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Patterns and processes of sediment sorting in gravel-bed rivers

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Abstract: Sedimentological studies of coarse-grained alluvial rivers reveal patterns of bed material sorting at a variety of spatial scales ranging from downstream fining over the length of the long profile to the vertical segregation of a coarse surface layer at the scale of individual particles. This article reviews the mechanisms that sort bed material by size during sediment entrainment, transport and deposition and discusses some of the inter-relationships that exist between patterns and processes of sediment sorting at different spatial and temporal scales. At initiation of motion, sorting can arise from the preferential entrainment of the finer fractions from the heterogeneous bed sediments. Bedload grain-size distributions are modified during transport as different size fractions are routed along different transport pathways under the influence of nonuniform bed topography and associated flow patterns, and during deposition as the variable pocket geometry of the rough bed surface and turbulence intensity of the flow control the size of the particles that deposit. The review highlights the poor understanding of the many feedback linkages that exist between patterns and processes of sediment sorting at different scales and the need for a greater awareness of the spatial and temporal bounds of these linkages.

Key words: sediment sorting, gravel-bed rivers, fluvial sedimentology, bed material, bedload transport.

I Introduction

Patterns of sediment sorting in coarse-grained alluvial channels result from the segregation of particles with differing physical characteristics during processes of erosion, transport and deposition. A knowledge of sediment sorting patterns and processes is important because it is fundamental to our understanding of modern and ancient fluvial systems (Carling and Dawson, 1996), boundary roughness (Robert, 1990), heavy mineral enrichment and the generation of economic placers (Force, 1991), the fate of chemical and metal pollutants (Webb and Walling, 1992; Macklin *et al.*, 1997) and for maintaining the ecological diversity of aquatic habitats (American Society of Civil Engineers Task Committee, 1992; Montgomery *et al.*, 1996). In sand-sized sediment, differences in mineral densities can be important to grain sorting (Slingerland and Smith, 1986; Komar,

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1989a). Coarser sediments are usually sorted by size, with shape of secondary importance (Carling *et al.*, 1992), although the effectiveness of shape selection may vary with particle size (Bluck, 1982).

The sorting of alluvial river gravels is conventionally attributed to size-selective entrainment whereby larger particles, because of their greater inertia, are intrinsically less mobile than smaller particles and require higher shear stresses to entrain them. Patterns of sediment sorting are therefore interpreted as a textural response to local differences in flow competence. However, recent research has suggested that entrainment from sediment mixtures is only weakly size selective. This has fuelled an ongoing debate about the strength and effectiveness of selective entrainment as a sorting process (e.g., Hoey and Ferguson, 1994) and generated a renewed interest in processes of selective transport which route different-size fractions along different transport pathways (e.g., Paola, 1989) and selective deposition by which the variable pocket geometry of a rough bed surface selectively accepts and rejects clasts of differing size (e.g., Bluck, 1987). After a brief description of the principal sedimentological features of gravel-bed rivers, this article reviews current understanding of the processes that sort bed material by size during sediment entrainment, transport and deposition and some of the interrelationships that exist between pattern and process at different spatial and temporal scales. Numerical models of sediment sorting are only briefly considered; readers interested in mathematical analyses of sediment sorting processes should consult Parker (1992), Kelsey (1996) and the references cited therein.

II Scales of sediment sorting in gravel-bed rivers

Gravel-bed rivers exhibit complex, yet systematic, patterns of sediment sorting. Perhaps the most obvious manifestation of sorting occurs at the channel-length scale with the downstream reduction in bed surface grain size (Figure 1a). Despite the discontinuities in grain size trends that arise from tributary inputs and valley side failures (Knighton, 1980; Dawson, 1988; Rice, 1994; Pizzuto, 1995), the sorting of river gravels over the longitudinal profile is commonly modelled as a simple downstream exponential decrease in particle size (Figure 1a):

$$D = D_o e^{\alpha L} \tag{1}$$

where D is some characteristic particle size (usually the median (D_{50}) or mean ($\bar{D}$) particle size of the surface material), D_o is the initial value, L is distance downstream, and α is an empirical diminution coefficient ($\alpha < 0$). Compilations of diminution coefficients indicate wide variations in downstream fining rates (Shaw and Kellerhals, 1982; Knighton, 1987). Distances within which the D_{50} is halved vary from tens of kilometres in large single-thread rivers to a few hundred metres in rapidly aggrading alluvial fans. Distal reaches often show a sudden reduction in bed material calibre from gravel to sand (Sambrook Smith and Ferguson, 1995), the abruptness of which may reflect the contrasting hydraulic characteristics of the two types of river system (Sambrook Smith *et al.*, 1997).

Superimposed on this downstream trend of decreasing particle size are reach-scale patterns of sediment sorting associated with the spatial organization of pool-bar units in rivers of contrasting channel pattern. The morphology and sedimentology of pool-bar

units often reflect the complex erosional and depositional histories of their formation. However, the influence of the topographic control of flow structure and sediment transport pathways on bed material sorting is often retained. For example, the riffle sediments of straight channels are often coarser and better sorted than those in adjacent pools (Keller, 1971; Lisle, 1979; Figure 1b) while point bars in meandering channels commonly fine laterally from the outer bank to the inner bank and, over the upper parts at least, longitudinally from barhead to bartail (Bluck, 1971; Bridge and Jarvis, 1976; Figure 1c). Downbar fining is also characteristic of medial bars in braided rivers (Boothroyd and Ashley, 1975; Bluck, 1982; Figure 1d).

Size segregation of bed material also occurs at the grain scale (Richards and Clifford, 1991). Most gravel-bed rivers develop a surface layer, one or two grain diameters thick, that is relatively coarse in comparison with the sand/gravel mixture beneath (Church *et al.*, 1987; Figure 1e). Although all size fractions present in the subsurface material are usually represented in the surface material, the latter is usually better sorted, with a median particle size some two to three times that of the former (Andrews, 1984). Following Moss (1963; 1972), Dunkerley (1990) suggests that the development of a coarse surface layer may represent a more extensive manifestation of grain–grain interactions that promote sediment sorting within small-scale gravel bedforms such as pebble clusters (Brayshaw, 1984; Figure 1f). Similar processes may be partly responsible for the development of transverse ribs and clast dams (McDonald and Banerjee, 1971; Boothroyd and Ashley, 1975; Koster, 1978; Figure 1g) and bedload sheets (Whiting *et al.*, 1988; Bennett and Bridge, 1995; Figure 1h).

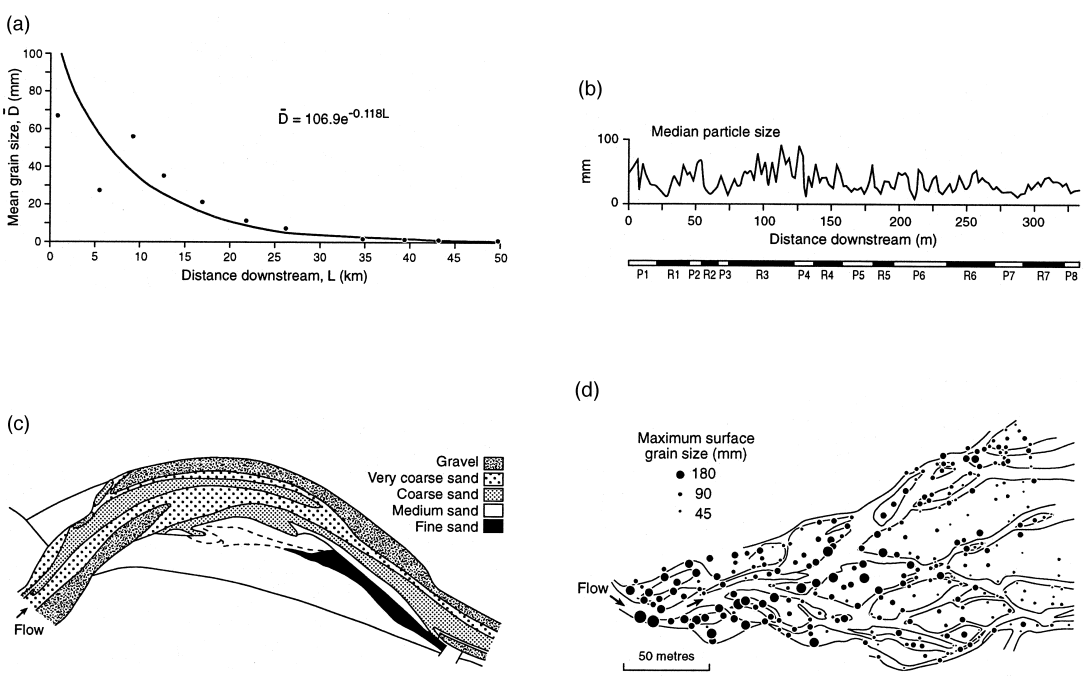

Figure 1 (Cont. on page 4)

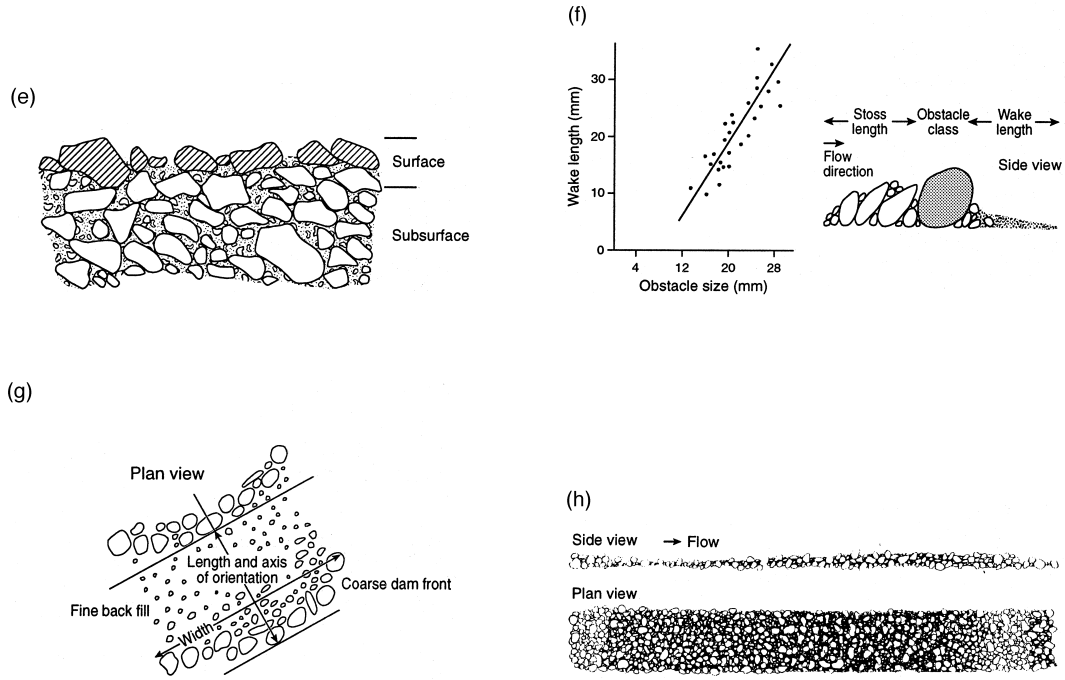

Figure 1 Patterns of sediment sorting common to gravel-bed rivers. (a) Downstream fining, the River Bollin, England, after Knighton (1980); (b) variation in median particle size in a riffle (R) and pool (P) sequence, Kingledoors Burn, England, after Milne (1982); (c) distribution of mean grain size in a meander bend, the River South Esk, Scotland, after Bridge and Jarvis (1976) © John Wiley & Sons, Limited. Reproduced with permission; (d) downbar and downstream fining of maximum particle size in a braided river, the proglacial Lyngsdalselva, Norway, after Ashworth and Ferguson (1986); (e) cartoon of surface armouring, after Church *et al*. (1987) © John Wiley & Sons, Limited. Reproduced with permission; (f) idealized side elevation of a cluster bedform and some associated geometrical properties, after Naden and Brayshaw (1987) reproduced with permission of the Royal Geographical Society; (g) idealized plan of a transverse clast dam, after Bluck (1987) reproduced with permission of the Royal Geographical Society; (h) pattern of sediment sorting within bedload sheets observed at Duck Creek, USA, after Whiting *et al*. (1988)

III Sediment sorting at entrainment

1 Size selective entrainments – the Shields entrainment function

Criteria for defining the onset of particle motion have largely been based on the work of Shields (1936). In a series of flume experiments with uniform material less than 3 mm in diameter organized into planar beds, Shields related the tangential fluid stress at the boundary responsible for grain movement (τ_c) to the weight per unit area of the particles forming its topmost layer by defining a dimensionless entrainment function τ_c^*:

$$\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)gD} \tag{2}$$

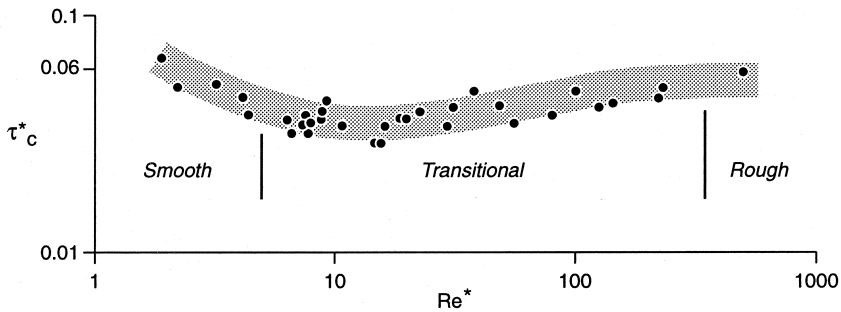

Figure 2 The entrainment function of Shields (1936). As noted by Buffington and Montgomery (1997), the commonly quoted value of $\tau_c^* \approx 0{\cdot}06$ for fully turbulent flow is based on a single point within a data set exhibiting considerable scatter. As a result of methodological bias inherent in most definitions of incipient motion and other systematic sources of uncertainty, Buffington and Montgomery (1997) conclude that it is not possible to define a definitive τ_c^* value for the rough turbulent flow characteristics of gravel-bed rivers. Rather, care should be exercised in choosing defensible values for particular applications

Source: Redrawn from Buffington and Montgomery (1997)

where ρ_s, ρ, g and D denote sediment density, fluid density, acceleration due to gravity and particle diameter, respectively. A plot of τ_c^* versus grain Reynolds number (Re^*) is shown in Figure 2. Although subject to considerable scatter (e.g., Gessler, 1971; Miller *et al.*, 1977; Hammond *et al.*, 1984) the results suggest that τ_c^* attains a constant value under the hydraulically rough condition of natural gravel-bed rivers. Consequently, critical shear stresses are directly proportional to particle size ($\tau_c \propto D$) suggesting that particle weight is the principal force restricting movement. Larger particles, because of their greater inertia, are intrinsically less mobile than smaller particles and require higher shear stresses to entrain them.

