Figure 5. Data are for the Erlenbach. Grain size distributions of the underlying patches and the original and mobile tracers for (a) boulder-Cobble, (b) gravel-Cobble, (c) boulder-gravel-Cobble, and (d) cobble-Gravel patches. Each transport event is labeled by its peak boundary shear stress (in Pa). (e) The mobile D_{50} on each patch class and (f) the ratio of the D_{50} of mobile tracers to that of the each patch are shown as functions of the peak boundary shear stress. Events with less than 5 mobile particles on a patch were excluded from Figures 5e and 5f.

3.1.2. Tracer Mobility by Patch Class and Location

[28] For each sediment transport event, every tracer particle originated on one of six different patch classes: cobble-Boulder (cB), boulder-gravel-Cobble (bgC), Cobble (C), gravel-Cobble (gC), cobble-Gravel (cG), and Gravel (G). We only discuss the general occurrence of motion and not the specific transported grain sizes for the G and C patches. These patches had a low number of installed tracer particles with grain-size distributions that did not closely match those of the underlying bed material.

[29] All patch classes had some degree of sediment motion during the smallest sediment transport event (Table 4,

Table 5. Summary of Sediment Transport Events in Fox Creek[a]

Event	Date	τ_{bm} (Pa)	Event Duration (min)	D_{50} (mm)	D_{84} (mm)	Average Sediment Transport Rate (g/s/m)
2	12/15/02	133	180	5	11	2.7E+00
3	12/16/02	167	1380	10	25	3.7E−01
5	12/30/02	96	240	5	10	1.1E−01
6	12/30/02	96	165	5	12	1.6E−01
7	12/31/02	105	470	N/A	N/A	4.4E−01
8	12/31/02	115	1000	4	8	2.8E−01
9	1/1/03	109	1000	4	8	2.6E−01
10	1/1/03	100	256	4	9	7.1E−02
11	1/2/03	99	1175	4	8	3.0E−02
14	1/14/03	90	434	3	5	1.7E−02
15	1/15/03	87	1271	3	5	2.7E−03

[a]Average sediment transport rate and grain sizes are for all buckets used to measure sediment flux during a given event. See Table 1 for an explanation of abbreviations.

Figure 5). The mobile grain-size distributions and the largest mobile grain size of most patches progressively coarsened with higher shear stresses (Figure 5, Table 4). The transported grain-size distributions (includes photographic and installed tracers) never equaled those of the tracers or underlying patches, even for the largest event. The coarsest size fraction on each patch remained immobile throughout our study. The bgC and bC patches generally had the lowest ratios of mobile tracer sizes to patch grain sizes (Figure 5f) but contained the coarsest mobile grain size distributions (Figure 5e). Thus, although coarser patches were not as mobile as finer patches, they transported larger quantities of coarse sediment.

[30] We also analyzed the amount of tracer exchange between patch classes by determining the depositional patch for each particle. We did not include any photographic measurements of tracer deposition because we could not distinguish these tracers' source locations. For all events combined, the patch class of tracer deposition was not systematically influenced by the patch class of tracer erosion (Table 6). For example, a tracer particle that was eroded from a Cobble patch did not preferentially deposit on downstream C patches. gC and cG patches generally captured the most sediment from all patch classes but this was likely because they comprised a large fraction of the total bed area (21 and 19%, respectively). In addition, 61% of the individual patches in these classes were in or near the thalweg.

3.1.3. Patch Response to Flow and Sediment Transport

[31] For a given patch, the elevation change after a sediment transport event did not correlate with shear stress, event duration, or sediment flux (Figure 6a). For a given shear stress integral (given event), the elevation changes also did not correlate with the patch D_{50}. In most cases, less than one grain diameter (D_{50}) of elevation change occurred on the patches. Only two patches (14 and 40) had elevation changes, for two events, that were statistically different from zero according to a Wilcoxon signed rank test [*Zar*, 1999].

