3. Spatial variability of bed-material size

Bed-material particle sizes may vary along the direction of stream flow (longitudinally), between the stream banks (cross-sectionally), and vertically within the bed. This variability occurs at various spatial scales. The objective of bed-material sampling may be to characterize this variability in detail, or through integration to characterize the streambed at a spatial scale larger than the bed-material variability (Section 6).

Bed-material sampling considers three spatial scales: the stream reach, a stream section, and the local scale. A stream reach is approximately 5 - 10 channel widths long, and the spatial variability of bed-material sizes in the reach scale is mainly tied to large bedforms such as riffles, bars, pools, and steps. A stream section is comprised of a series of several reaches that are either similar in stream type and bed-material composition or feature a shift in stream type and bed-material composition such as downstream fining. The local scale covers streambed areas of a few m^2 or less. Analysis at the local scale focuses on bed-surface structures such as particle clusters, sediment lobes and deposits of fines in pools or backwater areas, as well as local deposits of coarse particles. Patterns of spatial variability of bed-material size and the processes causing it are discussed in Section 3 of this document because spatial variability of bed-material sizes has implications for site selection and sampling schemes (Section 6).

3.1 Downstream fining

Spatial scale and processes

Downstream fining of the surface sediment is a process resulting in large-scale spatial variability of bed-material sizes. Usually, downstream fining occurs over a stream section several reaches long, but might occur over shorter distances as well. Downstream fining may be attributed to a number of mechanisms including local control of stream gradient, coarse tributary sediment supply, or particle abrasion and breakdown (Surian 2000). Local grade control may be caused by geological uplift, blockage of the valley by mass movement, or man-made dams. A decrease in stream gradient leads to a decrease in the amount and particle size of bedload transport (transport capacity and competence) (Sambrook Smith and Ferguson 1995; Ferguson et al. 1998). Log jams can also act as a local grade control and lead to downstream fining towards the upstream side of the log jam. Bed scour and a lag deposit of coarse bed material on the downstream side of the log jam can exacerbate the downstream fining trend in a series of log jams (Rice and Church 1996a). Coarse tributary sediment supply that can be transported only on rare occasions causes rapid downstream fining between tributaries (Rice and Church 1998). A supply of fluvial sediment that experiences particle abrasion and breakdown easily can cause rapid downstream fining as well (Sambrook Smith and Ferguson 1995).

Implications for sampling
The usual objective for sampling a stream section in which particle sizes become finer downstream is to demonstrate the degree of downstream fining and to link it to a potential cause. Sampling methods suitable to demonstrate a downstream fining trend vary depending on the situation. Transects selected at even-spaced intervals may be suitable if the cross-sectional variability is not too large. As the lateral variability increases, samples could be taken from a sequence of riffles because riffles tend to be laterally less variable than other cross-sections. Alternatively, one could sample the 30 largest particles within a preset geomorphological unit, e.g., a bar head, or sample all particles contained within a small sampling area, e.g., within 0.5 m^2 at the center of a bar (Sampling Procedures, Section 4). The downstream increase of fine sediment may cause a bimodal particle-size distribution (Section 2.1.5.9) and the development of patches of fine and coarse sediment, with the number and size of fine patches increasing downstream (Seal and Paola 1995; Seal et al. 1998). In this case, gravel and sand patches are sampled independently from patches intersected by a transect or falling within a preset area (Spatial Sampling Schemes, Section 6).

The stream situation determines not only the sampling locations, but also the particle-size parameter that should be analyzed. The D_{50} particle size may not be well suited to show downstream fining, particularly in bimodal sediment distributions. It might be necessary to analyze both the decrease of coarse (e.g., the D_{95}, Section 2.1.4.2), and the increase of fine sediment (e.g., the percent fines, Section 2.1.5.8).

3.2 Surface bed-material sizes within a reach

Bed-material sampling projects are often concerned with the spatial variability of bed-material size within the reach scale (about 5 - 10 channel widths long). At this scale, patterns of bed-material size variability are tied to channel morphology. The patterns, such as downbar fining or an alternation of relatively coarse riffles with finer-grained pools are recurring and generally predictable. Off-stream supply of non-transportable large clasts or the presence of large woody debris can disturb systematic patterns.

Patterns of bed-material size, stream morphology, the three-dimensional patterns of flow and bedload-transport processes are interdependent, but their relations may not necessarily be straight forward. The next chapters will first introduce the various geomorphological units of streambeds, and then show the spatial variability of bed-material particle sizes along geomorphological units such as downbar and landward fining on bars, lateral variability across riffles, and differences in riffle and pool sediment size.

3.2.1 Morphology of the bar-unit with pools, riffles, and bars

The longitudinal stream profile along the thalweg of regular riffle-pool sequences is undulating; pools form topographic lows and riffle crests topographic highs (Fig. 3.1). In plan view, the morphological units pools, riffles, and bars are part of a single three-dimensional bedform called the *pool-riffle-bar triplet* (Church and Jones (1982), or the *bar unit* (Dietrich 1987). The bar unit for a straight, a meandering, and a braided stream is shown in Fig. 3.2. The upstream end of the bar unit is the pool that widens and shoals

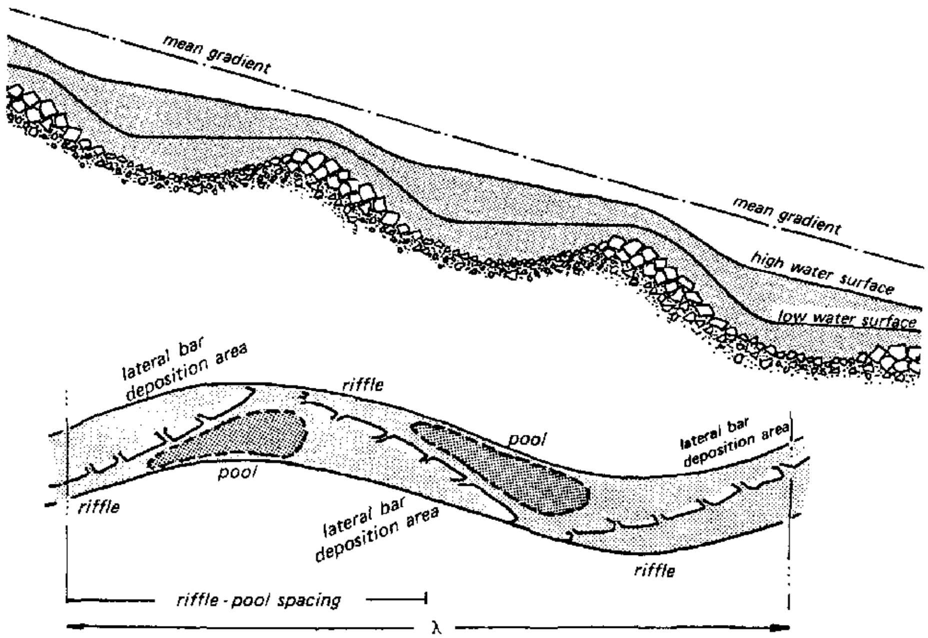

Fig. 3.1: Longitudinal (top) and plan view (bottom) of a riffle-pool sequence. The diagonal front lobe of the bar, the submerged part of which is the riffle. (Slightly modified from Church and Jones (1982), by permission of John Wiley and Sons, Ltd.).

downstream until it terminates in an oblique shallow lobe front that extends diagonally across the stream. The downstream part of this front lobe is usually above the water line during low flows and forms the exposed bar. Farther upstream and towards the other side of the stream, the lobe front becomes inundated. The deepest and submerged part of the lobe front is the riffle crest (Dietrich 1987).

The bar unit extends over the length of two visible bars. Bar patterns that are repeated along opposite banks are called alternate bars in straight streams or riffle bars (Dunne and Leopold 1978), and point bars in meandering streams (Fig. 3.2, top and center).

The relative position of the riffle crest (or the “topographic high”) with respect to the bar depends on whether the stream is meandering or straight, and on the angle with which the riffle-forming bar lobe crosses the stream. In straight streams with alternate bars, the lobe front crosses the stream not perpendicular, but at a rather low angle to the banks. This positions the riffle crest near the upstream end of the bar, or close to the downstream end on the next bar upstream (Fig. 3.2, top). If the lobe front crosses the stream almost perpendicular to the banks, the riffle appears in front of the bar (Fig. 3.3).

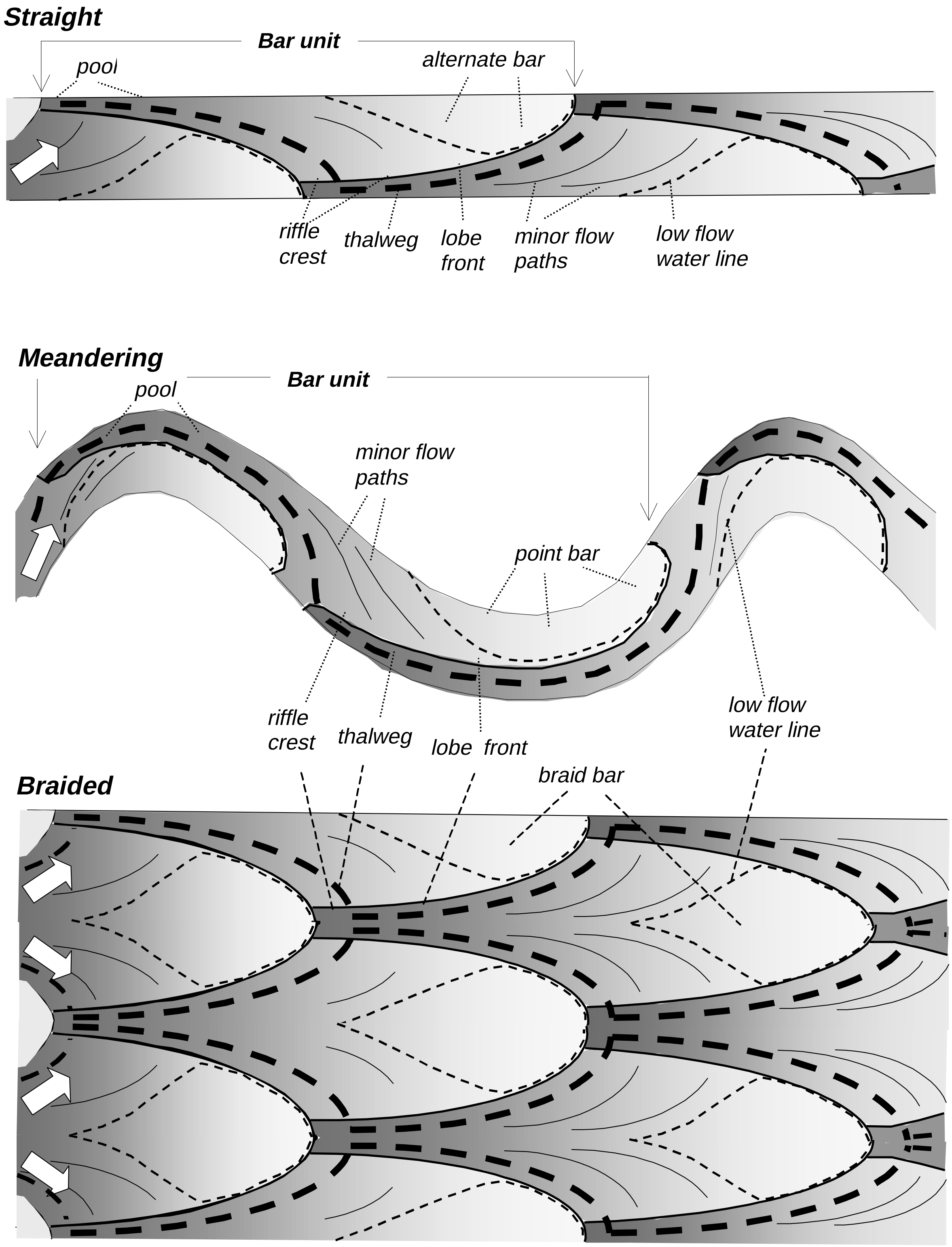

Fig. 3.2: Morphology of a bar unit in straight (top) and meandering (bottom) streams. Water depth is deepest in the areas with darkest shading, while areas of lightest shading are bars that are exposed during low flows. (Adapted after Dietrich (1987), Fujita (1989), and Whiting and Dietrich (1993)).

In meandering streams, the bar wraps around the bend and forms a point bar. The bar unit extends over the length of a complete meander (i.e., two bends) (Fig. 3.2, center). In meandering streams, the riffle is at the crossing of stream curvature between two bars. The pool in a bend is part of the bar unit that extends to the next point bar downstream. Table 3.1 summarizes riffle locations for various bar types in pool-riffle or C-type channels.

