WATER RESOURCES RESEARCH, VOL. 34, NO. 11, PAGES 3169–3179, NOVEMBER 1998

Stabilizing self-organized structures in gravel-bed stream channels: Field and experimental observations

Michael Church and Marwan A. Hassan[1]
Department of Geography, University of British Columbia, Vancouver, Canada

John F. Wolcott
Health Sciences Administration, University of Southern California, Los Angeles

Abstract. Stable reticulate structures, which we call "stone cells," have been observed in cobble-gravel channel beds with low bed material transport rates. Experiments show that such structures develop simultaneously with the armor layer during an extended period when flows do not exceed the Shields threshold by more than ~2 times, so that bed material transport is low. They are constructed by particles moving from less stable positions into more stable configurations against each other. Intermediate developments include clusters and stone lines. They reduce sediment transport by orders of magnitude and are evidently a major stability-promoting mechanism in gravel channels. The timescale for their development suggests that the boundaries of many gravel-bed channels are not in equilibrium with recent competent flows but reflect the history of recent "dominant" flows.

1. Introduction

Most alluvial stream channels change remarkably little over periods that can be as long as years or decades, even though they may be regularly subjected to sediment-transporting flows. Stream channels are stability-seeking entities. What we see is the product of a succession of changes; the morphology that persists is that which is most nearly stable in face of the usually imposed flows. Stability is gained when stream energy can be dissipated without the accomplishment of significant channel-deforming work, even though sediment transfer, including the exchange of sediment at the channel boundaries, may still occur. Energy-dissipating structures develop at all morphological scales within the channel, including the scales of channel pattern, pool and riffle, and sedimentary bed forms. However, the most basic level at which stability develops in gravel-bed channels is that of the granular boundary materials, the potentially mobile sediments themselves.

Grains are entrained in stream channels when the force of water acting on the alluvial bed material overcomes particle inertia. *Shields* [1936] expressed the force balance at entrainment as a "mobility number," a function of the ratio of fluid shear stress exerted on the bed to (submerged) particle weight. Subsequent investigators have considered the sheltering effect of large particles [*Einstein*, 1950], particle protrusion [*Fenton and Abbott*, 1977], the pivot moment to move a particle past its downstream neighbor [*Komar and Li*, 1988], and the effects of particle size grading [*Wilcock and Southard*, 1989] and particle shape [*Gomez*, 1993]. None of these factors eliminate the fundamental effect of particle weight. However, when particles become interlocked, the relative effect of particle weight becomes comparatively less dominant.

[1]Now at Department of Geography, Hebrew University of Jerusalem, Jerusalem, Israel.

Paper number 98WR00484.
0043-1397/98/98WR-00484$09.00

Shields [1936] estimated the threshold mobility number for particle motion as 0.06 on the basis of experiments using narrowly graded material, but subsequent experimental work and field studies have indicated a range of values varying from 0.01 for fully exposed grains [*Fenton and Abbott*, 1977] to more than 0.1 for some natural streambeds [*Church*, 1978; *Reid et al.*, 1985]. This wide variation has mainly been ascribed to the effects of variable exposure in mixtures of particles and to particle imbrication and interlocking [*Laronne and Carson*, 1976], but it has been observed that identifiable grain clusters may also influence conditions at entrainment [*Brayshaw et al.*, 1983].

In gravel-bed streams with low rates of bed material transport, we have observed much more complex grain structures, which we call stone cells [cf. *Gustavson*, 1974]. The purpose of this paper is to describe these features, to obtain some phenomenological understanding of the conditions under which they develop and persist, and to explore their influence on the promotion of streambed stability.

2. Field Observations

Figure 1 illustrates the pattern of bed material in Harris Creek, British Columbia, a cobble-gravel channel in the southern interior of British Columbia with a channel width of order 10 m and a snowmelt-dominated hydrological regime with mean annual flood 19 $m^3 s^{-1}$. The larger exposed grains form irregular reticulate networks within which finer material persists. Stones which form the evident cell-like structures are mainly larger than D_{84} (128 mm) (D represents bed material grain size), and the usually incomplete features have characteristic spacing of order 1 m, so the ratio of structure diameter to constituent clast diameter is of order 10:1. Visualizing the structures successively as linear features and as stone-bound circles, this ratio implies that the constituent stones occupy between 15 and 25% of the bed, which occupies the range of fractional areas ($0.12 < a < 0.25$, approximately) indicated from an analysis of experimental results by *Rouse* [1965; see

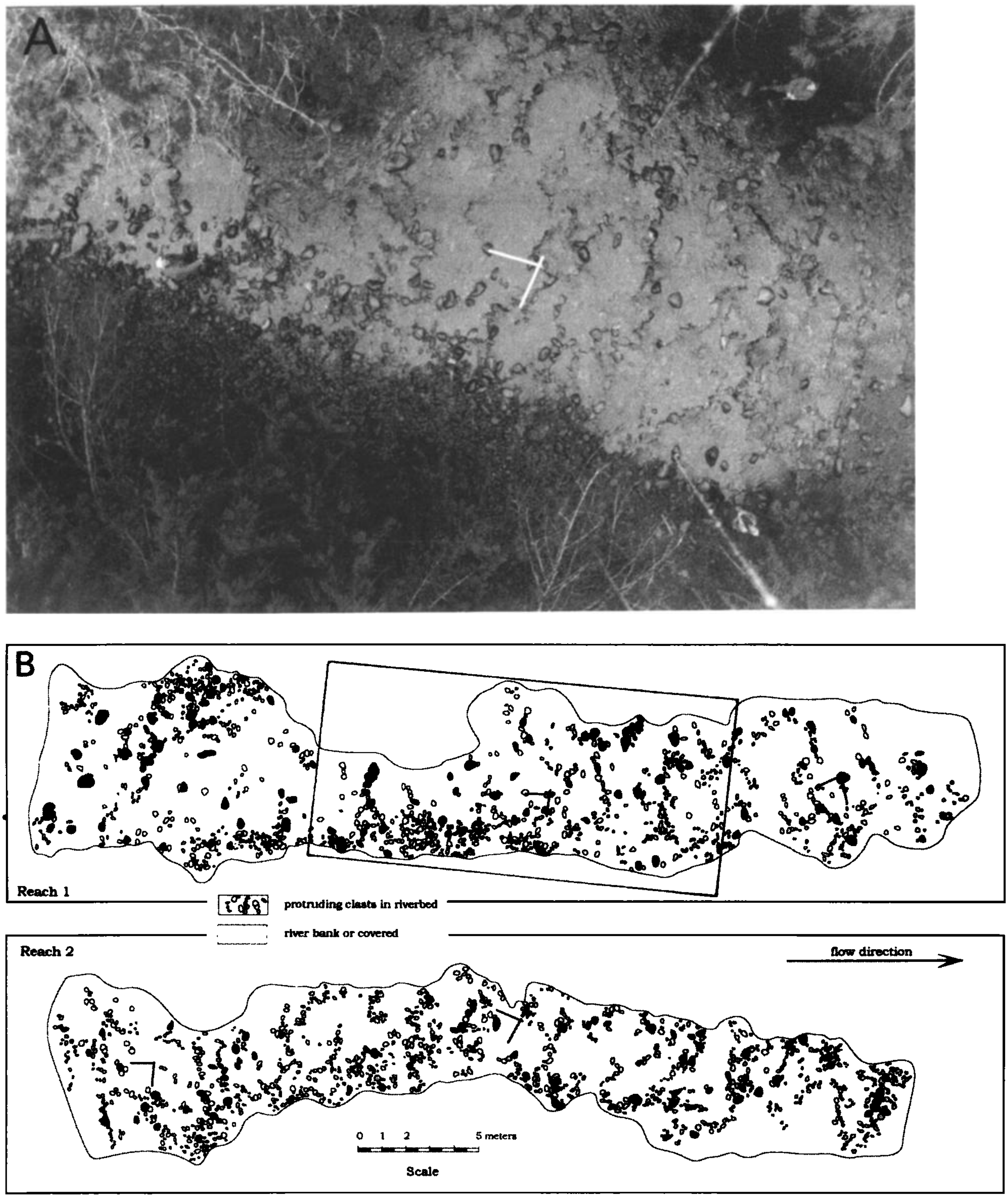

Figure 1. (a) Vertical air photograph of Harris Creek, a cobble-gravel channel near Vernon, British Columbia, with mean annual flood 19 m^3 s^{-1}. The photographs were made by suspending a radio-controlled camera in a gimbal mount below helium-filled balloons ~30 m above the surface. The rig was positioned along the channel by a "tripod" of kevlar lines (visible in the photograph). The scale bars are 1.2 m long. At low stage the cellular pattern of the dominant bed cobbles is clearly visible. (b) Map of stones which stand proud of the general surface level in the Harris Creek study reach. The map was constructed by tracing from stereo air photographs like that shown in Figure 1a, the position of which is outlined by the box. The solid black stones are those >260 mm in projected major axis diameter (this unusual definition was required by the automatic locating algorithm employed) and correspond approximately with the D_{99} of the riffle surface clasts in the stream. The generally reticulate but incomplete and irregular appearance of the stone cells is evident on this map (the map was constructed by S. Tribe).

also *Laronne and Carson*, 1976], to contribute most of the boundary frictional resistance to flow.