[32] Patch areas shrank (Patch 11), grew (Patches 40 and 14) or remained relatively constant (Patches 29 and 18a) with increasing shear stress, event duration and/or sediment flux (Figure 6b). Patches shrank and enlarged by as much as 25% and 60% of their original areas, respectively. For a given integral of shear stress, patch area changes did not vary with the patch D_{50}. Patches 11 and 40 had statistically significant elevation and area changes during the largest event, but the elevation and area changes within such patches occurred in opposite directions. Thus, although some patches changed in area or elevation, none of the patches consistently eroded or deposited a significant volume of sediment. The three patches (11, 14 and 40) with large area changes were located near the thalweg whereas the two patches (18a and 29) with stable areas were only inundated during the largest three events.

[33] Patches near the thalweg (11 and 14) significantly coarsened, while other patches (18a and 29) only coarsened slightly, if at all (Figures 6c and 6d). These grain size changes integrated the effects of the first five events (for Patches 14, 18a and 29) or only included the fifth event (for Patch 11).

Table 6. Percent of Mobilized Tracers From Each Patch Class That Deposited on a Given Patch Class in the Erlenbach[a]

Patches of Erosion	Total Number of Particles[b]	Patches of Deposition			
		G	cG	gC	C
C	34	3	24	31	9
gC	52	12	20	24	5
cG	94	2	53	13	7
G	22	0	13	8	28

[a]The percent of the total number of grains eroded from a given patch class that were deposited on each patch class. Percentages are for all sediment transport events combined.

[b]Total number of particles deposited on a G, cG, gC or C patch and is not equal to the total number of eroded particles. Note that some eroded tracers were deposited on other patch classes not shown here and therefore the percentages do not add to one. See text for abbreviations of patch classes.

3.2. Transport on a Patch in Fox Creek

[34] The transported grain-size distribution in the sediment traps coarsened with greater event magnitude although significant scatter exists for a given mean event shear stress (Figure 7a, Table 5). Part of this scatter was likely caused by variability of event duration and peak shear stress for a given mean shear stress, although use of the peak instead of mean shear stress did not reduce this variability. The maximum mobile D_{50} (9.7 mm) and D_{84} (25.2 mm) were significantly less than those of the immediately upstream cobble-Gravel patch (21.9 and 59.5 mm, respectively; Patch 1 in Figures 2 and 3d). However, the transported sizes were similar to those in Gravel patches (D_{50} of 7.3 mm and D_{84} of 26.3 mm) that were between 4 and 8 m upstream of the traps (Patches 4 and 5 in Figures 2 and 3d).