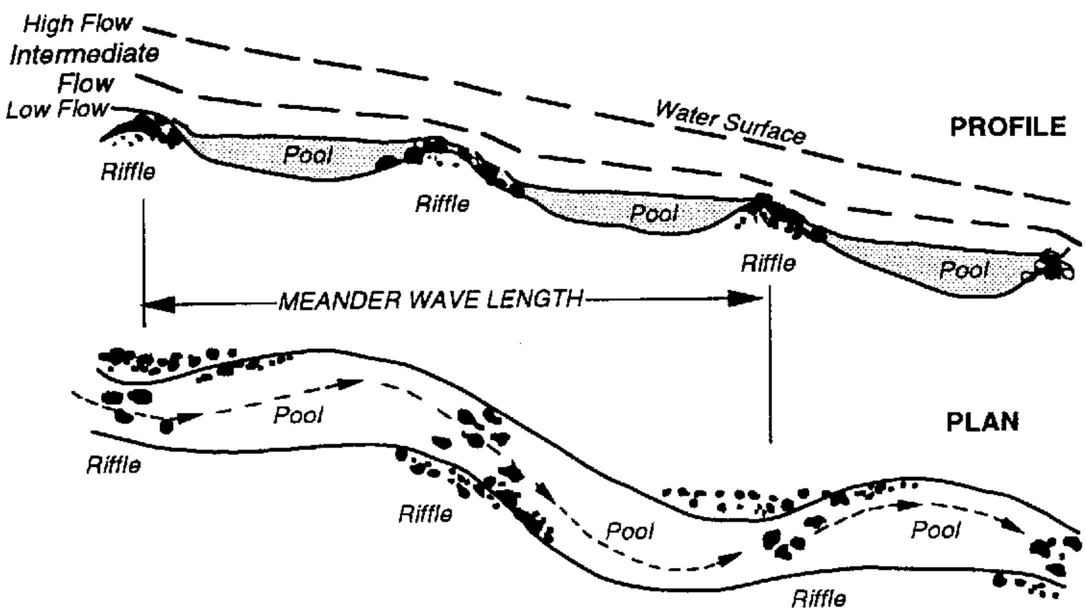

Fig. 3.3: Longitudinal (top) and plan view (bottom) of a riffle-pool sequence. Note that the riffle is located in front of the riffle bar. (Reprinted from Newbury and Gaboury (1993), by permission of Newbury Hydraulics, Ltd.).

Table 3.1: Riffle locations for various bar types in pool-riffle or C-type channels.

Bar type	Position of riffle relative to the bar	Figure providing example
Alternate bars	near the upstream end of a bar or further upstream close to the down-stream end of the next bar upstream	Fig. 3.2, top Fig. 3.1, bottom
Riffle bars	near the front or the center of the bar	Fig. 3.3, bottom
Point bars	at the crossing of curvature between two point bars	Fig. 3.2, center

Bars in mountain gravel-bed rivers with low sediment supply are usually poorly developed, small in size or confined to stream reaches with a low gradient or local backwater areas.

As sediment supply increases and stream gradient flattens, bars become more prominent: they increase in size, occupy larger proportions of the streambed and occur more regularly. Within single-thread streams, bars reach their fullest extent as alternate bars.

A further increase in sediment supply leads to a braided stream in which flow divides into several channels separated by bars that tend to shift and change during a high flow event. Bars in streams with high sediment supply and rapidly changing channels can occur at various locations within the streambed and assume a variety of different shapes (Fig. 3.4)

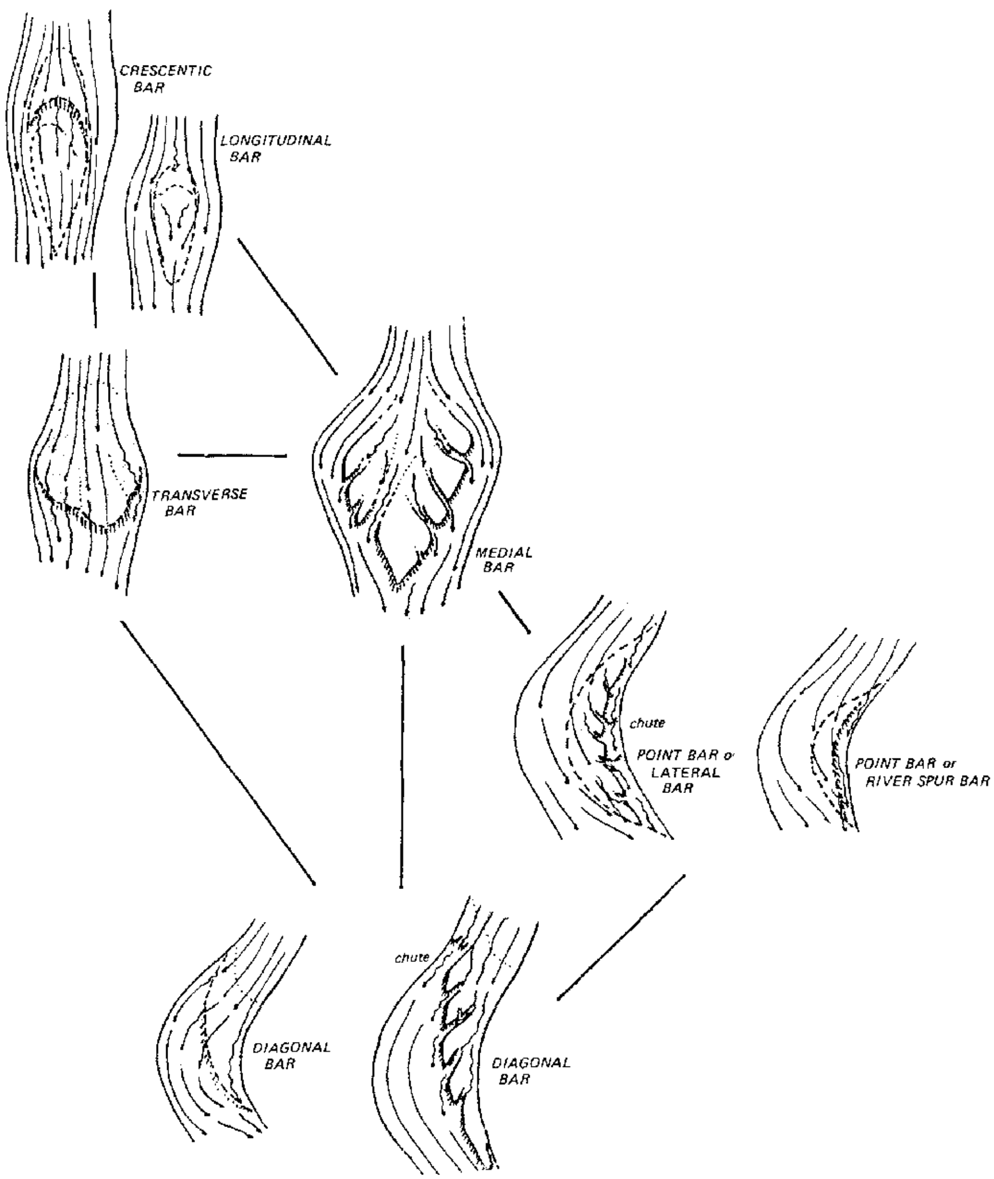

Fig. 3.4: Bar types in braided streams. Stability increases from longitudinal bars to transverse bars to medial bars to point, or lateral bars to diagonal bars. (Modified after Church and Jones (1982), by permission of John Wiley and Sons, Ltd.).

(Church and Jones 1982; Bluck 1982; Ashworth et al. 1992). A braided stream composed of longitudinal or medial bars is shown schematically in Fig. 3.2 (bottom).

3.2.2 Bed-material particle-sizes on pools, riffles, and bars

3.2.2.1 Helical flow and bed-material size in a bar unit

The three-dimensional model of helical flow in which surface and bottom flow are at angles to each other (Thompson 1986) can be used to describe longitudinal and lateral variability of bed-material sizes within the reach (Fig. 3.5). On the riffle at the crossover between meander bend curvatures, the near-bottom flow spreads diagonally across the stream, extending from the thalweg to the upstream part of the bar on the opposite side of the stream (Dietrich 1987). Flow traverses the bar head diagonally from the bank towards the thalweg (Fig. 3.6) (Dietrich 1987). The diagonal spread of flow, combined with the relatively low flow depth on riffles and bar heads reduces the flow velocity and leads to deposition of coarse bedload during high flows (Anthony and Harvey 1991). Flow velocities in the pool are high during high flows and can transport all but the largest particles. Thus, in accordance with the zones of highest shear stress, bed material is coarsest in pools, on riffle crests and on the upstream end of bars (Bridge and Jarvis 1982; Dietrich and Smith 1984; Dietrich and Whiting 1989).

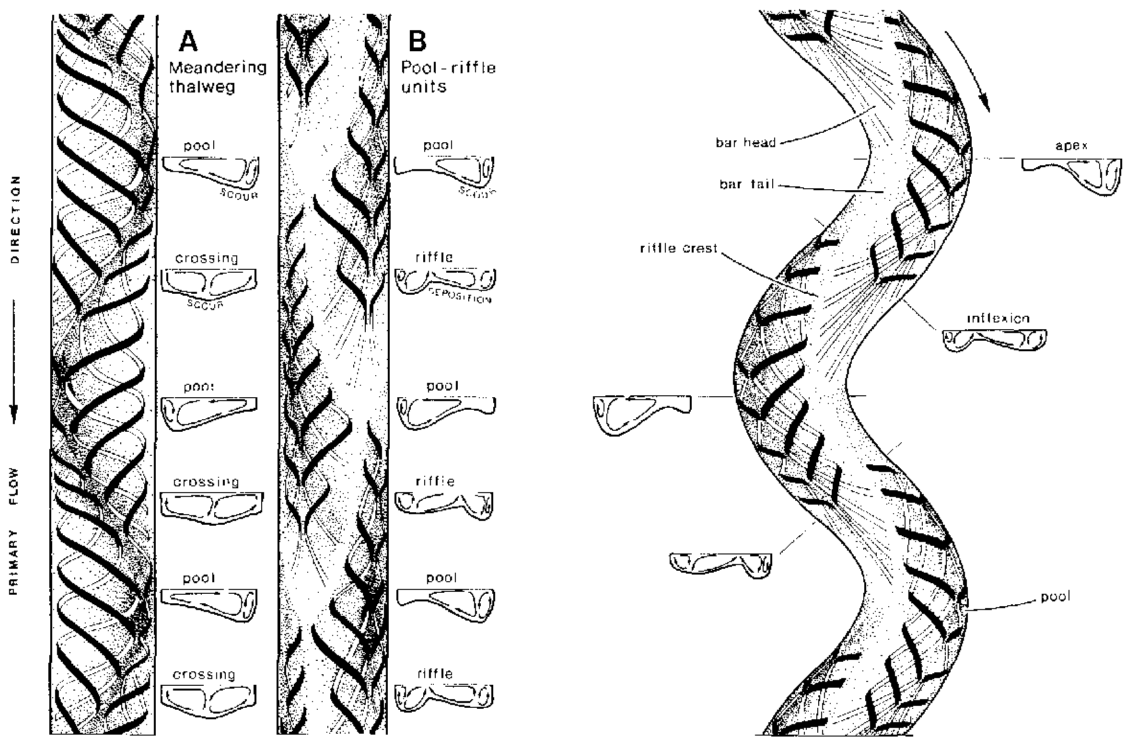

Fig. 3.5: Model of helical flow in a straight stream with a meandering thalweg (left), in a straight stream with riffle-pool units (alternate bars), and in a meandering stream (Reprinted from Thompson (1986), by permission of John Wiley and Sons, Ltd.).

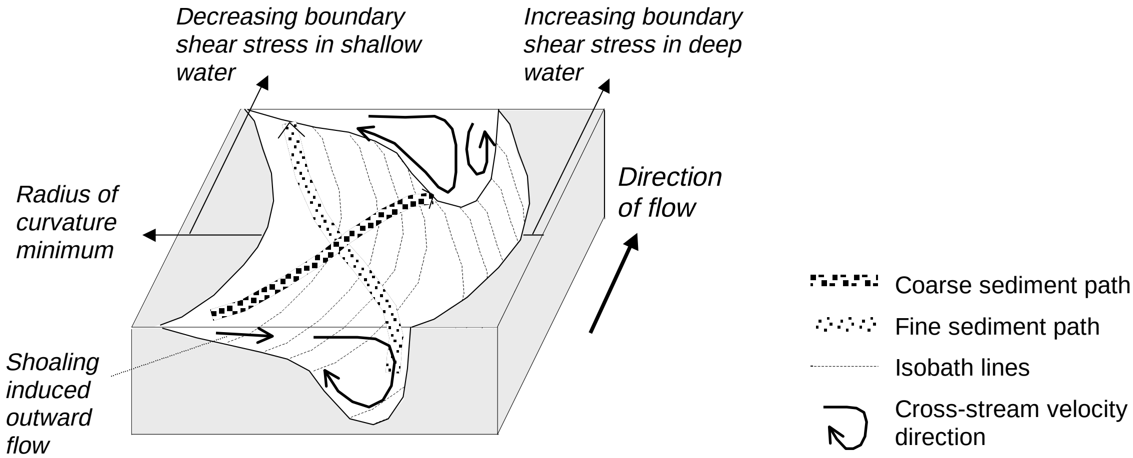

Fig. 3.6: Bottom and surface flow velocities and particle paths for coarse and fine bedload in a meander bend. (Redrawn and slightly modified from Dietrich and Smith (1984), by permission of American Geophysical Union).