The features in Harris Creek tend to be transversely oriented, the principal structural element being arcuate ridges (see Figure 1b), either upstream or downstream facing. Characteristic axial ratios of the features are ~2:1. Elements of these structures have been described previously, including imbrication [*Johnston*, 1922], which is a pervasive feature of the streambed; compact clusters of stones [*Dal Cin*, 1968; *Brayshaw*, 1984]; and stone lines [*Laronne and Carson*, 1976] or transverse ribs [*Gustavson*, 1974; *Martini*, 1977; *Koster*, 1978]. Successive abstractions of progressively larger stones from the total pattern indicate that the pattern consists of arrangements of large stones formed around a random distribution of the very largest stones, consisting of stones of rank D_{99} and larger (Figure 1b). The latter, least mobile subset appears to form the stable "seed" population for the entire pattern. Cell-like structures have been observed casually in other streams and have been reported before [e.g., *McDonald and Banerjee*, 1971; *Gustavson*, 1974; *Bluck*, 1987; *Tait and Willetts*, 1992a] but have not been investigated systematically and may even be difficult for the untrained eye to recognize.

3. Experimental Arrangements

Since cellular structures are known to have great strength against shear forces, we conducted experiments to see how the structures develop and to determine the effect of the structures upon bed stability. Analyses of trapped bed load and of the surface texture of the bed provided complementary views of the evolution of the bed. Both indicate that the reluctance of the bed material to be entrained is a function of the architecture of the surface material as well as a function of grain size; the former supercedes the latter as structure develops.

Exploratory experiments in a 6 m × 0.5 m recirculating flume [*Wolcott*, 1990] were approximately scaled to field conditions in Harris Creek, and the main runs were carried out in a 10 m × 0.8 m flume with geometric scale ratios 1:16 or 1:10. The bed material was also scaled except that material scaled to finer than 180 μm was excluded. This preserved the entire gravel distribution, with maximum size 512 mm (scaled to 32 mm). The model was "generic" rather than specific in that no attempt was made to reproduce the geometrical details of the prototype channel. In fact, the Froude number within the main flow in Harris Creek varies between ~0.45 at a discharge of 7 m^3 s^{-1} when the gravel component of the bed first starts to move, and 0.60 at 25 m^3 s^{-1} when the bed becomes fully mobile. In our experiments, Froude numbers exceeded 1.0 at the highest flows (when full bed mobilization occurred in the flume). The difference relates to the lack of major channel form resistance in the model and means that the flume was not an exact model of the prototype. Nonetheless, the phenomena associated with bed mobility were recreated.

The bed was fixed in the first 0.5 m of the flume and consisted of a ~7-cm depth of potentially mobile material in the rest of the flume. Because the purpose was to study the evolution of bed stability, there was no sediment feed. Material evacuated from the flume was trapped. In a series of runs in the 6-m flume, flow depth was increased in steps to produce integer multiples of Shields number between 0.01 and 0.08. In the 10-m flume most runs had Shields number τ_* based on D_{50} of the bed surface material between 0.06 and 0.08, that is, moderately above the nominal threshold for motion of the widely graded sediment, given as 0.045 by *Wilcock and Southard* [1988] and *Komar and Li* [1988] (compare 0.047 of *Meyer-Peter and Muller* [1948]). In these runs the average value of the ratio τ_*/τ_{*c} was 1.75 ± 0.09. In an individual run, flow was maintained for up to 104 hours. Most of the 10-m flume runs were repeated (see Table 1 for details) to study the replicability of our experiments (see Figure 2a).

Before each experimental run, the bed was reconstituted by replacing the material that was transported out of the flume in the previous run and trapped and by thoroughly hand mixing the entire bed, followed by screeding it flat. In the 6-m flume runs, this bed was then sampled to determine the surface grain size distribution by pressing onto it a 0.1-m^2 plate coated with soft potter's clay, and the bed was then remixed. Within sampling error these samples were similar to the bulk mixture (but it is difficult to maintain fine material on the surface in the dry state), so this procedure was abandoned for the 10-m runs. Water was initially added slowly in order to expel all the air from the bed. In some runs, the flow was periodically stopped to allow the bed surface to be sampled using either the plate described above or, in the 10-m flume, a 15-cm-diameter piston coated with clay. In the latter case, six impressions were taken to aggregate a sampled area of 0.1 m^2 (as recommended by *Fripp and Diplas* [1993]). This procedure provides sufficient material to assure a representative surface sample, provided that segregation effects due to the development of structures are not unusual. Sometimes, replicate samples were taken in order to provide insurance against any such effects. Velocity profiles and photographs of the streambed were made at a fixed position about three-fifths of the way down the flume.

Griffiths and Sutherland [1977] have pointed out that in experiments lacking sediment feed the measured transport must vary downstream so long as material is contributed from the bed. The fixed measurement position in our experiments yields internally consistent results. However, it should be recognized that the time rate of evolution of the bed and of the sediment transport will vary down the flume according to the upstream area contributing to the transport.

We later conducted runs with sediment feed in order to obtain comparative results, but they are not reported here. Summary data of our experiments are given in Table 2. At the lowest flows in the University of British Columbia (UBC) 6-m flume, grain Reynolds number was below the usually accepted threshold for fully rough turbulent conditions, and the Weber numbers indicate that surface tension effects may have been significant, but sediment transport was not obviously anomalous.

4. Experimental Observations

During the passage of the wetting front during the entry of water into the flume, fine material (<1.4 mm) was observed to move downward into the bed. During the first hour of a run, fine material was removed from the surface, and a well-developed layer of fines could be observed (through the flume sidewall) just below the surface. After that the transport rate became very low (Figure 2a), with only a small number of grains visibly moving at any time. The texture of the surface material initially became finer than the bulk sediment texture as fines were evacuated from upstream, and then the texture of the surface material returned to near original values or coarsened (Figure 2b). After ~24 hours there was very little further change in the surface material texture. Similar observations

Table 1. Data of UBC Experiments

Run[c]	R_b, m	$S \times 10^3$	D_{50sfc}, mm	D_{50tr}, mm	τ_{*sfc}	τ_{*tr}	D_{50sfc}/D_{50tr} Observed	D_{50sfc}/D_{50tr} Expected
				UBC 6-m Flume[a]				
3-1	0.0049	1.0	2.63[b]	0.45	0.0014[b]	0.0067	5.84[b]	
3-2	0.0097	1.0	2.63[b]	0.37	0.0028[b]	0.016	7.11[b]	
3-4	0.034	1.0	2.63[b]	4.11	0.0084[b]	0.0059	0.64[b]	
3-5	0.069	1.7	2.63[b]	1.25	0.033[b]	0.066	2.10[b]	
4-1	0.0050	10	2.63[b]	0.40	0.014[b]	0.076	6.58[b]	
4-2	0.0099	10	2.63[b]	0.54	0.0028[b]	0.112	4.87[b]	
4-3	0.020	10	2.63[b]	1.17	0.056[b]	0.104	2.25[b]	
4-4	0.029	10	2.63[b]	1.15	0.084[b]	0.158	2.29[b]	
				UBC 10-m Flume				
I/3-1[c]	0.043	10	3.97	1.32	0.066	0.197	3.00	4.40
4-1[c]	0.050	10	3.92	1.02	0.077	0.297	3.84	6.62
5-1[c]	0.036	10	3.02	0.85	0.072	0.255	1.63	5.68
6-1[c]	0.061	10	4.70	1.31	0.078	0.281	3.59	6.25
7-1[c]	0.074	10	4.12	1.67	0.109	0.269	2.47	5.98
II/8-1[c]	0.040	11.5	4.17	0.97	0.068	0.290	4.30	6.46
9-1[c]	0.048	11.5	4.22	1.12	0.080	0.300	3.77	6.68
10-1[c]	0.053	10.4	5.12	1.52	0.065	0.220	3.37	4.90
11-1[c]	0.060	10.5	4.75	1.38	0.081	0.279	3.44	6.20
12-1	0.068	10	5.51	2.98	0.075	0.139	1.85	3.10
13-1	0.029	11.3	3.20	1.02	0.062	0.194	3.14	4.32
H/3-1	0.035	10.5	1.90	0.75	0.117	0.297	2.53	6.62
3-2	0.053	8.1	3.36	1.10	0.077	0.237	3.05	5.27
1	0.066	8.0	4.20	1.20	0.076	0.267	3.50	5.94

UBC, University of British Columbia.

