

# The domain of bedload sheets

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**ABSTRACT:** Bedload sheets are low-amplitude bedforms that are formed by sorting patterns in mixed-size sediment (gravel or gravel-sand mixtures). The features have been functionally linked to dune forms developed in sandy sediments and gravel dunes formed in river channels. There have been a number of attempts to place bedload sheets on extended versions of the bedform phase diagrams used to predict sand bedform occurrence. There is no reason to suspect that this is problematic from the perspective of fluid and sediment particle interactions. However, it is well-known that bed surface texture and sediment flux in gravel bedded rivers are controlled by the magnitude and grain-size distribution of sediment supply to the channel. Here, we demonstrate that the occurrence of bedload sheets is not controlled hydraulically and that their occurrence, dimensions, and dynamics are primarily controlled by sediment supply. The results suggest that placing bedload sheets, and perhaps all bedforms developed in mixed size sediments, on hydraulically-based bedform phase diagrams is problematic. We suggest that a more appropriate approach may be to construct bedform occurrence diagrams for mixed-size sediments in the phase space formed by a sediment supply parameter and a bed mobility parameter.

## 1 INTRODUCTION

Bedload sheets are low-amplitude bedforms with heights of 1-2 grain diameters developed by sorting patterns in poorly sorted sediment. First identified by Whiting et al. (1988), they appear in river channels as bands of the coarser fractions of the bed material that grade upstream to the finer fractions. These features are commonly aligned across the primary flow path in river channels and migrate downstream, but it is not uncommon to see bedload sheets shoaling onto bars as a result of secondary flow patterns (Wooldridge and Hickin, 2005).

The formative mechanism for bedload sheets has not been fully elucidated, but they form and migrate downstream as a consequence of the 'catch and mobilize' process, in which large grains are caught in the wakes of other large grains, followed by infilling of their interstices by smaller particles, which can in turn smooth out hydraulic wakes causing large particles to be remobilized (Whiting et al., 1988; Venditti et al., in prep.). The sorting patterns across bedload sheets suggests that they pose abrupt changes in roughness and turbulence structure (Best 1996 and references therein) and Seminara et al. (1996) proposed that the stress perturbation due to this sorting structure allows for the growth of bedload sheets.

Bedload sheets are widely thought to be the precursor to gravel dune development when flows are sufficiently large that grain inertia is overcome to begin the vertical stacking process required for dune growth. This can only happen in flows well in excess of the critical threshold (Carling, 1999). Some authors regard bedload sheets as analogous to dunes (c.f. Bridge, 1993). There have been a number of attempts to include bedload sheets into the bedform phase diagrams used to predict bedform occurrence in sandy sediments (c.f. Best, 1996; Carling, 1999; Kleinhans, 2002). The results of these exercises have only been partially successful at distinguishing between bedform types in poorly sorted sediments (c.f. Kleinhans, 2002). Indeed, bedload sheets commonly fall into the dune existence field on bedform phase diagrams. This has provided some evidence of the linkage between bedload sheets and dunes formed in coarse sediments (gravel and sand-gravel mixes).

There is a fundamental assumption that underlies placing bedload sheets onto the bedform phase diagrams used for sandy sediments – that is that bedform occurrence is controlled hydraulically. In the specific case of bedload sheets, this control may not exist. Bedload sheets are one type of a wide variety of sediment patches of similar sorting that occur in gravel bedded rivers. Following the terminology of

proposed for bar types (e.g. Seminara, 1997), sediment patches can be identified as either ‘forced patches’ (spatially persistent associated with topographic controls), ‘fixed patches’ (spatially persistent due to coarsening), and ‘free patches’ (migrating patches) (Nelson et al., in prep). Bedload sheets belong to the latter type of migrating patches. Field and flume studies suggest that sediment supply and bed texture are dynamically linked, suggesting a linkage between sediment patch dynamics and sediment supply. For example, Dietrich et al. (1989) proposed that surface armoring depended on sediment supply. They imposed stepwise reductions in sediment supply to a flume with constant water discharge and observed the expansion of coarse, inactive zones on the channel bed. A number of more recent investigations have also documented that patch size, extent, distribution, and thickness are controlled by sediment supply (c.f. Kinerson, 1990; Gran et al., 2006; Yager, 2007). However, this work focused on patches that were largely fixed in space. Observations of the response of free patches such as bedload sheets have been more limited. Dietrich et al. (1989) observed that in response to sediment supply reduction bedload sheets became less frequent and distinct, but provided no quantitative support of this observation.