At the downstream end of a bar, bottom flow is directed from the thalweg up the bar slope, transporting and depositing fine sediment at the downstream end of the bar. Thus, gravel bars cover the full spectrum of transportable particle sizes, with the coarsest particles on the upstream end, and the finest particles at the downstream end (downbar fining). Downbar fining occurs on basically all free-formed bars, but has been demonstrated in particular detail on large gravel bars in braided rivers (Smith 1974; Bluck 1982, 1987; Church and Jones 1982; Ferguson and Werritty 1983; Mosley and Tindale 1985; Ashworth and Ferguson 1986; Brierley and Hickin 1985, 1991; Brierley 1991; Wolcott and Church 1991; Ashworth et al. 1992). The downbar fining trend is accompanied by a landward fining trend that extends from the bar toe to the bank (e.g., Bridge and Jarvis, 1976, 1982; Keller and Melhorn 1981; Dietrich and Smith 1984; Lisle and Madej 1992).

At first sight, bars may seem to be ideal sampling locations because they are exposed and dry during low flows. However, due to downbar and landward fining, no single bar location is representative of the particle-size distribution of the entire bar, nor is the particle-size distribution on bars necessarily representative of the entire stream reach. In coarse gravel-bed streams with low sediment supply, bar surface sediment tends to be finer than the reach-average bed-material size, especially if the bar is forced by an obstacle to flow. The difference in bar and channel particle size becomes less pronounced as the sediment supply to the stream increases. Another factor that may cause problems for bed-material sampling on bars is that bars may feature small-scale surface structures such as gravel lobes and particle clusters (Section 3.3).

Fig. 3.7 shows the spatial variability of surface bed-material size over morphological units of pools, riffles, and bars. Trends of downbar fining, landward fining, and a generally coarse thalweg occur in alluvial streams with different morphologies.

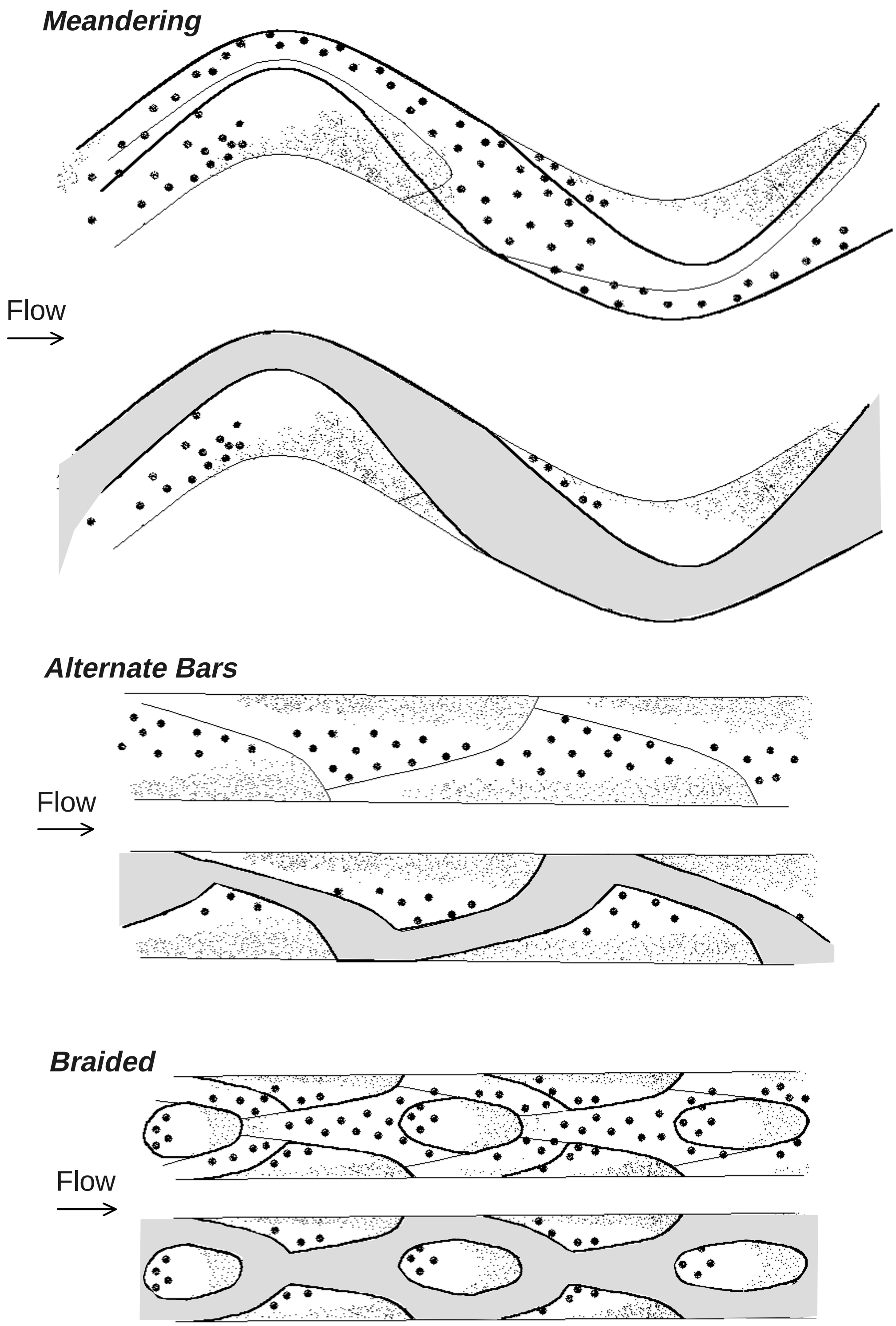

Fig. 3.7: Spatial variability of surface bed-material size on morphological units for meandering, straight, and braided streams. Large dots indicate coarse bed-material size, small dots indicate fine sizes. Top plots for each stream type show an empty streambed and the structure of the bar unit. Bottom plots show the channels during low flow. Comparison with Fig. 3.2 helps identify bar units. (Modified from Whiting (1996), by permission of John Wiley and Sons, Ltd.).

The formation of well developed pool-riffle-bar triplets, or bar units, does not only require a sufficiently large sediment supply and an appropriate stream gradient. It is also important that the interaction between flow and sediment transport is not controlled by the presence of large woody debris (LWD) or large boulders. Effects of LWD and boulders on channel morphology and the spatial distribution of bed-material size are discussed in Sections 3.2.4 and 3.2.5.

3.2.2.2 Riffle-related features: rapids, runs, glides, and pool-exit slopes

Riffles and pools, the two major constituents of the inundated part of the reach, can be further segregated into geomorphological (or habitat) units (Fig. 3.8). The form and bed-material size of riffles, and riffle-related features are discussed below. The relation

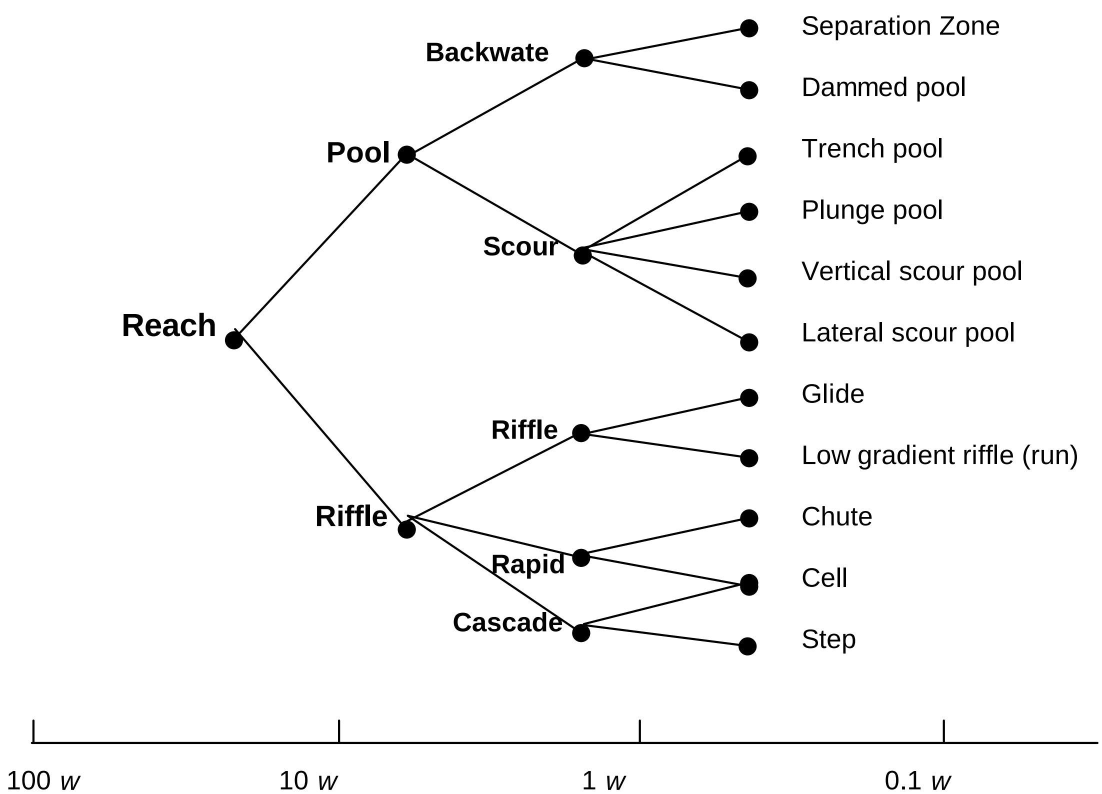

Fig. 3.8: A spatially hierarchical representation of channel morphology units; *w* = stream width. (Slightly modified from Church (1992), by permission of Blackwell Science, Ltd.)

between riffle and pool bed-material size is discussed in Section 3.2.2.3. The various pools indicated in Fig. 3.8 are caused by the presence of LWD that effectively controls flow hydraulics and sedimentation within a reach. Pools are therefore discussed in Sections 3.2.4 and 3.2.5.

Riffles, as well as the streambed area between pools and riffles can assume a variety of morphological forms with different flow dynamics and bed-material composition. Fluvial geomorphologists and fishery biologists distinguish between rapids, runs, and glides (e.g., Bisson et al. 1982; Church 1992), however, the terminology describing morphological units may not be entirely identical between authors. The descriptions are summarized below.

Rapids are steeper, contain larger particles, and have faster flow than riffles. Flow on riffles is usually subcritical (Froude number <1) during low flows, whereas much of the flow over rapids is generally critical, or supercritical (Froude number ≥ 1). Riffles might include a few untransportable large particles protruding through low flow, but these are not organized into transverse ribs (Section 3.4.1), as they tend to be on rapids. Riffles have local gradients of less than 0.02, while rapids have local gradients of about 0.02-0.04 (Grant et al. 1990; Church 1992). Cascades are steeper than rapids, and are comprised of cobbles and boulders. Small pools are common between large clasts.

Runs refer to stream segments with a straight downstream sloping bed surface (Platts et al. 1983) and relatively homogeneous bed material, similar to the plane-bed morphology described by Montgomery and Buffington (1997, 1998), whereas riffles are sections of locally steep gradient in the longitudinal stream profile. Compared to low flow conditions on riffles, runs have deeper flows, and lower flow velocities.

The term *glide* is sometimes used synonymously with run. A glide may refer to the transitional area between the deep part of the pool and the crest of the riffle in which stream width increases while flow depth decreases (Bisson et al. 1981). This transitional zone may be termed *pool-exit-slope* (Thompson et al. 1996), especially if the stream gradient is sloping upward over this area. Bed material on the glide or pool exit slope tends to be less coarse than on the riffle crest. Church (1992) applies the term glide to a former pool that has been completely filled with sediment. If a differentiation is made between runs and glides, glides have deeper flows and lower flow velocities than runs and have a closer resemblance to pools than to riffles (i.e., a nearly horizontal water surface).

3.2.2.3 Coarsest parts of the reach: pools, riffles, and bar heads

In alluvial, free-formed streams, pools, riffle crests, and bar heads are generally the coarsest areas in a stream reach. However, the relation of bed-material size between pools and riffles, and riffles and bar heads varies depending on whether erosional or depositional processes are predominant in forming the pool and riffle in a given bar unit.