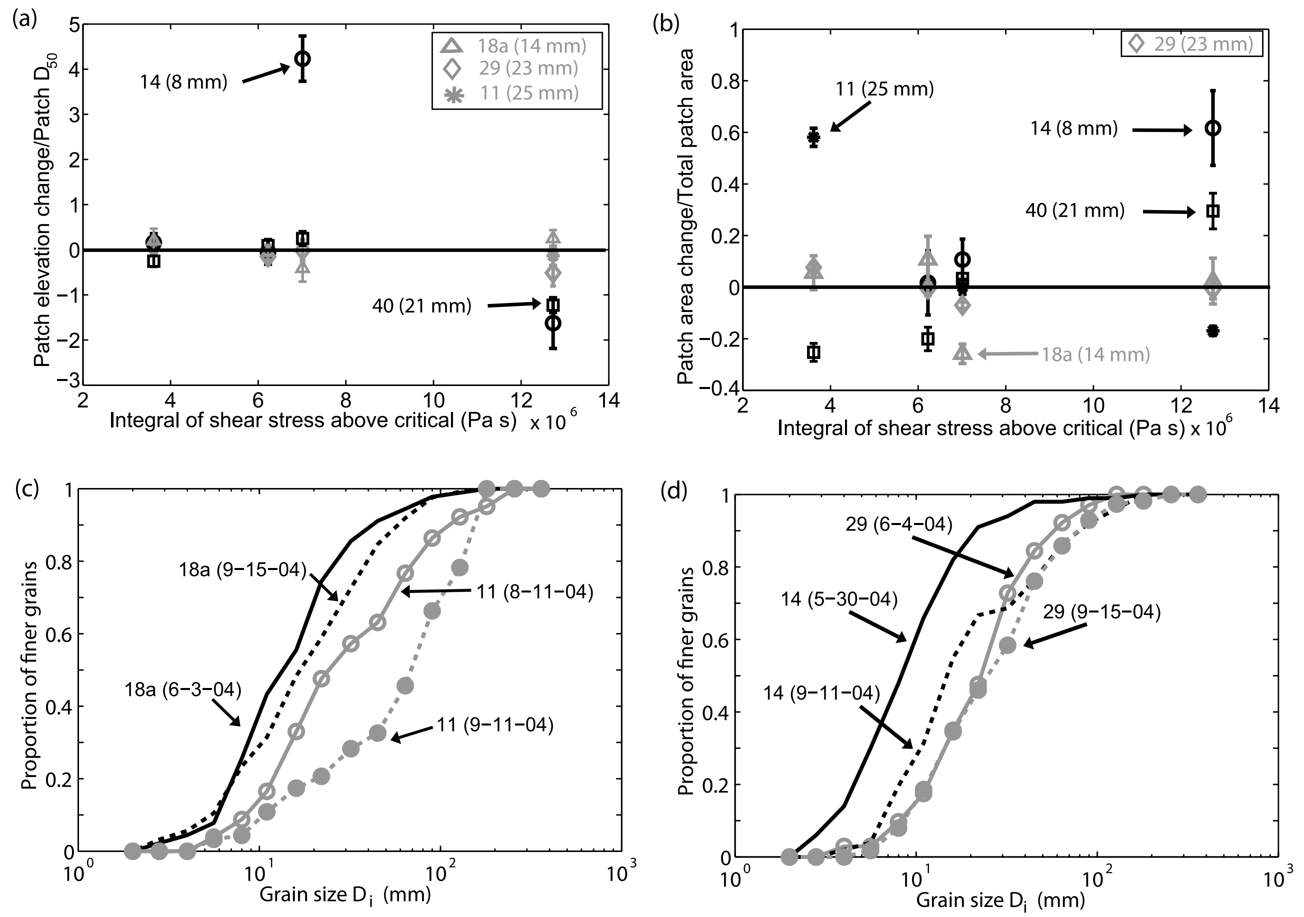

Figure 6. Data are for the Erlenbach. (a) Patch elevation changes normalized by the D_{50} of the patch and (b) fractional change in patch area versus the integral of the excess shear stress. The units of the temporal integral of shear stress are Pascals multiplied by seconds. Five patches are labeled by their patch number with their D_{50} (mm) in parentheses. Patches labeled with black symbols in Figure 6a are those with statistically significant changes in patch elevation and in Figure 6b are those that are near the thalweg. (c and d) Change in the grain-size distribution of four patches, which are labeled by their patch number with the date of measurement in parentheses.

[35] We also calculated the ratio of the transport rate for a given size (q_{bi}) to the frequency of that size on the patch immediately upstream of the traps (F_i), following *Wilcock and McArdell* [1997]. This ratio is an indicator of the degree of equal mobility or selective transport for each grain size. For a given shear stress, the fractional transport rate generally declined with increasing grain size, except for the largest event in which grain sizes up to ~10 mm fluctuated around the same q_{bi}/F_i value and could be equally mobile (Figure 7b). With increasing shear stress, finer grain sizes (less than 10 mm) transitioned from selective to close to equally mobile transport, moderate sizes from no transport to selective transport, and coarse particles (greater than 72 mm) remained immobile for all flows. In addition to transported grain size changes, the patch averaged sediment flux increased by three orders of magnitude with increasing shear stress (Figure 8a).

[36] For a given event, the sediment flux and mobile sediment sizes also varied spatially across the patch, as measured by the standard deviation of a given parameter between buckets. The bed load standard deviation systematically increased with greater shear stress (not shown in Figure 8a) but the coefficient of variation (CV, standard deviation divided by mean) was relatively constant (at ~100%) for small events and declined in larger events (Figure 8a). Bed load fluxes varied spatially between less than one to over two orders of magnitude, depending on the event (Figure 8c). The CV and standard deviation (not shown) of the transported grain sizes (D_{50} and D_{84}) generally increased with greater mean shear stress (Figure 8b). In all events, the maximum transported sediment volume and coarsest mobile grain sizes occurred at the patch center; flux magnitude and mobile grain sizes declined toward the patch edges (Figures 8c and 8d).

