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Spatial Variation in Armouring in a Channel with High Sediment Supply

T. E. LISLE
Pacific Southwest Research Station, Forest Service,
US Department of Agriculture,
Arcata, California, USA
& M. A. MADEJ
Redwood National Park,
Arcata, California, USA

ABSTRACT

Recent advances in our understanding of the origin and function of armouring in gravel-bed rivers have not addressed the role of non-uniformity and unsteadiness of *flow. These flow attributes have important influences on both the surface and subsurface bed material size distributions which are observed at low flow, from which we commonly make inferences concerning bedload transport at high flow.*

Bed armouring, measured as the ratio of surface to subsurface bed material grain size, is highly variable spatially in a channel in which past and present bed aggradation indicates that the sediment supply has exceeded the transport capacity. Alternate bar topography induces strong variations in boundary shear stress, especially at low flow. The resulting winnowing of *fine sediment from zones of high stress, such as riffles, and its deposition as thin sheets in zones of low stress, such as pools, produce wide variations in armouring. Linked winnowing and deposition of fine sediment in each bar pool sequence creates pronounced, local, streamwise sorting by grain size.*

Streamwise sorting can lead to pronounced apparent size-selectivity in bedload transport during subsequent rising stages. The relatively fine bedload transported during initial rising stages can originate from unarmoured deposits of *fines, where all particle sizes present on the bed surface may be nearly equally mobile. These surfaces are devoid of larger particles, however, that appear in the bedload only when coarser armoured surfaces become more widely entrained.*

13.1 INTRODUCTION

In the past decade importance advances have been made in our understanding of bedload transport over mixed-size gravel beds and, more specifically, the fractional transport rates of grain sizes in relation to their abundance in the bed surface and subsurface. The underlying assumption of theoretical approaches

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(Gessler, 1971; Parker & Kingeman, 1982; Wiberg & Smith, 1987; Andrews & Smith, Chapter 3 of this volume) and interpretations of field data (Andrews, 1983; Carling, 1989; Komar & Shih, Chapter 5 of this volume) is that under steady or quasi-steady flow conditions bedload transport rates and grain-size distributions are in equilibrium with both the hydraulic forces and the structure and grain-size distribution of a uniform bed. The same assumptions have also been the basis for laboratory experiments (Parker, Dhamotharan & Stefan, 1982; Wilcock & Southard, 1988; Kuhnle, 1989; Diplas & Parker, Chapter 15 of this volume). Although understanding equilibrium bedload transport for these relatively simple cases forms the foundation for further progress, natural channels are characterised by their non-uniformity and unsteadiness in flow. It is important to determine, therefore, how the spatial and temporal variability of a natural river affect processes observed or modelled in a local area of the bed.

The texture of channel beds is usually observed when much of the surface is out of water, or at least visible. Such observations only partially show how previous flows have modified the bed. As the flow varies over a channel with non-uniform bed topography, such as that typically produced by bars, local variability occurs in both the direction of sediment transport and the magnitude of the boundary shear stress. Some parts of the channel may continue to supply sediment to be transported, while others become sites of deposition. Non-uniformity in sediment transport leads to the wide variations in the degree of armouring that have been observed to occur locally on a streambed (Mosley & Tindale, 1985; Maloy, 1988; Church, McLean & Wolcott, 1987). The degree of armouring is the coarseness of the armour layer relative to that of the underlying bed material. In this chapter "armour layer" denotes the coarse surface layer of bed particles which is mobile during annual floods, and whose size range greater than 4 mm is completely represented by subsurface material.

The purpose of the study described here was to investigate the spatial variation in the degree of armouring and its relation to channel topography. We selected Redwood Creek for the study because it has a large in-channel supply of bedload and because we expected variations in armouring to be high and most of the bed surface to have been active during recent high flows.

13.2 REDWOOD CREEK

Redwood Creek drains a 720 km^2 basin in north coastal California, USA (Figure 13.1). Streamflow, sediment supply and transport rate, channel changes, and land-use history are well documented (Janda, 1978). The basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m; average hillslope gradient is 26% . For much of its 108-km length Redwood Creek flows along the trace of the Grogan Fault, which juxtaposes two distinct bedrock types. The east side of the basin is mostly underlain by unmetamorphosed sandstones and silt-stones of the Mesozoic Franciscan Assemblage, whereas the western side is mostly underlain by a quartz-mica schist. Both rock units have been deformed by numerous fractures and shear zones. The rock incompetence due to this deformation, coupled with high rainfall and steep terrain, contribute to the high erodibility of the catchment.

Annual sediment yields from Redwood Creek are higher than those from other rivers in the US that do not drain active volcanoes or glaciers. Water discharge records (since 1955) and sediment discharge records (since 1970) are available for five US Geological Survey (USGS) gauging stations in Redwood Creek (Figure 13.1). Sediment discharge is strongly flow-dependent and a large proportion of the annual sediment load is transported during infrequent, high-magnitude events. The estimated yield of suspended and bedload sediment from 1945 to 1980 was 2480 t/km^2 per year at South Park Boundary and 2100 t/km^2 per year at Orick (USGS, written communication, 1981). Bedload constitutes 10-30% of the clastic load. Since 1980 sediment loads have decreased to 1190 and 920 t/km^2 per year at the two stations, respectively, primarily due to mild winter storm seasons.

Logging and road construction since about 1950 have contributed greatly to the basin's high sediment yields. Early aerial photographs taken in 1936 and 1947 show that the basin was covered by old-growth redwood and