Coarse pool sediment due to scour

During high flows, shear stress is often higher in pools than on riffles and scours all but the coarsest sediment out of pools, leaving a coarse lag deposit behind. If pool scour is the prevailing mechanism, then pools may be the coarsest parts of the streambed.

Coarse riffle deposits and scour of finer gravel

Field measurements in gravel-bed rivers often show that riffles and not pools are the coarsest locations within a reach (e.g., Keller 1971; Richards 1976; Keller and Melhorn 1978, 1981; Lisle 1979; Hirsch and Abrahams 1981; Campbell and Sidle 1985; Lisle and Madej 1992, Keller and Florsheim 1993). This phenomenon is often attributed to the reversal of velocity, or shear stress, during a high flow event, a concept introduced by Keller (1971). During low flows, flow velocities are highest on riffles, and lowest in pools, owing to the steep gradient and shallow flow depth on riffles, while pools are deep and have a low stream gradient. During rising flows, flow velocity and bottom shear stress increases at a faster rate with discharge in pools than on riffles, so that at a certain high flow of approximately bankfull, flow velocity is higher in pools than on riffles. This high flow velocity scours and transports large particles from the pool, leaving a coarse lag deposit behind. The largest particles removed from pools are likely to be deposited on riffles where the flow velocity and shear stress are lower. As flow begins to wane, flow velocity on riffles is still lower than on pools, and falls below the competence to transport large particles before pools are affected, causing further deposition of coarse particles on riffles. Riffle coarsening is further augmented during low flows because flow velocity and shear stress do not drop as low on riffles as in pools. This allows scouring fines off riffles, leaving only the coarser and most stable particles in place. The finer gravel particles scoured off riffles are then deposited in pools (Bhowmik and Demissie 1982; Yang 1971). Both deposition of coarse particles on riffles and subsequent scour of fines can occur together (Campbell and Sidle 1985) and act on coarsening the riffle while fining the pool.

Riffles are not always coarser than pools

Field studies have not consistently verified the occurrence of velocity reversal and its sedimentary consequences, (i.e., that riffles are coarser than pools). Velocity reversal may occur at any discharge and is not necessarily limited to high flows around bankfull (e.g., Teleki 1972; Bhowmik and Demissie 1982; Carling 1991). Numerical modeling revealed that velocity reversal requires that pools are hydraulically rougher (i.e., coarser) than riffles, or that riffles are substantially wider than pools. The discharge at which velocity reversal occurs decreased with increasing riffle spacing and increasing stream width. Consequently, wide streams with wide riffle spacing and pools with coarse lag deposits seem to be most likely to experience velocity reversal (Carling and Wood 1994). Detailed measurements of flow patterns by Thompson et al. (1996) suggest that velocity reversal requires the presence of a recirculating eddy in the pool.

Structural stability on riffles

Clifford (1993) observed that within a series of riffle-pool sequences, some riffles were coarser than pools and some were not. Sear (1996) suggested that riffles do not need to be coarser than pools for purposes of stability, but that riffles maintain their stability by having structural elements, such as clusters, particle interlocking, and imbrication (Fig. 3.9). Clusters dissipate flow energy by creating turbulence, while imbrication and particle interlocking delay sediment entrainment by minimizing the particle area exposed to flow, and by high pivot angles. The presence of such structural features should therefore be recorded when sampling bed-material (see Section 3.4).

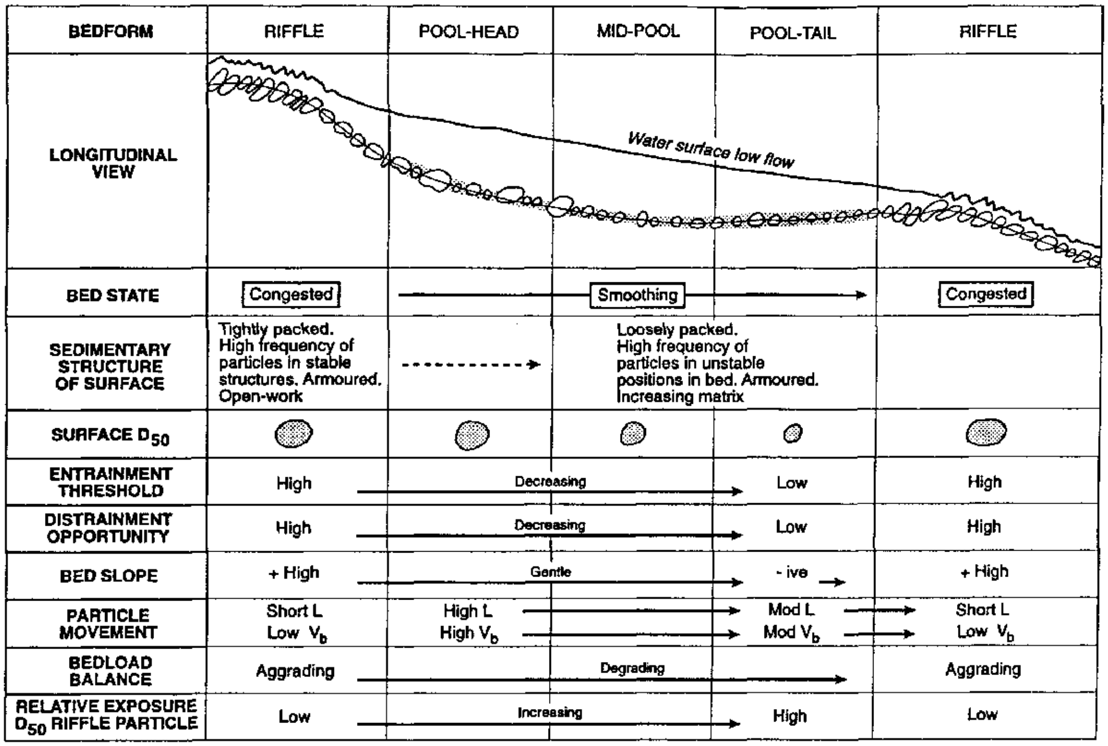

Fig. 3.9: Model of bed material properties and bedload parameters in a riffle-pool sequence. + = very, -ive = negative, L = particle transport distance, V_b= particle transport velocity, Relative exposure of D_{50} particle = *within the bed material*. (Reprinted from Sear (1996), by permission of John Wiley and Sons, Ltd.).

Deposition of fines in pools

Pool fining can become quite pronounced in streams with a high supply of sand and silt-sized sediment that is transported at low flow and deposited over the coarse bottom sediment in pools. Riffles are relatively unaffected by low flow sand transport because the higher flow velocities prevent deposition. Pool fines may cover the pool bottom as a thin veneer or fill a substantial portion of the pool volume (Lisle and Hilton 1992, 1999; Hilton and Lisle 1993). Sampling fine sediment in pools is discussed in Section 6.6.2.

Riffles and bar heads

Riffles and the upstream end of bars may be of similar coarseness if sediment supply is equal to the capacity of the stream to transport it or if sediment supply exceeds the transport capacity. If sediment supply is generally less than transport capacity, coarse gravel particles tend to be scoured off the riffle, leaving only the coarsest particles as a lag deposit, whereas the bar head sediment remains unchanged. This increases the difference in bed-material size between riffles and bar heads.

Lateral variability on riffles and runs

Some riffles do not have significant spatial variability of particle sizes; this homogeneity makes riffles preferred sampling locations, in spite of being submerged by flow. However, not all riffles have homogeneous particle size-distributions. The patterns of bottom flow near the bar can also lead to lateral variability of the particle size on riffles, particularly if the downstream spacing between bars is tight. In this case, riffle bed-material tends to be coarse between the thalweg and the side of the riffle that merges into the upstream end of the downstream bar, and finer at the opposite bank close to the next bar upstream.

A common form of lateral variability is bankward fining that may occur in any cross-section with self-formed banks. Bankward fining is not only due to gravel particles becoming finer towards the banks, but also due to the deposition of sand in the area between the low-flow and the high-flow bank line, whereas most of the mid-channel streambed is sandless. Thus, bed-material samples collected between the high-flow water lines of both banks often produce a finer bed-material size than sampling within the borders of the low-flow water line. Careful scrutiny of the sampling objectives should help deciding whether sampling should extend to the low-flow or the high-flow water line.

Table 3.2 summarizes features of bedform morphology, flow, and patterns of bed-material size for riffles, pools, and bars in C-type streams with riffle–pool morphology. Note that the transition between the upstream end of the bar and the riffle, as well as between the downstream end of the pool and the upstream end of the riffle can be smooth without any recognizable morphological boundaries.

An example of the spatial variability of bed-material particle sizes within a riffle-pool reach is provided by Lisle and Madej (1992) (Fig. 3.10). Generally, bed material is coarsest on riffles, and bar heads, both in the aggrading and degrading reach, while pools have deposits of fines. However, irregularities and patchiness in the spatial patterns of bed-material size may obscure underlying schematic spatial patterns of bed-material size.

Table 3.2: Morphological, hydraulic, and sedimentary features characteristic of riffles, pools and bars during low and high flows in C-type streams with riffle-pool morphology

Criterion	Riffles	Pool	Bar
Longitudinal form	ridge, or locally steep	depression, or locally flat	evenly inclined, but less steep than thalweg
Cross-section shape	± symmetrical or asymmetrical	asymmetrical	asymmetrical
Low flow situation			
Flow depth	shallow	deep	mostly exposed
Flow velocity	relatively fast	relatively slow	n/a
Water surface	locally steep and rippled	nearly horizontal, smooth	n/a
Stream width	wide	narrow	n/a
Bed-material size	coarse scour lag	coarse scour lag, or deposit of fines	transition from coarse to fine
Surface fines	not likely	possible	possible
Spatial variability	lateral & longitudinal		
Structural elements	clusters, wedging, imbric.	wedging, imbrication	clustering & imbrication
High flow situation			
Flow depth	shallow	deep	shallow
Flow velocity	slow	fast	slow
Water surface	evenly inclined over the reach		
Stream width	± even over the reach		
Bed-material size	coarse deposit	coarse scour lag	transition from coarse to fine
Surface fines	not likely	not likely	possible

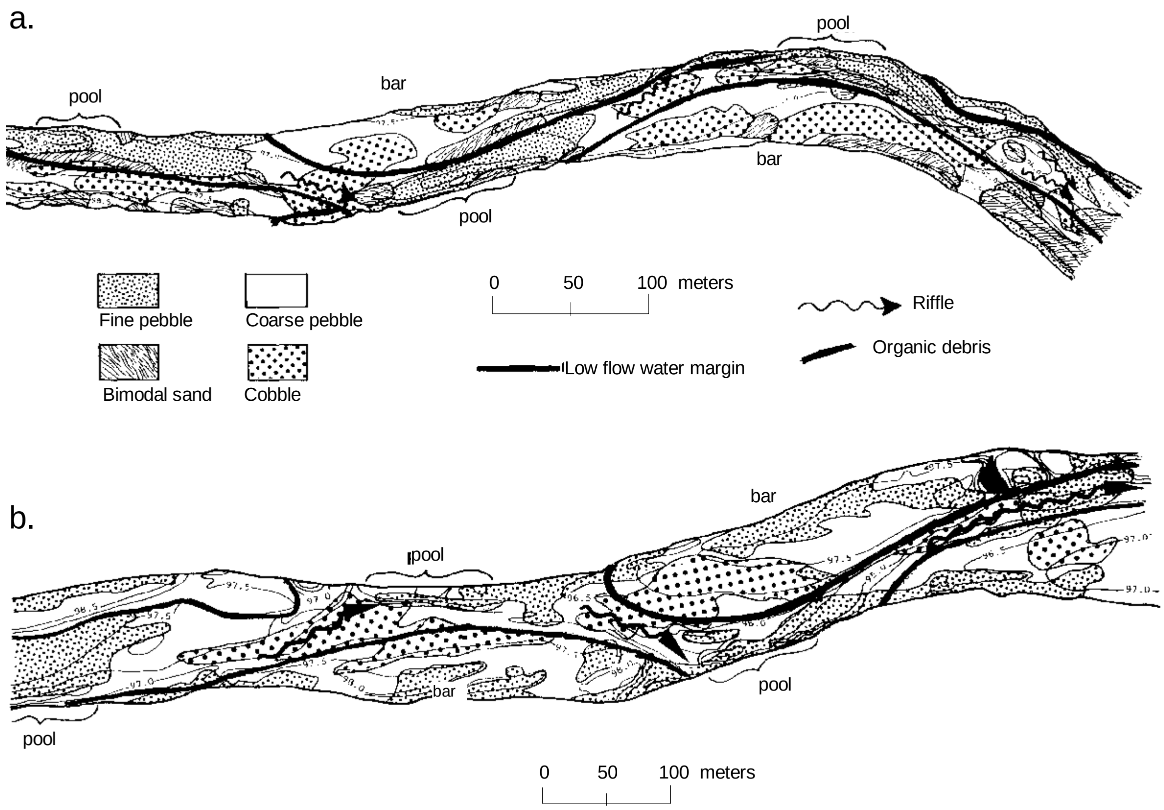

Fig. 3.10: Spatial variability of bed-material sediment sizes in a degrading (a) and aggrading (b) riffle-pool reach of Redwood Creek, northern California. (Reprinted from Lisle and Madej (1992), by permission of John Wiley and Sons, Ltd.).