4. Discussion

4.1. Influence of Patch Grain Size Distribution on Sediment Motion

[37] The transported grain sizes for the entire bed in the Erlenbach increased with greater shear stress (Figure 4). The transported grain-size distribution never equaled that of

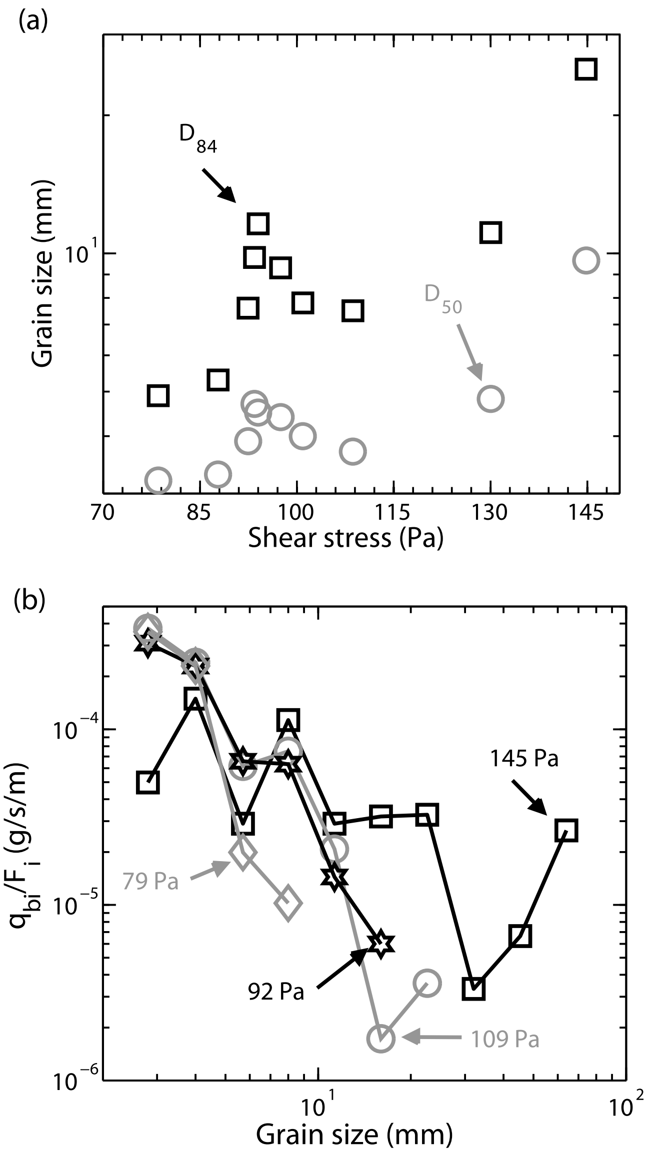

Figure 7. A range of events in Fox Creek are shown that represent the change in transport with shear stress. (a) The patch averaged transported D_{50} and D_{84} as functions of mean shear stress for a given event. (b) The ratio of the transport rate for each grain size to the proportion of that size on the patch, as a function of grain size and event magnitude (peak shear stress labeled).

the underlying bed sediment or original tracers, even when the flow was ~70% of bankfull. Thus, only a portion of the grain sizes were mobile and these grains did not move in proportion to their frequency on the bed. This demonstrates that the relatively mobile portion of the bed (excluding boulder steps) engaged in partial transport at low to moderate flows in the Erlenbach. The occurrence of selective and partial transport on the entire bed has also been documented in near-bankfull flows in a number of other steep streams [e.g., *Marion and Weirich*, 2003; *Ryan et al.*, 2005; *Mao et al.*, 2008] and our result is not surprising. We calculated (using discharge and and sediment transport data provided by the WSL) that 46% of the total sediment yield in the Erlenbach was transported by flows with recurrence intervals that were less than or equal to that of our fifth and largest event (0.6 years). Therefore, sediment transport during such events can comprise a large fraction of the sediment yield and low and moderate flows can be important to understand.

