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Sediment supply and the development of the coarse surface layer in gravel-bedded rivers

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THE bed surface of most gravel rivers is considerably coarser than the sub-surface or the gravel load transported over it, a phenomenon affecting river dynamics, morphology and ecology. The coarse surface layer, often called an armour or pavement, has been attributed to an inherent tendency for small grains to settle between larger ones during active transport of all sizes[1,2]; and to selective erosion or trapping of finer particles when the coarser grains are relatively immobile[3,4]. Where bedload supply is cut off below dams, selective erosion causes coarsening[5,6]. Using a simple quantitative model, we propose that surface coarsening develops in gravel-bedded rivers when local bedload supply from upstream is less than the ability of the flow to transport that load. We present laboratory results which support this hypothesis, and show that supply reduction causes changes in bedforms and progressive confinement of active bedload transport to a narrow band of finer bed surface bordered by a coarse, less active bed. It may therefore be possible to relate the degree of river-bed surface coarsening to sediment supply resulting from land use.

In rivers, when the boundary shear stress τ_b imposed by the flow exceeds the critical boundary shear stress τ_c required to mobilize grains on the stream bed, the bedload transport rate q_b is observed to increase rapidly with small increases in τ_b. The simplest approximate equation for predicting q_b is

$$q_b = k(\tau_b - \tau_c)^n \quad (1)$$

where k and n are empirically determined (n is usually close to 1.5)[7]. On a bed composed of many different grain sizes, τ_c is roughly proportional to the median grain size of the bed surface[8]. Flume and field studies indicate that a stream bed's sub-surface is similar in grain size distribution to the stream's bedload[9]. We propose that the disparity between median grain size of the surface and that of the sub-surface or load can arise when the transport rate exceeds the local supply rate. This imbalance may cause net erosion, but in poorly sorted sediment (that is, sediment with a wide grain size distribution), it may also cause selective erosion and deposition and vertical winnowing to coarsen the bed and raise the critical shear stress. Our model differs from those that argue that armouring is inherent in the transport of poorly sorted sediment[1,2]; we propose instead that surface coarsening occurs primarily where there is a transport-supply imbalance, and it may occur over small parts of the stream bed or over the entire stream bed.

Using equation (1), we can form a dimensionless sediment transport ratio q_*, which is the transport rate for the coarse surface normalized by the transport rate for a surface as fine as the sub-surface or load:

$$q_* = \left(\frac{\tau_b - \tau_{cs}}{\tau_b - \tau_{cl}}\right)^{1.5} = \left(\frac{\dfrac{\tau_b}{\tau_{cl}} - \alpha\left(\dfrac{D_{50_s}}{D_{50_l}}\right)}{\dfrac{\tau_b}{\tau_{cl}} - 1}\right)^{1.5} \quad (2)$$

where τ_{cs} and τ_{cl} are the critical boundary shear stresses of the surface and the sub-surface or load, respectively, the parameter α for gravel with uniform specific gravity is unity, and D_{50_s} and D_{50_l} are the median grain size of the surface and load, respectively. An alternative[7] to equation (1) can be manipulated to give

$$q_* = \frac{\left[\dfrac{\tau_b}{\tau_{cs}} - 1\right] - \dfrac{1}{a}\ln\left(1 + a\left[\dfrac{\tau_b}{\tau_{cs}} - 1\right]\right)}{\left[\dfrac{\tau_b}{\tau_{cl}} - 1\right] - \dfrac{1}{a}\ln\left(1 + a\left[\dfrac{\tau_b}{\tau_{cl}} - 1\right]\right)} \quad (3)$$

where the bracketed expressions represent the dimensionless excess shear stress for the median grain size of the surface and the load. Our hypothesis implies that q_* in equations (2) or (3) should be unity when sediment supply rate matches the river's ability to transport the load, and should decrease towards zero as the surface coarsens when supply is reduced.