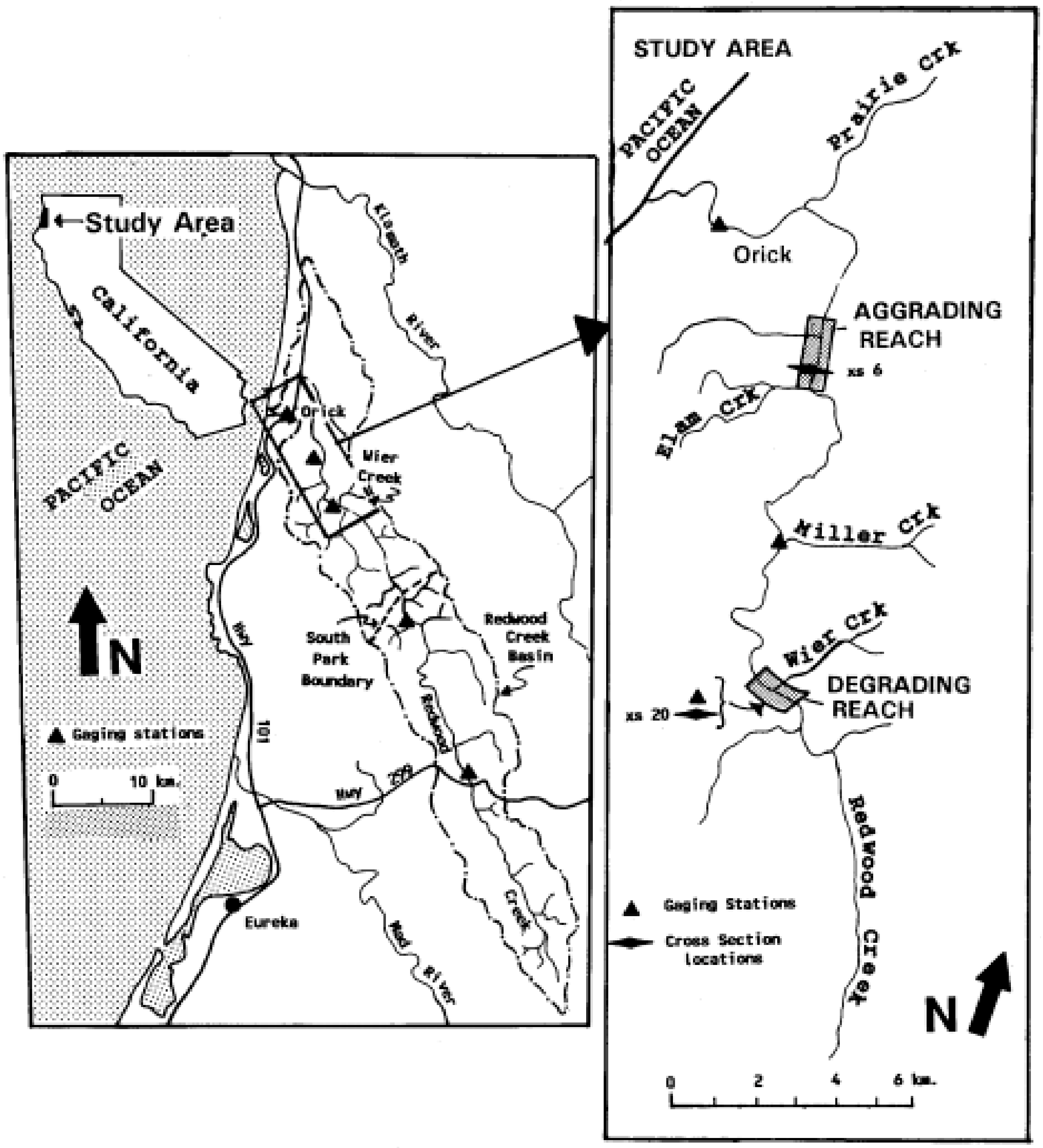


Figure 13.1 Location map showing Redwood Creek, aggraded and degraded study reaches, and five gauging stations

Douglas fir forests with only a few areas of grassland. Redwood Creek was narrow and sinuous in most reaches, and bordered by a thick canopy of trees over much of its length. Timber harvesting began in earnest in the early 1950s. By 1978, 81 % of the old-growth coniferous forest had been logged (Best, 1984) and thousands of kilometres of logging roads had been built. Erosion rates during the period of accelerated timber harvesting (Janda, 1978) were about 7.5 times greater than the natural rate estimated by Anderson (1979).

13.2.1 Channel-bed aggradation and degradation

Widespread channel-bed aggradation has occurred since 1964 in response to large floods and a destabilised landscape. Large floods occurred in the Redwood Creek basin in 1861, 1890, 1953, 1955, 1964, 1972, and 1975, but accelerated erosion and channel response was not substantial before the flood of 1964. From 1954 to 1980 a total of 30.5 x 10^6 tonnes of sediment entered Redwood Creek, mostly from streamside landslides (debris slides, streambank failures, forested block slides, and earthflows) and fluvial erosion originating on unpaved logging roads (gullies, stream diversions, failed stream crossings) (Kelsey *et al.*, 1981; Weaver, Hagans & Popenoe, 1992). Most of the sediment was input during the floods of 1964, 1972, and 1975. The 1964 flood was especially damaging. Even though the peak flow was not exceptionally high (recurrence interval of 50 years; Coghlan, 1984), the flood resulted in widespread streamside landsliding, channel aggradation (up to 7 m) and widening (Madej, 1992). Further floods of 1972 and 1975 resulted in additional aggradation in the downstream third of Redwood Creek.

Channel-stored sediment has continued to be a major source of sediment to downstream reaches. Of the total sediment eroded from 1954 to 1980, 31% was deposited in the channel and on floodplains; little sediment was stored on the steep hillslopes of the basin. From 1964 to 1980, 1.8 x 10^6 t of sediment was eroded from the channel bed in the upstream two-thirds of Redwood Creek and redeposited in large part in the downstream, lower-gradient reaches (Madej, 1992). Annual surveys since 1973 of 60 channel cross-profiles show that the 1975 flood (recurrence interval 25 years) caused the upstream third of the channel to degrade as much as 1.3 m, while the last 25 km of channel aggraded by as much as 1.5 m (Varnum & Ozaki, 1986). Since 1980 the upstream reach has stabilised at its pre-1964 level, a middle reach continues to degrade, and the last 16 km of channel either continues to aggrade or remains at an elevated level. Thus, the effects of high sediment input upstream have been felt downstream for decades.

13.2.2 Study reaches

We selected two study reaches, one showing recent degradation (Figure 13.2a), and the other, 12 km farther downstream, showing recent aggradation (Figure 13.2b). Although the upstream reach is actively degrading, stressed redwood trees rooted close to the present channel suggest that it has yet to scour down to its pre-1964 level. The reaches thus provide two case studies of armouring in channels with contrasting sediment supplies relative to capacity although, compared to many gravel-bed channels, sediment supply in both reaches is high. Both are straight, alluvial reaches at least 15 channel-widths in length and have similar channel characteristics (Table 13.1). Each reach begins and ends at a riffle crest and has well-developed alternate bars and pool-riffle sequences.

In 1988 field work commenced in the aggraded reach, and in 1989 in the degraded reach. Peak flows during 1988 and 1989 measured at a gauging station 5 km downstream of the lower study reach were 431 and 606 m^3/s, respectively (recurrence intervals of 1.3 and 1.7 years). These moderate flows caused only minor channel modifications, but were still capable of transporting considerable amounts of bedload. Annual bedload yield at Orick was similar in the two years being 56 500 t in 1988 and 55 300 t in 1989.

13.3 FIELD METHODS

13.3.1 Mapping of surface grain size and channel topography

The channel bed in both study reaches showed distinct spatial variation in bed surface texture. In order to map the spatial distribution of bed surface grain size and