Recognition of this prompted the authors to specifically investigate how free patches (bedload sheets) respond to variations in sediment supply. Our examination focuses on two sets of flume experiments conducted in sediment feed flumes. The first were conducted at the University of Tsukuba in Tsukuba, Japan, in 1987, and have been described in previous publications (Dietrich et al., 1989; Kirchner et al., 1990). The second set of experiments was conducted at the University of California, Berkeley Richmond Field Station in Richmond, CA USA in 2005. We believe the results of these experiments demonstrate that the occurrence of bedload sheets is not controlled hydraulically and that their occurrence, dimensions, and dynamics are primarily controlled by sediment supply.

## 2 EXPERIMENTS

The Tsukuba Experiments were conducted in a 7m long, 0.3m wide flume at the University of Tsukuba, Japan, using a constant unit water discharge ( $0.06 \text{ m}^2/\text{s}$ ), a bimodal sediment and a width-to-depth ratio of  $\sim 3$  in order to suppress development of any lateral channel topography. The sediment that composed the bed material and the sediment feed was a sand-gravel mixture of diameter ranging from 1 mm to 12 mm and with a median grain size ( $D_{50}$ ) of 3.6 mm (Fig 1a). Sediment was fed into the upstream end of the flume at a constant rate and bedload discharged from the end of the flume was col-

lected at 5-minute intervals, weighed, and sieved. The water surface slope, bed slope, and bed surface texture were allowed to equilibrate to the imposed water discharge and sediment supply rate. When the channel reached an equilibrium state, where the sediment flux magnitude and grain-size matched the sediment feed, and where the water surface slope became quasi-steady, the run was halted and the feed rate was reduced through successive rates of 17.4, 6.1, and 1.7 g/min/cm. The flow parameters at equilibrium for each run are given in Table 1.

The Berkeley Experiments were conducted in a larger 28m long and 0.86m wide flume channel at UC Berkeley and followed the same basic procedure, except we used a unimodal sediment composed entirely of gravel ranging in size from 2 to 32 mm with a median grain size of 8 mm. This allowed us to examine bedload sheets dynamics in the absence of sandy sediments that enhance the catch and

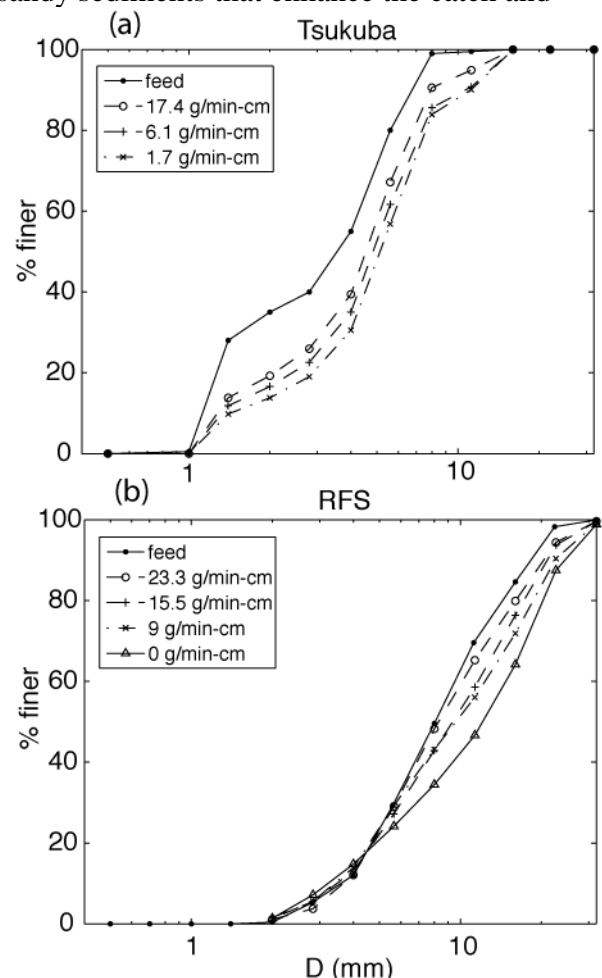


Figure 1. Grain size distributions for the bulk (feed) sediment and bed surface for the (a) Tsukuba and (b) RFS experiments.