We progressively reduced the sediment supply to a small flume, holding the water discharge and the bedload grain size distribution constant. Sediment identical to the supply was placed on the flume bed while damp to minimize settling of finer sediment between the larger grains. Nonetheless, simple wetting of the surface and grain vibrations (produced by water flow rates below that required for sediment transport) coarsened the bed significantly (Fig. 1) as the finer grains infiltrated the bed. As the surface reached equilibrium at a high bedload transport rate (17.4 g min^{-1} per cm width), it became distinctly finer and more poorly sorted; however, the median grain diameter, or D_{50}, of the bed surface was equal to that of the load (3.7 mm) within measurement error. Reducing the sediment supply rate to 6.1 g min^{-1} per cm width coarsened the surface to $D_{50} = 4.3$ mm, with a marked reduction in bed surface sand. Decreasing the sediment loading to 1.7 g min^{-1} per cm width coarsened the surface further ($D_{50} = 4.9$ mm).

The bed surface showed spatial segregation of grain sizes into distinct zones which varied with supply (Fig. 2). At the high transport rate, the surface was covered with mobile, thin (1–2 grain diameters) bedload sheets[10], consisting of alternating congested (coarse), smooth (fine), and transitional (intermediate) zones[11,12], migrating downstream (in that order), thus creating strong pulsations in bedload delivery to the flume outlet. As the sediment supply rate was reduced, sheets became less frequent and distinct, coarse inactive zones formed and expanded, and sediment transport became confined to a progressively narrower fine-textured active zone (Fig. 2) where bedload travelled in indistinct long-wavelength pulses.

The constriction of active bedload zones with decreasing supply probably results from interactions between coarse and fine grains. As the bed coarsens because of diminished supply, the finer bedload will tend to stop in the pockets formed by the coarser surface particles. Locally, if a sufficient number of fine particles stop, the pockets will partially fill, causing a reduction in local grain friction and a reduction in the fluid momentum loss from particle wakes. These effects will cause this local area to transmit more load and to have a higher flow velocity (causing locally convergent near-bed flow[11]), leading to an active bedload zone bounded by less active coarse sufaces.

Values of q_* predicted by equation (3) compare well with our experimental results (Fig. 3), supporting the simple explanation for surface coarsening proposed here. We used equation (3) rather than (2) for our own data and that of Parker *et al.*[9] because the Yalin bedload equation predicted the observed transport rates more accurately. We estimated τ_{cs} and τ_{cl} in equation (3) by using the relationship $\tau_{*_c} = \tau_c \times [(\rho_s - \rho) \times g D_{50}]^{-1} \approx 0.045$ (where ρ_s and ρ are the grain and fluid density, respectively, and g is gravitational acceleration), recently proposed[15,16] for poorly sorted coarse sediments. We calculated a in equation (3) as $a = 1.66\ \tau_{*_c}^{0.5} = 0.35$. The boundary shear stress was calculated from flow depth, water surface slope, and bed surface slope; it decreased (from 52 to 47 and then to 39 dyne cm^{-2}) with decreasing surface slope as the sediment supply was reduced between the three runs. The uncertainty in calculated τ_b (because of variability of bed slope over time) was close to the differences between these runs, however, and the family of curves shown in Fig. 3 all exhibit a similar rapid decline in q_*. Two data points calculated from experiments by Parker *et al.*[9] under similar conditions are shown (Fig. 3); their τ_b/τ_{ci} ratio was ~2.5. The q_* values for these two points were calculated from the observed initial and final bedload discharge rate in run 4 and from the estimated initial and observed final bedload discharge in run 2. For the Kuhnle and Southard[14] data, q_* was calculated in two ways: by assuming that the highest feed rate (run H5) defined the transport rate without a coarse surface layer, and by calculating this transport rate for the same τ_b/τ_{ci} 4.2 as their other runs. The predicted relationship is from equation (2) rather than from (3) because the bedload equation behind equation (2) gave a better estimate of observed sediment transport rates. Because the experiments of ref. 14 used supercritical flow, and the water surface slopes and equilibrium transport for all grain sizes were not reported, the quantitative interpretation of their results is uncertain. We assumed that their bed slope and average flow depth could be used to estimate the average boundary shear stress using the Williams[17,20] side-wall correction.