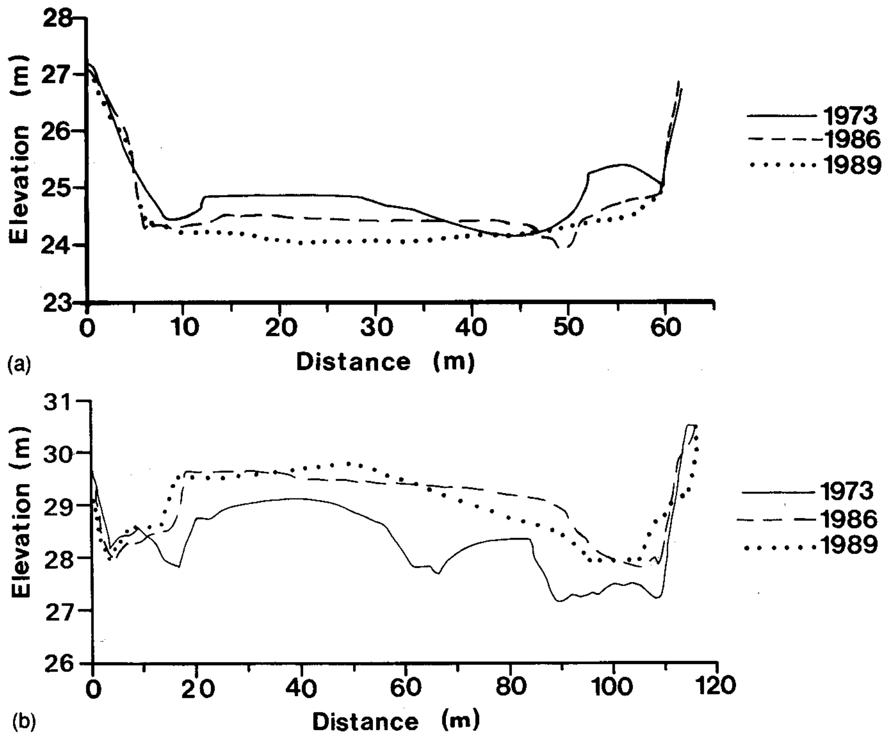


Figure 13.2 (**a**) Cross-section 20 of Redwood Creek showing a general lowering of the gravel bar surface and thalweg from 1973 to 1989. This scour is typical of the degraded reach. (**b**) Cross-section 6 of Redwood Creek showing both the gravel bar surface and thalweg at higher elevations in 1988 than in 1973. This pattern of elevated channel beds is typical of the aggraded reach

Table 13.1 Characteristics of study reaches

	Reach	
	Degraded	Aggraded
Drainage area (km^2)	523	605
Bankfull discharge (m^3/s)	370	430
Bankfull width (m)	60	110
Bankfull depth (m)	2.2	1.9
Channel gradient (m/m)	0.0026	0.0014
Length (m)	1284	1670
Sinuosity	1.09	1.03
D_{50} bed surface (mm)	22	15

to sample bed material efficiently, we stratified the bed into recognisable areas whose bed-surface grain-size composition fell into certain predetermined grain-size ranges, which were arbitrarily chosen to represent common grain-size ranges observed on the bed surface of both reaches. Individual mapped areas are referred to as facies; each facies representing one of the three or four facies types defined by a range of grain size. We delineated facies boundaries based on a visual estimate of the D_{75} of the surface particles, and then stratified individual facies by facies type for sampling purposes. In the aggraded reach the definitions of facies types were:

$D_{75} < 22$ mm = fine-pebble facies;
22 mm $< D_{75} <$ 64 mm = coarse-pebble facies;
$D_{75} > 64$ mm = cobble facies.

In the degraded reach the same definitions were used, but with the addition of a fourth facies type, bimodal sand, whose bed surface was covered with >25% sand, intermixed with coarse pebbles or cobbles.

Facies were mapped over each reach by staking out and surveying boundaries between facies. In most cases the boundaries between facies were distinct, and mappers independently delineated the same boundaries.

Table 13.2 Number of sampling units in study reaches

	Reach			
	Degraded		Aggraded	
Facies type	No. of units	Percentage of total area	No. of units	Percentage of total area
Fine-pebble	6	27.5	16	30.7
Coarse-pebble	13	43.4	19	52.9
Cobble	8	19.8	15	16.5
Bimodal	5	9.3	—	—
Total	32		50	

Topographic maps were constructed in the aggraded reach using elevation data from facies boundaries and surveying miscellaneous elevations. In the degraded reach elevation data were obtained by surveying a series of cross-sections spaced at intervals of one-third to two-thirds channel-width. Surveys encompassed the channel banks to at least bankfull height, and covered all significant topographic features of the channel bed.

We selected individual facies to be sampled on the basis of probability, proportional to size (in this case, facies area) without replacement. The number of facies sampled was proportional to the total area of the facies type relative to the total channel area (Table 13.2). We gave slightly more weight to sampling the cobble facies type because its size distribution was more variable than the other types. Total areas of each facies type were similar between the two reaches. The coarse-pebble facies, which differed most in area, would have been more similar if bimodal facies in the aggraded reach had been classified separately instead of, in most cases, being included in coarse-pebble facies. Facies types were well represented in both reaches. The bimodal facies type in the degraded reach had the smallest proportion of bed area (9.3%); the coarse-pebble type in the aggraded reach had the largest (52.9%).

13.3.2 Measurements of particle size

Surface and subsurface bed material in each selected facies were sampled systematically. Over each facies we selected 100-150 particles from paced grids (Wolman, 1954), and determined the sieve size range of each particle by passing it through a template with square holes whose sizes ranged at ½ϕ intervals down to 4 mm. The size distribution of material on the bed surface finer than 4 mm was estimated using the size distribution finer than 4 mm of sampled subsurface material, as described below.

Samples of subsurface material from each sample facies were compiled from nine to 12 subsamples taken from points on rectangular grids set up using random starts. Subsamples were taken instead of single large samples because a pilot study had shown that the median grain size of one large sample had a higher variance than that of several smaller samples of equal total weight taken from the same facies. Each compiled subsurface sample totalled about 100 kg. This sample volume was deemed adequate to give reproducible results based on the criteria of Church, McLean & Wolcott (1987) that the largest particle, which usually did not exceed 90 mm in this case, would comprise about 1% of the sample weight.

At each subsample location we removed the surface layer with a flat-bottomed shovel to a depth equal to the D_{90} size of the surface, although for fine-pebble facies we removed to about 2 cm regardless of surface grain size. We then collected a subsample of about 10 kg of subsurface material from a layer about twice as thick as that removed from the bed surface. Subsamples from areas under water were collected from inside a 30-cm-diameter cylinder that had been worked vertically into the bed (McNeil & Ahnell, 1964). Approximately 20% of all subsamples were taken under water.

Samples were air-dried and field-sieved into size classes at ½ϕ intervals down to 11 mm, and weighed. The fraction finer than 11 mm was split, and a 6-8 kg subsample was brought back to a laboratory to be sieved at ½ϕ size intervals down to 1 mm. The fraction finer than 1 mm was disregarded because suspended sediment samples (US Geological Survey, 1970-88) indicated that 1 mm was the approximate upper size limit of suspended sediment, which we assumed did not play a role in armouring processes. Samples taken under water were wet-sieved in the field down to 11 mm, the finer fraction was split and retained for dry-sieving in the laboratory, and wash water containing suspended material was discarded.

13.3.3 Data analysis

Particle size distributions of the surface and subsurface material, expressed as the percentage by weight falling within each size class, were computed for each sampled facies. Sampling of surface and subsurface material by different methods may lead to non-equivalent grain size distributions, but on the basis of the theoretical analysis of Kellerhals & Bray (1971), we assumed that grain-size distributions from grid-by-number measurements (pebble counts) are equivalent to those from sieve-by-weight measurements (subsurface material). This assumption is also supported by the results of an empirical test by Church, McLean & Wolcott (1987).