Many patterns of sediment sorting in gravel-bed rivers are consistent with the preferential entrainment of sediment by size. Surface coarsening (Figure 1e), for example, can result from the entrainment of finer, more mobile particles during periods of low to moderate flows that are incompetent for the coarser, less mobile clasts. Armouring of the channel bed by selective entrainment is common whenever a pronounced imbalance between sediment supply and the transporting capacity of the flow is maintained for any length of time. Such conditions are typical of lake outflows and rivers downstream of dams (e.g., Harrison, 1950; Komura and Simons, 1967; Williams and Wolman, 1984). The surfaces that result are immobile at all discharges up to the historical maximum sustained flow. As such, they are commonly called static or stable armours (Sutherland, 1987; Parker and Sutherland, 1990). However, as discussed below, coarse surface layers can be maintained in the presence of an upstream sediment supply and during flows capable of moving all available grain sizes. These surfaces are termed mobile armours. As for static armours, the conventional explanation assumes a wide range in entrainment thresholds for particles of differing size. The bed surface is broken when the coarsest material is entrained by the flow, thus allowing the underlying finer material to be transported. As the flow decreases, the bed surface reforms quickly through the preferential deposition of the coarser fractions of the bedload which eventually isolates the subsurface material

from the flow. Finer particles for which the flow is still competent to transport remain in motion and are winnowed from the bed leaving a coarse bed surface (Klingeman and Emmett, 1982; Gomez, 1983).

Size-selective entrainment of bed material according to spatial variations in bed shear stress provides a mechanism that links sediment sorting, channel topography and flow pattern in channels of different planform geometry. As discussed below, sediment sorting in meander bends (Figure 1c) has long been attributed to a nonuniform distribution of boundary shear stress and flow competence induced by the topographic control on flow structure (e.g., Dietrich, 1987). Similar processes may be responsible for braided river sedimentology (Bridge, 1993).

Selective entrainment is also consistent with the reduction of bed material calibre over the long profile (Figure 1a). Historically, downstream fining has been attributed to particle abrasion. This reflects past emphasis on the concept of the graded river (Mackin, 1948) with its assumption that the slope required to maintain transport continuity decreases in the downstream direction in response to an independently produced decline in grain size.

Equation 1 is, in fact, a derivative of Sternberg's (1875) law of particle abrasion in which α is a coefficient of abrasion. Results from abrasion tank experiments (Pettijohn, 1975: 45–58; Brewer and Lewin, 1993; Kodama, 1994a; 1994b; Mikos, 1994) and observations that clasts with different lithologies, but similar densities, fine at different rates within the same river system (Plumley, 1948; Bradley, 1970; Abbott and Peterson, 1978; Werritty, 1992) lend support to the particle abrasion hypothesis. Many rivers, however, exhibit rates of downstream fining that are one or two orders of magnitude greater than rates of abrasion (e.g., Brierley and Hickin, 1985; Dawson, 1988; Ferguson and Ashworth, 1991).

Notwithstanding secondary effects of chemical weathering (Bradley, 1970) and abrasion *in situ* (Schumm and Stevens, 1973), the recognition that downstream fining rates increase with aggradation rates (Shaw and Kellerhals, 1982) and that downstream fining can be modelled in laboratory flumes over distances too short for abrasion to be significant (Paola *et al.*, 1992b) indicate that the selective downstream transfer of finer fractions is a major cause of the longitudinal gradation of particle size. The assumption is that size-selective entrainment concentrates the coarser particles in the upper reaches and finer particles in the lower reaches through a process of 'sedimentary fractionation' (Paola, 1988) that results from the higher frequencies and velocities of movement of the finer fractions of the bed material. The diminution coefficient (α) in Equation 1, should, therefore, be interpreted to reflect the cumulative and undifferentiated effects of particle abrasion and sediment sorting, the relative importance of which will vary according to lithology, channel morphology and flow and sediment transport conditions.

IV Relative mobility of size fractions within sediment mixtures and the development of the equal mobility hypothesis

Shields' model of size-selective entrainment was derived in the laboratory using sediments of uniform size. Most natural sediments, however, are composed of mixed-size particles. In applying the Shields threshold curve to sediment mixtures, a characteristic grain size is usually chosen to represent the deposit as a whole, usually the median size (D_{50}). However, entrainment thresholds for individual size fractions in coarse, heterogeneous sediments differ significantly from those associated with the

movement of unisized sediment. Research conducted during the 1970s (e.g., Fenton and Abbott, 1977) and 1980s (e.g., Parker *et al.*, 1982a; 1982b) suggested that the critical shear stress (τ_{ci}) for a particle of size D_i depends on its size relative to the underlying bed material (D_i/D_{50}) as well as its absolute size and has led to a re-evaluation of the strength of sorting at entrainment and, therefore, of the conventional models of mobile armouring and downstream fining described above.

1 The relative mobility of particles in sediment mixtures

Natural river gravels are characterized by highly complex and variable pocket geometries and packing arrangements which affect the mobility of individual size fractions. The principal factors controlling the relative mobility of different size fractions within sediment mixtures are the particle's friction or pivoting angle (θ) which expresses a grain's resistance to removal by the flow and the height of the particle above the local upstream, maximum bed elevation (termed exposure, ε) and above the local mean bed surface elevation (termed projection, ψ) which affects the protrusion of the grain into the flow (Figure 3). From the geometry of Figure 3, it is apparent that grain protrusion and friction angle, and therefore particle mobility, will vary with the size, shape and orientation of individual particles and packing geometry of grains comprising the bed surface.

The importance of relative size effects in controlling the mobility of sediment mixtures has been known since the work of Einstein (1950) and Egiazaroff (1965). They both describe a phenomenon called hiding which can be viewed as a combination of grain projection and exposure (Figure 3). In a bed of mixed sizes, finer surface grains typically protrude less into the flow than surrounding coarser grains which also act to shelter them from its mobilizing influence. The lower protrusion of relatively fine grains above the surface and upstream obstacles is both a result of particle size and the greater

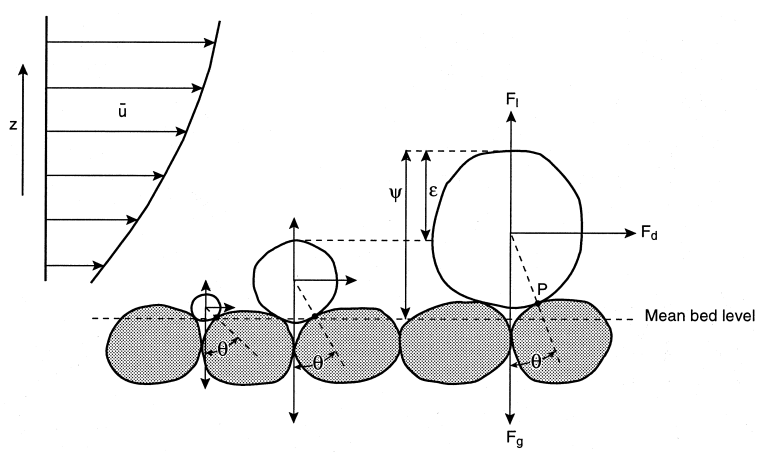

Figure 3 Forces acting on grains resting on a rough bed. F_l, F_d and F_g are the forces of lift, drag and gravity, $\bar{u}$ is mean flow velocity and z is the height above the local mean bed elevation. Factors affecting the force balance are friction angle (θ) about pivot point P, grain projection above the local mean bed surface (ψ) and grain exposure above the local upstream bed surface (ε)
Source: Redrawn from Richards (1990)

probability of small particles falling into gaps between surrounding grains and is commonly termed 'microscopic' hiding (Parker and Klingeman, 1982). As a result, relatively fine grains in a sediment mixture are less mobile than they would be in a bed of uniform sizes. Likewise, relatively coarse grains in a mixture are more mobile than they would otherwise be if surrounded by particles of similar size. Egiazaroff (1965) incorporated the effects of relative protrusion into the theoretically derived entrainment criterion:

$$\tau^*_{ci} = \frac{0{\cdot}1}{(\log_{10} 19 D/\bar{D})^2} \tag{3}$$

which models reasonably well the decrease in τ^*_{ci} with relative particle size that is typical of mixed-sized sediments (Figure 4a).

Grain mobility is also controlled by the grain pivot angle (Figure 3) which varies with relative particle size according to the relation:

$$\theta = e\left(\frac{D_i}{D_{50}}\right)^{-f} \tag{4}$$

(Miller and Byrne, 1966). Komar and Li (1986) found that the variation in the coefficients ($20 \leqslant e \leqslant 64$ and $0.32 \leqslant f \leqslant 0.75$) reflected the effects of particle shape, angularity, bed structure and the manner in which a particle moves from the pocket within which it resides. In general, pivoting angles increase as relative particle size, roundness and sphericity decrease. Komar and Li (1986) modelled the effect of the θ, D_i/D_{50} dependence on entrainment thresholds with a simple grain pivoting model which has been successfully applied to a number of field data sets (Figure 4b). In reality, however, particle mobility, and therefore entrainment thresholds, will be determined by a

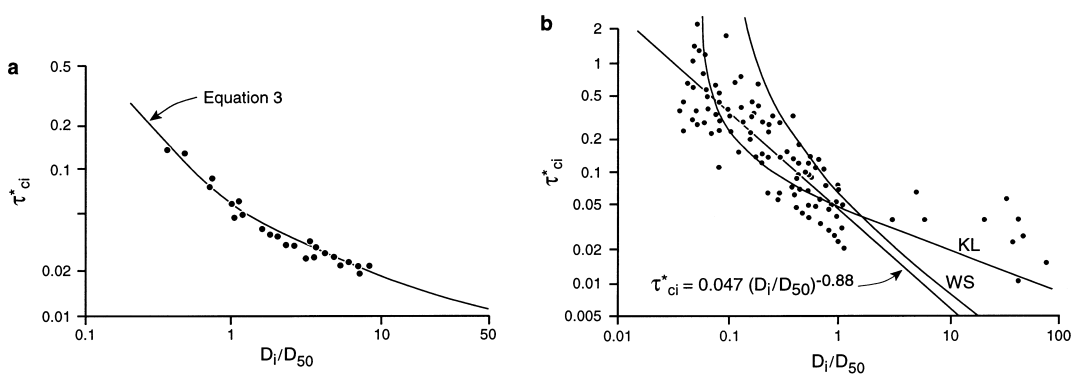

Figure 4 Variation of dimensionless critical shear stress with relative particle size after (a) Egiazaroff (1965) reproduced with the kind permission of the ASCE and (b) Ferguson *et al.* (1989). (a) Shows the data used to justify Eigazaroff's theoretical entrainment function (Equation 3); (b) compares the data of Ferguson *et al.* (1989) with the grain pivoting analyses of Komar and Li (1986) and Wiberg and Smith (1987) as indicated by the curves labelled KL and WS. The straight line represents an entrainment function (of the form of Equation 6) derived by least squares regression for $D_i/D_{50} < 2$.

combination of the effects of particle hiding and grain pivoting angle. The force-balance analysis of Wiberg and Smith (1987), for example, uses an alternative to Equation 4 of the form:

$$\theta = \cos^{-1}\left(\frac{D_i/D_{50} + \psi}{D_i/D_{50} + 1}\right) \tag{5}$$

(Figure 4b) while Komar and Li improved their grain pivoting model to incorporate hiding effects (Komar and Li, 1988). Subsequent work, however, has demonstrated that particle projection, exposure and pivoting angle vary widely for a given grain on a given bed surface as a result of the complex microtopography of natural river gravels (Kirchner *et al.*, 1990; Buffington *et al.*, 1992). Particle critical shear stresses should, therefore, be characterized by probability distributions, rather than single values.

These and other deterministic models of sediment entrainment differ in their consideration of particle geometry, lift and drag forces and the role of turbulence and are fitted to empirical data sets by adjusting poorly constrained parameters (Bridge and Bennett, 1992; Kelsey, 1996). However, they all indicate that grain protrusion and friction angle reduce the relative mobility of individual size fractions within heterogeneous sediments. In contrast to the analysis of Shields which suggests τ_c^* is a constant, Figure 4 indicates that in a bed of mixed sizes, τ_{ci}^* decreases with increasing relative particle size. This can be modelled by the entrainment function:

$$\tau_{ci}^* = \tau_{c50}^*\left(\frac{D_i}{D_{50}}\right)^{\beta} \tag{6}$$

(Figure 4b) in which τ_{c50}^* is the critical dimensionless shear stress when $D_i = D_{50}$ and β is a hiding factor which quantifies the dependence of τ_{ci}^* on relative particle size ($\beta < 0$). Substituting 6 into 2 yields:

$$\tau_{ci} \propto D_i^{1+\beta} \tag{7}$$

Equation 6, therefore, quantifies the extent to which relative size effects act to reduce the intrinsic differences in mobility between coarse and fine fractions in a mix of surface grains. Of particular significance are the values $\beta = 0$ and $\beta = -1$. If $\beta = 0$ then, as Shields suggested, sediment entrainment is dependent solely on particle size (i.e., $\tau_{ci} \propto D_i$). However, an exponent of -1 indicates that the absolute weight of a particle is completely compensated for by relative size effects and critical shear stresses for particles comprising sediment mixtures are independent of particle size ($\tau_{ci} \propto D_i^0$). All sizes of particles are, therefore, entrained at the same threshold shear stress (τ_{c50}^*) and the bedload grain size distribution approximates that of the bed material at all sediment transporting flows.