[38] Our results of partial transport are based on comparisons with the surface grain size distribution and we did not measure the subsurface sediment, which is often finer. We used the surface sediment because it is directly influenced by fluid forces and is a common measure of the degree of sediment mobility [e.g., *Wilcock and McArdell*, 1997; *Haschenburger and Wilcock*, 2003]. Use of the subsurface distribution would likely alter our results [e.g., *Wilcock and McArdell*, 1993]; when compared to the subsurface, more of the tracer grain sizes would be considered equally mobile.

[39] Although partial to selective transport on the entire bed can be common [e.g., *Parker and Toro-Escobar*, 2002; *Mao et al.*, 2008], the transport stage on individual patches has not been previously well documented. We were particularly interested if the patch grain size distribution influenced the relative mobility of a given grain size (see Introduction). For the Fox Creek patch (Figure 7) and most patch classes in the Erlenbach (Figure 5), the transported grain size distribution coarsened with greater shear stresses and each grain size was not transported in proportion to its frequency on the patch. We did not observe preferential transport of finer patches at low shear stresses; the smallest measured event transported tracer particles on all patch classes in the Erlenbach (Table 4). Thus, all Erlenbach patches began motion at similar shear stresses and engaged in partial to selective transport during low to moderate flow events. Our results in the Erlenbach and Fox Creek are supported by a tracer particle study in a lower-gradient channel, Wildcat Creek [*Dietrich et al.*, 2005], in which fine and coarse patches moved at the same shear stresses. Thus, the occurrence of partial or selective transport on the entire bed was not caused by the preferential transport of only finer patches, but the relative high mobility of fine sediment on all patch classes. Hiding effects caused by individual patch grain size distributions do not necessarily have a large influence on the first onset of motion of a given grain size.

[40] The exchange of sediment between relatively fine and coarse patches in the Erlenbach also demonstrates that grain depositional locations may not always depend on the patch grain size. Similar results were reported by *Lamarre and Roy* [2008], in which tracer particles did not sort by size when depositing in pools (fine bed) or steps (coarse bed). Our results of tracer particle motion being relatively independent of the underlying patch grain size distribution are supported by two other observations. First, we observed significant spatial variability in the transported sediment volumes and grain sizes on the Fox Creek patch, which had a spatially homogenous grain size distribution (Figure 8). These large sediment flux variations were unlikely to be caused by grain size variability, which demonstrates that patch grain-size distributions may not necessarily drive spatial differences in bed load transport. Second, Erlenbach patches near the thalweg experienced changes in area and thickness that did not correlate systematically to variations in the shear stress, sediment flux, and patch grain size (Figure 6). Thus, the