mobilize process responsible for bedload sheet movement. As in the Tsukuba Experiments, we used a constant unit discharge ( $0.238 \text{ m}^2/\text{s}$ ) and a small width-to-depth ratio of  $\sim 4$  to suppress lateral topographic development. Experiments proceeded by first establishing an equilibrium condition where the sediment flux magnitude matched roughly the sediment feed rate, then the feed was reduced through successive rates of 23.3, 15.5, and 9 g/min-

Table 1: Hydraulic conditions for the experiments

	Tsukuba (TE <sub>x</sub> )			Berkeley (BE <sub>x</sub> )			
Sediment feed (g/min-cm)	17.4	6.1	1.7	23.3	15.5	9	0
Water discharge m <sup>2</sup> /s	0.06	0.06	0.06	0.238	0.238	0.238	0.238
Mean flow depth (cm)	0.102	0.103	0.113	0.218	0.221	0.224	0.228
Water surface slope	0.0052	0.0046	0.0035	0.0048	0.0046	0.0040	0.0039
Bed slope				0.0055	0.0051	0.0048	0.0043
Mean flow velocity (m/s)	0.59	0.58	0.53	1.09	1.08	1.06	1.05
Boundary shear stress (Pa)	5.20	4.64	3.88	10.30	9.94	8.85	8.64
D50 (bed surface) (mm)	3.74	4.26	4.85	8.31	9.26	9.61	12.41
Armoring ratio	1.03	1.17	1.34	1.03	1.15	1.19	1.54
Shields number $\tau^*$	0.086	0.067	0.049	0.077	0.066	0.057	0.043
Width of active transport (cm)	-	-	-	61±10	51±12	46±9	0

Note:  $\tau^* = \tau / [(\rho_s - \rho)gD_{50}]$

cm. In addition, we extended the experiment beyond the feed reductions in the Tsukuba Experiments by completely eliminating the sediment feed and allowing the bed to equilibrate (Table 1).

## 2.1 Observations

Table 1 shows the mean hydraulic conditions at the end of each run for both sets of experiments. Flow in both experiments remained essentially constant. There is a moderate decrease in the water surface slope in both experiments, ~30% in the Tsukuba Experiments (TE<sub>x</sub>) and ~20% in the Berkeley Experiments (BE<sub>x</sub>), which is compensated by a slight increase in the flow depth (~10% in TE<sub>x</sub> and ~5% in BE<sub>x</sub>) a more substantial increase in the bed surface grain-size (~30% in TE<sub>x</sub> and ~50% in BE<sub>x</sub>). In effect, the channel surface becomes armored in response to the sediment supply reduction. However, the channel does not become armored uniformly. Instead, the channel develops inactive zones and a narrowing of the corridor of active transport (Table

1). Coincident with this process, there are changes in the bedload sheet occurrence, kinematics, and dynamics.

Figures 2 and 3 show the changes in the surface structure of the bed as sediment supply was reduced. These maps represent the structure of the bed frozen at an instant in time and it should be noted, that with the exception of the inactive transport zones, the grain-size patches were mobile throughout the experiments. The inactive zones in contrast were stationary, but they were exchanging particles with the rest of the bed. The patch maps show bedload sheets with coarse-grained fronts with heights of about 2 grain diameters and progressively fine toward their tails. In the Tsukuba experiments, coarse gravel particles became trapped in each other's wakes and accumulated into congested zones, forming the coarse front of bedload sheets. Sand particles then filled the interstices of the gravel front, which remobilized the gravel and allowed the coarse front to propagate downstream. Sheets propagated in a similar manner in the Berkeley Experiments even in the absence of