[a]The reported slope is bed slope, and depth and velocity distribution tests were conducted to assure that the flow was uniform.

[b]Indicates the data of the 6-m experiments that are estimated. In these experiments a first series of runs was conducted to study the surface coarsening phenomenon. Bed surface samples were taken, but transported sediments were not trapped or measured. Series 3 and 4 were designed to replicate series 1 except that transported sediment was monitored, but no bed surface samples were taken in order to avoid disturbing the surface during the runs (all the runs in a series were sequentially accomplished by step increases of depth). Hence it was necessary to project the surface coarsening observed in series 1 onto the results of the later series. The shear stresses remained very low throughout these experiments, so surface modification was slight. Surface coarsening in series 1 never exceeded an 11% increase in D_{50}. A complication in comparing the runs is that a coarser sediment was used in the earlier runs (D_{50} = 3.44 mm), but the shear stresses were also higher. Recognizing these circumstances, it was estimated that surface textural coarsening over the bulk sediment in the later runs should be ~10% in the D_{50}. Accordingly, a surface D_{50} of 2.63 mm was assigned to all observations. The estimates are reported because they extend the results to very low transport rates.

[c]Indicates that the run was replicated (10-m flume). Experiment 10-1 was repeated twice (see Figure 2a).

have been reported by *Tait and Willetts* [1992b] and, in somewhat similar experimental circumstances, by *Hassan and Reid* [1990]. Declining sediment transport in previous experiments has been ascribed to continued degradation of the bed and coarsening of the surface [e.g., *Gessler*, 1970]. In our experiments, total degradation varied between 2 and 13 mm, i.e., between $0.6D_{50}$ and $4D_{50}$ of the bed material, and never appreciably exceeded $1.0D_{84}$. Between 1 and 10% of the bed material charge of the flume was removed in a run; one half to three quarters of it was removed during the first hour. Transported material was always much finer than the bed, on average (Figure 2b), but it tended to coarsen slowly throughout a run, and all sizes were moved.

Within a series of runs, the initial surface proceeded to coarsen at the lowest imposed flows as fine material was winnowed away or sifted into voids between the larger particles [cf. *Beschta and Jackson*, 1979], but very little additional coarsening occurred at higher flows. Larger particles typically rolled into contact with a static particle of similar size and stopped. This process resulted in cluster development. The clusters grew into particle lines, which linked up to form the reticulate structure illustrated in Figure 3. We were dependably able to replicate the development of this structure in different runs. Characteristic dimensions of the stone cells are $\sim 10D_{84}$ (longitudinal) $\times$ $6.5D_{84}$ (lateral), quite similar to the observations reported by *Tait and Willetts* [1992a] but somewhat more elongate than the geometry at Harris Creek. At their fullest development the stones forming the reticulate structures occupied of order 20% of the bed surface, and the smallest stones regularly found in the structures were ~9 mm in diameter, corresponding with the D_{75}–D_{84} size of the developed bed surface (see Figure 2b), as in Harris Creek.

Finally, when at the end of some runs the shear stress was increased beyond ~2 times that nominally necessary for entrainment, the surface layer was completely mobilized. The developing surface structure was thereby destroyed, surface grain size declined, sediment transport increased, and incipient bed forms appeared. In several cases this increased flow took the form of a "flood pulse" of ~15 min duration, after which flow was returned to its former level. Phenomena included the incision of a talweg and bar formation; surface fining as the structure was destroyed, followed by the reestablishment of the coarse surface when flow was reduced; and a dramatic increase in sediment transport during the flood. These phenomena were not pursued systematically.

In later experiments we fed sediment with the same size distribution as that in the bulk bed material. We observed that the structural development varied with the sediment feed rate, becoming less complete as sediment transport increased. This seems reasonable, since to sustain higher rates of transport requires more frequent exchanges between the mobile sediment and the bed. If all sizes take part in the transport, this will include the larger, structure-forming clasts. This picture is consistent with the appearance that in a flume (or river reach) with sediment feed, the transport process and the surface adjust to transport material in proportion to the feed rate [see *Dietrich et al.*, 1989; *Parker and Wilcock*, 1993], and it is consistent with the concept of partial transport [*Wilcock and McArdell*, 1997] at moderate transport rates. We have not detected any systematic variation in the structure dimensions in our experiments, but we expect that our procedures may not be sufficiently sensitive to provide a critical test of that possibility. Our analysis of the sediment feed experiments will be reported elsewhere.

5. Analysis

It has been established that a Shields number calculation using D_{50} of bed surface material reliably determines the force ratio at the bed producing sediment transport [*Parker and Klingeman*, 1982; *Wilcock and McArdell*, 1993]. *Dietrich et al.* [1989] took advantage of this fact to estimate the degree to which bed surface armoring should reduce sediment transport. They formed the ratio of transport rate for the armored surface compared with the transport rate estimated for a surface as fine as the load:

$$q_* = [(\tau_b - \tau_{cs})/(\tau_b - \tau_{ct})]^{1.5} \tag{1}$$

in which q_* is the dimensionless sediment transport (the transport ratio); τ_b is the shear stress imposed on the bed; τ_{cs} is the critical shear stress for the surface material, which is supposed to be proportional to the D_{50} size of the surface material; and τ_{ct} is the indicated critical shear stress that would be associated with the transported load. This formulation assumes that the transport function is of the form $f(\tau_b - \tau_c)^{1.5}$ (as does, for example, the well-known formula of *Meyer-Peter and Muller* [1948]), which seems reasonable for gravel. We estimated τ_c as $0.045g(\rho_s - \rho)D_{50}$, in which the value of D_{50} appropriate for the calculation is used. At the end of our experiments, the bed material transport rate q_b was typically of the order 0.1 kg h^{-1}. In comparison with $q_{b|t=1}$, the value after 1 hour, which we take to be a reasonable estimate of the transport over an undeveloped surface, $q_* = q_{b|t=100}/q_{b|t=1}$ is of order 0.001 (Figure 2a). Using this value, (1) yields the approximate equality $D_{50s}/D_{50t} \approx (\tau_b/\tau_{ct})$, from which we may obtain an expected ratio of surface to transported grain sizes. Over the 14 experimental runs in the 10-m flume, we obtain an expected mean value of $D_{50s}/D_{50t} = 5.60 \pm 0.29$ (the second number is the standard error). The observed value of this ratio was 3.11 ± 0.20. The difference between these two results is the direct consequence of the surface structure. Conversely, (1) predicts values of q_* in the range $0.21 \leq q_* \leq 0.62$, more than 2 orders of magnitude larger than the observed results.