As noted by Church *et al.* (1991), the equivalence of bedload and bed material grain-size distributions is implicit in many engineering bedload formulae. However, the extent to which relative size effects reduce the mobility of different size fractions within sediment mixtures has been the subject of much debate, the outcome of which determines our understanding of sediment transport and sediment sorting processes generally, and surface coarsening and downstream fining in particular.

2 Equal mobility and mobile armouring

Parker and co-workers instigated the debate with a series of articles that assumed equal sediment mobility as a first approximation for predicting the rate of transport of sediment mixtures (Parker *et al.*, 1982a; 1982b; Parker and Klingeman, 1982). Parker *et al.* (1982a) analysed data from Oak Creek, a small, flume-like stream with a well-developed coarse surface layer in Oregon, USA. Using data collected at flows above the critical discharge for the break-up of the armour and the particle size distribution of the subsurface bed material, they derived an entrainment function with a hiding factor of -0.982. This implies a very small dependence of critical shear stress on D_i. The exponent was considered to be so close to -1 as to render all subsurface grains equally mobile such that for flows in excess of the threshold required to break up the armour, the bedload grain-size distribution approximated that of the bulk bed material. However, an analysis of material contained within the surface armour suggested that coarser particles were less mobile than finer particles: relative size effects eliminated most, but not all, of the mobility differences between coarse and fine particles. This result was used to argue that under equilibrium transport conditions when the transport rate of each size fraction entering the system is identical to that leaving the system, the lesser (greater) mobility of coarser (finer) grains is compensated by their over- (under-) representation on the bed surface through a process of 'vertical winnowing' (Parker and Klingeman, 1982). The essential difference between mobile armouring by 'downstream winnowing' (see above) and by 'vertical winnowing' is that the former process requires that the larger particles do not move, while the latter process requires that they do.

The above model of sediment entrainment has come to be known as the equal mobility hypothesis. It states that under equilibrium transport conditions, surface coarsening through vertical winnowing acts to equalize the mobility of different sizes by counterbalancing the intrinsic lesser mobility of relatively coarse particles (Parker *et al.*, 1982b; Andrews and Parker, 1987). Consequently, the D_{50} can be used in conjunction with an appropriate value of the Shields parameter to derive an estimate of the shear stress required to initiate general movement (Gordon *et al.*, 1992: 334; Wilcock, 1992a), above which all grain sizes are transported at rates in proportion to their presence in the bed material. The coarse surface layer is not destroyed during periods of competent flow because the entrainment of bed particles is sporadic and only a small proportion of the available bed material is active at any one time (Andrews and Erman, 1986).

An important aspect of the equal mobility hypothesis is that the lower the transport rate (i.e., low excess shear stresses), the greater the degree of surface coarsening required to equalize the mobility of different-size fractions (Parker, 1990). Mobile and static armours are, therefore, genetically linked; the former will degrade into the latter under conditions of reduced sediment supply (Dietrich *et al.*, 1989; Parker and Sutherland, 1990). At high flows and transport intensities, the degree of surface coarsening declines until it is eventually 'washed out' (Kuhnle, 1989; 1992; Lisle and Madej, 1992; Laronne *et al.*, 1994; Figure 5).

The evidence for and against the equal mobility hypothesis has been discussed exhaustively in the literature (e.g., Andrews and Parker, 1987; Richards, 1990; Gomez, 1995; Lisle, 1995; Wathen *et al.*, 1995; Komar, 1996). Discussion has usually centred on the strength of the τ_{ci}:D_i dependence as quantified by the exponent (hiding factor) in Equation 6. Although the results demonstrate general agreement that the relative mobility of different size fractions in heterogeneous sediments is considerably reduced

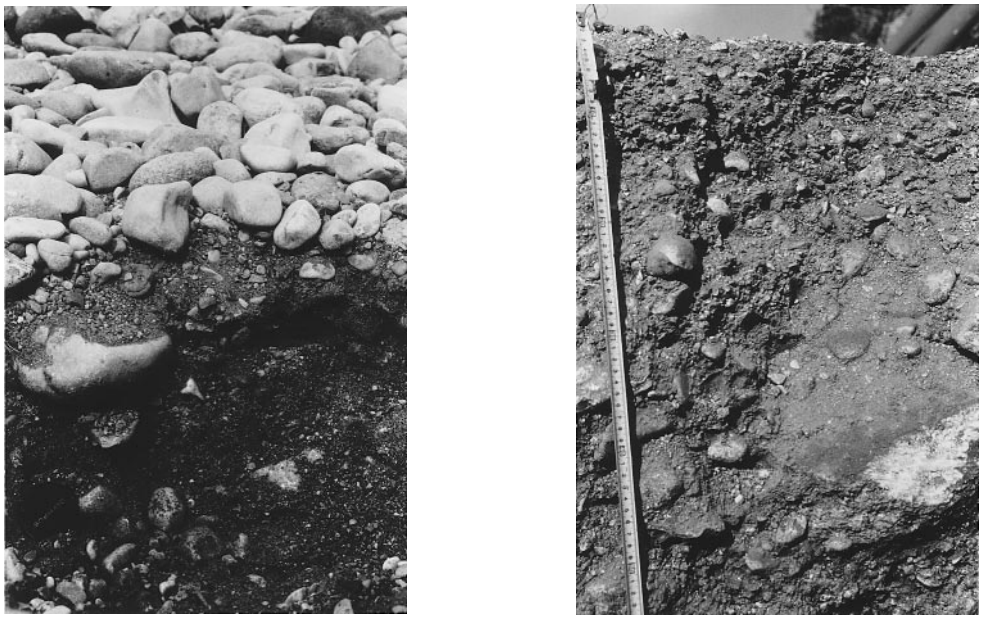

Figure 5 Contrasts in surface armouring between the River Wharfe, UK, a perennial stream characterized by low rates of sediment supply and bedload discharge (left), and Nahal Yatir, Israel, an ephemerally flowing stream with high rates of sediment supply and bedload discharge (right)
Source: Photographs supplied by Ian Reid

by relative size effects, it is apparent that there is considerable discrepancy in the published results. In part, this may reflect variations and differences in field and analytical methodologies (Richards, 1990). Wilcock (1988; 1992b) argues that the reference transport rate method (e.g., Parker *et al.*, 1982a; Wilcock and Southard, 1988; 1989) which defines τ_c as that shear stress required to produce a low, but arbitrarily defined transport rate gives results that indicate little, if any, τ_{ci} dependence on D_i ($\beta \approx -1$) while the largest grain method (e.g., Komar, 1989b), in which the shear stress calculated for the largest particle in a bedload sample ($D_{\max}$) is assumed to approximate the critical shear stress as long as coarser particles are available on the bed, produces a variation in τ_{ci} with $D_i^{0.5}$ ($\beta \approx -0.5$). In principle, the two initial motion methods should give identical results except when τ_{ci} is independent of D_i. That they do not is largely a result of scaling and sampling problems which makes it very difficult to obtain accurate, representative and comparable estimates of τ_{ci} for different size fractions (Dietrich and Whiting, 1989; Komar and Shih, 1992; Wilcock, 1988; 1992b). The strength of selective entrainment can also be expected to vary according to mixture sorting and bimodality (Kuhnle, 1993a; 1993b; Wilcock, 1992a; 1993) and flow intensity (Parker *et al.*, 1982b; Diplas, 1987; Ashworth and Ferguson, 1989).

The work cited above suggests that natural gravel-bed rivers might display a wide range of initial motion conditions according to local hydraulic and sedimentological conditions and cautions against the use of aggregated data sets or the uncritical comparison and application of initial motion results between rivers (Richards, 1990).

Size-dependent and size-independent entrainment may, therefore, represent end members of a spectrum of possible initial motion conditions (Ferguson, 1987). The general consensus to have emerged over the past few years has been that particle mobility is governed more by its relative particle size than its absolute size such that gravel entrainment is closer to the equal mobility end of the spectrum (Hoey and Ferguson, 1994). Coarser particles are therefore slightly less mobile than finer particles, at least at the low excess shear stresses and transport intensities that predominate in gravel-bed rivers. Grain size distributions can, therefore, be expected to coarsen with increasing shear stress (Shih and Komar, 1990a; 1990b; Komar and Carling, 1991) until bed material and bedload similarity is achieved (e.g., Kuhnle, 1992). Wilcock (1992a) suggests that the threshold for equal mobility of unimodal and weakly bimodal sediments is approximately $\tau^*/\tau^*_{c50} = 2$. At these high transport stages, fractional transport rates are a function of only their proportion on the bed surface and on the total transport rate. At lower flows and in more bimodal sediments, a condition of 'partial transport' may persist (Wilcock and McArdell, 1993) where the transport rate of largely immobile coarser fractions is determined by the relatively infrequent movement of only a few grains.

3 Implications for downstream fining

The recognition that sediment sorting during entrainment is weak has led to renewed interest in the mechanisms promoting downstream fining. Given that bedload transport rates and grain size distributions are sensitive to small differences in the τ_{ci}:D_i dependence (Komar and Shih, 1992), one approach has been to assume slight, but consistent, deviations from equal mobility (e.g., Parker, 1991a; 1991b; van Niekirk *et al.*, 1992; Vogel *et al.*, 1992; Hoey and Ferguson, 1994). In these models, downstream fining is driven by the differential mobility of coarse and fine particles within the bed sediment mixture. For example, using a one-dimensional sediment routing model consisting of three submodels relating to channel hydraulics, bedload transport and bedload/bed material exchange, Hoey and Ferguson (1994) model successfully the rapid downstream fining of Allt Dubhaig in the Scottish Highlands with a hiding factor of -0.905 (Figure 6a). Although a full sensitivity analysis has yet to be undertaken, they conclude that the degree and location of downstream fining are sensitive to the strength of size selectivity as determined by β, the rate of sediment supply, and the assumptions made in the sediment exchange submodel. Parker's (1991a) model incorporates the effects of abrasion to derive a unified theory of downstream fining by abrasion and sorting. The former process is modelled as binary collisions between bedload particles and the bed with abrasion coefficients determined from abrasion mill tests, while the latter is modelled as in the Hoey and Ferguson (1994) model with a hiding factor of -0.905. The model demonstrates the importance of both processes in controlling downstream fining rates. Abrasion and sorting are equally important in controlling the rate of fining of limestone, while sorting is primarily responsible for the fining of more resistant quartzite (Figure 6b). In channels containing a mix of limestone and quartz sediments, abrasion would cease to be an important process beyond the downstream distance required to abrade the limestone to sands and silts.

In a more radical departure, Paola and Seal (1995) and Seal and Paola (1995) develop a model that allows for, but does not require, equal mobility. They criticize the common assumption of a spatially homogeneous grain size distribution in favour of a surface characterized by a mosaic of texturally differentiated units or 'patches' of differing mean size. Each 'patch' is assumed to satisfy equal mobility. However, as the transport rate of

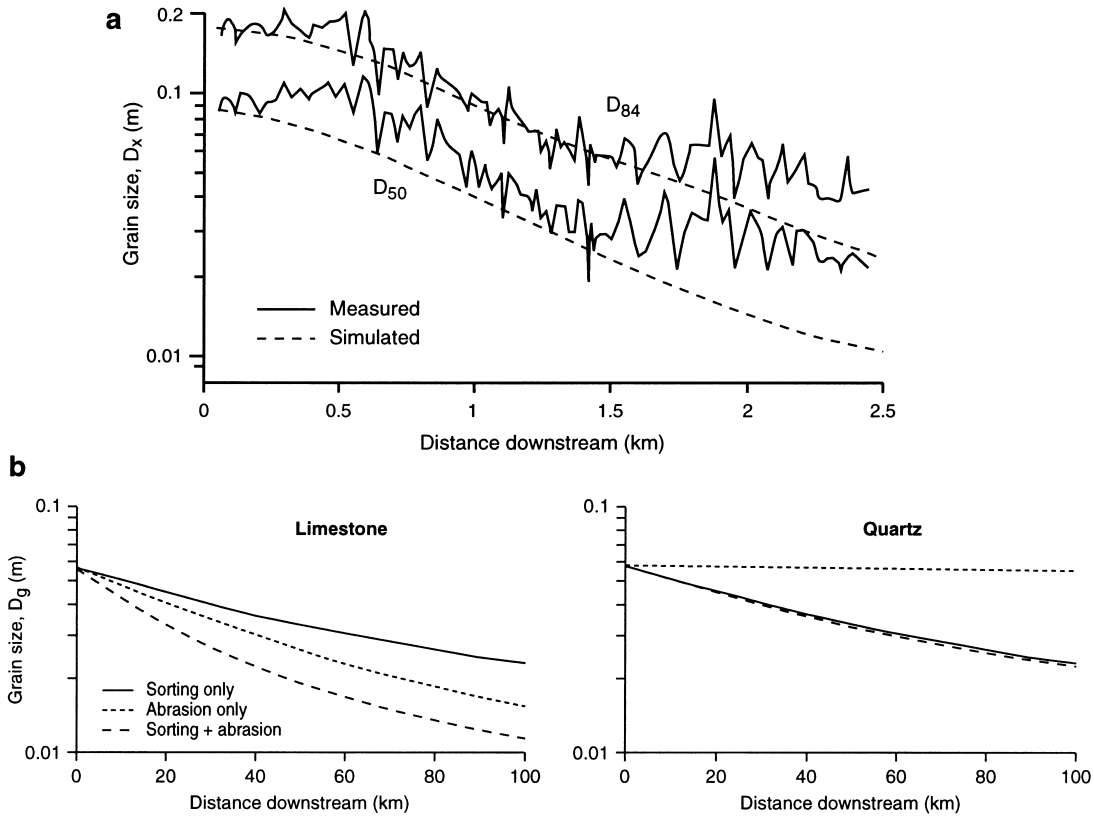

Figure 6 Numerical simulations of downstream fining. (a) The role of size-selective entrainment, the Alt Dubhaig, after Hoey and Ferguson (1994); (b) the relative roles of selective entrainment and abrasion, two hypothetical rivers with contrasting lithologies, after Parker (1991b), reproduced with the kind permission of the ASCE. D_x and D_g are the xth percentile and geometric mean of the grain size distribution respectively

any particular patch grain size distribution is determined by the mean grain size of the patch, coarser 'patches' will have lower transport rates, and thus contribute less sediment to the overall downstream flux than finer 'patches' (Figure 7). Thus, even though equal mobility is satisfied locally within a patch, the spatial organization of bed material and inherent nonlinearity of the sediment transport process result in a section average, or global, relative mobility between different size fractions which increases as the number, sorting and range of patch mean sizes increase and the magnitude of the sediment transporting flows decreases. Applications of the theory to the North Fork Toutle River, in Washington, USA, led them to conclude that global relative sediment mobility arising from local equal sediment mobility was sufficient to explain the observed pattern of downstream fining.