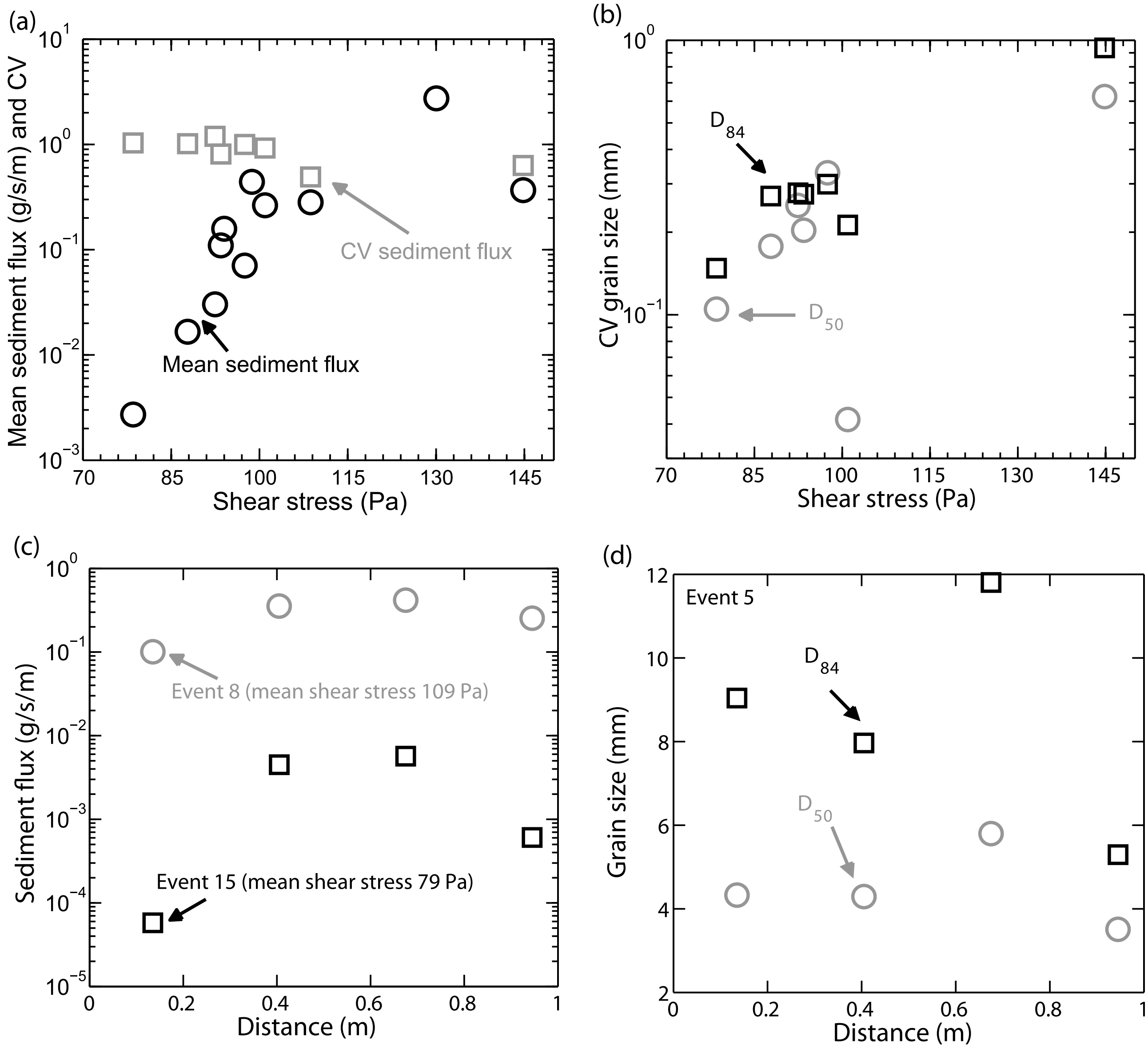

Figure 8. Data are for Fox Creek. The (a) transported bed load flux and coefficient of variation (CV) of this flux and (b) CV of the transported D_{50} and D_{84} as functions of mean event shear stress. The (c) measured bed load fluxes and (d) transported D_{50} and D_{84} in each bucket are shown for individual events.

patch grain size may not be indicative of the relative dynamics and stability of a given location.

[41] All of these results suggest it may be possible to neglect the spatial variability in grain size when calculating sediment flux for flows dominated by partial to selective transport. Such calculations would need to account for the preferential movement of fine sediment within a single reach-averaged grain size distribution. In addition, although other studies show that relatively fine patches were the only transient bed sediment sources (temporary sources for a given event) during low to moderate flow events [e.g., *Garcia et al.*, 1999; *Vericat et al.*, 2008], all patches in the Erlenbach, Wildcat Creek [see *Dietrich et al.*, 2005] and an ephemeral channel [*Yuill et al.*, 2010] were mobile (Table 4). Although more sediment may be eroded from fine patches because they have a greater quantity of relatively mobile fine grains [e.g., *Lisle*, 1995; *Garcia et al.*, 1999], it is not because the coarse patches are fundamentally immobile. Therefore, calculations of bed load transport cannot neglect the fine sediment in coarse patches during most flows.

4.2. Spatial Variability in Transport

[42] Although it could be possible to neglect spatial grain size variations, the local sediment supply and flow hydraulics could significantly impact patch-scale dynamics. For the Fox Creek patch, large spatial variations in sediment transport may be from either variable flow conditions across the patch, which drive local bed load transport rates, or upstream sediment supply variations. The transported grain size distributions more closely approximated those of the less proximal upstream Gravel patches (Patches 4 and 5 in Figures 2 and 3d) than the cobble-Gravel patch (Patch 1),

which could imply that sediment supply is important. However, the cobble-Gravel patch engaged in partial transport (coarser gravel and cobbles immobile) and contained enough sediment volume of each mobile grain size (calculated as patch area multiplied by grain diameter and proportion of the patch occupied by a grain size) to be the primary sediment source for the traps. It is likely that a combination of variability in the local flow on the proximal patch and in the sediment supply from finer upstream patches controlled the spatially variable sediment transport rates in the traps.