From these distributions, values of median grain size (D_{50}) weighted by area in each step were computed for each sampled facies, then each facies type and, finally, for the reach as a whole. Similarly, the distributions for each facies were weighted by area to compute mean percentages of each size class for each type and for each study reach, using a method suggested by James Baldwin of the US Forest Service, Berkeley, California. Values of D_{50} for surface and subsurface material and D_{50} (surface)/D_{50}(subsurface), hereafter referred to as the D_{50} ratio, were computed for each facies type and a mean weighted average determined for the study reach.

13.4 RESULTS

13.4.1 Spatial distribution of facies types

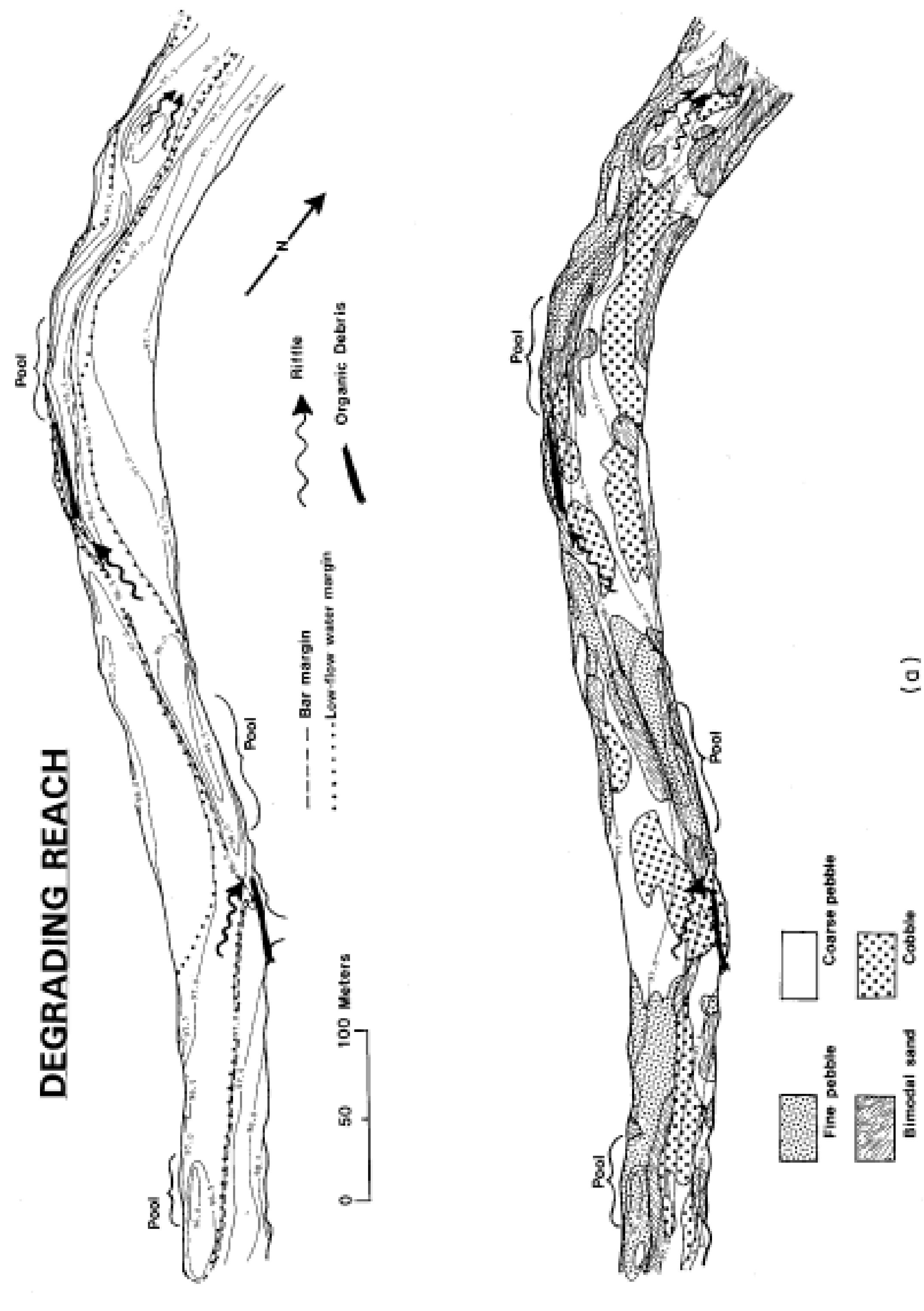
The coarseness of the bed surface correlated commonly with the qualitative magnitude of boundary shear stress at moderate flow when the bed surface was last active. Cobble facies commonly occurred in zones of high or downstream-increasing boundary shear stress where the thalweg crossed a bar and entered the pool downstream. At low flow these areas appeared as riffles and the upstream sub-aerial portions of bar surfaces (Figure 13.3). Fine-pebble facies occurred in zones of low or downstream-decreasing shear stress such as pools, downstream portions of bars, and along streambanks. Bimodal facies in the degrading reach were commonly found near riffle crests. Regarding the wetted channel at low to moderate flow, a downstream repeating sequence was formed in concert with bar-pool sequences: coarse riffles with high boundary shear stress were followed by fine-grained pools with low shear stress.

13.4.2 Size distributions of facies types

Mean surface and subsurface grain size distributions for the reaches as a whole and for each facies type showed distinct patterns (Figure 13.4). All the grain-size distributions (except surface sizes of bimodal facies) were unimodal, spanning sizes from sand to large cobbles. All sizes present in surface material of each facies type were also present in the respective sub-surface material. Subsurface grain-size distributions were similar between the different facies, particularly near the coarse end of the size spectrum.

Coarser facies were more strongly armoured than finer ones. With increasing coarseness of facies type, subsurface material became coarser, but not as much so as surface material. Similar results in another channel are reported by Maloy (1988). As quantified by D_{50} ratios (Table 13.3), cobble facies in Redwood Creek were most strongly armoured while coarse-pebble facies exhibited an intermediate degree of armouring approximately equal to that of the channel as a whole.

The coarse limbs of the frequency distributions of surface and subsurface material of the coarse-pebble and cobble facies appeared to be similar. To evaluate this similarity we matched the mode of the surface material to the corresponding frequency of the same grain size of the subsurface material and reduced the remainder of the distribution of surface material by the same proportion. The coarse limbs of surface and sub-surface material of the coarse-pebble and cobble facies then corresponded closely, while the fine limbs


DEGRADING REACH
Pool
Pool
Pool
Riffle
Organic Debris
Bar margin
Low-flow water margin
N
0
50
100 Meters
Pool
Pool
Pool
Fine pebble
Bimodal sand
Coarse pebble
Cobble
(a)