As noted above, equal mobility appears to break down for poorly sorted and bimodal sediment. Patches, it is suggested, form in such sediments by the natural process of local sorting and sediment redistribution which, over time, force discrete areas of the bed towards a condition of approximate local equal mobility (Paola and Seal, 1995).

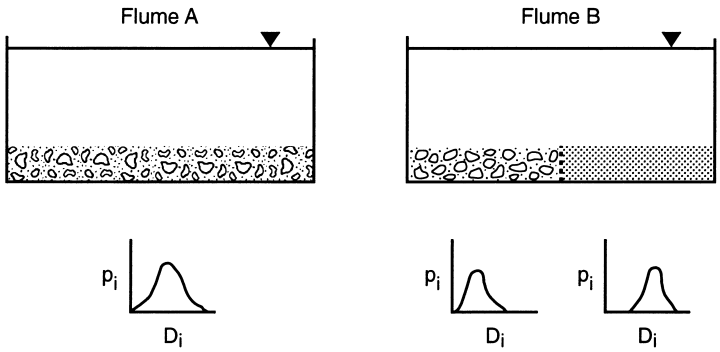

Figure 7. Illustration of the mechanism for enhanced downstream fining due to bed material patchiness. In flume A the size distribution is uniform. In flume B, the same size distribution is separated into a coarser and a finer patch (p_i is the proportion of the sediment of size D_i). If the same boundary shear stress is applied to both flumes, the finer patch of flume B will contribute finer sediment at a higher rate than flume A and the coarser patch of flume B will contribute coarser sediment at a lower rate than flume A. As a result, the load transported in flume B is finer in size and larger in magnitude than that transported in flume A
Source: After Parker (1992)

Alternatively, patches may result from patterns of sediment sorting controlled by meso- (e.g., Parker and Andrews, 1985) or micro- (Sambrook Smith and Ferguson, 1996) scale variations in bed topography. In this way, patterns of sediment sorting at one scale have consequences for processes and patterns of sediment sorting at other scales. Thus, although sorting mechanisms during transport have received less attention than those operating at entrainment, the conclusion of Paola and Seal (1995) that lateral size segregation results in enhanced downstream fining establishes an important, but under-researched, link between patterns and processes of sediment sorting operating at different spatial and temporal scales.

V Sediment sorting during transport

Although initial motion conditions determine the calibre of the sediment entrained from the bed material, bedload grain-size distributions can undergo substantial modification during transport. Forces promoting sediment sorting during transport arise from downstream changes in channel curvature and bed topography. For example, the beds of straight reaches are usually deformed into topographic lows and highs termed pools and riffles respectively. Several workers (e.g., Dietrich, 1987; Ferguson, 1993) have argued that the pool and riffle are part of a single bedform, the bar unit (Figure 8a). The bar unit consists of a downstream widening and shoaling scour zone (pool) terminating at an oblique shallow lobe (riffle). When the bar is repeated along-side opposite banks, it is termed an alternate bar. In channels with readily erodible banks, the presence of alternate bars typically leads to a meandering channel pattern (Figure 8b) in which the bar 'wraps' around the bend forming a point bar. Braided channel patterns can be represented by spacing the bar unit across the channel width (Figure 8c) and have the additional features of flow confluences and bifurcations. As noted above, each channel

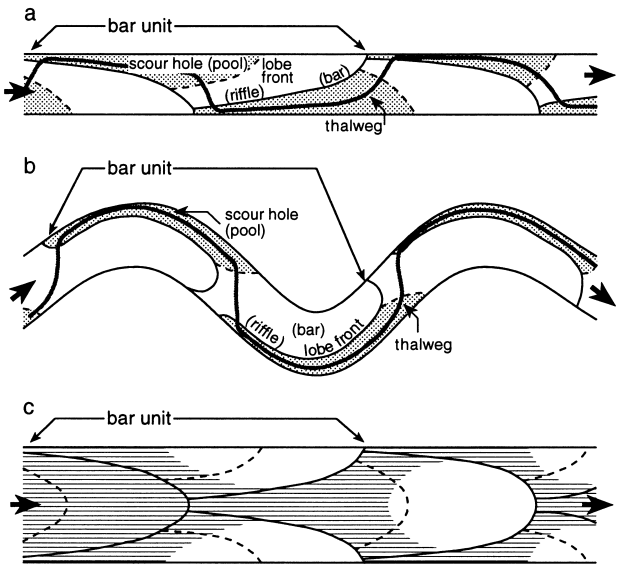

Figure 8 Pool-bar morphology in (a) straight, (b) meandering and (c) braided channels. Each bar unit consists of a deep narrow scour zone (pool) that widens and shoals to an oblique lobe front (riffle-bar). The pool is shaded in (a) and (b) whereas the shading in c) represents the low flow water level
Source: Dietrich (1987) reproduced with permission of the Royal Geographical Society

pattern is usually associated with a distinctive pattern of sediment sorting (Figures 1b–d). These characteristic bed topographies and sedimentologies result from, and in turn reinforce, complex flow, boundary shear stress and sediment transport fields in which different grain sizes are moved in different directions. The theory for flow over non-uniform bed topography is beyond the remit of this review (comprehensive discussions can be found in Ikeda and Parker (1989) and Ashworth *et al.* (1996)). However, its key aspects can be readily demonstrated with respect to flow through channel bends for which the theory is most advanced.

1 Planform, bed topography and flow structure

Flow structures in gravel-bed rivers are controlled largely by forces arising from channel curvature, changes in curvature and gradients in bed topography (Dietrich and Smith, 1983; Smith and McLean, 1984; Dietrich and Whiting, 1989). In a meander bend, channel curvature results in a depth-dependent, centrifugal force acting in a cross-stream direction which forces fast-flowing surface water towards the outer bank region causing a build-up of water adjacent to the bank known as super-elevation. Conversely, the water surface at the inner bank is drawn down. The result is a tilting of the free water surface and a balancing inward-acting pressure gradient force. However, as the inward-acting radial force is independent of flow depth, the balance between the centrifugal and pressure gradient forces only holds in the vertically averaged sense. Consequently, near the surface, centrifugal force exceeds the cross-stream pressure gradient and the water is driven outwards. Near the bed, the pressure gradient force is dominant and the flow is

turned inwards. The result is a spiral-like, secondary circulation confined to the thalweg (Figure 9a). The tilt of the water surface slope varies in direction between successive bends. The effect is an important modification of the longitudinal water surface slope that results in a zone of maximum water surface slope (and hence boundary shear stress) that shifts from the inside upstream bank to the outside downstream one as the flow progresses through the zone of minimum radius of curvature (Figure 9b). Bed topography effects are also important. Downstream convective accelerations associated with

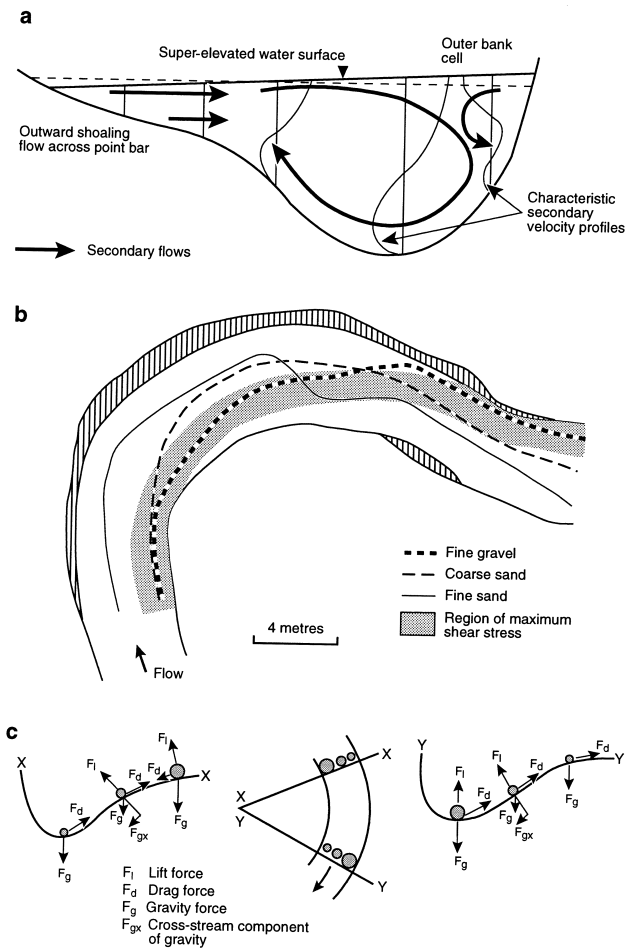

Figure 9 Flow structure (a), shifting loci of maximum boundary shear stress and sediment transport pathways (b), and forces acting on a bedload particle (c) in meander bends. Secondary flow is dominated by a skew-induced, helicoidal cell in the thalweg, shoaling over the point bar and a smaller, outer bank cell. Sediment sorting results from the balance of forces acting on particles during transport. The net result is a sorting mechanism whereby relatively fine particles move inwards under the action of near-bed, cross-stream circulations and coarser particles avalanche outwards under the influence of gravity
Source: (a) and (c) Markham and Thorne (1992) © John Wiley & Sons, Limited. Reproduced with permission; (b) after Dietrich and Whiting (1989)

shoaling of the flow over the bar platform reduce the cross-stream water surface slope causing a significant net cross-stream discharge towards the pool (Figure 9a). If the bar is extended well into the flow, the effect is an orientation of the near-bed velocity and boundary shear stress vectors towards the outer bank. The shoaling flow meets the secondary circulation at the point bar face causing upwelling. At the outer bank, a less important cell of reverse circulation is observed. Pronounced downwelling occurs where the outer-bank cell and main secondary circulation meet.

Similar controls of flow structure and boundary shear stress can be expected to operate in the pool-bar units of braided rivers (Bridge, 1993; Rhoads and Kenworthy, 1995). However, a full understanding of flow dynamics in braided reaches is hampered by the occurrence of confluences and diffluences and the corresponding zones of flow convergence and divergence, the dynamics of which vary with the discharge and momentum of the combining and combined flows, the junction angle and the depth and orientation of scour zone. However, detailed flume experiments (e.g., Mosley, 1976; Ashmore, 1982; Best 1987) and field studies (e.g., Davoren and Mosley, 1986; Roy and Bergeron, 1990; Ashmore *et al*., 1992; Bridge and Gabel, 1992; Ferguson *et al*., 1989; 1992; Rhoads and Kenworthy, 1995) of flow patterns through simple 'Y' or 'X' shaped pool-bar units indicate that the primary flow structure consists of twin cores of high velocity from each tributary that accelerate and converge into the confluence zone. Downstream, the flow decelerates as it diverges out of the pool and as it shoals over the downstream bar, the flow is deflected outwards. The cross-stream flow structure within the confluence consists of two cells of secondary circulation that plunge at the channel centre line and diverge at the bed (Figure 10), a feature that results from either the curvature-induced imbalance between the cross-stream pressure gradient and the centrifugal force as described above for meander bends (e.g., Mosely, 1976; Ashmore and Parker, 1983; Rhoads, 1996), and/or horizontal separation vortices downstream of the avalanche faces that border the scour zone (e.g., Biron *et al*., 1993; McLelland *et al*., 1996). Downstream of the convergence zone, the strength of the secondary circulation decreases as the core of intensely turbulent flow lifts from the bed, the depth decreases and radius of curvature increases. Flow in the gently curving anabranch distributaries may resemble that of low-sinuosity meander bends (Ashworth *et al*., 1992b; Bridge, 1993).

2 Implications for sediment sorting

Particle trajectories over a nonuniform bed topography are controlled by near-bed fluid vectors and cross-channel and downstream bed slopes. A particle moving over a transversely inclined bed surface will be deflected towards the base of the slope by gravity. The gravitational force acting down the slope is proportional to the cube of the diameter of the grain (particle mass) but the drag force of the flow varies with the square of the diameter (particle area). Hence, for the same near-bed velocity, coarser particles will be deflected downslope more directly than finer particles. This results in a process called 'topographic sorting' (Paola, 1989) which concentrates coarser grains on topographically low surfaces such as the downstream margins of alternate bars (Lisle *et al*., 1991), the base of point bars (Bluck, 1971) and the scour holes downstream of confluences (Ashworth *et al*., 1992a).