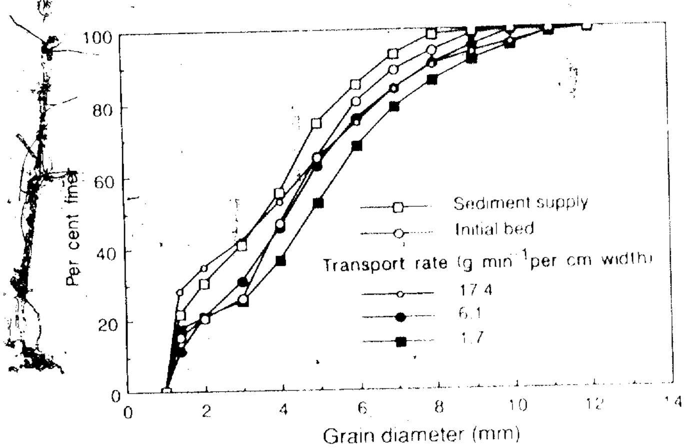

FIG. 1 Changes in bed-surface grain size distribution with sediment supply reduction. Cumulative size distributions shown for grain mixture fed into the flume (sediment supply), initial bed surface after wetting but before any sediment transport (initial bed), and bed surfaces under bedload transport rates of 17.4, 6.1, and 1.7 g min^{-1} per cm width.

METHODS. The flume was 7.5 m long, 0.3 m wide, and was kept at a constant slope of 0.0046. Water surface slope, gravel bed slope, and bed surface texture were free to equilibrate at the imposed rates of water discharge (0.6 l s^{-1} cm^{-1}) and sediment loading (varied between runs as above). The highest sediment loading rate was adjusted to the observed bedload discharge from the initial bed. Fresh sediment was fed constantly into the upstream end of the flume by hand or conveyor belt. Discharged bedload was collected from the flume outlet at 5 min intervals, weighed, and sieved to determine grain size distribution. Samples of the bed surface were recovered at the end of each run by removing plates (0.5 m long, 0.3 m wide) which had previously been buried in the flume bed. The undisturbed bed surfaces on these plates were fixed with glue and analysed for grain size distribution by measuring grains located at fixed points on an overlaid grid[20]. Water surface and bed slope were determined every 6 min by reading point gauges placed at the 1-m intervals along the flume centreline. The mean water surface slope of each run decreased with reduced sediment loading, from 0.0052 to 0.0046 and then to 0.0035 (all ±15%), while the mean depth increased from 10 to 11 cm. Runs lasted six to eight hours, and were terminated at equilibrium when water surface slope stabilized and when rate and size distribution of bedload discharge matched those of bedload supply.

Parker and Klingeman[2] argued that the coarse surface layer developed by vertical winnowing of fines, making coarser grains more abundant at the surface and giving the coarse and fine fractions of the load equal mobility. They proposed that a coarse surface layer was generally required to transmit poorly sorted coarse bedload when boundary shear stresses were not far above critical. Our analysis suggests that their experiments were conducted under very low sediment feed rates, relative to the boundary shear stress imposed. This imbalance between sediment supply and transport led to surface coarsening which reduced the difference between the imposed boundary shear stress and the critical shear stress. Kuhnle and Southard[14] varied sediment feed and water discharge in experiments which they interpret as supporting the Parker–Klingeman equal-mobility hypothesis. They imposed large initial excess boundary shear stresses ($\tau_b/\tau_{ci} > 4$) relative to the imposed load, however, and consequently a coarse surface layer developed in a manner consistent with our theory (Fig. 3). Although they conclude that their results support the equal-mobility hypothesis, they also propose that the initial surface in their experiments was too fine to accomplish equal mobility for the imposed flow and sediment feed rate. Hence, indirectly, they recognized the importance of sediment supply in their experiments.