3.2.3 Stream morphology and particle-sizes in B-type and A-type streams

Riffle-pool sequences and bar units typical of C-type streams with riffle-pool morphology (Section 1.3.1 and 1.3.2) and gradients within the range of about 0.001 to 0.02 become less well developed as the stream gradient steepens and stream morphology approaches a plane-bed in B-type streams with gradients of 0.01 or 0.02. Steep C-type streams tend to have only intermittent sequences of riffle-pool units, whereas low-gradient B-type streams tend to have only a few pools interspersed in a plane-bed morphology consisting largely of runs. Gravel bars as sediment storage features are poorly developed, because transport capacity often exceeds sediment supply. The few bars present have irregular forms, are tied to locations of stream widening, and occur isolated and non-sequential. Thus, free-formed pools and bars are rare in plane-bed streams with gradients around 0.01-0.03 (Montgomery and Buffington 1993). Most of the streambed could be classified as a run with little spatial variability in bed-material particle size beyond landward fining towards the bankline. This relative homogeneity in bed-material particle size is a factor that makes bed-material sampling easy in plane-bed streams. However, this ease is counteracted by the difficulty of extracting the large and often wedged particles off the streambed.

The morphology of step-pool or A-type streams (Section 1.3.1 and 1.3.2) is a sequence of steep steps composed of cobbles and boulders that alternate with pools of finer bed material (Montgomery and Buffington 1997; 1998, Church 1992; Section 1.3.1). Thus, step-pool streams have a systematic longitudinal sorting. The lateral variability is mostly random (Fig. 3.11). Bed-material sampling in step-pool streams is difficult for several reasons. Particles comprising steps are often large, tightly wedged, and cannot be extracted from the bed. Large particles also require a large spacing between individual sampling points of pebble counts to avoid serial correlation (Section 4.1.1.4). The requirement for large spacing extends sampling over a long stream distance because most step-pool streams are only a few meters wide. Individual steps or pools are too small to provide an adequately large sample size. Therefore, several steps and pools have to be sampled. Many of the step-forming particles can be transported only by catastrophically large floods. The researcher needs to decide the largest boulder size that should be included in the sample.

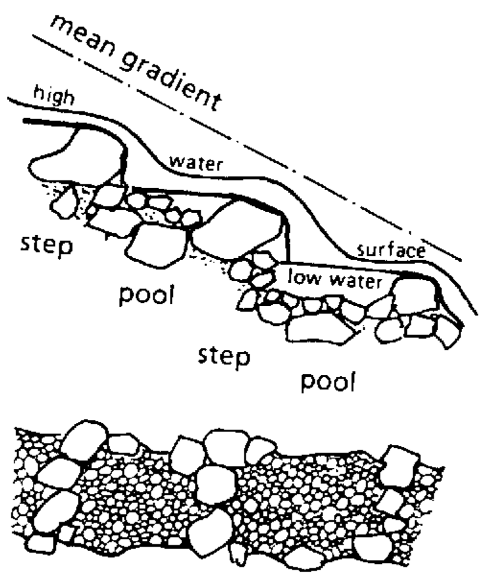

Fig. 3.11: Longitudinal and plan view of a step-pool stream. (Reprinted from Church (1992), by permission of Blackwell Science, Ltd).

3.2.4 Effect of large woody debris and other stream blockages on stream morphology and particle sizes

The presence of large woody debris (LWD), debris flow or landslide deposits, and beaver dams in streams affect the sediment-transport dynamics in streams, the channel morphology, and the spatial distribution of sediment size in various spatial scales. LWD or other material can block the downstream bedload conveyance entirely or partially. This may lead to the deposition of coarse sediment upstream of the blockages, of fine sediment in areas of backwater or water ponding, and to coarse lag deposits in scour and plunge pools. Reaches downstream of the obstruction may be cut off from sediment supply and become degraded. Even isolated pieces of LWD or large boulders may alter the local flow field and affect stream morphology and particle sizes in their vicinity.

Large-scale effects: upstream sediment wedge and downstream scour

A log jam consisting of several large tree trunks and finer woody debris can effectively block the downstream conveyance of sediment. Blockage causes the deposition of bedload sediment on the upstream side. The alluvial wedge (Fig. 3.12 a) resulting from this deposition may extend over a distance of several 100 m. The channel gradient upstream of the log jam decreases as the alluvial wedge starts to grow, so that particle sizes deposited close to the log jam become finer over time. The downstream side of the log jam receives no sediment from upstream. Thus, excess shear stress winnows sand and gravel particles from the bed until only large particles that are commonly untransportable are left on the bed as a coarse lag deposit or erosion pavement (Rice 1994, 1995; Rice and Church 1996a; Buffington and Montgomery 1999b). Depending on the duration of the log jam, the downstream erosion pavement may extend over a 100 m or more as well. Some log jams are long-lived, and remain in place for decades depending on the rotting resistance of the wood. Eventually, as the log jam begins to deteriorate, it becomes increasingly permeable to sediment. Sediment starts to be scoured off the upstream deposit which then coarsens over time. The downstream bed starts to become finer as the lag deposit is replenished with upstream supply. Not all log jams are long-lived. Some log jams shift annually, causing an annual change in the morphology and particle-size distribution of the streambed.

Medium-scale morphological and sedimentary effects

Channel blockage may also affect stream morphology and particle sizes in the medium scale of several meters. One or a few logs blocking a stream may cause upstream deposition of relatively coarse bedload (Fig. 3.12 b). A plunge pool may form at the downstream side if flow overtops the channel obstruction (Thompson 1995; Montgomery et al. 1995; Montgomery and Buffington 1997, 1998). The plunging water is likely to scour all but the largest particles, leaving a coarse erosion pavement. Fine sediment might deposit in the backwater area of plunge pools during low flows, or flow in plunge pools may be continually large enough to winnow all fines. Downstream degradation of the bed does not occur when bedload passes over the obstruction after having filled the upstream void. A closely-spaced sequence of large woody debris pieces extending over the width of the stream may produce a sequence of log steps (forced step-pool channel) (Fig. 3.12 c).

If the stream blockage extends high above the water surface and if the sediment supply from upstream is low, a *dammed* pool may form on the upstream side of log jams (Bisson et al. 1981; Thompson 1995). Dammed pools may have only small deposits of fines or may become filled with sediment given enough time (Fig. 3.12 d).

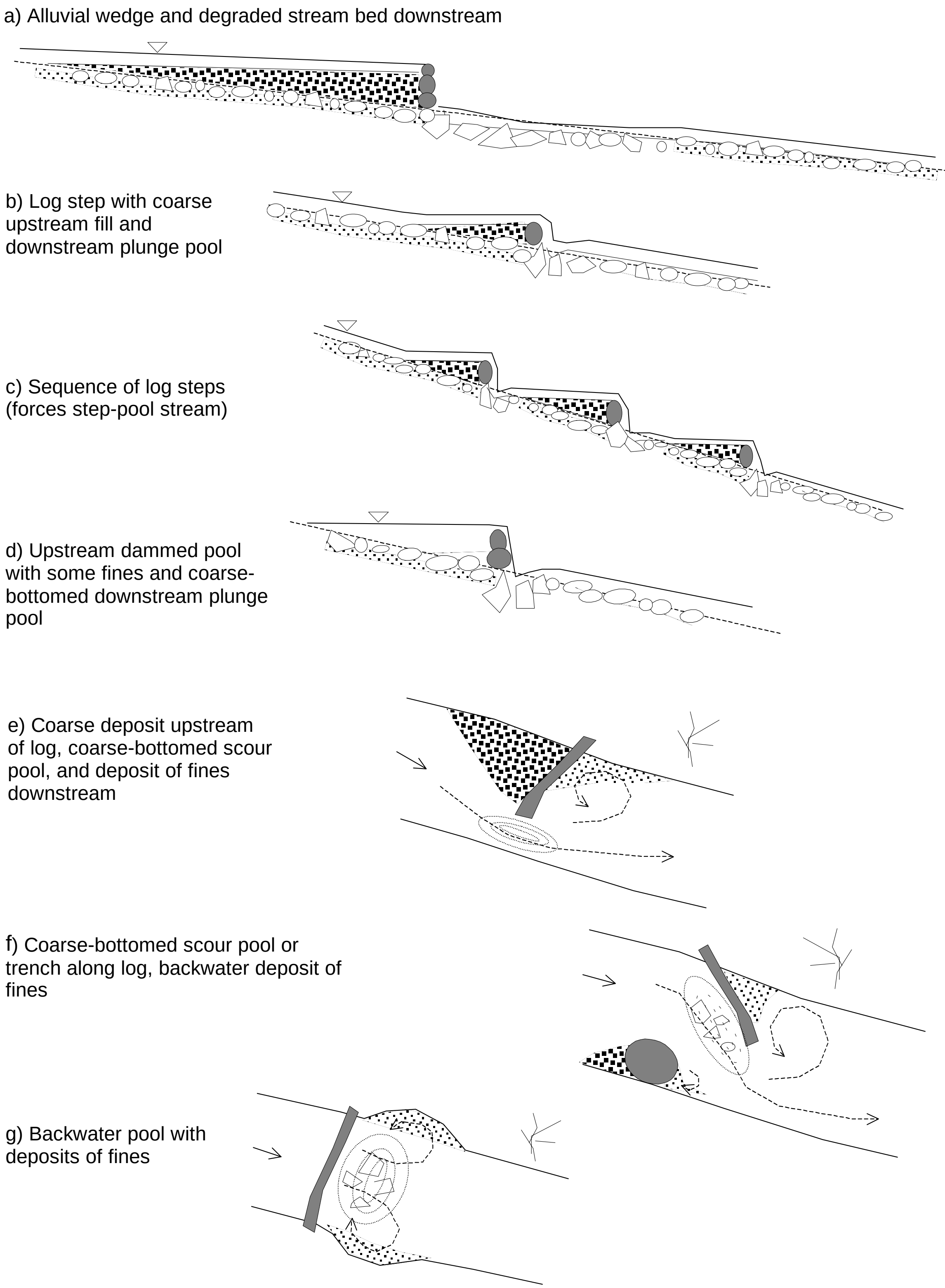

Fig. 3.12: Stream morphology and bed-material size around large woody debris. Deposit of coarse and fine sediment, lag deposit of coarse particles, unaffected streambed, and LWD or other stream obstructions. (a - d) side view, (e - g) plan view.

The stream blockage does not have to be complete to have a pronounced morphological and sedimentary effect on the stream. Partial blockage of the downstream sediment conveyance by individual pieces of large woody debris interrupts the necessary three-dimensional patterns of flow and disturbs the formation of riffle-pool sequences. A piece of LWD extending from the banks partially into the stream may have a deposit of relatively coarse sediment on the upstream side, while finer sediment is deposited in the backwater area on the downstream side (Fig. 3.12 e). A coarse-bottomed scour pool with a coarse lag deposit may develop where a piece of LWD confines or constricts the flow within the cross-section (Fig. 3.12 f, see also Fig. 3.12 e). A *backwater pool* with deposits of fine sediment may be created in the backwater area of a log (Fig. 3.12 g).

Chaotic patterns of bed-material size

The presence of LWD may erase any apparent systematic patterns in spatial variability of bed material size (Buffington and Montgomery 1999b) (Fig. 3.13). The resulting patchy appearance of bed-material size has implications for bed material sampling locations and sampling schemes.