As discussed above, the near-bed flow in a meander bend is orientated towards the inner bank by a cross-stream pressure gradient (Figure 9a). The trajectory of a particle moving through a bend depends, therefore, on the relative magnitudes of the drag

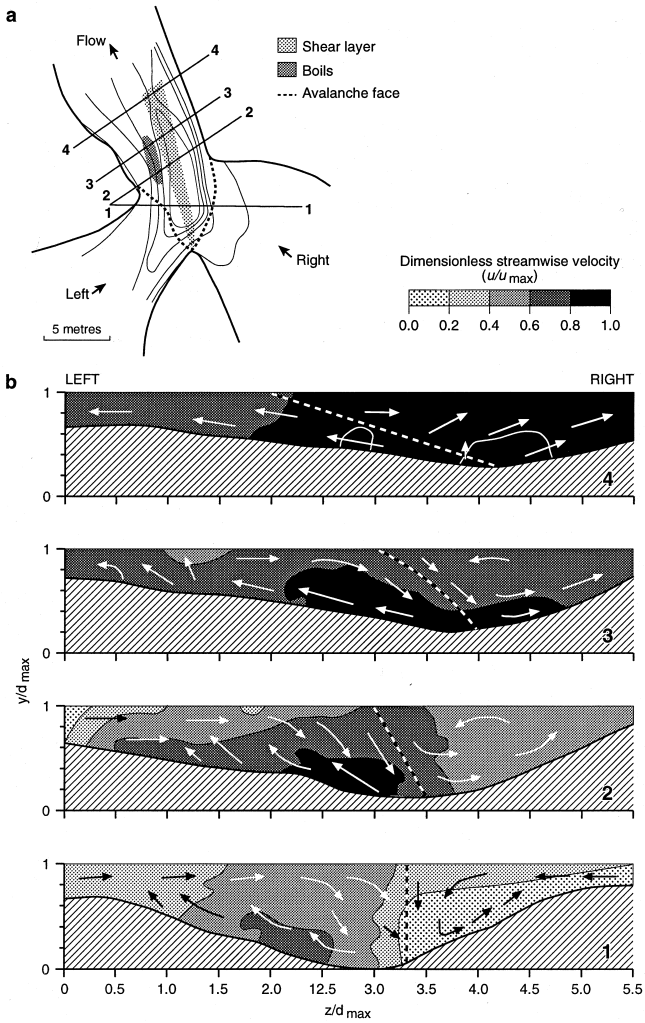

Figure 10 Channel morphology (a) and three-dimensional flow structure (b) at a confluence in the braided Sunwapta River, Alberta, Canada. Contours in (a) are at 0.1 m intervals. In (b) the downstream flow direction is into the page and distances across the channel (z) and above the bed (y) are expressed in relation to the maximum flow depth (d_{max}). The secondary flow pattern is superimposed on contours of the streamwise flow velocity, nondimensionalized with respect to the maximum velocity (u/u_{max}), which correspond to the divisions specified on the shaded bar. The dashed lines represent the position of the mixing interface shear layer

Source: McLelland *et al.* (1996) © John Wiley & Sons, Limited. Reproduced with permission

exerted by the inward-acting secondary flow and the outward-acting gravitational force (Figure 9c). Since finer particles have more surface area per unit of mass than coarse particles, the smaller diameter grains will move inward under the net influence of the secondary currents, while the larger diameter particles move outwards under the net

influence of the gravitational force. The differential effect of transverse bed slopes on particles of different diameter forces fine and coarse particles to trade positions as they move through the bend (Figures 9b and c). This results in a consistent pattern of sediment sorting in which the pool tends to be coarser than the inside point bar which itself fines downstream (Figure 1d).

Although predictions of sediment sorting arising solely from cross-stream 'tipping' under the relative action of a spatially uniform inward drag and outward gravitational acceleration on particles compare favourably to those observed in natural river bends (e.g., Parker and Andrews, 1985), a fully developed theory for meander morphology and sedimentology requires a correct understanding of the relationships between the distribution of boundary shear stress and channel topography and the relationship between the distribution of boundary shear stress and the spatial pattern of bedload transport rate and grain size (Dietrich and Whiting, 1989). Early theories of equilibrium bed topography and grain size distribution in channel bends modelled the transverse force balance acting on particles moving over the outward-sloping surface of the point bar (e.g., Allen, 1970; Bridge, 1977). At equilibrium, the cross-stream component of particle weight is exactly balanced by the inward-acting fluid drag of the helical secondary circulation. Although there is no net cross-stream transport of sediment, the locus of the coarser fractions follows the shift in the zone of the maximum shear stress through the bend, thus suppressing a tendency for erosion to increase. Since finer sediment moves inward into the low shear stress zones, the zone of the maximum transport is maintained near the channel centre-line.

Although early theories simulate observations reasonably well (e.g., Bridge and Jarvis, 1982; Bridge, 1984; Dietrich, 1987) they do not include the effects of topographic accelerations induced by flow shoaling over the point bar (Smith and McLean, 1984). The supply and removal of sediment from the point bar by the shoaling flow cause net outward sediment transport which, in sand-bedded rivers, forces the zone of maximum bedload transport rate to track the outward-shifting zone of maximum shear stress (Dietrich and Smith, 1984). In this way, the outward-directed flow over bars exerts an important control on equilibrium bend morphology by balancing the spatial variation in shear stress with convergent sediment transport. A particle force balance that assumes no net cross-stream transport, is therefore, only possible at the downstream end of a bend where the distribution of shear stress might not vary in a downstream direction. In addition to topographically induced near-bed flow, Dietrich and Smith (1984) highlight the importance of cross-stream transport caused by strong, troughwise currents along the crestlines of bedforms that have been skewed by the migrating shear stress field. They argue that sediment transport pathways through equilibrium meander bends are the result of a dynamic, rather than static, balance of forces (Figure 11).

The relationship between the boundary shear stress field and the sediment transport field depends, however, on the size and heterogeneity of the bed material (Bridge and Jarvis, 1982). Close correspondence between the zone of maximum shear stress and bedload transport rate may only occur in very well sorted and/or fine-grained sediments (e.g., sand-bedded rivers) where excess shear stresses are high (e.g., Hooke, 1975). Sediment transport in gravel-bed rivers is generally a close-to-threshold process. As such, the cross-stream shift in the zone of maximum shear stress is more likely to be accommodated by coarsening of the bed in the pool. The control exerted on the relationship between the boundary shear stress and sediment transport fields by spatial adjustments in surface grain size is illustrated by Whiting and Dietrich's (1991) study of the

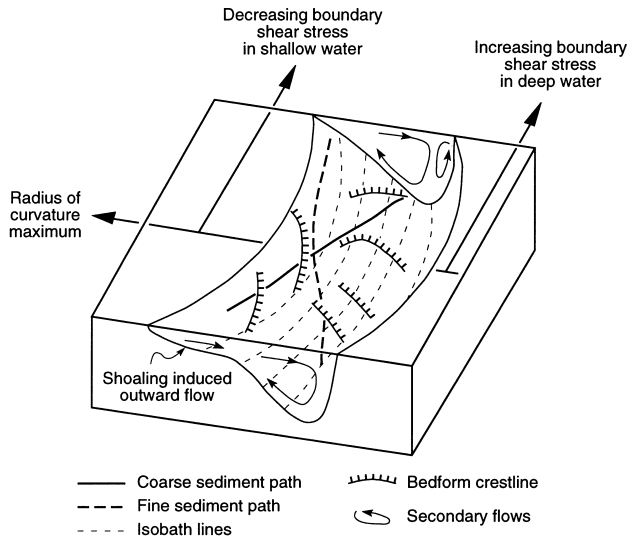

Figure 11 Flow processes controlling equilibrium bed topography and sediment sorting in meander bends. Flow direction is from the lower to the upper end of the figure
Source: After Dietrich and Smith (1984)

distribution of stress over an alternate gravel bar. They describe how a large variation in shear stress is matched by a strong size sorting of surface bar material. The segregation of the coarser fractions of the bed material in zones of high shear stress zones prevents topographic modification of the bedform. Grain size and sediment flux adjustments to changing boundary shear stress fields are not, however, mutually exclusive. An assessment of factors controlling their relative importance awaits further field studies in a wider range of morphological, sedimentological and hydrological settings (e.g., Carson, 1986).

Similar topographic controls on sediment pathways have been proposed for braided rivers. Ashworth (1988) and Ashworth *et al*. (1992b) studied the distribution of bedload transport rate and grain size in a scaled model of a braided reach of the White River, Washington, USA. Bar growth led to the segregation of bedload grain size and the routing of the finer bedload fractions through the distributaries and coarser fractions on to the barhead. Interpreting the pattern of bedload transport in terms of the primary (i.e., downstream) velocity field, Ashworth (1996) suggests that the routing of different grain sizes along selective transport pathways occurs when the velocity at the barhead switches from a maximum to a minimum and the surface flow pattern changes from one of convergence to divergence (Figure 12). The flume study showed that the velocity and flow pattern changes occur concurrently when the bar height was just over half that of the water depth.

Braid-bar sorting will be enhanced by the three-dimensional flow structure of confluence zones (Figure 13). Surface-convergent secondary flow cells at the confluence zone cause divergent flow at the bed. Although the strength of the secondary flow decreases with increasing distance from the tributary mixing zone, the lateral near-bed velocity components of the double helical flow cell act to drive sediment bankwards. Since the secondary circulation is much weaker than the primary flow direction, it only affects the finer bedload fractions which are swept down either one or both distributaries

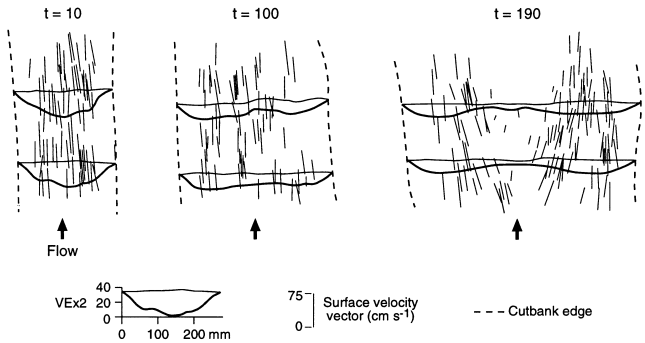

Figure 12 Change in magnitude and direction of surface flow velocity during mid-channel bar growth in a laboratory channel. *t* is the elapsed minutes since the start of the experiment. After about 100 minutes, the height of the bar is sufficient to force a change from flow maximum to minimum and flow convergence to divergence over the bartop. Note the vertical exaggeration (VE)
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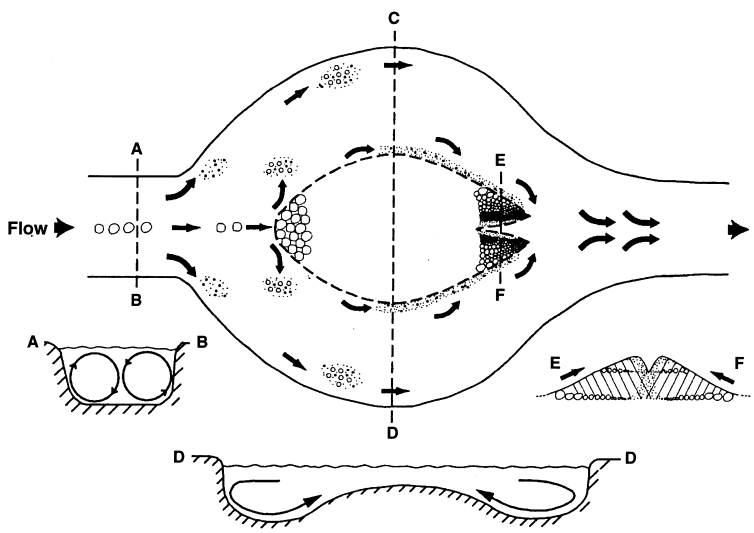

Figure 13 Schematic model of sediment sorting and downbar fining mechanisms in a simple braided reach. Bedload transport paths are shown by arrows in the main diagram. Arrows in the cross-sections indicate secondary flow patterns
Source: Ashworth *et al.* (1992b) © John Wiley & Sons, Limited. Reproduced with permission

depending on the maturity and morphology of the bar form. The coarser fractions have sufficient momentum to resist the secondary flow circulation and continue to move downstream to the barhead. If the bar has reached a critical bar-height to water-depth ratio, only relatively coarse particles may have sufficient momentum to move up on to the bar; finer fractions are more likely to be routed by flow divergence through the distributaries. Sediment sorting at the barhead may also be aided by selective deposition

under the influence of variable bed pocket geometry (see below). In the distributaries which resemble back-to-back meander bends (an eroding outer bank, asymmetrical thalweg and inner point bar), fines may be swept inwards by surface divergent flow cells (Richardson *et al.*, 1996) leading to an accumulation of fines at the bar tail (Figure 13).

VI Sediment sorting during deposition

Depositional dynamics have received considerably less attention than those of sediment entrainment or transport. However, several researchers have argued that sediment sorting during deposition occurs through the continual interaction between the moving bedload and the texture of the bed surface. Moss (1963) and Kuenen (1966) describe a 'like seeks like' effect whereby newly arriving sediment is preferentially deposited in pockets where it can resist the imposed fluid drag. This suggests that selective deposition may be controlled by processes very similar to those that determine the relative mobility of different size fractions at entrainment. As discussed above, the mobility of a particle is, in part, determined by the pocket geometry in which it rests. Coarse grains project relatively far out of pockets on a finer bed, experience a large drag force across their exposed surface area and are therefore more mobile than they would be on a bed of similar large grains. Conversely, small grains sit in deep pockets on a coarse bed, are partly hidden from the flow and are therefore less mobile than they would be on a bed of similar grains. A corollary of these hiding and protrusion effects is that during deposition, coarser particles are less likely to deposit on a finer bed except where chance accumulations of other large grains provide a suitable stable pocket geometry, or where the wakes of these other coarse grains reduce the drag across the grain.

The efficiency of this process may, in part, be a function of the local turbulence characteristics of the bed surface (Bluck, 1987; Clifford *et al.*, 1993). Differences in bed height created by heterogeneous sediments of natural river-beds generate a turbulence intensity and scale which control the size of clasts which can exist on the surface. This control is exerted in two ways. First, flow turbulence effects a more thorough removal of relatively fine grains from an initially poorly sorted deposit. Secondly, the turbulence scale and intensity may create a 'turbulence template' (Clifford *et al.*, 1993) in which only those clasts large enough to tolerate the local turbulence can deposit. In this way, the bed surface may 'select' and 'reject' particles from the bedload grain size distribution (Figure 14).