Further consideration of (1) yields quantitative insight into the effect of bed structure on the entrainment threshold. Inspection of (1) shows that q_* approaches zero within a reasonable range of τ_* only when τ_{*cs} increases, so that the numerator approaches zero. For $D_{50s} = 4.2$ mm, $D_{50t} = 1.35$ mm, and $\tau_b = 5.1$ Pa (all values being close to the means recorded in our 10-m flume runs), the upper limit of τ_{*cs} for nonzero sediment transport is 0.075. The mean-indicated value of τ_{*cs} in the same runs (using the observed values of D_{50s}) was 0.079 ± 0.005. At $\tau_{*cs} = 0.060$, $q_* = 0.12$. The function becomes very sensitive above that value. It appears, then, that

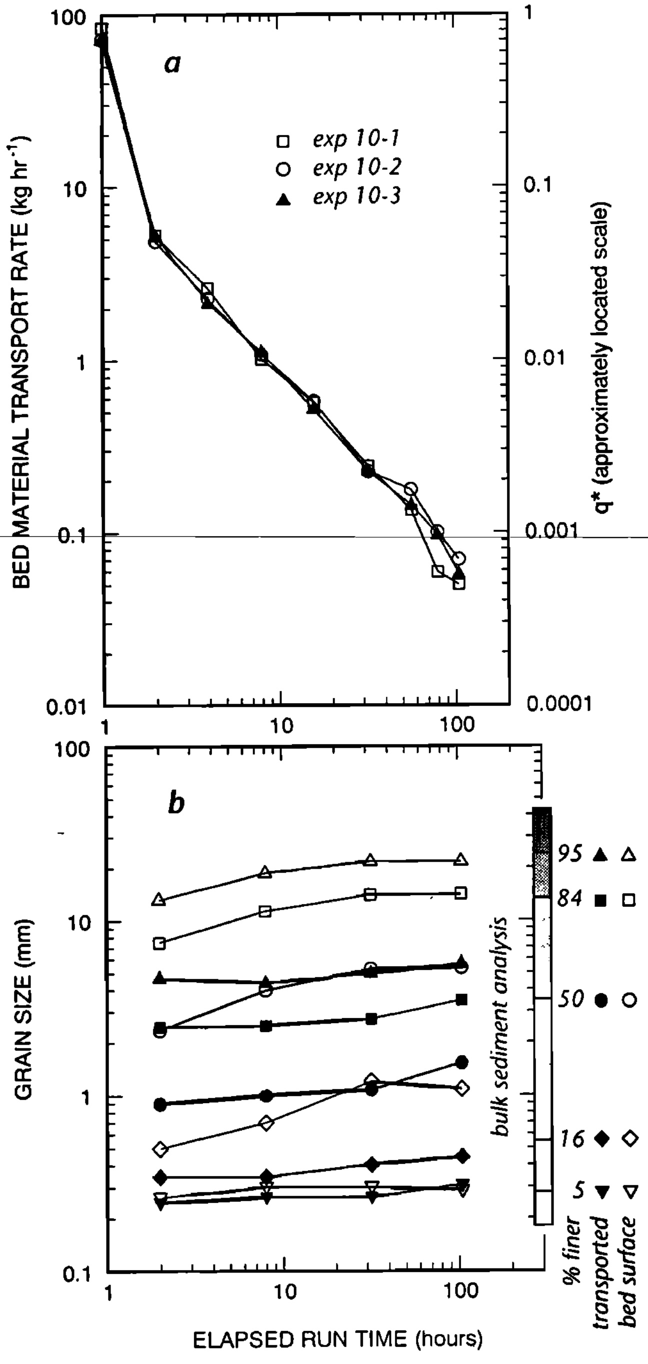

Figure 2. (a) Sediment transport at the end of the flume during three replicate runs. The similarity indicates that the results may be duplicated except that, late in the experiment, the vagaries of structure development influence the residual transport. The scale on the right-hand ordinate is approximately located. The definition of q_* is given by equation (1). (b) Evolution of bed surface and transported sediment texture over time, experiment 10-2. The bar graph on the right-hand ordinate indicates the size distribution of the initial bulk sediment placed in the flume, and the symbols code the corresponding proportions for the bed surface and the transported sediment trapped at the end of the flume.

Table 2. Range of Conditions Within Each Series of Experiments and Some Other Experiments Used in Our Analysis

Series	Key Grain Sizes of Bulk Sediment			Grain Reynolds Number		Froude Number		Weber Number[a]	
	D_{50}	D_{84}	Tr[b]	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
				UBC Experiments					
6 m	2.39	3.90	11.8	153	13.9	0.98	0.25	190	0.33
10 m/I	2.20	8.10	16.2	530	311	1.2	0.65	1000	27
10 m/II	3.20	14.5	29.0	908	640	1.2	0.88	920	63
10 m/H	1.41	7.9	20.8	302	114	1.31	1.18	711	276
				Lamberti and Paris [1992]					
I	2.69	5.27	3.63	316	311	0.74	0.47	210	110
II	3.68	7.73	7.73	456	433	1.1	0.42	1400	390
III	2.36	6.54	5.95	386	353	1.0	0.46	1200	160
				Gomez [1993]					
Round	6.33	16.1	5.34	1733[c]	528[c]	0.77	0.63	2414[c]	957[c]
Flat	10.7	19.6	4.22	1417[c]	811[c]	0.89	0.73	2262[c]	1308[c]
Angular	7.61	14.7	4.43	1663[c]	793[c]	0.75	0.66	2373[c]	1225[c]

UBC, University of British Columbia.

[a]The Weber number is $\rho R v^2/\sigma$, in which ρ is the density of the fluid, v is the hydraulic radius, v is the mean velocity, and σ is the surface tension of water. It indicates the ratio of gravitational to surface forces and indicates the possibility for surface tension effects to be significant.

[b]$Tr = D_{84}/D_{16}$, which is different than the conventional definition.

[c]Data are estimated (water temperature is estimated as 15°C).

an increase of τ_{*cs} by ~67% above the nominal threshold for widely graded mixtures and by ~30% above the classical Shields datum covers a surface structural effect sufficient to reduce the transport of sediment derived from the bed in the same vicinity to near zero. A. C. Brayshaw [*Naden and Brayshaw*, 1987] has previously reported a 12% increase in shear stress necessary to entrain clasts from clusters in comparison with that necessary to entrain material from the open bed. This sensitivity has probably militated against the casual observation of complex structural effects in previous works.

Some investigators have noted that a decline in the bed sediment transport rate is associated with increasing resistance to flow associated with increasing bed roughness. *Hassan and Reid* [1990] demonstrated the effect by systematically increasing the density of stable cluster bed forms in experimental flume runs. They supposed that minimum transport would be associated with the onset of skimming flow, when substantially all of the fluid stress is borne by the stable structures [*Morris*, 1955] (further references given by *Hassan and Reid* [1990]). The question arises whether stone cells represent this "optimally stable" condition, as is suggested by spacing criteria in both the field and the flume.

We studied resistance to flow and roughness length by making measurements of the velocity profile at five positions in a cross pattern within our observing reach. The difficulty in making such measurements yields relatively poor estimations of these quantities [*Wilcock*, 1996]. Nonetheless, Figure 4 suggests that the roughness length k_s increases in our experiments by as much as an order of magnitude, although apparently by a lesser amount at the highest flow tested. Roughness length k_s is a conceptual length commonly supposed to be a small multiple of bed surface D_{50} or D_{84}. In the experiments illustrated, D_{84} was 8 mm, so k_s, so far as it is determined by grain roughness, ought to be in the range 0.016–0.032 m (i.e., for $2D_{84} < k_s < 4D_{84}$, which encompasses the range of commonly quoted results) and could not appreciably exceed 0.10, even if the surface coarsened to the point that it consisted only of the uppermost few percentiles of bed material (in the range 22–32 mm). In fact, the lowest observed value is ~0.1, and values increase to order 1.0. The range is far greater than that which could be accounted for by textural coarsening of the surface, and this range leads to roughness length estimates an order of magnitude greater than the grain sizes could support. Evidently, structural effects are significant. Total flow resistance, as indexed by Manning's n, behaves similarly, although these results are not conclusive because of the high variance associated with our measurements. Most of the change in n occurs in the first 24 hours while surface coarsening occurs, the main elements of the surface structure develop, and sediment transport declines most dramatically. *Whiting and Dietrich* [1990] concluded that the larger clasts on the surface constitute the most significant source of flow resistance in gravel-bed channels. However, *Gessler* [1990], following a careful analysis of experimental results on armored beds, claimed that the friction factor is indeed related to the arrangement of the coarser grains. The conditions at the end of our experiments present approximately the same situation as that analyzed by Gessler, and our roughness length estimates confirm his conclusion.