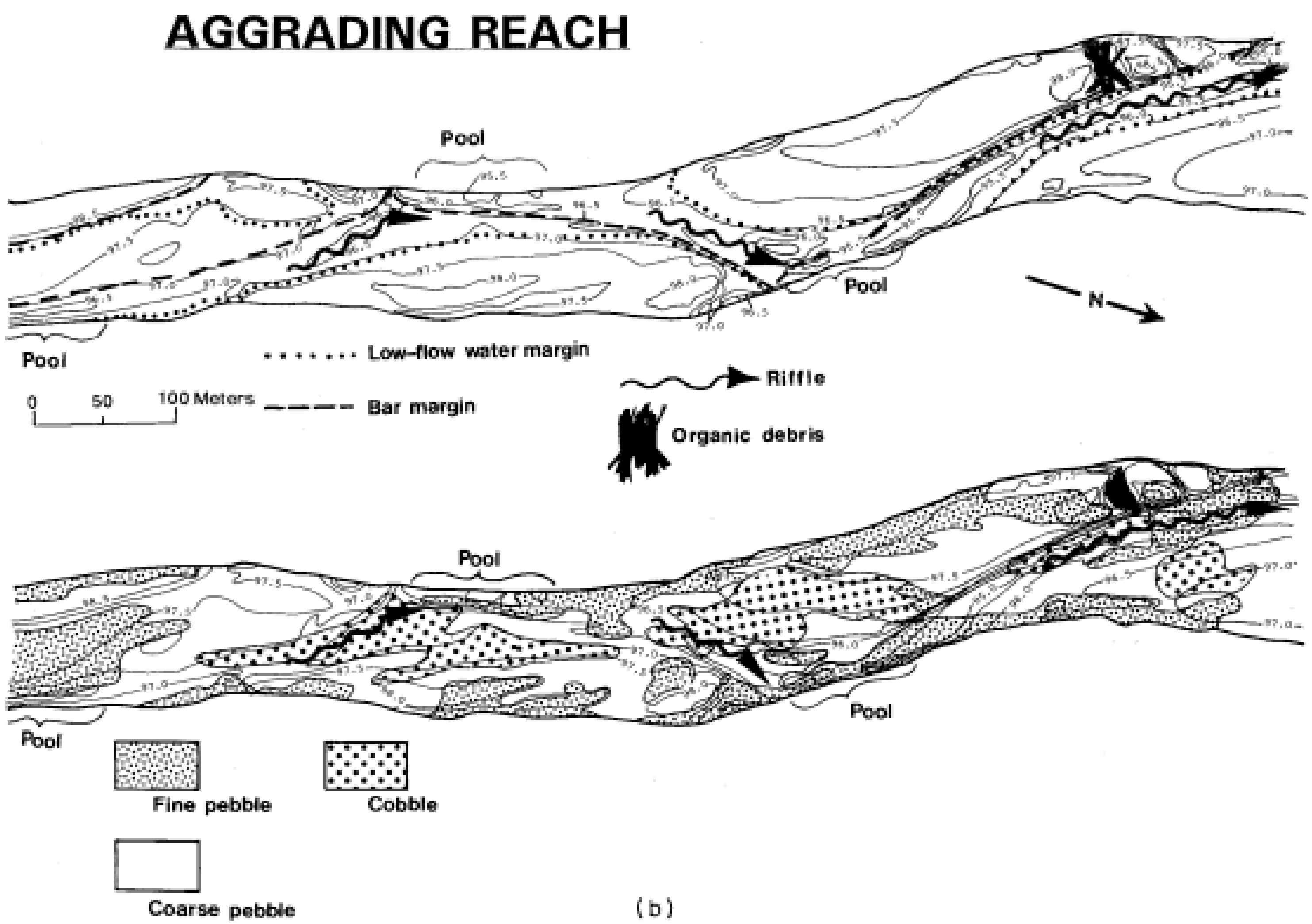


Figure 13.3 Channel bed topography and facies of the degraded and aggraded study reaches, Redwood Creek. Contour interval is 0.5 m

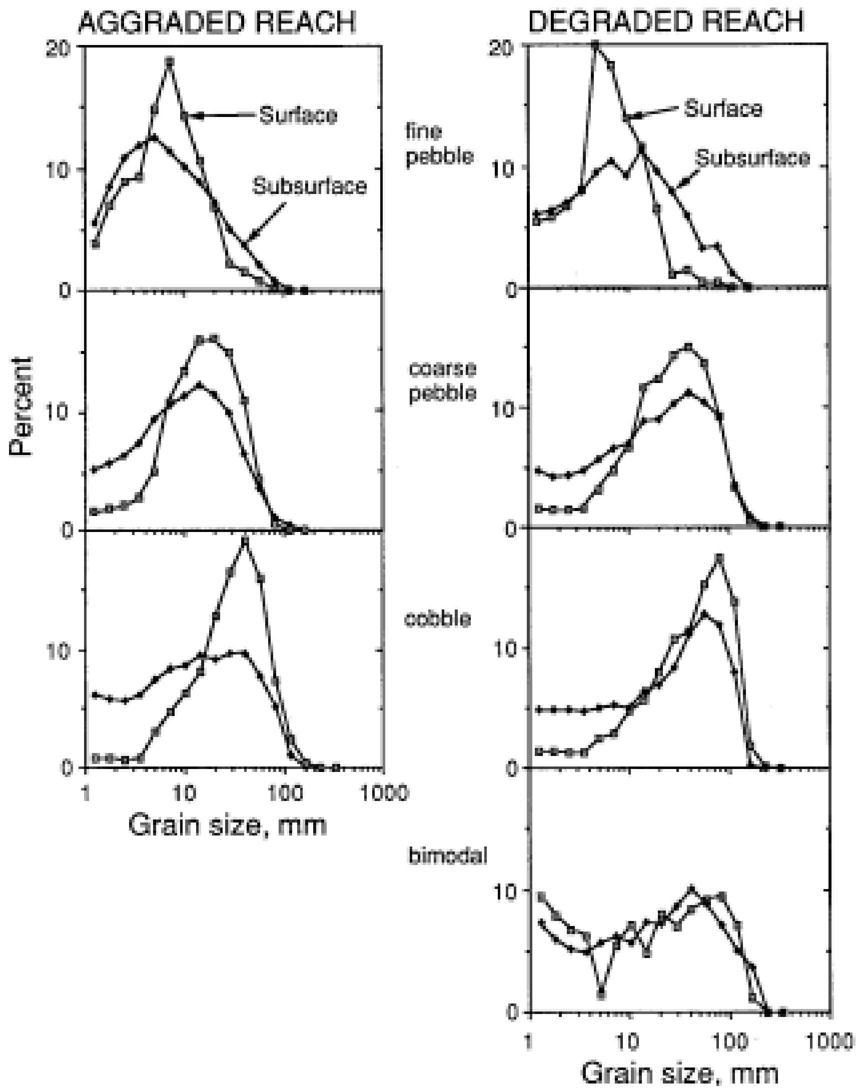


Figure 13.4 Grain-size distributions for surface and subsurface bed material averaged for facies types and for study reaches, Redwood Creek

diverged towards the finer side of the distributions (Figure 13.5). The fine-pebble facies did not display this pattern, and the frequency distributions of the bimodal facies matched without any adjustment of the distribution of surface material. This suggests that the grain-size distribution of surface material of the coarse-pebble and cobble facies could have resulted by winnowing of the finer fractions more abundantly represented in their subsurface materials.