Such a sorting mechanism was recognized as being potentially important in the model of down-bar fining summarized in Figure 13. The rough bar surface creates a coarse

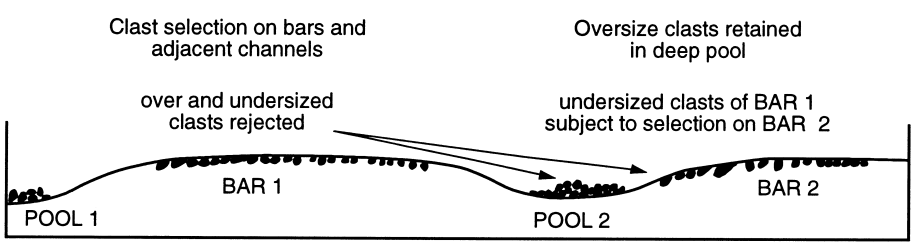

Figure 14 Size-selective deposition in sequential bar-pool units
Source: Bluck (1987) reproduced with permission of the Royal Geographical Society

pocket geometry which encourages the deposition of similar sizes and decreases the likelihood of finer particles settling due to increased turbulence around the coarse clasts. Relatively fine particles 'rejected' by the barhead are transported downstream to the bartail where they may be deposited. The internal sorting of bar material produces a down-bar decrease in grain size which may be maintained by a corresponding down-bar decrease in the intensity of turbulence at the water–sediment interface (Robert *et al.*, 1992; 1996). In a series of connected chute-bar units, sorting of bedload during bar deposition may control the supply of coarse material to downstream aggrading barheads creating a larger-scale pattern of downstream sorting (Figure 1d). If there are sufficient relatively large particles in the bedload, the coarse surface fabric of the barhead may stabilize, thus preventing further migration downstream (cf. Lisle *et al.*, 1991). Similar processes may be responsible for patterns of sediment sorting within transverse ribs and clast dams (Figure 1g).

Pebble clusters also exhibit a distinctive pattern of sediment sorting although they differ from clast dams and transverse ribs in that their axes are orientated parallel to the flow direction (Figure 1f). Obstacle clasts are formed from a coarse, relatively immobile grain, typically greater than the D_{95} of the bed surface grain size distribution. The stoss particles also comprise relatively coarse fractions of bed material (*c.* D_{75} to D_{95}) that often develop an imbricate structure. The wake particles, in contrast, are relatively fine (*c.* D_{10} to D_{50}) and form a streamlined tail. The pattern of size sorting within cluster bedforms results from the differential response of coarse and fine grains to the bed pressure and velocity fields generated by the obstacle clast (Brayshaw *et al.*, 1983; Paola *et al.*, 1986). Reid *et al.* (1992) use tracers to analyse how particle transport distance varies with site of deposition within cluster bedforms. Although they do not segregate their data by size, particle travel distances are least for wake and stoss deposits and greatest for loosely clustered and open framework deposits. Sambrook Smith and Ferguson (1996) note how fines deposited in the lee of pebble clusters in a flume study grew into longitudinal ribbons. As described above, the presence of patchiness in bed surface texture can lead to enhanced rates of downstream fining. In this way, processes of size segregation operating at the local scale can have an important influence on larger-scale patterns of sediment sorting. Since bedform dimensions are a function of local grain size (Figure 1f), the converse will also be true.

In a study of the transport of sand and gravel mixtures, Iseya and Ikeda (1987) describe how processes of smoothing, exposure and collision sorted the bed material into longitudinal smooth, transitional and congested bed states. Smoothing, whereby sand particles infill the interstices of gravel deposits, leads to a reduction in bed roughness. As the sand loading increases, bed roughness decreases to such an extent that gravel material is remobilized. Aided by their greater exposure to the flow, gravels extract greater momentum from the flow and are thus able to travel at higher speeds than they could under a bed comprising solely gravel. They continue to move downstream until they become trapped by the coarse pocket geometry of the congested bed. Finally, momentum is exchanged from the gravel to the sand through the collision of gravel particles. The process of longitudinal sorting induced a rhythmic pulsation of bedload transport rates and hence aggradation and degradation at a given cross-section as well as a variation in the structural characteristics of the bed surface (Figure 15).

Similar sorting processes have been used to explain the development of bedload sheets, thin, migrating accumulations of sediment with coarse grains clustered at the leading edge (Whiting *et al.*, 1988; Figure 1h), and the development of spatially variable bed

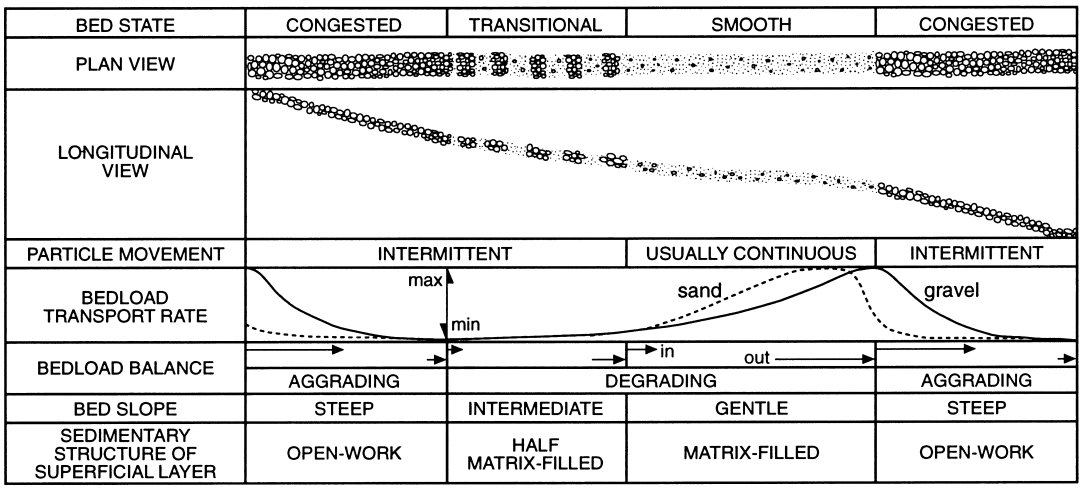

Figure 15 Patterns and processes of sediment sorting arising from self-mediated entrainment/disentrainment during the transport of poorly graded sediments
Source: After Iseya and Ikeda (1987)

amouring in conditions of reduced sediment supply (Dietrich *et al.*, 1989). These observations suggest that within an imposed flow and sediment supply regime, many bed surfaces may be controlled by the presence of coarse grains inhibiting the entrainment of fines and the presence of fines mobilizing coarse grains (Dunkerley, 1990; Kirchner *et al.*, 1990). This contrasts with the mobile pavement and equal mobility hypothesis which treats particles as individual entities and, under equilibrium transport, requires a coarse surface layer to compensate for the inherent lower mobility of coarse particles.

VII Conclusions

The sorting of bed material over the long profile and within individual reaches indicates that size-selective transfers of sediment must occur during the process of bedload transfer. Although size segregation at entrainment has been shown to be weak, the relatively long periods of time over which alluvial channels adjust their morphology and sedimentology suggest that these subtle deviations from equal mobility may be sufficient to generate systematic patterns of sediment sorting (Church, 1987). Modification of the bedload grain size distribution occurs during transport. Of particular importance is the topographic routing of different size fractions along different transport pathways which gives rise to the sediment sorting patterns exhibited by reaches of contrasting channel pattern. Finally, the variable pocket geometry of bed surfaces and the associated turbulence intensity of flow promote sorting during deposition. The process of self-mediated entrainment/disentrainment during transport is a particularly powerful sorting mechanism, especially in poorly graded sediments.

This review demonstrates that sorting at all three stages of the bedload transfer process is important in the development of fluvial sedimentology. It has also highlighted some of the interdependencies that exist between patterns and processes of sorting at different spatial and temporal scales. These scale dependencies are poorly understood. Future

research should, therefore, move on from the study of individual morphological and sedimentological components of gravel-bed rivers and focus more on the feedback linkages that exist between patterns and processes of sorting across scales ranging from assemblages of only a few particles to the grading of sediment over the longitudinal profile.

The recognition that processes generate pattern and that patterns have consequences for higher/lower-level processes is an important one, but it should not be pursued uncritically. Relationships between pattern and process are likely to vary as a function of scale. For example, the simulations of downstream fining described above are the results of modelling sediment transport mechanics at engineering-geomorphic timescales and are therefore constrained by initial profile configuration, stream hydrology and sediment supply. The rapidity at which significant downstream fining can develop and the length of time it can persist suggest that autogenic modification of bed surface texture is an important mechanism of gravel-bed river adjustment to disequilibrium conditions. Because of the fundamental causal links between subsidence, deposition and downstream fining, such studies can be extended to model the filling of alluvial basins with gravel and sand (e.g., Paola, 1988; Paola *et al.*, 1992a). Geological models that relate sedimentation to subsidence can be used to reconstruct the palaeohydraulics of ancient deposits (e.g., Robinson and Slingerland, in press) and interpret basinal stratigraphy (e.g., Heller and Paola, 1992). However, the extent to which the controls of downstream fining that operate at geomorphic timescales are manifested at geological timescales is, at present, uncertain (Robinson and Slingerland, in press). Moreover, other studies have shown that the sedimentary response of infilling basins to changes in governing variables depends on the timescale of change as well as the magnitude of the change (Paola *et al.*, 1992a). If different controls are dominant at different timescales, great care is required in making comparisons between studies undertaken at different scales. Understanding gained from laboratory-based experiments or studies undertaken at individual field sites may not, for example, scale up to the drainage network where spatial variations in sediment supply (e.g., Rice, 1994; Pizzuto, 1995) and transport dynamics (e.g., Lisle, 1995) become important. In a similar vein, understanding the controls on grain size variation at drainage-basin scales may not be relevant for understanding the stratigraphy of basin fills and other geological deposits. Clearly, improvements in our understanding of modern and ancient sedimentary deposits require a greater awareness of the spatial and temporal bounds of the linkages that exist between patterns and processes of sediment sorting at different scales.

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References

Abbott, P.L. and **Peterson, G.L.** 1978: The effects of abrasion durability on conglomerate clast populations: examples from Cretaceous and Eocene conglomerates of the San Diego area, California. *Journal of Sedimentary Petrology* 48, 31–42.

Allen, J.R.L. 1970: Studies in fluviatile sedimentation: a comparison of fining-upwards cyclotherms, with special reference to coarse-member composition and interpretation. *Journal of Sedimentary Petrology* 40, 298–323.

American Society of Civil Engineers Task Committee 1992: Sediment and aquatic habitat in river systems. *Journal of Hydraulic Engineering* 118, 669–87.

Andrews, E.D. 1984: Bed material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. *Bulletin of the Geological Society of America* 95, 371–78.

Andrews, E.D. and **Erman, D.C.** 1986: Persistence in the size distribution of surficial bed material during an extreme snowmelt flood, Sagehen Creek, northeastern California. *Water Resources Research* 22, 191–97.

Andrews, E.D. and **Parker, G.** 1987: Formation of a coarse surface layer as the response to gravel mobility. In Thorne, C.R., Bathurst, J.C. and Hey, R.D., editors, *Sediment transport in gravel-bed rivers*, Chichester: Wiley, 269–300.

Ashmore, P.E. 1982: Laboratory modelling of gravel, braided stream morphology. *Earth Surface Processes and Landforms* 7, 201–25.

Ashmore, P.E., Ferguson, R.I., Prestegaard, K., Ashworth, P.J. and **Paola, C.** 1992: Secondary flow in coarse-grained braided river confluences. *Earth Surface Processes and Landforms* 17, 299–311.

Ashmore, P.E. and **Parker, G.** 1983: confluence scour in coarse braided streams. *Water Resources Research* 19, 392–402.

Ashworth, P.J. 1988. Gravel transport in braided stream systems using a combined field/laboratory approach. Unpublished fellowship report, Natural Environment Research Council.

—— 1996: Mid-channel bar growth and its relationship to local flow strength and direction. *Earth Surface Processes and Landforms* 21, 103–23.

Ashworth, P.J., Bennett, S.J., Best, J.L. and **McLelland, S.J.**, editors, 1996: *Coherent flow structures in open channels*. Chichester: Wiley.

Ashworth, P.J. and **Ferguson, R.I.** 1986: Interrelationships of channel processes, changes and sediments in a proglacial braided river. *Geografiska Annaler* 68A, 361–71.

—— 1989: Size selective entrainment of bedload in gravel bed streams. *Water Resources Research* 25, 627–34.

Ashworth, P.J., Ferguson, R.I., Ashmore, P.E., Paola, C., Powell, D.M. and **Prestegaard, K.L.** 1992a: Measurements in a braided river chute and lobe. 2. Sorting of bedload during entrainment, transport and deposition. *Water Resources Research* 28, 1887–96.

Ashworth, P.J., Ferguson, R.I. and **Powell, D.M.** 1992b: Bedload transport and sorting in braided channels. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*. Chichester: Wiley, 497–513.

Bennett, S.J. and **Bridge, J.S.** 1995: The geometry and dynamics of low-relief bedforms in heterogeneous sediment in a laboratory channel, and their relationship to water flow and sediment transport. *Journal of Sedimentary Research* 65A, 29–39.

Best, J.L. 1987: Flow dynamics at river channel confluences: implications for sediment transport and bed morphology. In Ethridge, F.G., Flores, R.M. and Harvey, M.D., editors, *Recent developments in fluvial sedimentology. Society of Economic Palaeontologists and Mineralogists, Special Publication* 39, Tulsa, OK: SEPM, 27–35.

Biron, P., De Serres, B., Roy, A.G. and **Best, J.L.** 1993: Bed morphology and sedimentology at the confluence of unequal depth channels. *Geomorphology* 8, 115–29.

Bluck, B.J. 1971: Sedimentation in the meandering R. Endrick. *Scottish Journal of Geology* 7, 93–138.

—— 1982: Texture of gravel bars in braided streams. In Hey, R.D., Bathurst, J.C. and Thorne, C.R., editors, *Gravel-bed rivers: fluvial processes, engineering and management*, Chichester: Wiley, 339–55.

—— 1987: Bed forms and clast size changes in gravel-bed rivers. In Richards, K.S., editor, *River channels: environment and process*, Oxford: Blackwell, 159–78.