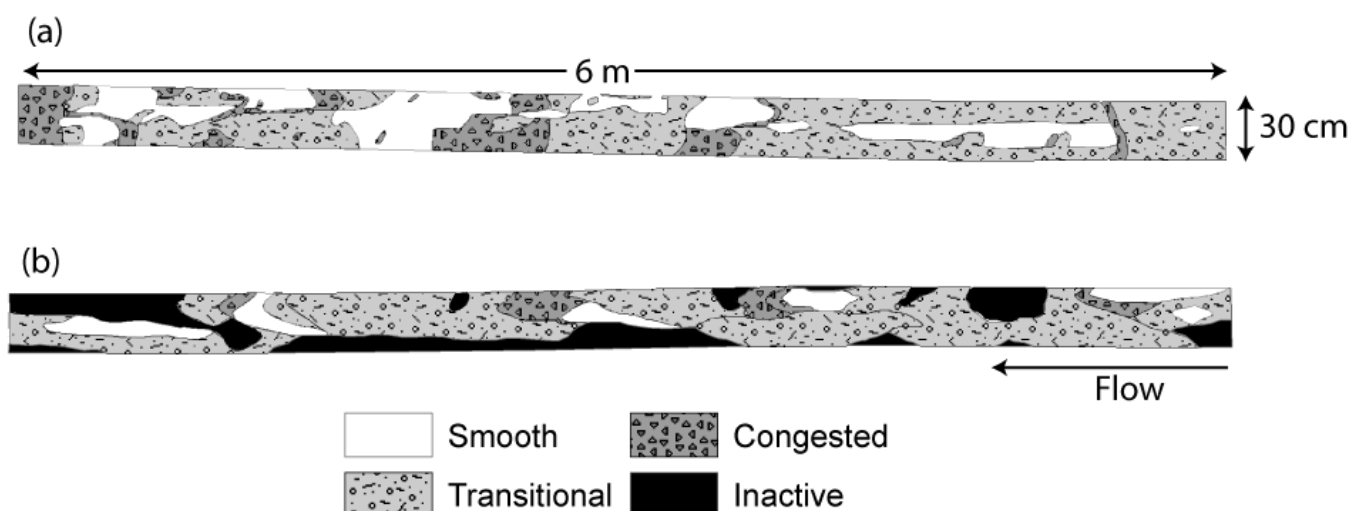


Figure 2. Bed facies map of the Tsukuba experiments at the end of the a) 17.4 g/min-cm and b) 6.1 g/min-cm sediment feed runs. Patches were classified as ‘congested’ (coarse – median grain size D50 = 4.68 mm, geometric standard deviation  $\sigma = 1.76$ ), ‘transitional’ (D50 = 3.63 mm,  $\sigma = 2.16$ ), ‘smooth’ (fine - D50 = 2.62 mm,  $\sigma = 2.16$ ), and ‘inactive’ (coarse zones with no active bedload transport, D50 = 5.49 mm,  $\sigma = 1.77$ )