6. Discussion

The stability of the gravel bed is enhanced by two mechanisms. Textural coarsening of the surface, seen in the initial stage of our experiments when sediment transport was still substantial, has been widely remarked [e.g., *Parker and Klingeman*, 1982; *Dietrich et al.*, 1989; *Wilcock and Southard*, 1989; *Tait et al.*, 1992]. The bed derives stability from the relatively great inertia of the exposed surface material. Such vertical sorting has variously been described as "armor," "pavement," or simply as surface coarsening [*Harrison*, 1950; *Parker and Klingeman*, 1982; *Sutherland*, 1987]. *Gessler* [1970] expected that the bed would continue to coarsen until sediment transport fell to zero. The conventional Shields approach to bed stability encompasses only this aspect of bed character, which is indexed satisfactorily by texture.

Our results indicate that structural modification of the bed surface plays an important role. The implications of bed struc-

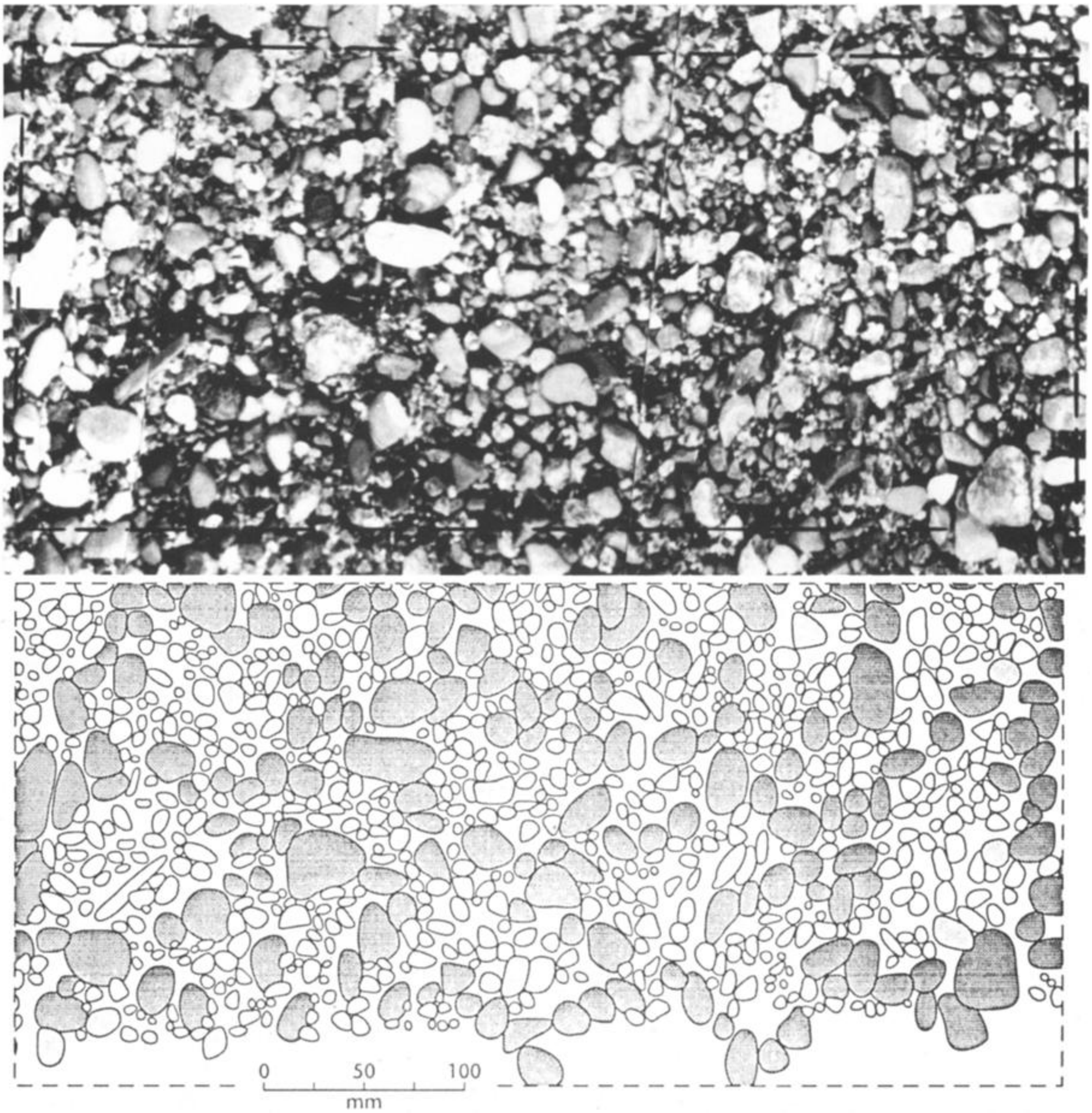

Figure 3. Pattern of large stones on the bed surface after the experimental flume run 10-3; the vertical photograph and drawing are to the same scale. The darkly shaded stones are those larger than D_{84} (12 mm) and the smaller stones in interlocked contact with them that form the reticulate structure of the bed surface. Different analysts operating independently identify the same structural pattern from the photographs.

ture for bed stability have been considered only qualitatively, except insofar as pivot angle analysis [*Wiberg and Smith*, 1987; *Komar and Li*, 1988], the analysis of friction angles [*Kirchner et al.*, 1990; *Buffington et al.*, 1992], and the stability of cluster bed forms [*Brayshaw et al.*, 1983; *Brayshaw*, 1985] approach the problem. The development of persistent structures on the bed surface, in fact, appears to limit the textural modification of the bed, since transport rates become much smaller than the change in surface grain size indicates it should. The key effect is substantial further reduction in the mobility of the larger stones, which then effectively hide smaller material. A self-organized reticulate web, as described in this study, appears to be the stable end point of structural development. Advanced stages of development are reached in channels with sufficiently wide grading of the bed material (see Figures 1 and 3) after an extended period of low to negligible sediment influx, such as is characteristic of the nival flow regime of Harris Creek and as is replicated in our flume.

A careful reading of *Shields'* [1936] report suggests that he controlled the effect of surface structure by creating a uniform particle arrangement prior to taking each set of measurements. He achieved this by using narrowly graded materials and by following the same starting procedure for each of his runs. If particle arrangement is held constant, bed strength is a reliable function of particle weight, as Shields discovered. If it is not, the development of an interlocked structure dominates the bed strength in mixed-size sediments.

The effect of the developing bed structure is quantified in Figure 5, which compares the critical Shields number based on the transported sediment with that expected for the surface bed material (data given in Table 1). Figure 5 includes results obtained by *Lamberti and Paris* [1992] and *Gomez* [1993] in

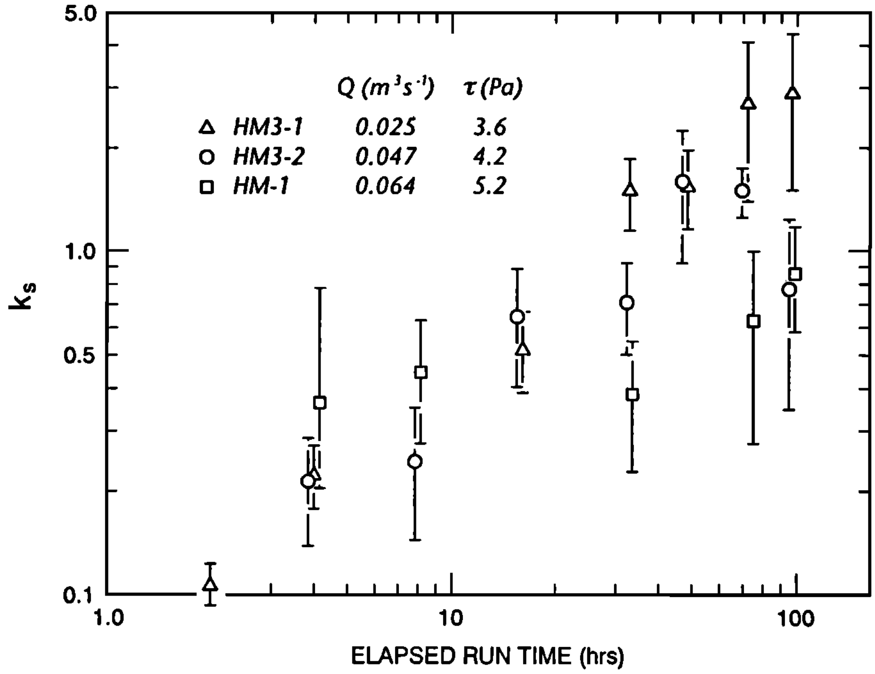

Figure 4. Evolution of k_s during relatively low, intermediate, and high flows, based on the average of four or five determinations from velocity profiles. The error bars represent two standard error ranges about the observations. It may be assumed that the observed changes depended on the evolution of the bed surface, since larger-scale form roughness was absent during these experiments. Estimates of flow and shear stress are the averages for the runs; minor variations occurred during the runs.

experiments conceptually similar to ours, conducted for the purpose of studying armor development (data given in Table 3). The effect is parameterized by a modest increase in Shields number. Eventually, however, the fluid shear may become so great that the surface configuration is destroyed and the difference between the two estimates of shear stress returns again to zero.