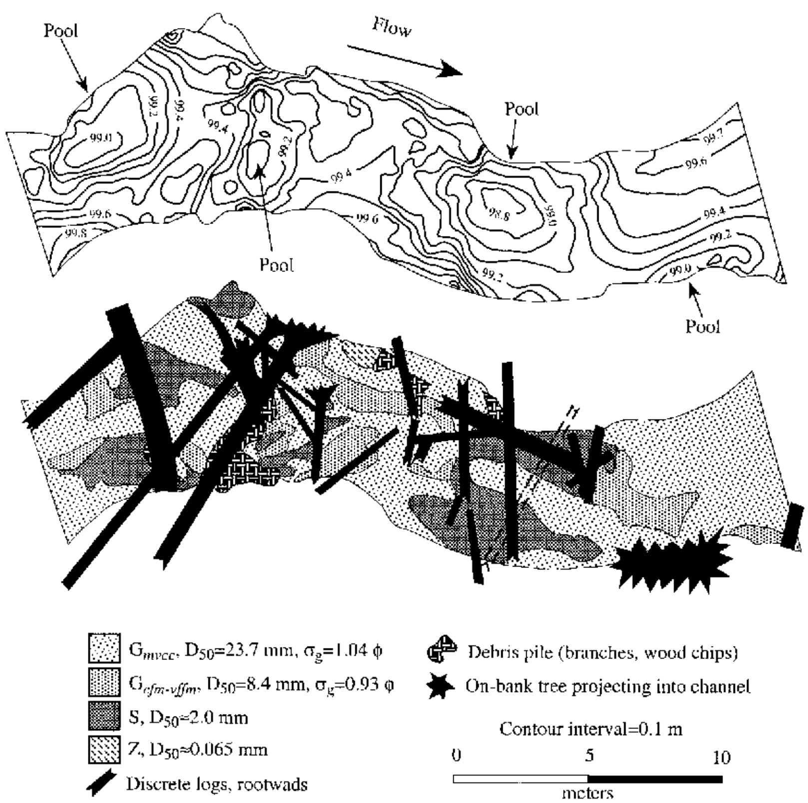

Fig. 3.13: Stream morphology and chaotic patterns of bed-material particle size in a stream containing a large amount of large woody debris. Flow direction is from left to right. *G* = gravel (see Section 4.1.3.4 for more detailed definition of facies descriptions), *S* = sand, and *Z* = silt; σ_{gs} = Inman (1952) sorting coefficient (Section 2.1.5.4). (Reprinted from Buffington and Montgomery (1999b), by permission of the American Geophysical Union).

If possible, reaches with LWD should be avoided when sampling bed-material with the aim of characterizing a reach. A reach that consistently displays a particular stream type with its recurring features of fluvial geomorphology should be selected instead. However, some streams, especially in the Pacific Northwest, consist of a sequence of log jams and are continually loaded with large woody debris. If such streams need to be sampled, it is important to identify the sedimentary processes and the resulting sedimentary units. That knowledge forms the basis for selecting which of the sedimentary units to sample, and for determining how they are to be included in the sampling project.

3.2.5 Bed-material particle sizes around boulders

Isolated boulders supplied from rockfall or unearthed from glacial deposits likewise cause complicated local hydraulic conditions in their vicinity and thus affect the bed morphology and the spatial variability of bed-material size.

Coarse sediment may be deposited on the upstream side of boulders. Coarse-bottomed plunge pools may form where flow overtops logs or boulders. Coarse-bottomed scour pools form if flow is confined vertically or laterally by logs or boulders and scours the adjacent stream bed (Bisson et al. 1981, 1987; Sullivan et al. 1987; Church 1992; Wood-Smith and Buffington 1996). A horse-shoe vortex scour may form at the upstream side of boulders, while fine sediment is deposited in the downstream wake (Section 3.4.4). Boulders or logs may also create backwater in which fine sediment is deposited.

It is important to understand the sedimentary processes in the vicinity of untransportable stream objects. This understanding helps to evaluate whether sediment from the vicinity of boulders is representative or appropriate for sampling. The presence of untransportable large boulders also poses the question of whether or not to include these boulders in a particle-size analysis. The answer depends on the specific questions of the sampling project. If, for example, local channel *form roughness* is to be determined, immobile boulders need to be included.

Flow around immobile boulders dissipates energy which otherwise may have been utilized for transporting coarse bedload. Thus, immobile boulders may also have an effect on the general bed-material size of the reach, causing perhaps less coarse and less armored deposits than would develop were the boulders not present (Buffington and Montgomery 1999b). Immobile boulders might also cause flow confinement and scour, leading to a coarse lag deposit and a bed coarser than if the boulders were absent. Thus, if boulders are expected to cause general bed fining or coarsening, both the mobile and the immobile bed material should be sampled. Immobile boulders are usually not included in a sampling project if the bed-material size analysis is used to compute bedload transport rates.

3.3 Vertical variability in bed-material size

Gravel deposits can have a variety of different vertical structures depending on the supply of transportable sediment in the streambed, the bed-material particle-size distribution, and the interaction with the hydraulics of flow. Various processes causing a vertical structure (stratification) in the bed-material of gravel-bed streams are discussed in Section 3.3.1. Implications for sampling are discussed in Section 3.3.2.

3.3.1 Sedimentary processes causing vertical stratification

Three distinct particle-size distributions are commonly observed in gravel-bed rivers: (1) Coarse gravel distributions are often skewed towards fines and have a median particle size of 32 to 64 mm. The median particle size of the coarse part is cobbles, whereas the median size class of the fine part is medium gravel. (2) Cobble distributions without much fine and medium gravel have a median particle size in the cobble range. (3) Fine gravel distributions with mostly medium gravel and sand and only a few coarse gravel particles and cobbles. Even within one stream location, the bed-material particle-size distribution may change over time, owing to a change in sediment supply or hydraulics of flow. These changes are reflected in the vertical profile of the streambed sediment.

The vertical profile of a streambed usually shows that particle-size distributions do not change gradually with depth, but change abruptly in the form of layers (or strata). The particle-size distribution in each layer is the result of an interaction between flow hydraulics and sediment. The strata can therefore be used to obtain information on the amount of sediment supplied to the stream, the sediment particles sizes, and the manner in which the sediment was transported and deposited. Although the interpretation of the sedimentation processes may not always be straight forward in a given strata, an analysis of the sequence of the strata can provide information of the temporal sequence of flow and sediment interactions. An analysis, for example, may show an increase in the fine sediment supply and that result may be important for protecting aquatic habitat or for streambed monitoring of watershed management effects. Implications of stratified sediment for bed-material sampling are discussed in Section 3.3.2.

One example of a sediment strata is the *framework-supported* gravel deposit (Fig. 3.14 a). It forms when fine sediment is relatively scarce so that large, adjunct particles touch. If fines exceed about 20-30% of the sediment volume (which is roughly the volume of the voids between large clasts) large particles no longer touch, and the deposit starts to become *matrix-supported* (Fig. 3.14 d).

A frequently observed stratification feature in gravel-bed rivers is that the surface sediment is coarser than the subsurface sediment (Fig. 3.14 a). Surface coarsening (as opposed to subsurface fining) is attributed to three different processes: (1) selective scour of fines (erosion pavement), (2) selective deposition of large particles, or (3) armoring to facilitate equal mobility transport. These processes are discussed in Section 3.3.1.1.

Another example of stratified bed material is the *filled gravel* (Fig. 3.14 c). The presence of gravel with empty voids in the underlying strata supports the interpretation that fine

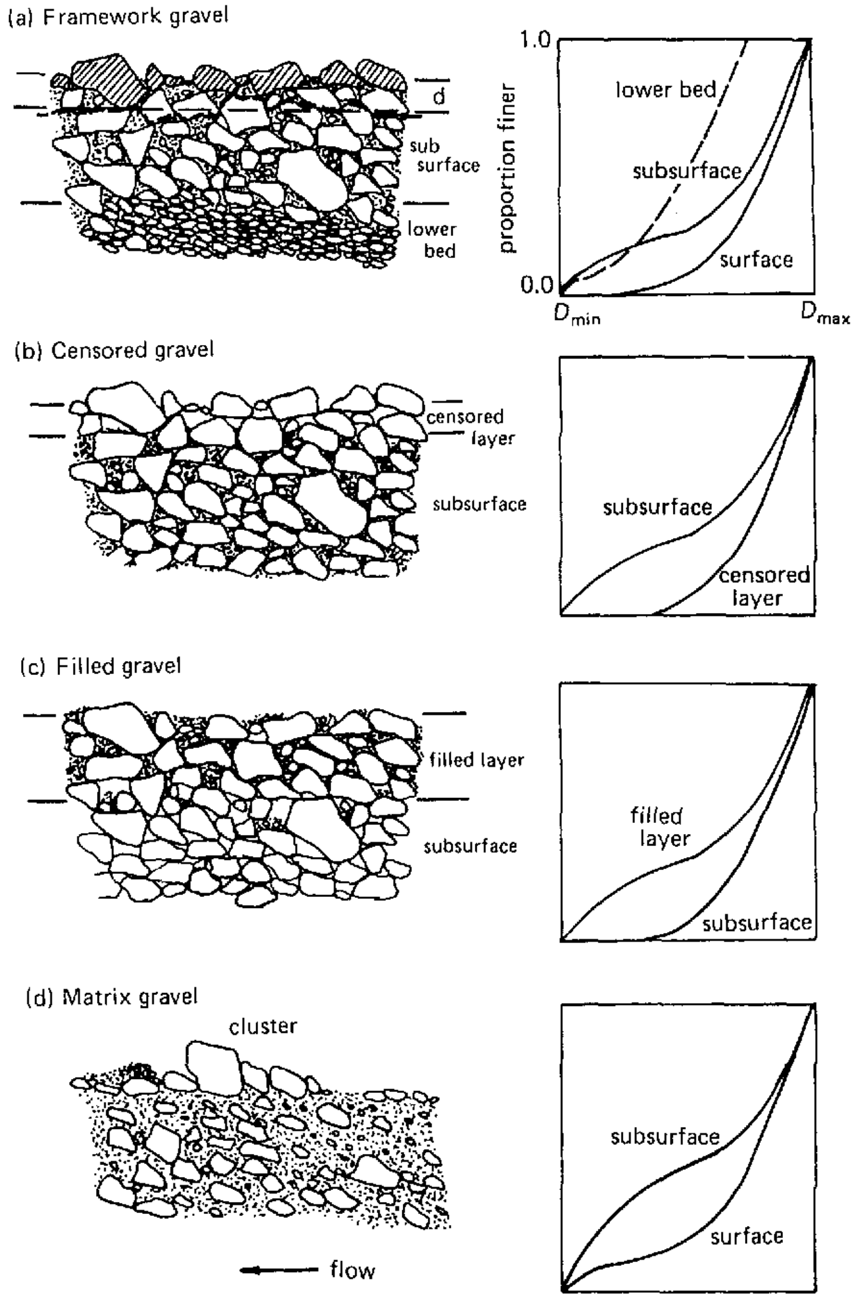

Fig. 3.14: Typical bedding and grain-size distribution curves for fluvial gravel. Note the hatched surface particles in the top figure. Only those particles are part of a *surface* sample. The *armor layer* with a thickness *d* in Fig. 3.14 a extends from the surface down to a depth defined by the deepest reaching particle in the sampling area. (Reprinted from Church et al. (1987), by permission of John Wiley and Sons, Ltd).

sediment infiltrated into a deposit of originally coarse gravel. Two main mechanisms have been identified which cause an infiltration of fines into a coarse open framework. These are discussed in Section 3.3.1.2.

Another example of stratification in gravel-beds is a *censored layer* of coarse gravel, one or several particle sizes thick, in which the voids are free of fines (Carling and Reader 1982) (Fig. 3.14 b). The presence of voids filled with fines in the strata below leads to the interpretation of initial scour, followed by either a preferential deposition of coarse particles, or by vertical winnowing (piping) of fines that leaves coarse gravel behind.

3.3.1.1 The coarse surface layer: armoring and pavement

Many gravel-bed rivers have surface sediment that is coarser than the subsurface sediment (Fig. 3.14 a). Three processes are attributed to surface coarsening (as opposed to subsurface fining):

- selective scour of fines (erosion pavement),
- selective deposition of large particles, or
- armoring to facilitate equal mobility transport.

Selective scour of fines

Selective winnowing of fines from the surface leaves a coarse lag deposit on the surface about one particle diameter thick. The reasons for surface winnowing can be decreased sediment supply, and/or increased flow. Long-term coarsening of the surface occurs in the absence of sediment supply on the downstream side of log jams (Section 3.2.4), in plunge and scour pools, or below reservoir dams (erosion pavement).

Selective deposition of large particles

Selective deposition of coarse particles with surface coarsening occurs when waning flows are no longer competent to transport the largest particles - which then begin to settle. The supply of fine particles may be low, at least during flows at which they would settle.

Armoring to facilitate equal mobility transport

Another explanation for the formation of a coarse surface armor is that a coarse surface is the prerequisite for *equal mobility* transport of coarse and fine particles (Parker et al. 1982; Andrews and Parker 1987). If the surface was not armored (i.e., surface and subsurface particle size were the same), coarse particles would move less frequently than fine particles. Bedload then has a finer distribution than the bed sediment. The frequently observed similarity between the size distribution of bedload and the subsurface sediment requires that the mobility of coarse particles is increased, while the mobility of small particles is decreased. This mechanism can be facilitated by the presence of a coarse armor layer in which coarse particles are exposed to the surface that provides them with an increased chance of transport. Fine particles are hidden below the surface where their transport probability is diminished. Thus, the preferential exposure of larger particles in the armor layer acts to equalize the mobility of coarse and fine particles and eliminates most of the differences in the mobility of small and large particle sizes.