We propose that surveys of rivers to determine patterns of q_* may provide a quantitative method to determine the sensitivity of rivers to sediment supply changes resulting from land use. Such a tool would be useful where conflicts arise between land use (such as forest cutting) and river use (such as fish production). Spatial variation in bed surface texture can be related to channel topography through detailed mapping of rivers at low flow. The local dimensionless transport rate q_* can then be estimated directly from τ_b (from the bankfull channel geometry), τ_{cs} (from bed-surface grain size analysis) and τ_{ci} (from sampling of the bed sub-surface, whose grain size distribution approximately equals the load[9]) for different grain-size zones. Such field surveys of rivers in California have revealed significant q_* variation with sediment supply similar to that predicted by our theory (D. Kinerson and W. E. Dietrich, manuscript in preparation).

We suggest that, in rivers with predominantly low q_* values, increased bedload supply as a result of accelerated erosion may be primarily accommodated through a local increase in q_* values

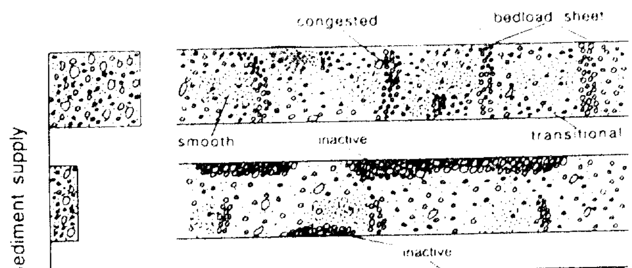

FIG. 2 Plan view of the flume bed, showing effect of sediment loading rate (indicated by 'supply' box) on lateral and longitudinal grain size segregation of flume bed surface (flow is left to right). At a high (17.4 g min^{-1} per cm width) sediment supply rate, bedload travelled as thin rapidly migrating bedload sheets (see text) with relatively well sorted coarse (4.7 mm median diameter) 'congested' leading edges, followed by poorly sorted 'smooth' and 'transitional' zones (2.7 mm and 3.7 mm median diameter, respectively). Reductions in sediment supply resulted in expansion of the coarse 'inactive' zones, in which little or no transport took place.

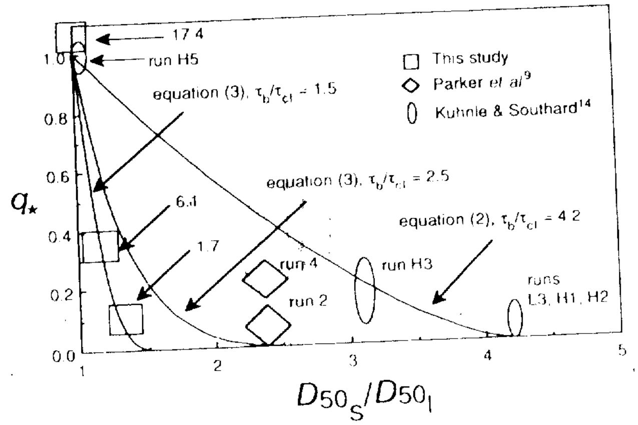

FIG. 3 Comparison of the predicted transport ratio q_* as a function of median grain diameter (D_{50}) ratio, with the observed transport ratio and grain ratio at transport rates of 17.4, 6.1, and 1.7 g min^{-1} per cm width. The symbol size represents the approximate range of observed values for each run.

and widening of high-q_* zones. In streams with high initial q_* values, grain size adjustment resulting from increased load is limited, and hence increased bedload supply should lead to net deposition and consequently to altered channel morphology, such as pool infilling and channel migration. If accelerated erosion leads primarily to increased fine bedload supply, it should cause fining of the bed, which may in turn lead to mobilization of the coarser fraction and an increase in q_*. These hypotheses are being tested in continuing field studies on California rivers.