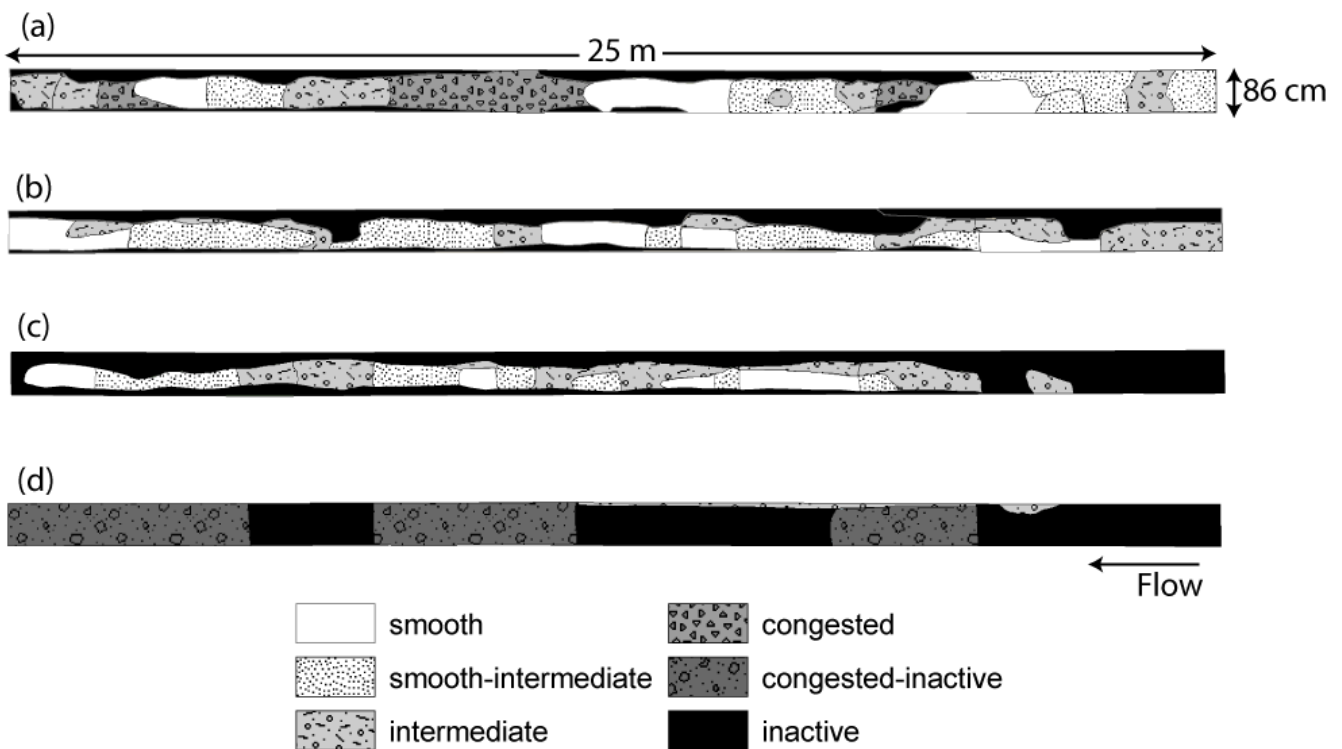


Figure 3. Facies map of the bed of the RFS experiments at the end of the a) 23.3 g/min-cm, b) 15.5 g/min-cm, c) 9 g/min-cm, and d) 0 g/min-cm sediment feed runs. Smooth, smooth-intermediate, and intermediate patch types had a grain-size of  $\sim 9$ mm, but smooth patches were well-sorted and intermediate patches were poorly-sorted. Congested and inactive patches had similar sorting, but inactive zones ( $D_{50} \sim 9$  mm) were coarser than congested zones ( $D_{50} \sim 13$  mm).

sand. In the Berkeley Experiments, the front of bedload sheets was composed of relatively well-sorted moderately coarse (8-14 mm) gravel, where gravel of like-sized material became deposited over a coarser inactive bed. Fine (3 mm) gravel then filled the interstices of the sheet front and the front material was remobilized. Both of these processes illustrate of the ‘catch and mobilize’ phenomenon described by Whiting et al. (1988). This process creates the downstream-sorted structure of a bedload sheet and also provides a mechanism for its movement. While this phenomenon has thus far only been observed in poorly sorted sand-gravel mixtures, our observations in the sand-free Berkeley Experiments suggest that the ratio of coarse and fine grain sizes is probably more important to this process than the mere presence or absence of sand. The mobilization effect of the fine grains on the coarse grains is likely related to a hydrodynamic smoothing effect that increases the near-bed velocity and drag on the coarse particles (Venditti et al., in prep.).

The bedload sheets caused order of magnitude fluctuations in sediment flux that decreased as the feed was reduced. Figure 4 plots the variations in sediment flux caused by bedload sheets exiting the Berkeley flume. Observations during the experiment suggest that flux spikes occurred when fine gravel filled the interstices of a coarse head, dramatically increasing the transport of both the coarse and fine fractions of the grain-size distribution. This is supported by observations from the Tsukuba Experiments where dramatic increases in sediment flux are linked to increases in gravel transport, and not nec-

essarily sand. Decreased transport events are linked with periods when a coarse sheet head is trapping like-sized particles. Careful mapping during the Tsukuba Experiments permitted examination of bedload sheet celerity and length. These results suggest that both bedload sheet velocity and length decrease as sediment supply is reduced.