Boothroyd, J.C. and **Ashley, G.M.** 1975: Process, bar morphology and sedimentary structures on braided outwash fans, northwestern Gulf of Alaska. In Jopling, V.A. and MacDonald, B., editors, *Glaciofluvial and glaciolacustrine sedimentation. SEPM Publication* 23, Tulsa, OK: SEPM, 193–222.

Bradley, W.C. 1970: Effect of weathering on abrasion of granitic material, Colorado River, Texas, *Bulletin of the Geological Society of America* 81, 61–80.

Brayshaw, A.C. 1984: Characteristics and origin of cluster bedforms in coarse grained alluvial channels. In Koster, E.H. and Steele, R.J., editors, *Sedimentology of gravels and conglomerates. Canadian Society of Petroleum Geologists Memoir* 10, Calgary: CSPG, 77–85.

Brayshaw, A.C., Frostick, L.E. and **Reid, I.** 1983: The hydrodynamics of particle clusters and sediment entrainment in coarse alluvial channels. *Sedimentology* 30, 137–43.

Brewer, P.A. and **Lewin, J.** 1993: In-transport modification of alluvial sediment: field evidence and laboratory experiments. In Marzo, M. and Puigdefabregas, C., editors, *Alluvial sedimentation. International Association of Sedimentologists Special Publication* 17, Oxford: Blackwell, 23–35.

Bridge, J.S. 1977: Flow, bed topography, grain size and sedimentary structure in open channel

bends: a three-dimensional model. *Earth Surface Processes* 2, 401–16.

—— 1984: Flow and sedimentary processes in meander bends: comparison of field observations and theory. In Elliott, C.M., editor, *River meandering*, New York: American Society of Civil Engineers, 857–72.

—— 1993: The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In Best, J.L. and Bristow, C.S., editors, *Braided rivers: form, process and economic applications. Geological Society Special Publication* 75, London: Geological Society, 13–71.

Bridge, J.S. and **Bennett, S.J.** 1992: A model for the entrainment and transport of sediment grains of mixed sizes, shapes and densities. *Water Resources Research* 28, 337–63.

Bridge, J.S. and **Gabel, S.L.** 1992: Flow and sediment dynamics in a low sinuosity river: Calamus River, Nebraska Sandhills. *Sedimentology* 39, 125–42.

Bridge, J.S. and **Jarvis, J.** 1976: Flow and sedimentary processes in the meandering river South Esk, Glen Cova, Scotland. *Earth Surface Processes* 1, 303–36.

—— 1982: The dynamics of a river bend: a study in flow and sedimentary processes. *Sedimentology* 29, 499–541.

Brierley, G.J. and **Hickin, E.J.** 1985: The downstream gradation of particle sizes in the Squamish River, British Columbia. *Earth Surface Processes and Landforms* 11, 643–52.

Buffington, J.M., Dietrich, W.E. and **Kirchner, J.W.** 1992: Friction angle measurements on a naturally formed gravel stream bed, implications for critical boundary shear stress. *Water Resources Research* 28, 411–25.

Buffington, J.M. and **Montgomery, D.R.** 1997: A systematic analysis of eight decades of incipient motion studies with special reference to gravel-bedded rivers. *Water Resources Research* 33, 1993–2029.

Carling, P.A. and **Dawson, M.R.**, editors, 1996: *Advances in fluvial dynamics and stratigraphy*. Chichester: Wiley.

Carling, P.A., Kelsey, A. and **Glaister, M.S.** 1992: Effect of bed roughness, particle shape and orientation on initial motion criteria. In Thorne, C.R., Bathurst, J.C. and Hey, R.D., editors, *Sediment transport in gravel-bed rivers*, Chichester: Wiley, 23–37.

Carson, M.A. 1986: Characteristics of high energy 'meandering' rivers: the Canterbury Plains, New Zealand. *Bulletin of the Geological Society of America* 97, 886–95.

Church, M.A. 1987: Discussion of Andrews, E.D. and Parker, G., *Formation of a coarse surface layer as the response to gravel mobility*. In Thorne, C.R., Bathurst, J.C. and Hey, R.D., editors, *Sediment transport in gravel-bed rivers*, Chichester: Wiley, 314–22.

Church, M.A., McLean, D.G. and **Wolcott, J.F.** 1987: River bed gravels: sampling and analysis. In Thorne, C.R., Bathurst, J.C. and Hey, R.D., editors, *Sediment transport in gravel-bed rivers*, Chichester: Wiley, 43–79.

Church, M.A., Wolcott, J.F. and **Fletcher, W.K.** 1991: A test of equal mobility in fluvial sediment transport: behaviour of the sand fraction. *Water Resources Research* 27, 2941–51.

Clifford, N.J., Hardisty, J., French, J.R. and **Hart, S.** 1993: Downstream variation in bed material characteristics in the braided River Swale: a turbulence-controlled form-process feedback mechanism. In Best, J.L. and Bristow, C.S., editors, *Braided rivers: form, process and economic applications. Geological Society Special Publication* 75, London: Geological Society, 89–104.

Davoren, A. and **Mosley, M.P.** 1986: Observations of bedload movement, bar development and sediment supply in the braided Ohau River. *Earth Surface Processes and Landforms* 11, 643–52.

Dawson, M. 1988: Sediment size variations in a braided reach of the Sunwapta River, Alberta, Canada. *Earth Surface Processes and Landforms* 13, 599–618.

Dietrich, W.E. 1987: Mechanics of flow and sediment transport in river bends. In Richards, K.S., editor, *River channels: environment and process*, Oxford: Blackwell, 179–227.

Dietrich, W.E., Kirchner, J.W., Ikeda, H. and **Iseya, F.** 1989: Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature* 340, 215–17.

Dietrich, W.E. and **Smith, J.D.** 1983: Influence of the point bar on flow through curved channels. *Water Resources Research* 19, 1173–92.

—— 1984: Bedload transport in a river meander. *Water Resources Research* 20, 1355–80.

Dietrich, W.E. and **Whiting, P.** 1989: Boundary shear stress and sediment transport in river meanders of sand and gravel. In Ikeda, H. and Parker, G., editors, *River meandering. Water Resources Monograph* 12, Washington DC: American Geophysical Union, 1–50.

Diplas, P. 1987: Bedload transport in gravel-bed streams. *Proceedings of the American Society of Civil Engineers, Journal of Hydraulic Engineering* 113, 277–92.

Dunkerley, D.L. 1990: The development of armour in the Tambo River, Victoria, Australia. *Earth Surface Processes and Landforms* 15, 405–15.

Egiazaroff, I.V. 1965: Calculation of nonuniform sediment concentrations. *Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division* 91, 225–47.

Einstein, H.A. 1950: *The bed load function for sediment transportation in open channel flows. United States Department of Agriculture Technical Bulletin* 1026. Washington DC: US Department of Agriculture.

Fenton, J.D. and **Abbott, J.E.** 1977: Initial movement of grains on a stream bed: the effect of relative protrusion. *Proceedings of the Royal Society* 352A, 523–37.

Ferguson, R.I. 1987: Discussion of Andrews, E.D. and Parker, G., *Formation of a coarse surface layer as the response to equal mobility*. In Thorne, C.R., Bathurst, J.C. and Hey, R.D., editors, *Sediment transport in gravel-bed rivers*. Chichester: Wiley, 306–309.

—— 1993: Understanding braiding processes in gravel-bed rivers: progress and unresolved problems. In Best, J.L. and Bristow, C.S., editors, *Braided rivers: form, process and economic applications. Geological Society Special Publication* 75, London: Geological Society, 73–87.

Ferguson, R.I., Ashmore, P.E., Ashworth, P.J., Paola, C. and **Prestegaard, K.L.** 1992: Measurements in a braided river chute and lobe. 1. Flow pattern, sediment transport and channel change. *Water Resources Research* 28, 1877–86.

Ferguson, R.I. and **Ashworth, P.J.** 1991: Slope-induced changes in channel character along a gravel-bed stream: the Alt Dubhaig, Scotland. *Earth Surface Processes and Landforms* 16, 65–82.

Ferguson, R.I., Prestegaard, K. and **Ashworth, P.J.** 1989: Influence of sand on hydraulics and gravel transport in a braided, gravel-bed river. *Water Resources Research* 25,635–43.

Force, E.R. 1991: Placer deposits. In Force, E.R., Eidel, J.J. and Maynards, J.B., editors, *Sedimentary and diagenetic mineral deposits: a basin analysis approach to exploration. Reviews in Economic Geology*, 5, Society of Economic Geologists, 131–40.

Gessler, J. 1971: Beginning and ceasing of sediment motion. In Shen, H.W., editor, *River mechanics*, Fort Collins, CO: Colorado State University, 7: 1–7:22.

Gomez, B. 1983: Temporal variations in bedload transport rates: the effect of progressive bed armouring. *Earth Surface Processes and Landforms* 8, 41–54.

—— 1995: Bedload transport and changing grain size distributions. In Gurnell, A. and Petts, G., editors, *Changing river channels*, Chichester: Wiley, 177–99.

Gordon, N.D., McMahon, T.A. and **Finlayson, B.L.** 1992: *Stream hydrology: an introduction for ecologists*. Chichester: Wiley.

Hammond, F.D.C., Heathershaw, A.D. and **Langhorne, D.N.** 1984: A comparison between Shields' threshold criterion and the movement of loosely packed gravel in a tidal channel. *Sedimentology* 31, 51–62.

Harrison, A.S. 1950: *Report on special investigation of bed sediment segregation in a degrading bed. US Army Corps of Engineers, Missouri River Division, Sediment Series* 30.

Heller, P.L. and **Paola, C.** 1992: The large-scale dynamics of grain-size variation in alluvial basins. 2. Application to syntectonic conglomerate. *Basin Research* 4, 91–102.

Hoey, T. and **Ferguson, R.I.** 1994: Numerical modelling of downstream fining by selective transport in gravel-bed rivers: model development and illustration. *Water Resources Research* 30, 2251–60.

Hooke, R.L. 1975: Distribution of shear stress and sediment transport in a meander bend. *Journal of Geology* 83, 543–65.

Ikeda, S. and **Parker, G.**, editors, 1989: *River meandering. American Geophysical Union Water Resources Monograph*. 12. Washington, DC: American Geophysical Union.

Iseya, F. and **Ikeda, H.** 1987: Pulsations in bedload transport rates induced by a longitudinal sediment sorting: a flume study using sand and gravel mixtures. *Geografiska Annaler* 69A, 15–27.

Keller, E.A. 1971: Areal sorting of bedload material: the hypothesis of velocity reversal. *Bulletin of the Geological Society of America* 82, 753–56.

Kelsey, A. 1996: Modelling the sediment transport process. In Carling, P.A. and Dawson, M.R., editors, *Advances in fluvial dynamics and stratigraphy*, Chichester: Wiley, 229–61.

Kirchner, J.W., Dietrich, W.D., Iseya, F. and **Ikeda, H.** 1990: The variability of critical shear stress, friction angle and grain protrusion in water-worked sediments. *Sedimentology* 37, 647–72.

Klingeman, P.C. and **Emmett, W.W.** 1982: Gravel bedload transport processes. In Hey, R.D., Bathurst, J.C. and Thorne, C.R., editors, *Gravel-bed rivers: fluvial processes, engineering and management*, Chichester: Wiley, 141–69.

Knighton, A.D. 1980: Longitudinal changes in size and sorting of stream-bed material in four English rivers. *Bulletin of the Geological Society of America* 91, 55–62.

—— 1987: River channel adjustment – the downstream dimension. In Richards, K., editor, *River channels: environment and process*, Oxford: Blackwell, 95–128.

Kodama, Y. 1994a: Downstream changes in lithology and grain size of fluvial gravels, the Watarase River, Japan: evidence of the role of abrasion in downstream fining. *Journal of Sedimentary Research* 64A, 68–75.

—— 1994b: Experimental study of abrasion and its role in producing downstream fining in gravel-bed rivers. *Journal of Sedimentary Research* 64A, 76–85.

Komar, P.D. 1989a: Physical processes of waves and currents and the formation of marine placers. *CRC Critical Reviews in Aquatic Sciences* 1, 393–423.

—— 1989b: Flow competence evaluations of hydraulic parameters of floods: an assessment of the technique. In Beven, K. and Carling, P.A., editors, *Floods: hydrological, sedimentological and geomorphological implications*, Chichester: Wiley, 107–34.

—— 1996: Entrainment of sediments from deposits of mixed grain sizes and densities. In Carling, P.A. and Dawson, M.R., editors, *Advances in fluvial dynamics and stratigraphy*, Chichester: Wiley, 128–81.

Komar, P.D. and **Carling, P.** 1991: Grain sorting in gravel bed streams and the choice of particle sizes for flow competence evaluations. *Sedimentology* 38, 489–502.

Komar, P.D. and **Li, Z.** 1986: Pivoting analyses of the selective entrainment of sediments by shape and size with application to the gravel threshold. *Sedimentology* 33, 425–36.

—— 1988: Applications of grain pivoting and sliding analyses to selective entrainment of gravel and to flow competence evaluations. *Sedimentology* 35, 681–95.

Komar, P.D. and **Shih, S.-M**. 1992: Equal mobility versus changing bedload grain sizes in gravel-bed streams. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*, Chichester: Wiley, 73–93.

Komura, S. and **Simons, D.B.** 1967: River bed degradation below dams. *Journal of the Hydraulics Division, American Society of Civil Engineers* 93, 1–14.

Koster, E.H. 1978: Transverse ribs: their characteristics, origin and paleohydraulic significance. In Miall, A.D., editor, *Fluvial sedimentology. Canadian Society of Petroleum Geologists Memoir* 5, Calgary, CSPG, 161–86.

Kuenen, P.H. 1966: Experimental turbidite lamination in a circular flume. *Journal of Geology* 74, 523–45.

Kuhnle, R.A. 1989: Bed surface size changes in a gravel bed channel. *Journal of Hydraulic Engineering* 115, 731–43.