Of all facies types, bimodal facies showed the closest correspondence between surface and subsurface grain-size distributions. The lack of actual bimodality arises from variations in size distribution of the fine mode among the samples from which the average distributions were computed. In the field the surface of bimodal facies gave the impression of an exposure of a horizontal section of streambed, revealing the framework of coarse particles as well as the matrix of

Table 13.3 D_{50} of surface and subsurface material and D_{50} ratios and their respective standard errors (s.e.) for study reaches of Redwood Creek

	Reach					
	Degraded			Aggraded		
	D_{50} (s.e.)		D_{50} ratio (s.e.)	D_{50} (s.e.)		D_{50} ratio (s.e.)
Facies type	Surface	Subsurface		Surface	Subsurface	
Fine-pebble	5.7 (1.0)	10.5 (1.6)	0.68 (0.14)	6.1 (0.7)	6.2 (0.5)	1.05 (0.14)
Coarse-pebble	26.2 (1.5)	19.2 (1.1)	1.44 (0.06)	14.9 (0.6)	9.7 (0.4)	1.60 (0.09)
Cobble	38.2 (2.6)	24.4 (2.6)	1.66 (0.19)	30.0 (1.3)	13.0 (0.6)	2.45 (0.16)
Bimodal	18.4 (4.1)	22.0 (3.1)	0.96 (0.19)	—	—	—
Weighted average	22.2 (0.9)	18.1 (0.9)	1.23 (0.06)	14.7 (0.4)	9.1 (0.3)	1.57 (0.07)

fine particles.

Fine-pebble facies were also unarmoured and many appeared to be "anti-armoured", that is, having a surface layer finer than the subsurface layer. For example, the D_{50} ratio averaged for the fine-pebble facies of the degraded reach (0.68) was considerably less than unity. Anti-armouring is, however, to some degree an artifact of our method of sampling the subsurface. In scraping away the surface of fine-pebble facies that were thin, we essentially removed those facies - that is, the bedload material that was last transported over that area of bed - and sampled coarser, underlying material. Thin fine-pebble facies were prevalent sub-aerially or in shallow water, where we were able to sample the subsurface. Fine-pebble facies in deep water were commonly thick. Considering these uncertainties, it is perhaps prudent to assume that fine facies have D_{50} ratios no less than unity.

The thickest and most extensive fine-pebble facies, particularly in the degraded reach, consisted of sheets of sand and small pebbles less than 0.5 m thick, that mantled coarser material in the beds of pools (Figure 13.6). These deposits thinned downstream from pool deeps and, approaching riffle crests, graded into bimodal facies and then into coarse-pebble or cobble facies as the large particles covered by fine sediment were increasingly exposed.

In summary, bed material grain sizes and the distribution of boundary shear stress revealed streamwise particle sorting within each bar-pool sequence. During waning flows, sand, gravels, and small pebbles were winnowed from riffles where boundary shear stress was relatively high, resulting in a high degree of armouring. Winnowed material was carried downstream and deposited as thin sheets of unarmoured, fine-grained material over pools, where shear stress was low.

13.5 DISCUSSION

13.5.1 Winnowing and streamwise sorting

Winnowing has a strong influence on the bed surface of Redwood Creek, at least as seen at low to moderate flow when the bed can be readily observed. Although selective accumulation of coarse particles on the bed surface can be responsible in part for surface coarsening, the surface layer of the armoured facies appeared to be depleted in fines rather than being enriched in coarse particles. The largest size of particles in the coarse armour layers of individual facies were also present in the underlying material. The coarser facies types, moreover, exhibited similarities between the coarse limbs of the frequency distributions of surface and subsurface layers. In contrast, the surface of the bed classified as the finest facies type was enriched in fines and commonly consisted of a veneer of fine material overlying a coarser bed. Together, these results suggest that the winnowing of fines from coarse facies and their deposition downstream to form fine-grained facies was largely responsible for spatial variations in armouring observed at low flow. The coincidence of high boundary shear

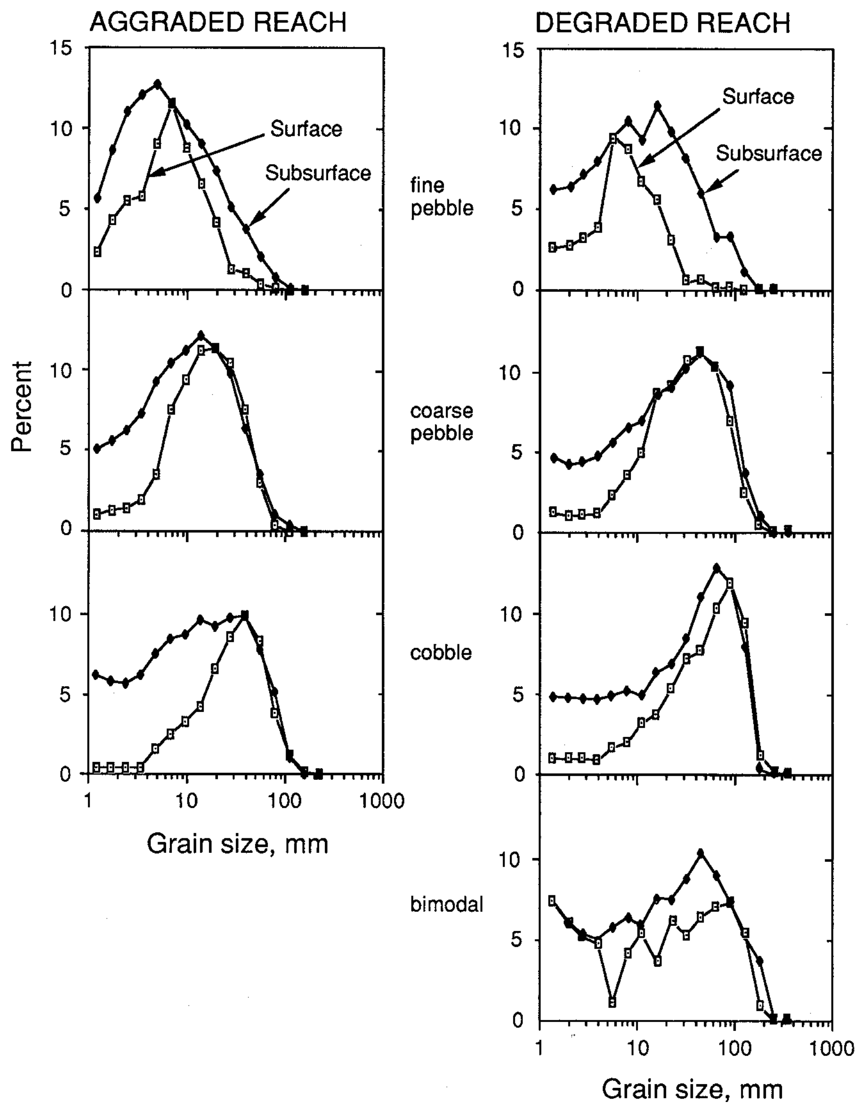


Figure 13.5 Adjusted grain size distributions from Figure 13.4. The frequency of the mode of the surface material was reduced to the value of the frequency of the same grain size of the subsurface material, and the remainder of the distribution of surface material was reduced by the same proportion

stress at low flow with coarse (winnowed) facies and low shear stress with fines–enriched facies is consistent with this interpretation.