When sediment supply was completely eliminated in the Berkeley Experiments, the coarse stationary patches expanded to encompass the entire bed. Thus bedload sheets no longer occur, but the channel hydraulics remain essentially the same. Collectively, these results appear to demonstrate that bedload sheet dynamics, extent, abundance, and occurrence are controlled by sediment supply and not the hydraulics of the channel.

### 3 DISCUSSION AND CONCLUSIONS

These results have important implications for inclusion of bedload sheets and, potentially all bedforms in mixed-size sediment, on traditional bedform phase diagrams for sandy bedforms. Indeed, the fact that sheet dynamics and occurrence are controlled by sediment supply, suggest that hydraulically-based phase diagrams are not appropriate predictors of bedload sheet occurrence.

We suggest that the way forward lies in development of bedform occurrence diagrams for mixed-size sediments in the phase space formed by a sediment supply parameter and a bed mobility parameter

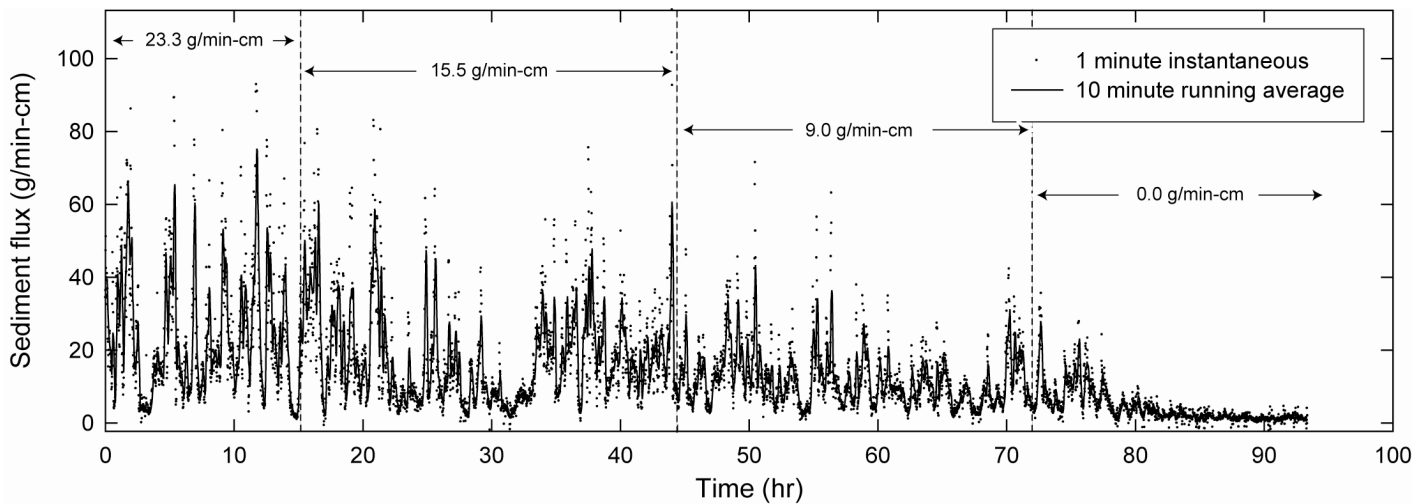


Figure 4. Time series of sediment flux obtained during the Berkeley Experiments. Dashed lines indicate transitions in the sediment feed rate.

An appropriate dimensionless excess shear stress parameter takes the form of:

$$\theta = \frac{\tau^* - \tau_c^*}{\tau_c^*} = \frac{\tau - \tau_c}{\tau_c} \quad (1)$$

where  $\tau^* = \tau / [(\rho_s - \rho)gD_{50}]$  and is the Shields number,  $\tau_c^*$  is the critical Shields number for the bed (normally taken as 0.047 for a mixed gravel-sized sediment),  $\tau$  is the dimensional shear stress,  $\rho_s$  is sediment density,  $\rho$  is water density, and  $g$  is gravitational acceleration. There is no widely accepted sediment supply parameter, but we suggest a simple one that has the following form:

$$Q^* = \frac{\text{supply}}{\text{capacity}} \quad (2)$$

Both supply and capacity can be calculated using a number of different methods and sediment transport models, but here they serve as conceptual constructs and we do not tie their value to any particular sediment supply regime or transport theory. Kleinhans (2002) developed a similar plot of  $\tau^*$  against a parameter that was the ratio of the transport capacity, calculated using Meyer-Peter and Muller's model, to the measured transport. The plot nicely discriminated between the sandy bedforms developed over gravel armor layers under partial transport conditions.