[43] Low sediment transport rates at the patch edges corresponded to locations where wall drag and a large boulder likely reduced the local near-bed stresses and acted as areas of low sediment availability for transport (Figure 8c). The importance of shear stress fluctuations, rather than grain size variability (see section 4.1), is supported by numerical modeling results of *Nelson et al.* [2009]. In their model, a larger change in grain size than shear stress is needed to cause an equivalent alteration in the sediment transport rate. Calculations of grain mobility and sediment flux at the patch scale may therefore require accurate estimates of local shear stress and/or upstream sediment supply, at least for the flows represented in this study (up to ~70% of bankfull).

[44] The area, thickness, and grain size of patches in the Erlenbach should vary with sediment supply. In flume experiments, coarse and fine patches expanded and contracted, respectively, at relatively low sediment supplies [*Dietrich et al.*, 1989; *Nelson et al.*, 2009]. The lack of trends in Erlenbach patch changes with reach-averaged parameters is because patch extent is dictated by local conditions. We did not measure the local shear stresses and sediment fluxes and these are likely different from reach-averaged values. Patches outside of the thalweg did not have significant changes in extent (Figure 6) because they presumably experienced lower temporal variability in local shear stresses and sediment fluxes than patches near the thalweg. A similar lack of relationship between patch area and reach–averaged flow conditions were reported in a lower-gradient ephemeral channel [*Yuill et al.*, 2010]. However, patch changes could also be caused by variable scour and fill during a given event and could be driven by the specific conditions throughout a hydrograph and not the integrated event magnitude.

[45] Our results imply that a better understanding of the impact of local flow and sediment supply on patch sediment motion is needed. Sediment transport equations that assume reach-averaged values of shear stress may not accurately predict the transport dynamics and stability of individual patches [e.g., *Ferguson*, 2003; *Nelson et al.*, 2009] particularly in steep, rough streams. However, at the reach scale, such spatial variability in flow and sediment transport may be averaged to obtain relatively accurate predictions of reach-averaged sediment flux [*Nelson et al.*, 2009; *Yager et al.*, 2012].

5. Conclusions

[46] Relatively little is known about the dynamics and formation of sediment patches, especially in steep streams. To better understand patch dynamics, we measured patch sediment transport in two steep streams and changes in patch characteristics (grain size, area, elevation) in one of these channels. The transported grain-size distribution and sediment flux varied significantly within patches. For example, during a given flow event, the bed load flux varied by many orders of magnitude across a patch with a spatially uniform grain size distribution. This observation, combined with the wide range in patch stability (grain size and extent), demonstrate that reach-averaged and possibly even patch-averaged flow and sediment supply conditions do not accurately represent the processes that drive local patch stability and motion. In addition, local variations in shear stress or sediment supply may be more important than bed grain size variations in controlling the spatial variability in sediment flux on a given patch. Fine patches are often assumed to be the majority of the transient bed sediment sources during low to moderate flows. However, coarse and fine patch classes started motion at the same shear stress and coarse patches also acted as locations of significant transport. Thus, the occurrence of selective transport on the entire bed may not be caused by the preferential transport of only finer patches but the preferential movement of fine sediment in general.

Appendix A

A1. Pebble Counts

[47] Multiple counts of individual grains were included in our measurements because the largest grain diameters were a significant fraction of the patch length and/or width [*Church et al.*, 1987]. Such counts only occurred on a total of five patches and, with the exception of two of these patches, were small proportions (1–4%) of the total measurements on a given patch. Published recommendations for sediment sampling and exclusion of multiple counts are generally for much better sorted beds with no limitation on sampling area (i.e., not patches) and therefore no standard exists for sampling patches in steep streams. We assumed that partially buried boulders on gravel-Cobble (gC), cobble-Gravel (cG), and Gravel (G) patches were not available for motion unless the entire patch was excavated and we excluded these grains from the pebble counts. We included all measured boulders in the grain-size distributions of the boulder-Cobble (bC) and boulder-gravel-Cobble (bgC) patches because these grains were largely exposed and could become mobile.