In this discussion it is important to distinguish between vertical and downstream winnowing (Parker & Klingeman, 1982). In vertical winnowing, fines are temporarily lost to the subsurface layer; in downstream winnowing fines are carried downstream. As Gomez (1984) points out, vertical winnowing requires that the coarse particles in the surface layer be mobile, while downstream winnowing requires that they be temporarily immobile. Most importantly, downstream winnowing leads to streamwise sorting of bed material, but vertical winnowing does not. The juxtaposition of coarse and fine facies indicates that downstream winnowing of coarse armour layers in Redwood Creek

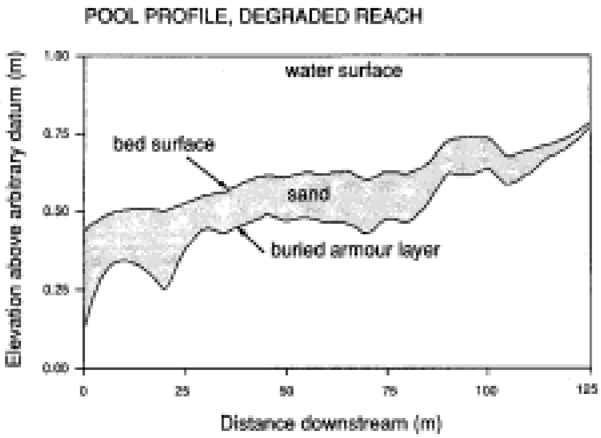


Figure 13.6 Longitudinal profile of the water surface, bed surface, and armour layer buried under fine sediment in a pool of the degraded reach, Redwood Creek. The survey was conducted on 31 August 1989 during low flow

was prevalent during waning stages of flood hydrographs.

13.5.2 The compatibility of equal mobility and size-selective transport

A result of streamwise sorting within each bar-pool sequence in Redwood Creek is that, over most of the bed at low flow, the surface grain-size composition is a product of various degrees of winnowing or deposition of winnowed material during waning flow. These bed surface conditions would not be expected to prevail during high bedload-transporting stages. As a result, bed surface grain size in a local area could not necessarily be used to predict bedload grain sizes or transport rates at that point, at all flows. This is because bedload transport would be a function not only of local bed conditions, but also of those along the sediment transport path leading to that point from upstream. In other words, a simple model of equilibrium between bedload transport and bed surface grain size at a point, which has formed the foundation for theories of sediment transport over mixed-size beds, is not entirely valid for a natural channel such as Redwood Creek.

Streamwise sorting can provide a resolution to a paradox of equal mobility and size-selective *transport.* Theoretical treatments of initial particle motion from a mixed bed (Wiberg & Smith, 1987; Komar & Li, 1988; Kirchner *et al.*, 1990) fail to show conclusively a mechanism for size-selective *entrainment* of particles, because of uncertainties in the magnitude of lift and drag forces, and wide variations in pocket geometry and pivot angles. On the other hand, bedload transport measurements from natural channels can show some degree of selective *transport* over a range of stage (Milhous, 1973; Carling, 1983; Ashworth & Ferguson, 1989; Kuhnle, Chapter 7 of this volume). Selective transport is very pronounced in Redwood Creek. At discharges as low as 5 % of bankfull we have observed sand and fine gravel transported as migrating dunes over an armour layer. Bedload samples at high flow (USGS, 1970-88) contain the largest particles that can fit into a Helley-Smith bedload sampler with a 7.6-cm orifice, and cross-sectional changes and painted-rock experiments (unpublished data, Redwood National Park, Arcata) show that all particle sizes represented on the bed surface are transported at high stages. Grain sizes of bedload samples taken over a range of flows could lead one to conclude that there is strong stage-dependent, size-selective *entrainment* from a streambed where a large range of grain sizes are present.

Extrapolation of observations of bedload transport at a point or section to a reach of channel as a whole can be erroneous, however. In Redwood Creek the most mobile sources of bedload at discharges when only sand and fine gravels are transported are fine-grained, winnowed sediment that was deposited in pools during the previous waning stages. These areas are the last to be deposited in and the first to be entrained from. All particle sizes on the surface of these areas may be nearly equally mobile; coarse gravel and cobbles are merely absent. This fine bedload is carried downstream and overpasses the stable armour layer of coarser facies as streaks of moving material that disappear as stage drops and the bed is winnowed. Thus, the apparent degree of size selection in entrainment and transport depends on the part of the bed observed. At rising stages bedload may be first entrained from fine areas that exhibit equal mobility. The initial fineness of bedload arises not from selective entrainment of particles from an overall population with a wide range of grain size, but from streamwise sorting that provides fine, unarmoured areas of the bed that are exceptionally mobile. The resolution of the paradox, therefore, is that equal mobility can coexist with size-selective transport in a channel with streamwise sorting.

13.6 CONCLUSIONS

Wide spatial variations in boundary shear stress in response to varying flow in Redwood Creek have created large spatial variations in the grain sizes of surface and subsurface materials. The bed at low flow, when it is practical to observe armouring of the entire channel, is to a large degree the product of waning flows. Although low flows are too feeble to transport significant volumes of bedload, spatial variations in boundary shear stress near entrainment thresholds enhance heterogeneity in bed texture through size-selective transport and deposition. As general transport ceases fine sediment is winnowed from the bed surface of riffles, where shear stress remains relatively high, and deposited in pools, where shear stress is low. During rising stages the process is presumably reversed with pools switching from being the sink for fine-sediment transport to becoming the source of fine sediment transported over the armoured beds of riffles.

A result of pronounced streamwise sorting in a channel with a large in-channel supply of bedload is that sediment can be entrained from different areas of the bed over a wide range of flow. Collectively, therefore, the channel is highly mobile despite a high degree of armouring in some areas.

The organisation of bed surface texture and boundary shear stress in a natural channel present challenging complications to the prediction of bedload transport. Firstly, predictions employing mean values of hydraulic variables and channel-boundary conditions for the channel as a whole exclude the influence of spatial variations in bed mobility. They can fail, therefore, to predict accurately the onset of bedload transport and transport at moderate stages. Such an approach can also lead to the erroneous conclusion that fine-grained bedload transported at low to moderate stages originates from size-selective entrainment from a uniform bed having a wide range of particle sizes present over the entire bed. Instead, the sediment source is most likely to be highly mobile, fine-grained areas of the bed surface.

Secondly, spatial variations in the bed surface texture measured at low stages may not be representative of those at high stages, when bedload transport rate predictions may be more important. Predictions of bedload transport may be more appropriately based on values of hydraulic and boundary conditions in small unit areas of the bed that are linked along sediment transport paths in such a way as to account for the disequilibrium imposed by discontinuities in sediment transport and the progressive changes in conditions as flow varies.

13.7 ACKNOWLEDGEMENTS

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13.9 DISCUSSION

13.9.1 Discussion by N. R. Jaeggi

Obviously, armouring processes are complicated by the occurrence of alternate bars. The situation described in the paper is thus more complex than an armouring process in the flume with plane bed. However, locally, over a short distance, the process on a bar or in a pool will be the same as for plane bed conditions with same shear stress. The problem is to define the representative shear stress in a complex field situation.

One-dimensional numerical modelling of bed level changes and bedload transport in the Danube (see Chapter 30 in this volume) and in the Alpine Rhine was successful despite the occurrence of alternate bars. In the model a critical shear stress for erosion of the armour layer was used. Assumptions had to be made on form roughness induced by bars at lower flows and shear stress variation over the cross-sections. The validity of these assumptions could be controlled by comparison with surveyed bed level changes.