In most rivers, many factors (limited supply of gravel-sized material to streams from hillslopes, chemical and mechanical breakdown of bed material, net loss of material to floodplains and increasing distance downstream from upland sediment sources) restrict bedload supply and promote bed surface coarsening. On a very local scale, topographically induced flow divergence and cross-channel rolling of particles can reduce the sediment supply and coarsen individual patches of the bed surface[18,19]. Our sediment-supply hypothesis suggests a continuum of surface responses, from the well-armoured river beds below dams (where all bedload supply is eliminated) to the armour-free surface found on bars below landslides or other local high-supply sources.

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A new, post-stishovite high-pressure polymorph of silica

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THE possibility of 'post-stishovite' phases of silica (SiO_2) has been the subject of extensive study during the past two decades, not only because of the intrinsic crystallographic interest but also because of its relevance to the geochemistry of the lower mantle. Here *in situ* X-ray diffraction observations of SiO_2 compressed to pressures of up to 124 GPa using a laser-heated diamond-anvil cell. Stishovite was formed by heating α-quartz or amorphous silica at pressures of up to 92 GPa; on heating at 108 and 124 GPa, however, the materials crystallized into a $CaCl_2$-type structure, which results from a distortion of the stishovite structure and is slightly denser. The quenched and recovered sample was always stishovite; thus the transformation from stishovite to the $CaCl_2$ structure is reversible on release of pressure.

Silica is one of the most abundant minerals in the Earth's crust and occurs in many different forms, or polymorphs. Since the discovery of the rutile-type polymorph (stishovite) above 10 GPa, many attempts have been made to find further high-pressure polymorphs of SiO_2. Both α-PbO_2-type and Fe_2N-type SiO_2 have been synthesized at very high pressures using either shock or static compression[1,2], but neither polymorph has yet been confirmed to exist as a stable phase. Based on systematic studies of AX_2-type compounds, it is generally believed that stishovite may ultimately transform into an eightfold-coordinated fluorite structure[3].

A recent theoretical prediction using a first-principles electronic structure calculation[4] has indicated, however, that fluorite-type SiO_2 has a much higher free energy than stishovite, making it an unlikely candidate for the 'post-stishovite phase'. Instead, it was pointed out that stishovite may ultimately transform into a Pa3 (pyrite-like) structure; the aim of our experiments was to test this theoretical prediction.

Synthetic single crystals of quartz, natural quartz sand and amorphous silica were used as starting materials. These samples were finely ground and mixed with platinum black, which absorbs the Nd YAG laser light. Details of the experiments are described elsewhere[5]. Powdered samples were embedded in a small hole (100 μm) in a stainless-steel gasket and concentric

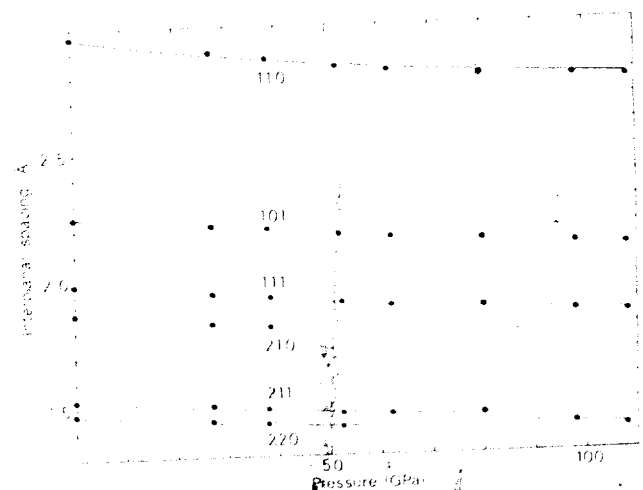

FIG. 1 Interplanar spacing of SiO_2 observed after α-quartz and amorphous silica have been heated at each pressure.