We have sketched the general form of such a plot in Figure 5. At excess shear stresses below the threshold for motion of the finest particles on the bed, there will obviously be little or no general bed movement. At excess shear stresses below the threshold for the entire bed,  $\theta < 0$ , the bed exists in a partial transport regime (only finer fractions transported) and above this threshold,  $\theta > 0$ , the bed ex-

ists in a full mobility mode (all fractions transported).

The magnitude of sediment flux is ultimately controlled by the magnitude of sediment supply to a river channel, and this defines three zones on the vertical axis. At  $Q^*$  values  $< 1$ , the bed will degrade slightly under a partial transport regime until the fine surface material is exhausted. If  $Q^* > 1$ , the bed will aggrade, and move into a full mobility regime. A special circumstance can exist if there is a sediment supply that is finer than the bed material. Under this condition, the partial transport mode can persist at  $Q^* < 1$ . However, if  $Q^* > 1$ , the bed will transition to a fully-mobile finer bed.

A full transport regime with  $Q^* > 1$  will induce significant aggradation while at  $Q^* < 1$ , bed degradation will occur. In the case of either degradation or aggradation, the channel will adjust its morphology, hydraulics and gradient to pass the incoming load and thus these should be viewed as transient states.

These conditions define a number of unique existence fields for bedforms in mixed sized sediments. In the region of low  $\theta$  and low  $Q^*$ , the cluster, cell and transverse rib bedforms described by Church, Hassan, and collaborators will form (c.f. Church et al., 1998; Hassan and Church, 2000). Although general movement of the bed will not occur, particles are jostled into an orientation that strengthens the bed to higher flows. In the region bounding  $0.1 < Q^* < 1$ , the partial transport regime will produce bedforms composed of the finer fractions of the bed and include the ribbons, barchans, and dunes, providing a fine sediment supply is available. Kleinhans' (2002) work suggests that sand ribbons, barchans and dunes will occur with increasing  $Q^*$  values and that ultimately the bed will transform to a sand-bedded river at very high  $Q^*$  values, at which point bedforms controlled by hydraulic conditions will dominate because supply is no longer a limiting factor. We observed similar results to that of Klein-

hans (2002) (ribbons and barchanoid dune features) when we added fine gravel to an otherwise immobile bed during the Berkeley Experiments. If a fine sediment supply does not exist for the partial transport regime, the bed will exhaust the fine sediment at the surface, and the cluster, cell and transverse rib bedforms described by Church, Hassan, and collaborators will dominate.

The domain of bedload sheets lies somewhere between the aggradation and degradation extremes at high and low  $Q^*$  values in the full mobility regime. Indeed, all observations of bedload sheets under equilibrium transport are within the zone bounding  $Q^* \approx 1$  and  $\theta \approx 0$ . As  $Q^*$  values decrease from just above 1 to just below 1, the bed armoring observed by Dietrich et al., (1989) and in the Berkeley Experiments will occur. Although the bed remains in a fully mobile state, the armoring process essentially ceases sediment transport. As this occurs, bedload

sheets will disappear.

Only under the unique case where  $\theta \gg 0$  can gravel dunes form. This requires that gravel be abundantly available in the channel when relatively rare flow events greatly exceed the threshold for gravel in the channel bed. Indeed, the rare observations of gravel dunes in the field occur in locations where this condition can be met (c.f. Dinehart, 1989; 1992a; 1992b).

At this time, there are relatively few observations of bedforms developed in mixed size sediment where sediment supply can be separated from channel hydraulics. Most work has focused on sediment recirculating flumes (or partial-recirculating flumes where sand is recirculated and gravel is not) where the sediment 'supply' is intricately intertwined with the channel hydraulics. We sorely need data to confirm or refute the ideas presented in Figure 5.