The Alpine Rhine degrades while bars migrate, so the erosion is about the same on the whole cross-section. In the Danube the bars are fixed by groynes and thus the thalweg tends to incise and the bars tend to form terraces. The terraces formed with about a 4% slope (Ova da Bernina, Switzerland). It would be interesting to know what happened in the degrading reach of Redwood Creek.

13.9.2 Discussion by D. A. Sear

The authors mention the influence of spatial variation in armouring upon the transport and grain size of the bedload. Work on the River North Tyne in the UK supports the idea of topographic control on spatial armouring but also suggests that regard should be made to the distribution of bed compaction.

Figure 13.7 illustrates a dynamic penetrometer survey of bed compaction within a riffle-pool-riffle sequence. A distinct spatial pattern in compaction is evident and can be linked to topography, bed micro-morphology and reach hydraulics. Compaction of riffle beds extends into the pool head in association with a region of high shear stress, or jetting. Accentuated levels of compaction also correspond to stable bar forms and to a boulder zone along the right bank of the pool. These areas also exhibit profound bed micro-morphology that increases the compaction.

Zones of low compaction, independent of grain size, exist in the pool tail and in the region of low shear stress adjacent to the high-velocity jet. Very little bed structure is apparent within these regions and "anti-armour" is absent.

Under these circumstances the mutual interlock of particles leading to a state of compaction might reasonably be expected to exert a control on the stability of the bed and, therefore, the initiation of sediment transport within the reach which is independent of the surface grain size.

13.9.3 Discussion by P. A. Carling

The authors draw attention to the fact that both winnowing of fine matrix from the interstitial space of a static gravel surface, and selective accumulation of coarse gravel above finer gravels may result in a texturally stratified bed. The fact that a variety of mechanisms may be involved in the process has been remarked upon before (Caning, 1981; Bray & Church, 1982; Gomez, 1984). I would, however, question whether the term "anti-armour" is an appropriate new term, as these latter deposits seem to bear no structural relationship to the underlying deposits and are, apparently, low-flow drapes or veneers (see Carling & Reader, 1982, Figure 8).

The mechanism of selective accumulation is the one most commonly associated with armouring (paving), whereby a dynamic segregation process associated with bed material transport of fine and coarse fractions leads to surface coarsening. In addition, the process is often associated with bed degradation. The result is a surface which is more resistant to entrainment than the parent bed material which underlies it. Commonly, the D_{50} of the armour is some 2.5 times larger than that of the sub-armour (e. g. Parker, Klingeman & McLean,

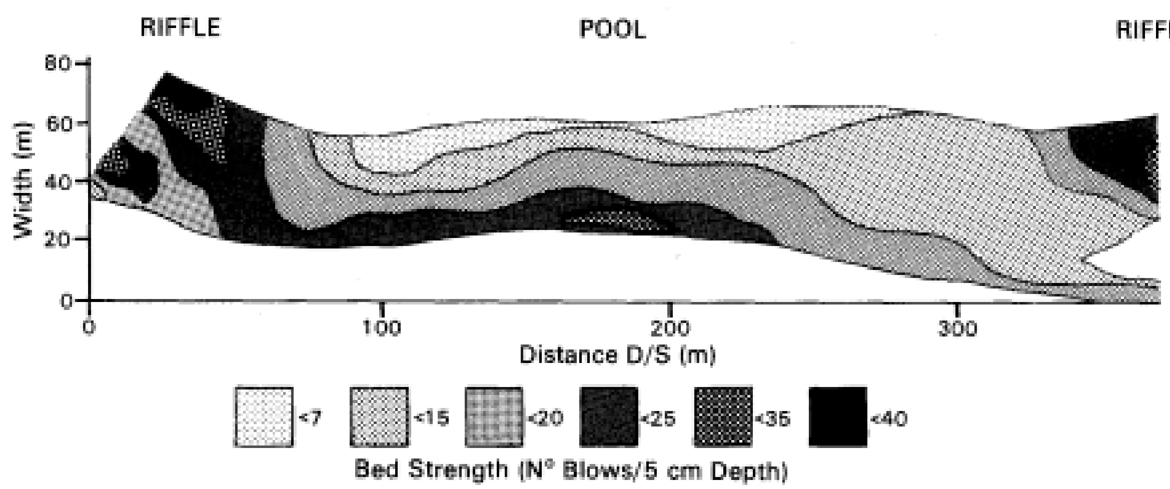

Figure 13.7 Spatial variation in bed compaction within a riffle-pool-riffle section of the River North Tyne, UK. Measurements were made using a Mackintosh Probe dynamic penetrometer. Flow direction is from left to right

1982), but in extreme cases the armour may consist of a pebble layer over-lying sands (Leopold, Wolman & Miller, 1964, p. 209).

In contrast, surface winnowing by traction or suspension of fines does not entail bed degradation, leaves a static coarse framework (see Chapter 15 in this volume) and does not entail the rearrangement of the coarse component of the bed. The resultant coarse surface imparts little in the way of increased bed stability; indeed stability may be decreased by the removal of a previously well-packed matrix.

In view of the current interest in the detailed structure of riverbeds I would welcome the authors' views on whether a variety of segregated surfaces exist, and if it would be useful to develop a more detailed classification.

13.9.4 Reply by T. E. Lisle and M. A. Madej

Sear and Carling rightly state that particle arrangement as well as grain size govern the mobility of bed surfaces under given hydraulic environments. Mapping surface particle arrangements and measuring their effect on entrainment thresholds in the field is problematic at this point, although Sear's penetrometer technique offers a quantitative parameter. Arrangements of coarse particles in armour layers of Redwood Creek vary widely. Although we did not measure compaction as Sear did, we would concur that bed firmness, or particle arrangement, does not always correlate with surface grain size. Some coarse, well-armoured areas are imbricated, suggesting either selective deposition of coarse material or at least reorientation *in situ* of coarse particles as finer particles are winnowed away downstream. Many cobbles on some riffles in the degraded reach lie loosely on the bed and, as Carling suggests, may have been left by winnowing of a well-packed fine matrix, and thereby rendered less stable.

We do not intend to introduce a new term, "anti-armouring". It is used only to refer to an apparent phenomenon that was widespread in fine-grained areas of Redwood Creek and, as Carling warns and we describe, should not imply a contemporary sedimentological relation between a thin surface layer of fines and the underlying coarser bed material.

Jaeggi indicates that detailed measurements of bed topography and bed-surface particle size may not be necessary for practical solutions to sediment transport problems in rivers with alternate bars. Our research in Redwood Creek is intended to increase understanding of effects of non-uniformity and unsteadiness of flow on bedload transport in gravel-bed rivers, and not necessarily to provide new engineering applications.

The bars in Redwood Creek do not migrate downstream because the sinuosity of the channel is commonly bounded by hillslopes. The study. reaches were chosen to be straighter than is characteristic of the channel in general. Terraces of recent flood deposits left by channel degradation are absent in the degraded study reach, but do appear upstream, where the channel has degraded more deeply and valley bottoms are wider.

13.10 DISCUSSION REFERENCES

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