A range of material sizes is obviously necessary for recognizable structures to develop. Figure 5 suggests that when the modified sediment Trask coefficient D_{84}/D_{16} falls below 10 (compare our values with those of other investigators in Table 1), the difference between the two Shields numbers becomes more limited and so, correspondingly, does the structural modification of the bed. In their experiments, conducted mainly with only moderately graded material, neither *Lamberti and Paris* [1992] nor *Gomez* [1993] reported structural modifications other than armor development (but nor, probably, were they searching for any). There is also a hint that, based on Gomez's data, particle shape exercises a minor effect on the outcome.

Structural development occurs in the regime of partial transport of *Wilcock and McArdell* [1997] (Figure 6) because of the "keystone" role played by the mainly immobile largest stones. Early development occurs in the regime of "mobile armor" (all sizes in motion) because the largest stones are displaced, albeit relatively infrequently. However, late in the process, a stable armor in the sense of *Gomez* [1994] develops; bed load transport is reduced to a low rate and is systematically finer than the surface material. *Gomez* [1994, p. 2237] remarked that the development of stable armor entails "wholesale rearrangement of the surficial bed material," but he was no more specific. *Gessler* [1992] had previously considered pattern development in armor and reported statistical results of *Ahmed* [1989], which demonstrated that the grouping of the largest clasts becomes stronger with increasing stress, up to the point when the armor structure breaks down. These observations are consistent with ours.

Data of Figures 2 and 5 suggest the following qualitative model of gravel-bed surface response to increasing flows. If a widely graded surface initially has no structure, it will first coarsen by winnowing at flows with relatively low stresses and sediment supply. Fine material is transported away or sifted into voids just below the surface where it is sheltered from entrainment. The coarse grains move or settle into more stable individual positions and joint configurations on the surface (see *Tribe and Church*, this issue]. This process is self-limiting because the increasing bed stability limits further sediment transport. In our experiments this is exemplified by the asymptotic decline of sediment transport during an individual run, when the shear stress remains essentially constant.

Figure 1 suggests the time necessary to decrease the sediment transport by 1 or 2 orders of magnitude. Froude scaling of the flume provides a time ratio of 4 for a river 0.5 m deep; 100 hours in the flume is equivalent to 16 days in nature. Since flume conditions were steady within a run, whereas most rivers are not steady for 2 weeks at a time, it would appear that the beds of most small rivers are unlikely to be in dynamic equilibrium with flows over them during conditions of competent flow with low sediment influx. A similar conclusion has been reached with respect to primary bed form development on sand beds [*Allen*, 1973].

Since the degree of structural development depends on the history of recent flows, we may expect flow history to have a systematic but complex effect upon the history of bed material transport in natural rivers. This phenomenon has been observed by *Reid et al.* [1985]. They drew the conclusion, which our results emphasize [see also *Tait and Willetts*, 1992a], that simple functional relations between sediment transport and measures of stream power or tractive force, derived largely on the basis of equilibrium experimental studies (such as *Shields'* [1936] original experiments), are unlikely to cover the phenomena in nature. Natural streams exploit widely graded materials to create critically stable conditions at the bed, but the condition is not simply maintained because of the fluctuating flows. Most of the time, conditions are either subcritical, in the sense that the flow is insufficient to disturb the bed significantly, or the stresses applied by the flow create a transient situation in which the bed is adjusting toward a new critical state, so far as the accompanying sediment influx from upstream will allow it. One hopes that further study of the phenomena associated with the development of bed structures will reveal a satisfactorily expanded parameterization of the sediment transport problem.

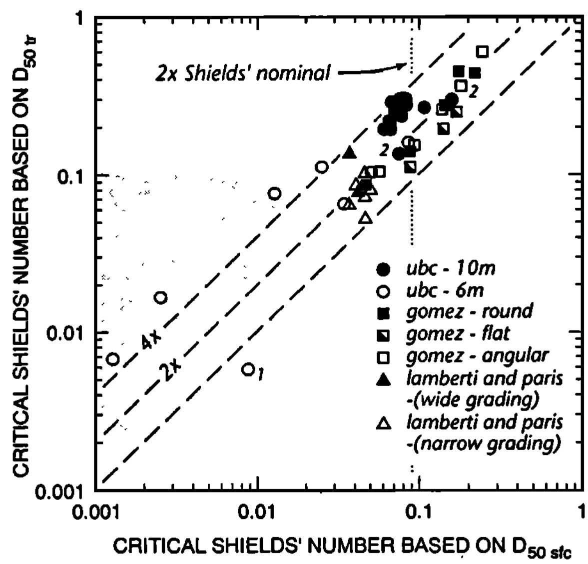

Figure 5. Shields number based on the bed surface material versus the ratio based on the transported sediment. The number is calculated as $\tau/g(\rho_s\text{-}\rho)D_{50}$, in which the shear stress τ is estimated by ρgRS, a uniform flow estimate which is appropriate in the present circumstances because it estimates an average value over an extended area of the bed; ρ_s is material density; ρ is the density of water; g is the acceleration of gravity; R is the hydraulic radius of the flow; and S is the energy gradient of the flow (the surface slope of the water in uniform flow). The stippled area encloses points with low grain Reynolds numbers. The point marked 1 had anomalously low transport of mainly larger material; points marked 2 were the high flows in which bed forms developed. The results of logistically similar experiments by *Lamberti and Paris* [1992] and *Gomez* [1993], with much narrower sediment grading, are shown for comparison (a summary of the experiments is given in Table 2, and data are given in Table 3). In the experiments of Lamberti and Paris, sediment transport was allowed to decline until it was a few percent of the initial value before flow conditions were changed; in Gomez's experiments, runs were ended when the transport was <1% of the initial value. However, results on τ_{*ct} may be slightly biased because the reported transport grain size is based on a composite sample of material transported during the entire experiment, not just on material trapped near the end of the run. Gomez replicated his runs 3 times; we have plotted the mean of each set.

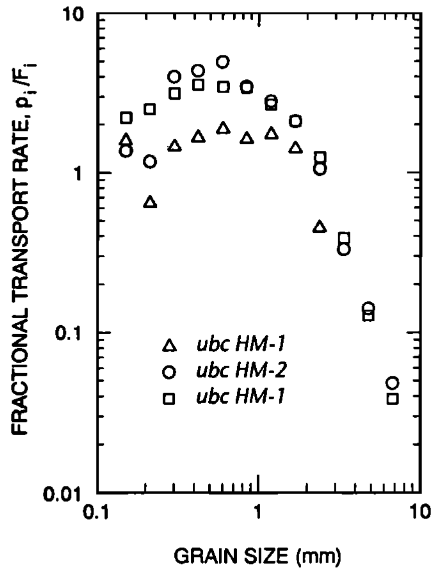

Figure 6. Fractional transport rate late in the experimental run as a function of grain size for the University of British Columbia (UBC) 10-m experiments with relatively low, intermediate, and high flow. The fraction of transported sediment in the ith size fraction is indicated by p_i; F_i indicates the fraction of bed surface material in the same fraction. The diagram shows that the largest material contributes very little to the transport, whereas most of the transported material is substantially smaller than D_{50} of the bed. These are the same runs as are illustrated in Figure 4.