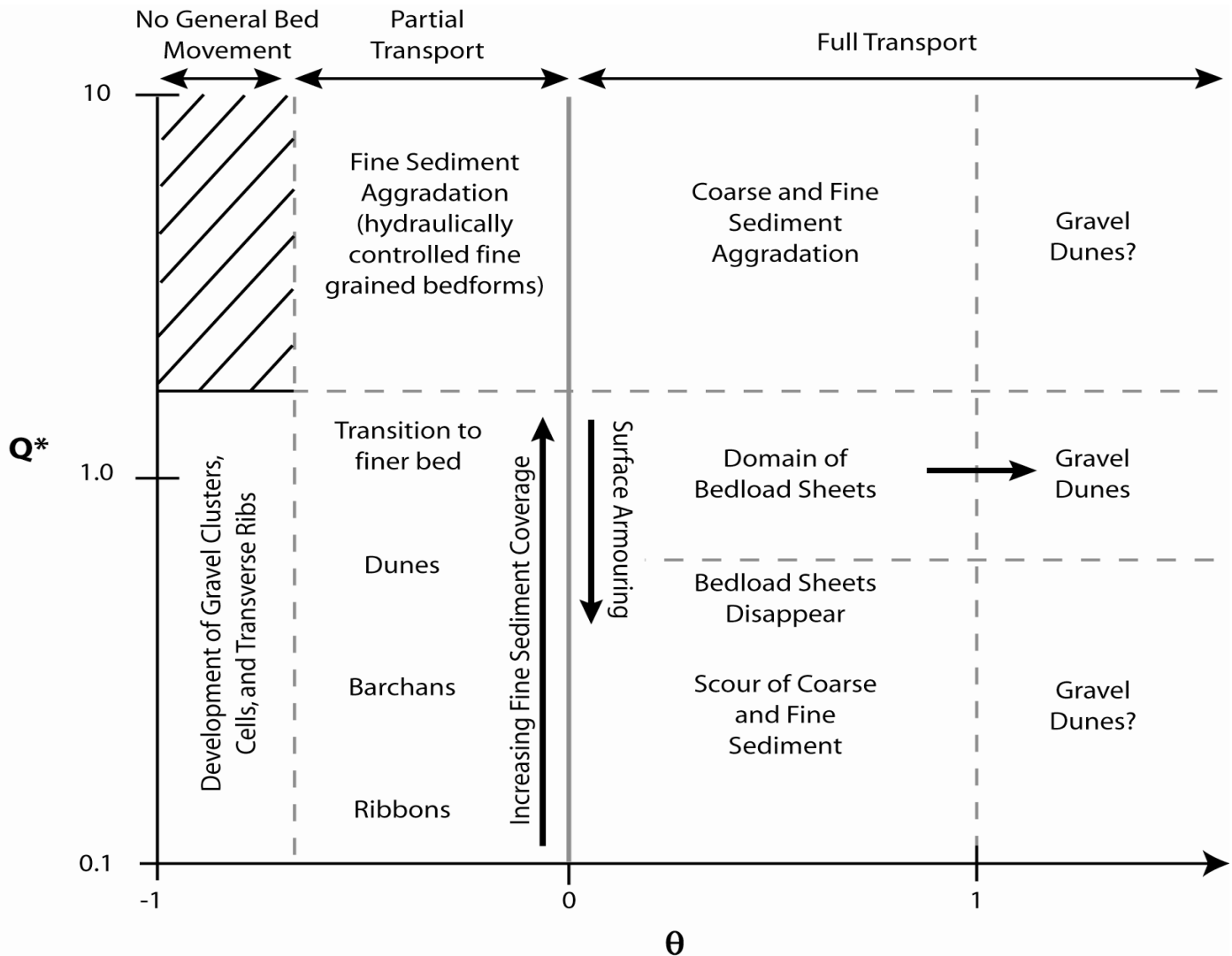


Figure 5. Proposed schematic of a bedform phase diagram for sediment supply-controlled bedforms formed in mixed-size sediment.

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