A coarse surface layer can be termed *armor* or *pavement*. In the terminology used by Sutherland (1987), armoring refers to episodic surface coarsening when, over the course of commonly occurring high flows, large particles have a chance to be mobile, albeit infrequently. By contrast, pavement refers to static conditions under which the largest particles are immobile given the prevailing flow regime and sediment supply. Andrews and Parker (1987) use the terminology in the opposite way: pavement is the coarse bed that develops to achieve equal mobility, whereas armor denotes a coarse and static lag deposit. Since the terms armor and pavement are not used consistently in the literature, the reader needs to determine the exact meaning of the terms armor or pavement in any given context. This text follows the terminology by Sutherland (1987): armor is mobile and pavement is static.

A surface armor is less developed in streams where transport capacity (i.e., the largest amount of bedload that a given stream reach can transport) equals the amount of sediment supplied to the reach. This is common in braided streams. The particle-size distributions of surface, or armor layer, and subsurface sediment are relatively similar under these conditions. Transport capacity is often larger than sediment supply, and a coarse surface armor becomes prominent. This situation is common in many armored gravel-bed streams. High energy mountain streams usually have high transport capacity but low sediment supply which leads to the formation of an erosion pavement that may only be mobilized by the largest floods.

The degree of armoring may be quantified by the ratio of the D_{50} surface sediment size to the D_{50} subsurface sediment size. This ratio approaches a value close to 1 in streams with high sediment supply, whereas streams in which transport capacity exceeds sediment supply, the ratio approaches a factor of approximately 2. The ratio of D_{50surf}/D_{50sub} may reach values of 3 or more in high-energy mountain streams or when sediment supply is completely shut off and an immobile, coarse lag deposit forms. For example, such conditions are found below reservoir dams. High values in the ratio of D_{50surf}/D_{50sub} may also be produced by the presence of untransportable, large particles supplied to the stream from non-fluvial sources (rockfall, exhumed boulders), or in the presence of censored layers (Fig. 3.14 d). The surface sediment may also be finer than the subsurface sediment, for example, when a high supply of fine sediment covers the surface. This may decrease the D_{50surf}/D_{50sub} ratio to values below 1. (See also Sections 6.1.6.2 and 6.5.2 for the ratio surface/subsurface sediment size).

3.3.1.2 Mechanisms of fine sediment intrusion into open framework gravel

Research on fish spawning habitat has identified two main mechanisms for fine sediment intrusion into framework gravel with open pores: infiltration based on gravity and intrusion of fine sediment by interstitial flows. In gravity-based infiltration, fine gravel and sand moving over the bed surface as bedload becomes trapped between large particles and falls into the voids between surface particles. The rate of fine sediment infiltration increases with the supply of fine-sized bedload, and with the number and size of open pores. Fine sediment intrusion is due to downwelling flows that bring fine particles from suspended sediment into the pore space (Alonso 1993). The rate of fine-sediment intrusion increases with the concentration of suspended sediment, the severity of downwelling, the size and number of open pore spaces, and the rate of interstitial flows (Lauck et al. 1993).

Fine sediment intrusion into a non-stratified deposit of coarse gravel can cause different vertical stratification, depending on the intragravel pore sizes and the size of the infiltrating particles. If the infiltrating particles are finer than the intragravel pores, the infiltrating sediment fills the pore space from the bottom up, causing no pronounced vertical variation of infilled particle sizes. If the fine sediment is a mixture of silt, sand and fine gravel, fine gravel can eventually seal the pore spaces near the surface and prevent finer sediment from infiltrating into deeper pores. Depending on how fast the near-surface pore space is sealed, there can be a gradually upward coarsening of the infiltrated fines, or a layer below the surface that is free of infilled fines.

3.3.2 Implications of vertical stratification for bed-material sampling

When sampling bed material that is vertically stratified, it is important to distinguish between different strata because each stratum represents different channel-bed processes. Sampling and analyzing each strata individually is not only important for analyzing sedimentation processes, but also for analyzing the habitat of aquatic ecosystems (Bjornn and Reiser 1991; Montgomery et al. 1996) or for monitoring a change in fine sediment supplied to the stream following a change in watershed management.

The question arises whether sediment strata have a fixed thickness and to what thickness strata should be sampled. The short answer is that some strata have a relatively fixed thickness, while the thickness of other strata is variable.

Surface coarsening (Fig, 3.14 a and Section 3.3.1.1) affects not only the immediate sediment surface, but the armor layer that extends from the surface down to approximately the depth of some large surface-particle size, e.g., the D_{90} size. Thus, one could sample surface particles (pebble counts, Section 4.1.1; areal samples, Section 4.1.3) or take a volumetric sample of the armor layer (Section 4.2.1). The depth to which surface fining extends downward into the bed (Fig. 3.14 c) depends on how deeply the fines have infiltrated the bed (Section 3.3.1.2). Similarly, the thickness of censored gravel (Fig. 3.14 b) depends on the duration and magnitude of the sedimentary processes. The exact depth of sediment strata can only be determined by digging gravel pits or by taking core samples. All sediment layers below the surface are sampled volumetrically (Section 4.2.2 - 4.2.4).

3.4 Bed-surface structures

Bed surface-structures are arrangements of particles into groups of various sizes or arrangements of particles into a particular packing, or a combination of both. These arrangements are caused by the interaction between flow hydraulics and particles. Bed surface-structures may either cause small-scale or local variations of bed-material size, or form beds with little variation in particle size.

Bed-surface structures may cause problems for bed-material sampling. Surface structures require a large spacing between sampling points, and extracting a particle out of a surface structure may be difficult. Particles involved in surface structures are partially hidden from view, which complicates visual and photographic methods of bed-material size analysis. The presence of any bed-surface structures should be recorded in the sampling notes because bed-surface structures can either increase or decrease erosion thresholds and hydraulic roughness.

Bed-surface structures may have a transverse or longitudinal orientation in the stream. They may cover much of a reach, or occur spatially isolated. Various forms of bed-surface structures are introduced in Section 3.4.1 – 3.4.6. Implications for bed-material sampling are discussed in Section 3.4.7.

3.4.1 Transverse and longitudinal bedforms

Large particles transported in a relatively steep stream during a major flood event with high sediment supply produce several kinds of bedforms during deposition. The general mechanism is that the largest particles settle first and control the deposition of other large and small particles in their vicinity.

Transverse clast dams have a lobate front of large, loosely fitted and well-sorted clasts. After the coarse lobe front is deposited, finer sediment deposits on the upstream end of the dam (backfill) (Bluck 1987; Krumbein 1940, 1942). Clast dams may vary in size. They may be up to 1 m high or more, and several m or even several 10 m wide and long. The largest particles in the clast dam may reach cobble and boulder size. Height, width, the largest particles, and length of the dam (or spacing between dams) are related. The dam length is approximately equal to the dam width, about 5 times longer than the dam height, and 5 - 7 times the diameter of the largest clast in the dam. Dam width is approximately 5 times the dam height, and the height is 2 to 0.8 times the largest clast size. Height and width of the dam fronts increase with the magnitude of the flood event. The backfill that consists of finer sediment than the coarse clast dam typically coarsens towards the dam. Fines at the upstream end of the backfill can form as a wake deposit from the next front upstream (Fig. 3.15). The largest particle within a lobe is usually not found in the lobe front, but in the backfill. Large particles may destroy the front while passing over it. The height and length of transverse clast dams typically decrease in a downstream direction, and the decrease is more pronounced in steeper channels. Transverse clast dams are found in streams with gradients larger than 1%.

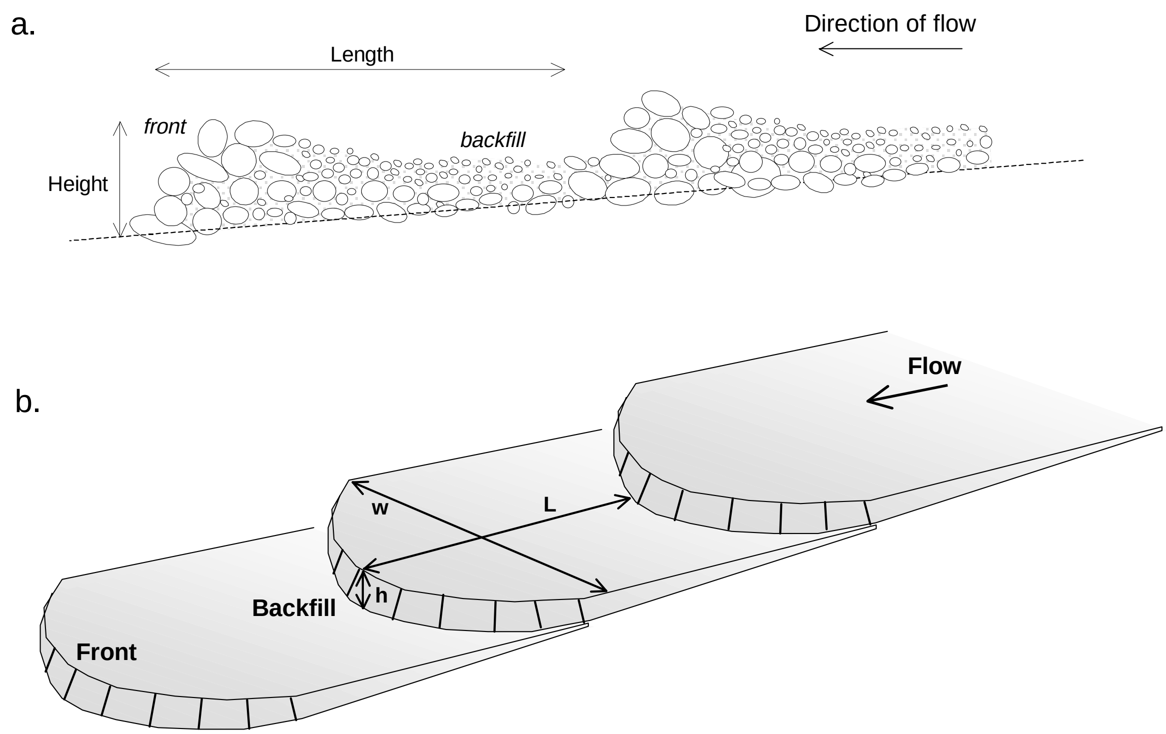

Fig. 3.15: Side view (a) and oblique view (b) of a transverse clast dam. *h* is the height of the bedform, *w* is the width, and *l* is the length.

Transverse ribs are sequences of regularly spaced ridge-like deposits of coarse particles that are transverse to flow (McDonald and Banerjee 1971; Boothroyd and Ashley, 1975; Koster 1978) (Fig. 3.16). Particles that form the ribs are oriented with their *a*-axes perpendicular to flow, and dip upstream along the *a*-*b* particle plane (Fig. 3.16). The coarsest particles within ribs are on the downstream side, and individual particles are often imbricated (Section 3.4.2). Height, width, length and particle size of transverse ridges are related. The rib height equals about one large particle, the width is 2 - 4 large particles, and the length 5 - 10 large particles. Width and length decrease with stream gradient. The area between the ribs contains finer sediment and sometimes fine sand. This difference in particle sizes makes the presence of the ribs recognizable. Transverse ribs are not restricted to steep channels, but can form on any locally steep depositional surfaces with shallow but high-energy flow. Koster (1978) suggests that transverse ribs form when flow over standing and upstream braking waves starts to wane and interprets transverse ribs as relict antidunes.

Longitudinal clast ribs are elongated ribs that form in steep channel sections when large particles are arranged parallel to flow (Bluck 1978). Longitudinal clast ribs may be several meters long and up to 1 m high. Particles in longitudinal clast ribs are well sorted, imbricated, and not longitudinally graded.