7. Conclusions

In this paper we present observations of stable, reticulate stone cells developed on the bed surface in cobble-gravel streams with relatively widely graded sediments, and we give an experimental demonstration that these structures promote streambed (and therefore channel) stability by dramatically reducing the transport of bed material. The development of surface structure is a self-organized, critical phenomenon, the emergent product of stochastic encounters among individual grains.

The joint effect of armoring and structural development in our experiments increased the critical Shields number by ~2 times (above the accepted value of 0.045 for widely graded gravels), but a range of other observations indicates that larger changes may occur. Sediment transport is reduced by up to 10^3 times, in the partial transport regime of *Wilcock and McArdell* [1997]. Indeed, the development of persistent surface structures (including armor) appears to be the reason why most gravel-bed streams exhibit partial transport on most occasions when bed material moves at all. Some grains, although partially exposed on the surface, remain too well constrained by their neighbors to be entrained. As the proportion of streamflow energy expended in turbulent motion promoted by the streambed configuration approaches 100%, the friction factor also increases.

Since variable grain size is a prerequisite for recognizable structures to develop, the structural effect unsurprisingly appears to depend on particle grading. Characteristic particle

Table 3. Data of Other Experiments

Run	R_b, m	$S \times 10^3$	D_{50sfc}, mm	D_{50tr}, mm	τ_{*sfc}	τ_{*tr}	D_{50sfc}/D_{50tr} Observed
			Lamberti and Paris [1992]				
1-1	0.130	1.9	4.10	2.21	0.035	0.064	1.86
1-2	0.142	2.0	3.61	3.20	0.046	0.052	1.13
1-3	0.058	6.3	5.07	2.41	0.042	0.089	2.10
1-4	0.057[a]	5.0	3.78	2.26	0.044	0.074	1.67
2-7	0.057[a]	6.7	5.33	1.21	0.042	0.086	4.40
2-8	0.160	2.0	5.15	1.38	0.037	0.136	3.73
3-9	0.132	2.4	3.94	1.84	0.047	0.101	2.14
3-10	0.051	5.1	3.06	1.87	0.050	0.082	1.64
			Gomez [1993][b]				
1A	0.109	9.2	12.0	7.2	0.049	0.082	1.67
1B	0.106	10.3	12.9	5.9	0.050	0.109	2.19
1C	0.112	8.0	12.1	8.2	0.044	0.064	1.48
1D	0.124	15.8	13.3	9.7	0.087	0.119	1.37
1E	0.133	14.3	13.6	7.2	0.082	0.155	1.89
1F	0.140	15.2	13.6	8.9	0.092	0.141	1.53
1G	0.141	22.9	14.7	5.6	0.129	0.339	2.63
1H	0.151	24.3	13.7	9.0	0.158	0.240	1.52
1I	0.150	22.2	13.4	7.2	0.146	0.272	1.86
1J	0.153	30.7	14.8	6.3	0.187	0.439	2.35
1K	0.164	28.0	14.8	5.9	0.183	0.458	2.51
1L	0.161	24.8	14.5	5.2	0.162	0.452	2.79
1M	0.166	35.8	17.5	7.0	0.198	0.499	2.50
1N	0.170	31.1	15.2	7.7	0.205	0.404	1.97
1O	0.172	35.1	14.5	8.2	0.245	0.433	1.77
2D	0.125	13.9	10.0	9.3	0.102	0.110	1.08
2E	0.118	12.0	10.3	7.9	0.081	0.105	1.30
2F	0.124	12.1	11.1	8.2	0.080	0.108	1.35
2G	0.140	18.7	11.1	9.9	0.139	0.156	1.12
2H	0.138	21.0	12.1	7.4	0.141	0.230	1.64
2I	0.139	22.4	12.0	9.0	0.153	0.204	1.33
2J	0.147	26.2	12.2	8.4	0.186	0.270	1.45
2K	0.136	27.3	13.2	7.9	0.165	0.276	1.67
2L	0.140	24.6	13.2	8.3	0.153	0.244	1.59
3D	0.128	12.5	11.8	7.3	0.080	0.129	1.62
3E	0.134	15.0	11.6	7.2	0.100	0.164	1.61
3F	0.128	13.1	11.2	7.5	0.088	0.131	1.49
3G	0.148	22.8	12.5	6.8	0.159	0.292	1.84
3H	0.141	21.2	13.0	6.4	0.135	0.275	2.03
3I	0.139	23.3	13.8	6.9	0.138	0.276	2.00
3J	0.158	26.9	13.8	7.0	0.181	0.357	1.97
3K	0.162	29.3	14.3	6.4	0.195	0.436	2.23
3L	0.167	26.6	14.3	6.9	0.183	0.379	2.07
3M	0.169	39.3	16.8	7.5	0.233	0.521	2.24
3N	0.170	33.6	15.7	7.6	0.214	0.442	2.07
3O	0.178	37.1	14.5	7.2	0.268	0.540	2.01

[a]Data are estimated.
[b]The *Gomez* [1993] data are plotted in Figure 5 as averages of successive sets of three data.

shape also appears to have a minor influence. Critical Shields numbers based on the transported material increase above the critical number based on the bed surface by ~2 times for armored surfaces with cluster development and by as much as 4 times (see Figure 5) for highly structured surfaces. This is the basis for the high critical Shields numbers reported in some field studies and for a parameterization of the effect on sediment transport of the development of surface structures.

The timescale for the development of surface structures, which occurs at relatively low rates of sediment transport, is long in comparison with typical fluctuations in water discharge. A consequence is that most gravel-bed streams are probably not in equilibrium with imposed flows of typically limited competence.

Acknowledgments. The work reported in this paper was supported by the Natural Sciences and Engineering Research Council of Canada. Discussions with Rob Ferguson led to substantial improvements in the analysis, as did helpful reviews from Peter Wilcock and an anonymous reviewer.

References

Ahmed, M. M. E., Patterns in armor coats, Ph.D. thesis, 186 pp., Colo. State Univ., Fort Collins, 1989.

Allen, J. R. L., Phase differences between bed configuration and flow in natural environments, and their geological relevance, *Sedimentology*, *20*, 323–329, 1973.

Beschta, R. L., and W. L. Jackson, The intrusion of fine sediments into a stable gravel, *J. Fish. Res. Board Can.*, *36*, 204–210, 1979.