A2. Tracer Particles

[48] We assumed any installed tracer that was temporarily lost (buried) between sediment transport events only moved to its found location during the event that immediately preceded its exposure, rather than during the event(s) in which it was likely buried. Such lost tracers were a small portion (0–6%) of the total installed particles for each event and their inclusion did not significantly impact the transported grain size distributions. For example, in the fifth event, inclusion and exclusion of temporarily lost tracers gave a mobile D_{50} for the entire reach of 65 and 68 mm, respectively. Particles that were never recovered and were permanently lost were excluded from our analysis because they were dominantly (91–100%, depending on the event) small particles (<32 mm) and therefore could have been either easily buried or transported out of the reach. Inclusion of these

particles would systematically fine the transported mobile grain size and therefore our results are a coarse estimate of this grain-size distribution for a given event.

[49] For the photographic tracers, we assumed that any missing grains were not buried in place because the patch bed elevations were relatively constant over our study period (see section 3.1.3). This differs from our assumption that temporarily lost installed tracers were buried in place because most (81–88%) of those tracers were much smaller (<38 mm) than the patch elevation changes. Conversely, all photographic tracers were larger than 32 mm and would require a large elevation change to be buried.

A3. Fox Creek Traps

[50] The bed load traps contained large quantities of sand (average of 20% of the total transported weight), which we did not include in our analysis because of uncertainty if the sand was suspended and then deposited in the falling hydrograph limb. We calculated, using the stress borne by the mobile sediment (to determine the shear velocity) and the *Dietrich* [1982] settling velocity equation, the grain sizes that may have been suspended during our measurements. We used a Corey Shape Factor (CSF) of 0.7 and a Powers roundness scale of 3.5 and assumed grains would start suspension when the shear velocity and settling velocity were equal. The stress borne by the mobile sediment corrects for the effects of the immobile step roughness and was determined from the stress-partitioning equations and measurements in Fox Creek outlined by *Yager et al.* [2012]. Use of the total shear stress would dramatically over-estimate the stress borne by the more mobile gravel and sand in Fox Creek [*Yager et al.*, 2007]. Grains as large as 1.3 and 4.5 mm may have been suspended during the peak discharges of our smallest and largest events, respectively. These calculations show that the traps may have sampled sand that was transported as both bed load and suspended load through many of our measured flow hydrographs. The saltation hop length for sand could be larger than our downstream trap opening and therefore the traps were not 100% efficient for sand [see *Sterling and Church*, 2002]. We also excluded sand to obtain comparable bed load and patch surface (from pebble counts) grain size distributions.

[51] The maximum size that can be captured by a trap depends on the trap aperture and shape (see *Sterling and Church* [2002] for a review) and our trap was not able to capture the largest sizes present on the upstream patch. The maximum transported grain sizes (64 mm) were still significantly less than the maximum patch grain size (180 mm) and the trap opening (15.5 cm). *Sterling and Church* [2002] estimated that their pit traps (circular diameter of 29 cm, 38 cm deep) were 100% efficient in trapping sediment between 45.3 and 4 mm. These are likely maximum estimates of the efficiency of our traps, which were smaller (29 cm wide perpendicular to flow, 28 cm deep, 15.5 cm long in the downstream direction) than those of Sterling and Church. Although it is possible that we underestimated the transported bed load grain sizes during the largest events, this would not change our fundamental conclusions. The spatial variation in sediment transport and occurrence of selective transport for even small gravel sizes (10 mm) would still occur even if our traps could not capture the largest mobile grain sizes. Finally, we sampled from all four traps in most events, but only one trap (third trap from the channel wall) was able to be emptied (because of dangerous flow conditions) for a few events. This trap usually had the coarsest transported sediment sizes and the largest bed load transport rates and thus, could over-estimate the mean transport for these events (2, 6 and 7).

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