—— 1992: Fractional transport rates of bedload on Goodwin Creek. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*, Chichester: Wiley, 141–55.

—— 1993a: Incipient motion of sand-gravel sediment mixtures. *Journal of Hydraulic Engineering* 119, 1400–15.

—— 1993b: Fluvial transport of sand and gravel mixtures with bimodal size distributions. *Sedimentary Geology* 85, 17–24.

Laronne, J.B., Reid, I., Frostick, L.E. and **Yitshak, Y.** 1994: The non-layering of gravel streambeds under ephemeral flood regimes. *Journal of Hydrology* 159, 353–63.

Lisle, T.E. 1979: A sorting mechanism for a riffle-pool sequence. *Bulletin of the Geological Society of America* 90, 1142–57.

—— 1995: Particle size variations between bed load and bed material in natural gravel bed channels. *Water Resources Research* 31, 1107–18.

Lisle, T.E., Ikeda, H. and **Iseya, F.** 1991: Formation of alternate stationary bars in a steep channel with mixed size sediment: a flume experiment. *Earth Surface Processes and Landforms* 16, 463–69.

Lisle, T.E. and **Madej, M.A.** 1992: Spatial variation in armouring in a channel with high sediment supply. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*, Chichester: Wiley, 277–91.

Mackin, J.H. 1948: Concept of the graded river. *Bulletin of the Geological Society of America* 59, 463–512.

Macklin, M.G., Hudson-Edwards, K.A. and **Dawson, E.J.** 1997: The significance of pollution from historic metal mining in the Pennine orefields on river sediment contaminant fluxes to the North Sea. *Science of the Total Environment* 194, 391–97.

Markham, A.J. and **Thorne, C.R.** 1992: Geomorphology of gravel-bed river bends. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*, Chichester: Wiley, 432–50.

McDonald, B.C. and **Banerjee, I.** 1971: Sediments and bedforms on a braided outwash plain. *Canadian Journal of Earth Sciences* 8, 1282–301.

McLelland, S.J., Ashworth, P.J. and **Best, J.L.** 1996: The origin and downstream development of coherent flow structures at channel junctions. In

Ashworth, P.J., Bennett, S.J., Best, J.L. and McLelland, S.J., editors, *Coherent flow structures in open channels*, Chichester: Wiley, 459–90.

Mikos, M. 1994: The downstream fining of gravel-bed sediments in the Alpine Rhine River. In Ergenzinger, P. and Schmidt, K.-H., editors, *Dynamics and geomorphology of mountain rivers*, Springer, 93–108.

Miller, M.C., McCave, I.N. and **Komar, P.D.** 1977: Threshold of sediment motion under unidirectional currents. *Sedimentology* 24, 507–27.

Miller, R.L. and **Byrne, R.J.** 1966: The angle of repose for a single grain on a fixed rough bed. *Sedimentology* 6, 303–14.

Milne, J.A. 1982: Bed material grain size and the riffle-pool sequence. *Sedimentology* 29, 267–78.

Montgomery, D.R., Buffington, J.M., Peterson, N.P., Schuett-Hames, D. and **Quinn, T.P.** 1996: Streambed scour, egg burial depths and the influence of salmonid spawning on bed surface mobility and embryo survival. *Canadian Journal of Fisheries and Aquatic Science* 53, 1061–70.

Mosley, M.P. 1976: An experimental study of channel confluences. *Journal of Geology* 84, 535–62.

Moss, A.J. 1963: The physical nature of the common sandy and pebbly deposits. Part II. *American Journal of Science* 261, 297–343.

—— 1972: Bedload sediments. *Sedimentology* 18, 159–219.

Naden, P.S. and **Brayshaw, A.C.** 1987: Small- and medium-scale bedforms in gravel-bed rivers. In Richards, K., editor, *River channels: environment and processes*, Oxford: Blackwell, 249–71.

Paola, C. 1988: Subsidence and gravel transport in alluvial basins. In Kleinspehn, K.L. and Paola, C., editors, *New perspectives in basin analysis*, New York: Springer-Verlag, 231–43.

—— 1989: Topographic sorting. *EOS* 70, 323.

Paola, C., Gust, G. and **Southard, J.B.** 1986: Skin friction behind isolated hemispheres and the formation of obstacle marks. *Sedimentology* 3, 269–93.

Paola, C., Heller, P.L. and **Angevine, C.L.** 1992a: The large-scale dynamics of grain size variation in alluvial basins. 1. Theory. *Basin Research* 4, 73–90.

Paola, C., Parker, G., Seal, R., Sinha, S.K., Southard, J.B. and **Wilcock, P.R.** 1992b: Downstream fining by selective deposition in a laboratory flume. *Science* 258, 1757–60.

Paola, C. and **Seal, R.** 1995: Grain size patchiness as a cause of selective deposition and downstream fining. *Water Resources Research* 31, 1395–407.

Parker, G. 1990: Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research* 28, 417–36.

—— 1991a: Selective sorting and abrasion of river gravel. I. Theory. *Proceedings of the American Society of Civil Engineers, Journal of Hydraulic Engineering* 117, 131–49.

—— 1991b: Selective sorting and abrasion of river gravel. II. Applications. *Proceedings of the American Society of Civil Engineers, Journal of Hydraulic Engineering* 117, 151–71.

—— 1992: Some random notes on grain sorting. In Vischer, D., editor, *Proceedings of the international grain sorting seminar, October, 1991, Ascona, Switzerland*, 19–76.

Parker, G. and **Andrews, E.D.** 1985: Sorting of bedload sediments by flow in meander bends. *Water Resources Research* 21, 1361–73.

Parker, G., Dhamotharan, S. and **Stefan, H.** 1982b: Model experiments on mobile, paved gravel-bed streams. *Water Resources Research* 18, 1395–408.

Parker, G. and **Klingeman, P.C.** 1982: On why gravel bed streams are paved. *Water Resources Research* 18, 1409–23.

Parker, G., Klingeman, P.C. and **McLean, D.C.** 1982a: Bedload and size distribution in paved, gravel-bed streams. *Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division* 108, 544–71.

Parker, G. and **Sutherland, A.J.** 1990: Fluvial armour. *Journal of Hydraulic Research* 28, 529–44.

Pizzuto, J.E. 1995: Downstream fining in a network of gravel-bedded rivers. *Water Resources Research* 31, 753–59.

Pettijohn, F.J. 1975: *Sedimentary rocks*. New York: Harper and Row.

Plumley, W.J. 1948: Black hills terrace gravels: a study in sediment transport. *Journal of Geology* 56, 527–77.

Reid, I., Frostick, L.E. and **Brayshaw, A.C.** 1992: Microform roughness elements and the selective entrainment and entrapment of particles in gravel-bed rivers. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*, Chichester: Wiley, 253–66.

Rhoads, B.L. 1996: Mean structure of transport effective flows at an asymmetrical confluence when the main stream is dominant. In Ashworth, P.J., Bennett, S.J., Best, J.L. and McLelland, S.J., editors, *Coherent flow structures in open channels*, Chichester: Wiley, 491–518.

Rhoads, B.L. and **Kenworthy, S.T.** 1995: Flow structure at an asymmetrical stream confluence. *Geomorphology* 11, 273–93.

Rice, S. 1994: Towards a model of changes in bed material texture at the drainage basin scale. In

Kirkby, M.J., editor, *Process models and theoretical geomorphology*, Chichester: Wiley, 159–72.

Richards, K.S. 1990: Fluvial geomorphology: initial motion of bed material in gravel-bed rivers. *Progress in Physical Geography* 14, 395–415.

Richards, K.S. and **Clifford, N.J.** 1991: Fluvial geomorphology: structured beds in gravelly rivers. *Progress in Physical Geography* 15, 407–22.

Richardson, W.R.R., Thorne, C.R. and **Mahmood, S.** 1996: Secondary flow and channel changes around a bar in the Brahmaputra River, Bangladesh. In Ashworth, P.J., Bennett, S.J., Best, J.L. and McLelland, S.J., editors, *Coherent flow structures in open channels*, Chichester: Wiley, 519–43.

Robert, A. 1990: Boundary roughness in coarse-grained channels. *Progress in Physical Geography* 14, 42–70.

Robert, A., Roy, A.G. and **De Serres, B.** 1992: Changes in velocity profiles at roughness transitions in coarse grained channels. *Sedimentology* 39, 725–35.

—— 1996: Turbulence at a roughness transition in a depth limited flow over a gravel bed. *Geomorphology* 16, 175–87.

Robinson, R.A.J. and **Slingerland, R.L.** in press: Origin of fluvial grain-size trends in a foreland basin: the Pocono formation of the central Appalachian Basin. *Journal of Sedimentary Research*.

Roy, A.G. and **Bergeron, N.** 1990: Flow and particle paths at a natural confluence with coarse bed material. *Geomorphology* 3, 99–122.

Sambrook Smith, G.H. and **Ferguson, R.I.** 1995: The gravel–sand transition along alluvial river channels. *Journal of Sedimentary Research* 65A, 423–30.

—— 1996: The gravel–sand transition: a flume study of channel response to reduced slope. *Geomorphology* 16, 147–59.

Sambrook Smith, G.H., Nicholas, A.P. and **Ferguson, R.I.** 1997: Measuring and defining bimodal sediments: problems and implications. *Water Resources Research* 33, 1179–85.

Schumm, S.A. and **Stevens, M.A.** 1973: Abrasion in place: a mechanism for rounding and size reduction in coarse sediments in rivers. *Geology* 1, 37–40.

Seal, R. and **Paola, C.** 1995: Observations of downstream fining on the North Fork Toutle River near Mount St Helens, Washington. *Water Resources Research* 31, 1409–19.

Shaw, J. and **Kellerhals, R.** 1982: *The composition of recent alluvial gravels in Alberta river beds. Alberta Research Council Bulletin* 41. Edmonton: Alberta Research Council.

Shields, A. 1936: *Anwendung der ähnlichkeitsmechanik und der turbulenzforschung auf die geschiebebewegung. Mitteilung der Preussischen versuchsanstalt fuer Wasserbau und Schiffbau* Heft 26, Berlin (trans. Ott, W.P. and van Uchlen, J.C., Pasadena, CA: United States Department of Agriculture, Soil Conservation Service, Coop Lab., California Institute of Technology).

Shih, S.-M. and **Komar, P.D.** 1990a: Hydraulic controls of grain size distributions of bedload gravels in Oak Creek, Oregon, USA. *Sedimentology* 37, 367–76.

—— 1990b: Differential bedload transport rates in a gravel-bed stream: a grain size distribution approach. *Earth Surface Processes and Landforms* 15, 539–52.

Slingerland, R. and **Smith, N.D.** 1986: Occurrence and formation of water-laid placers. *Annual Review of Earth and Planetary Sciences* 14, 113–47.

Smith, J.D. and **McLean, S.R.** 1984: A model for flow in meandering streams. *Water Resources Research* 2, 1301–15.

Sternberg, H. 1875: Untersuchungen über Längen- und Querprogil Geschiebeführende Flüsse. *Zeischrift für Bauwesen* 25, 483–506.

Sutherland, A.J. 1987: Static armour layers by selective erosion. In Thorne, C.R., Bathurst, J.C. and Hey, R.D., editors, *Sediment transport in gravel-bed rivers*, Chichester: Wiley, 243–60.

van Niekirk, A., Vogel, K.R., Slingerland, R.L. and **Bridge, J.S.** 1992: Routing of heterogeneous sediments over moveable bed: model development. *Journal of Hydraulic Engineering* 118, 246–61.

Vogel, K.R., van Niekirk, A., Slingerland, R.L. and **Bridge, J.S.** 1992: Routing of heterogeneous sediments over moveable bed: model verification and testing. *Journal of Hydraulic Engineering* 118, 263–79.

Wathen, S.J., Ferguson, R.I., Hoey, T.B. and **Werritty, A.** 1995: Unequal mobility of gravel and sand in weakly bimodal river sediments. *Water Resources Research* 31, 2087–96.

Webb, B.W. and **Walling, D.E.** 1992: Water quality. II. Chemical characteristics. In Calow, P. and Petts, G.E., editors, *The rivers handbook: hydrological and ecological principles*, Oxford: Blackwell, 73–100.

Werritty, A. 1992: Downstream fining in a gravel-bed river in southern Poland: lithologic controls and the role of abrasion. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*, Chichester: Wiley, 333–50.

Whiting, P.S. and **Dietrich, W.E.** 1991: Convective accelerations and boundary shear stress over a channel bar. *Water Resources Research* 27, 783–96.

Whiting, P.S., Dietrich, W.E., Leopold, W.E., Shreve, R.L. and **Drake, T.G.** 1988: Bedload sheets in heterogeneous sediments. *Geology* 16, 105–108.

Wiberg, P.L. and **Smith, J.D.** 1987: Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. *Water Resources Research* 23, 1471–80.

Wilcock, P.R. 1988: Methods for estimating the critical shear stress of individual fractions in mixed-sized sediment. *Water Resources Research* 24, 1127–35.

—— 1992a: Experimental investigation of the effect of mixture properties on transport dynamics. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P., editors, *Dynamics of gravel-bed rivers*, Chichester: Wiley, 109–30.

—— 1992b: Flow competence: a criticism of a classic concept. *Earth Surface Processes and Landforms* 17, 289–98.

—— 1993: Critical shear stress of natural sediments. *Journal of Hydraulic Engineering* 119, 491–505.

Wilcock, P.R. and **McArdell, B.W.** 1993: Surface-based fractional transport rates: mobilisation thresholds and partial transport of a sand-gravel sediment. *Water Resources Research* 29, 1297–312.

Wilcock, P.R. and **Southard, J.B.** 1988: Experimental study of incipient motion in mixed-sized sediment. *Water Resources Research* 24, 1137–51.

—— 1989: Bed-load transport of mixed-sized sediment: fractional transport rates, bedforms and the development of a coarse bed-surface layer. *Water Resources Research* 25, 1629–41.

Williams, G.P. and **Wolman, M.G.** 1984: *Downstream effects of dams on alluvial rivers. United States Geological Survey Professional Paper* 1286. Washington, DC: US Government Printing Office.