Bluck, B. J., Bed forms and clast size changes in gravel-bed rivers, in

River Channels: Environment and process, *Inst. Br. Geogr. Spec. Pub.*, vol. 17, edited by K. Richards, pp. 159–178, Blackwell, Cambridge, Mass., 1987.
Brayshaw, A. C., Characteristics and origin of cluster bedforms in coarse-grained alluvial channels, in *Sedimentology of Gravels and Conglomerates*, edited by E. H. Koster and R. J. Steel, *Mem. Can. Soc. Pet. Geol.*, *10*, 77–85, 1984.
Brayshaw, A. C., Bed microtopography and entrainment thresholds in gravel-bed rivers, *Geol. Soc. Am. Bull.*, *96*, 218–223, 1985.
Brayshaw, A. C., L. E. Frostick, and I. Reid, The hydrodynamics of particle clusters and sediment entrainment in coarse alluvial channels, *Sedimentology*, *30*, 137–143, 1983.
Buffington, J. M., W. E. Dietrich, and J. W. Kirchner, Friction angle measurements on a naturally formed gravel streambed: Implications for critical boundary shear stress, *Water Resour. Res.*, *28*, 411–425, 1992.
Church, M., Palaeohydrological reconstructions from a Holocene valley fill, in *Fluvial Sedimentology*, edited by A. D. Miall, *Mem. Can. Soc. Pet. Geol.*, *5*, 743–772, 1978.
Dal Cin, R., Pebble clusters: Their origin and utilization in the study of paleocurrents, *Sediment. Geol.*, *2*, 233–241, 1968.
Dietrich, W. E., J. F. Kirchner, H. Ikeda, and F. Iseya, Sediment supply and the development of the coarse surface layer in gravel-bedded rivers, *Nature*, *340*, 215–217, 1989.
Einstein, H. A., The bedload function for sediment transport in open channel flows, *Tech. Bull. U.S. Dep. Agric.*, *1026*, 78 pp., 1950.
Fenton, J., and J. E. Abbott, Initial movement of grains on a stream bed: The effect of relative protrusion, *Proc. R. Soc. London, Ser. A*, *352*, 523–537, 1977.
Fripp, J. B., and P. Diplas, Surface sampling in gravel streams, *J. Hydraul. Eng.*, *119*, 473–490, 1993.
Gessler, J., Self-stabilizing tendencies of alluvial channels, *J. Waterw. Harbors Coastal Eng. Div. Am. Soc. Civ. Eng.*, *96*, 235–249, 1970.
Gessler, J., Friction factor of armoured river beds, *J. Hydraul. Eng.*, *116*, 531–543, 1990.
Gessler, J., Armoring on the surface of gravel bed rivers revisited, in *Grain Sorting Seminar: Centro Stefano Franscini, Monte Verita, Ascona, Switzerland, October 21–26, 1991*, *Eidg. Tech. Hochsch. Zurich Vers. Wasserbau Hydrol. Glacial.*, *117*, 299–309, 1992.
Gomez, B., Roughness of stable, armoured gravel beds, *Water Resour. Res.*, *29*, 3631–3642, 1993.
Gomez, B., Effects of particle shape and mobility on stable armor development, *Water Resour. Res.*, *30*, 2229–2239, 1994.
Griffiths, G. A., and A. J. Sutherland, Bedload transport by translation waves, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, *103*, 1279–1291, 1977.
Gustavson, T. C., Sedimentation on gravel outwash fans, Malaspina glacier foreland, Alaska, *J. Sediment. Petrol.*, *44*, 374–389, 1974.
Harrison, A. S., Report on special investigation of bed sediment segregation in a degrading bed, *Rep. 33(1)*, 205 pp., Inst. of Eng. Res., Univ. of Calif., Berkeley, 1950.
Hassan, M. A., and I. Reid, The influence of microform bed roughness elements on flow and sediment transport in gravel bed rivers, *Earth Surf. Processes Landforms*, *15*, 739–750, 1990.
Johnston, W. A., Imbricated structure in river-gravels, *Am. J. Sci.*, *Ser. 5*, *2*, 387–390, 1922.
Kirchner, J. W., W. E. Dietrich, F. Iseya, and H. Ikeda, The variability of critical shear stress, friction angle, and grain protrusion in water-worked sediments, *Sedimentology*, *37*, 647–672, 1990.
Komar, P. D., and Z. Li, Application of grain-pivoting and sliding analyses to selective entrainment of gravel and to flow-competence evaluations, *Sedimentology*, *35*, 681–695, 1988.
Koster, E. H., Transverse ribs: Their characteristic origin and paleohydraulic significance, in *Fluvial Sedimentology*, edited by A. D. Miall, *Mem. Can. Soc. Pet. Geol.*, *5*, 161–186, 1978.
Lamberti, A., and E. Paris, Analysis of armouring process through laboratory experiments, in *Dynamics of Gravel-Bed Rivers*, edited by P. Billi et al., pp. 227–250, John Wiley, New York, 1992.
Laronne, J. B., and M. A. Carson, Interrelationships between bed morphology and bed-material transport for a small, gravel-bed channel, *Sedimentology*, *23*, 67–85, 1976.
Martini, I. P., Gravelly flood deposits of Irvine Creek, Ontario, Canada, *Sedimentology*, *24*, 603–622, 1977.
McDonald, B. C., and I. Banerjee, Sediments and bedforms on a braided outwash plain, *Can. J. Earth Sci.*, *8*, 1282–1301, 1971.
Meyer-Peter, E., and R. Muller, Formulas for bedload transport, paper presented at 2nd Meeting, Int. Assoc. of Hydraulic Res., Stockholm, 1948.
Morris, H. M., Flow in rough conditions, *Trans. Am. Soc. Civ. Eng.*, *120*, 373–398, 1955.
Naden, P. S., and A. C. Brayshaw, Small- and medium-scale bedforms in gravel-bed rivers, in *River Channels: Environment and process*, *Inst. Br. Geogr. Spec. Pub.*, vol. 17, edited by K. Richards, pp. 249–271, Blackwell, Cambridge, Mass., 1987.
Parker, G., and P. C. Klingeman, On why gravel bed streams are paved, *Water Resour. Res.*, *18*, 1409–1423, 1982.
Parker, G., and P. R. Wilcock, Sediment feed and recirculating flumes: A fundamental difference, *J. Hydraul. Eng.*, *119*, 1192–1204, 1993.
Reid, I., L. E. Frostick and J. T. Layman, The incidence and nature of bedload transport during flood flows in coarse grained alluvial channels, *Earth Surf. Processes Landforms*, *10*, 33–44, 1985.
Rouse, H., Critical analysis of open-channel resistance, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, *91*(HY4), 1–25, 1965.
Shields, A., Anwendung der Aehnlichkeitsmechanik der Turbulenzforschung auf die Geschiebebewegung, *Mitt. Preuss. Versuchsanst. Wasserbau Schiffbau*, *26*, 5–24, 1936. (English translation by W. P. Ott and J. C. van Uchelen, 43 pp., U.S. Dep. of Agric. Soil Conser. Serv. Coop. Lab., Calif. Inst. of Technol., Pasadena, 1950.)
Sutherland, A. J., Static armour layers by selective erosion, in *Sediment Transport in Gravel-Bed Rivers*, edited by C. R. Thorne, J. C. Bathurst, and R. D. Hey, pp. 243–260, John Wiley, New York, 1987.
Tait, S. J., and B. B. Willetts, Characterisation of armoured bed surfaces, in *Grain Sorting Seminar: Centro Stefano Franscini, Monte Verita, Ascona, Switzerland, October 21–26, 1991*, *Eidg. Tech. Hochsch. Zurich Vers. Wasserbau Hydrol. Glaciol.*, *117*, 207–225, 1992a.
Tait, S. J., and B. B. Willetts, Physical and numerical experiments on bed armouring, paper presented at 5th International Symposium on River Sedimentation, Inst. of Hydraulic Structures and Agric. Eng., Univ. of Karlsruhe, Karlsruhe, Germany, 1992b.
Tait, S. J., B. B. Willetts, and J. K. Maizels, Laboratory observations of bed armouring and changes in bedload composition, in *Dynamics of Gravel-Bed Rivers*, edited by P. Billi et al., pp. 205–225, John Wiley, New York, 1992.
Tribe, S., and M. Church, Simulation of cobble structure on a gravel streambed, *Water Resour. Res.*, this issue.
Whiting, P. J., and W. E. Dietrich, Boundary shear stress and roughness over mobile alluvial beds, *J. Hydraul. Eng.*, *116*, 1495–1511, 1990.
Wiberg, P. L., and J. D. Smith, Calculations of the critical shear stress for motion of uniform and heterogeneous sediments, *Water Resour. Res.*, *23*, 1471–1480, 1987.
Wilcock, P. R., Estimating local bed shear stress from velocity observations, *Water Resour. Res.*, *32*, 3361–3366, 1996.
Wilcock, P. R., and B. W. McArdell, Surface-based fractional transport rates: Mobilization thresholds and partial transport of a sand-gravel sediment, *Water Resour. Res.*, *29*, 1297–1312, 1993.
Wilcock, P. R., and B. W. McArdell, Partial transport of a sand/gravel sediment, *Water Resour. Res.*, *33*, 235–245, 1997.
Wilcock, P. R., and J. B. Southard, Experimental study of incipient motion in mixed-size sediment, *Water Resour. Res.*, *24*, 1137–1151, 1988.
Wilcock, P. R., and J. B. Southard, Bed-load transport of mixed-size sediment, *Water Resour. Res.*, *25*, 1629–1641, 1989.
Wolcott, J. F., Flume studies of gravel bed surface response to flowing water, Ph.D. thesis, 110 pp., Univ. of B.C., Vancouver, B.C., Canada, 1990.

M. Church, Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z2. (e-mail: mchurch@geog.ubc.ca)
M. A. Hassan, Department of Geography, Hebrew University of Jerusalem, 91904 Jerusalem, Israel.
J. F. Wolcott, Health Sciences Administration, University of Southern California, University Park, Los Angeles, CA 90089-0663.

(Received July 21, 1997; revised February 2, 1998;
accepted February 6, 1998.)