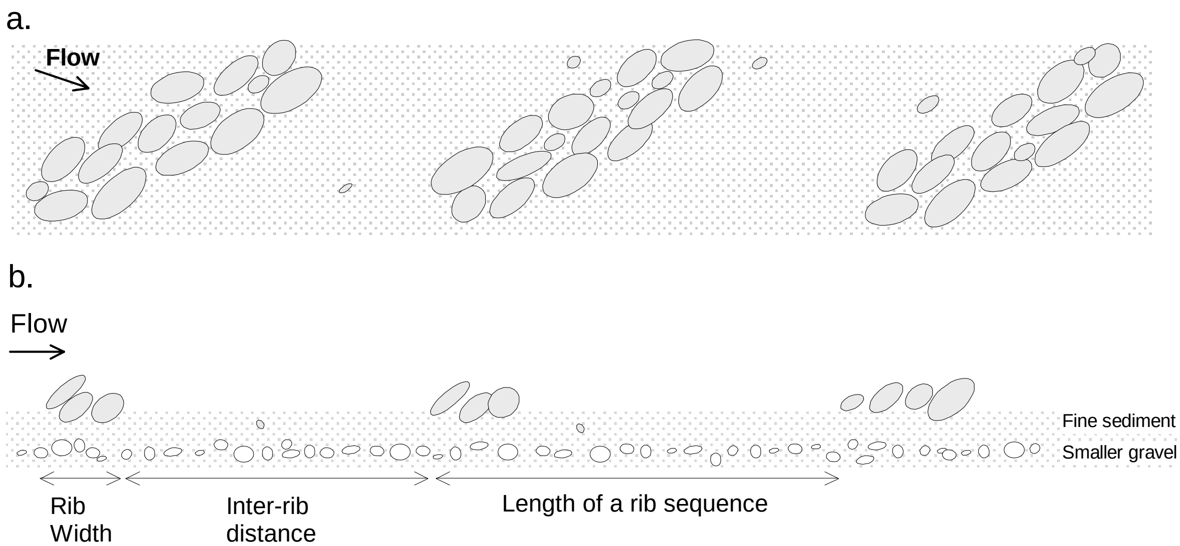

Fig. 3.16: Sequence of transverse ribs in (a) oblique view, and (b) side view.

Boulder and cobble berms are elongated deposits in the direction of flow, often curved, and commonly found in wide bends following a more constricted channel upstream. Boulder and cobble berms may form parallel ridges and contain negligible amounts of fine sediment. Boulder and cobble berms develop during turbulent overbank flow with high Froude numbers[1] and a large supply of coarse sediment when part of the flow turns upstream near the stream bank (Carling 1989).

Bedload or gravel sheets are a layer of particles with a thickness of 1 – 2 coarse particles. Bedload or gravel sheets travel downstream during flow events with high sediment supply. Coarse particles form the leading edge of this bedform that is much longer than it is high, and fine particles trail behind. Bedload sheets require a proper mixture of fine and coarse gravel. The formation of bedload sheets starts when several large bedload particles come to rest on a rough bed surface. Fine sediment passes over the accumulation of coarse particles, and fills interstices in front of the deposited coarse particles. The smooth surface of fines decreases roughness and increases drag on the coarse particles. This action remobilizes the coarse particles which then travel downstream over a surface of fine particles until coming to rest on the next rough bed-surface downstream (Iseya and Ikeda 1987; Whiting et al. 1988). Migrating bedload sheets travel in sequences and form a bed surface with alternately coarse and fine strips that may extend over much of the stream width. If bedload sheets are preserved during low flow, the alternate strips of coarse and fine sediment form a pattern of longitudinal

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[1] *Froude number* $F = \frac{v}{\sqrt{g \cdot d}}$, *v = flow velocity, g = acceleration due to gravity, and d = depth of flow. F>1 = supercritical flow.*

sorting on the bed (Fig. 3.17). Bedload transport rates measured during the passage of a bedload sheet are very high.

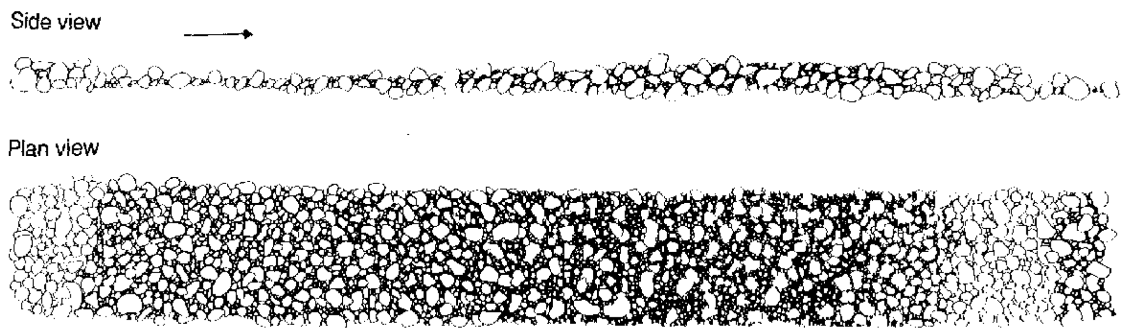

Fig. 3.17: Deposit from a bedload sheet with coarse front and fining towards the tail. Flow is from left to right. The downstream distance of the bedload sheet is about 0.8 m. (Reprinted from Whiting et al. (1988), by permission of the Geological Society of America).

Stone cells are bed-material patterns that may form in streams with relatively low bedload supply as a means of bed stability (Church et al. 1998). Stone cells are curved ridges of large particles. The ridges are transversely oriented and may face upstream or downstream, giving the impression of a coarse-grained ring around a cell filled by finer sediment. The development of a stone cell begins with the random deposition of the largest particles. Other large particles are then deposited in their vicinity.

3.4.2 Imbrication

Another form of bed-surface structure refers to the packing of particles of similar sizes. Imbrication is a shingle-like deposit in which the upstream particle partially overlaps its downstream neighbor. Flat particles of similar size are most susceptible to form imbricated surfaces. Imbrication can be limited to a few particles within a cluster (see below), be part of linear features such as longitudinal clast ribs (see above), or cover large streambed areas. Imbrication can be classified by the position of the three particle axes in relation to flow (Todd 1996). Particles set in motion by fluid forces roll about their *a*-axis (longest axis) in contact with the bed and are arrested by the particle in front. The *a*-axis is transverse to the flow, and imbrication occurs along the *b*-axis (Fig. 3.18). The thickness of the imbricated layer comprises 1 - 2 particles. Imbrication along the *b*-axis is characteristic of relatively low transport rates.

In streams with high bedload transport rates associated with traction carpets or debris flows, imbrication occurs along the particle *a*-axis, and the *a*-axis is parallel to flow (Fig. 3.18). This indicates that particles move by sliding and with grain-to-grain contact. Particles imbricated along the *a*-axis are separated from each other by finer matrix sediment. Both imbrication structures pose a high erosion threshold.

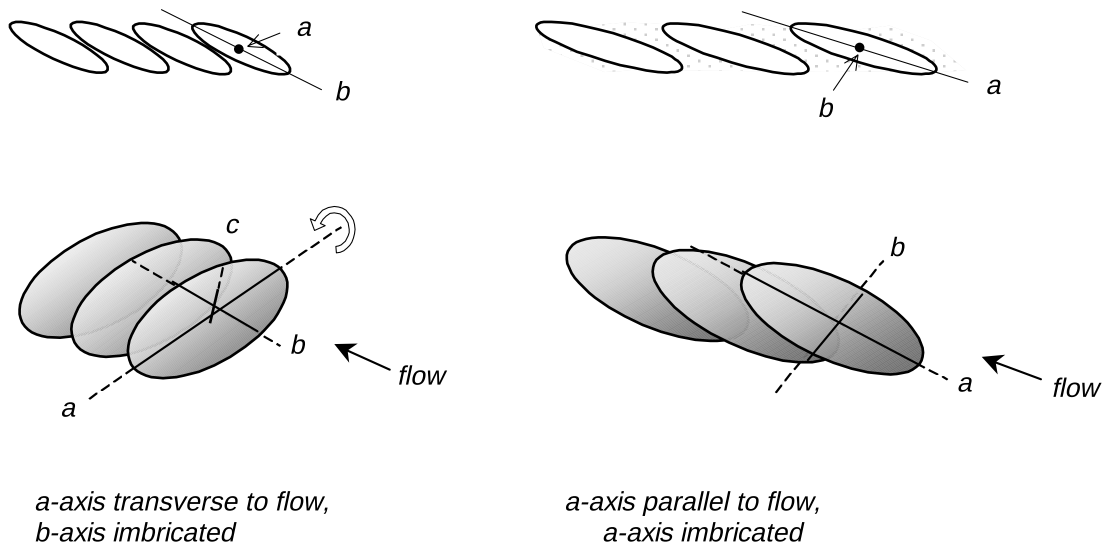

Fig. 3.18: Imbrication along the *b*-axis with the *a*-axis transverse to flow, characteristic of individual particle movement in fluid flows and low to moderate bedload transport rates (left); imbrication along the *a*-axis with the *a*-axis parallel to flow, characteristic of grain-to-grain interaction during high intensity sediment transport such as traction carpets and debris flows (right). Side views (top), and oblique views (bottom). (Redrawn from Todd (1996), by permission of John Wiley and Sons, Ltd.).

3.4.3 Clustering

A particle cluster is an accumulation of a few coarse particles on the upstream side of a large particle and is formed when a large obstacle clast comes to rest and one or more particles lean against the upstream side of it. Finer particles often accumulate in the wake downstream of the obstacle clast due to the inward-curling eddies of the flow separation zone (Brayshaw, 1984; Naden and Brayshaw 1987; Reid et al. 1992) (Fig. 3.19 a and b). Clusters with stoss and wake deposit are called complete clusters. The length of the wake deposit increases with the size of the obstacle clast. However, the wake deposit may be absent if the obstacle clast has a pointed shape or is aligned parallel to the direction of flow (De Jong 1992) (Fig. 3.19 c). Clusters without wake deposits are called incomplete clusters.

Clusters can be comprised of two or more particles, be one or more particles wide, and form one or several distinct rows of particles. Clusters can be solitary features, or form ribs that extend transversely, diagonally, or in lobate orientation across the stream. Clusters can also cover the streambed or parts of it in rhombic patterns (De Jong and Ergenzinger 1995).

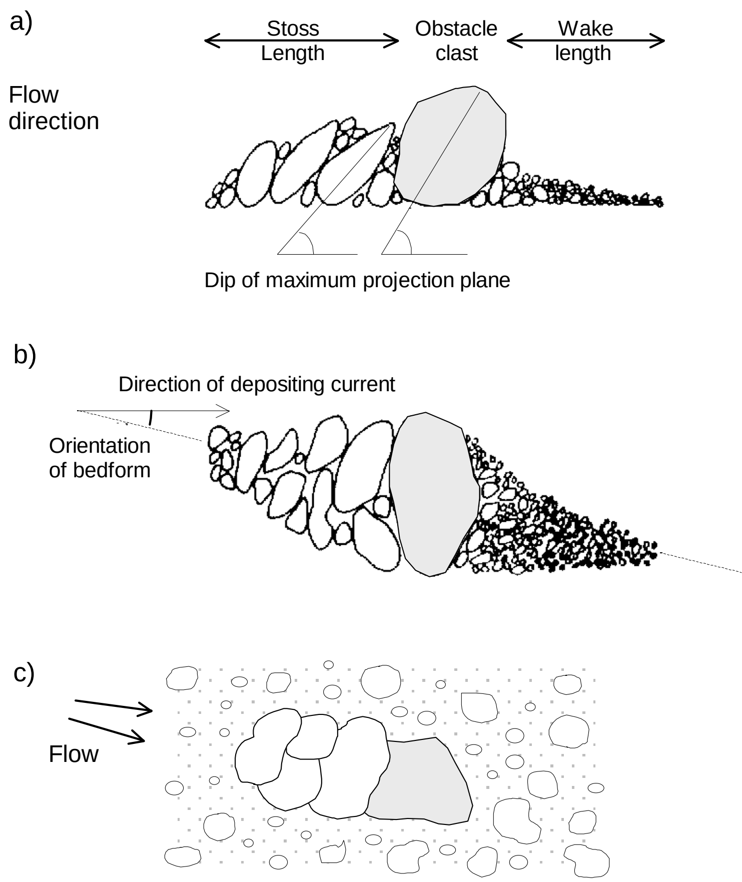

Fig. 3.19: Cross-sectional (a) and plan view (b) of a complete particle cluster with stoss and wake deposit. Flowlines form inward-curling eddies in the wake of the obstacle clast where fine sediment is deposited. (Reprinted from Brayshaw (1984), by permission of the Canadian Society of Petroleum Geologists). Incomplete cluster without wake deposit of fines (c).

3.4.4 Horseshoe vortex scour

Horseshoe vortex scour is scour around the upstream side of an immobile object and deposition of the scoured sediment at the downstream side. This form of scour is usually associated with scour around bridge piers, but it also develops around any large immobile obstacle surrounded by erodible finer sediment. As flow increases above a threshold, a helical vortex develops at the upstream side of the object and scours a semicircular trench. Fine sediment scoured from the trench as well as sediment from upstream that is transported through the scour trench is deposited by the inward-curling wake eddy on the downstream side of the obstacle (Fig. 3.20) (Bunte and Poesen 1994). Although horseshoe vortex scour is most prominent in sandy environments (e.g., around pebbles on a sandy streambed or sea shells on a sandy beach), it can also occur around boulders in a gravel streambed.

Horseshoe vortex scour increases particle mobility, because particles begin to be scoured from the vortex at flows much lower than needed for particles entrainment from the bed in the absence of horseshoe vortex erosion.

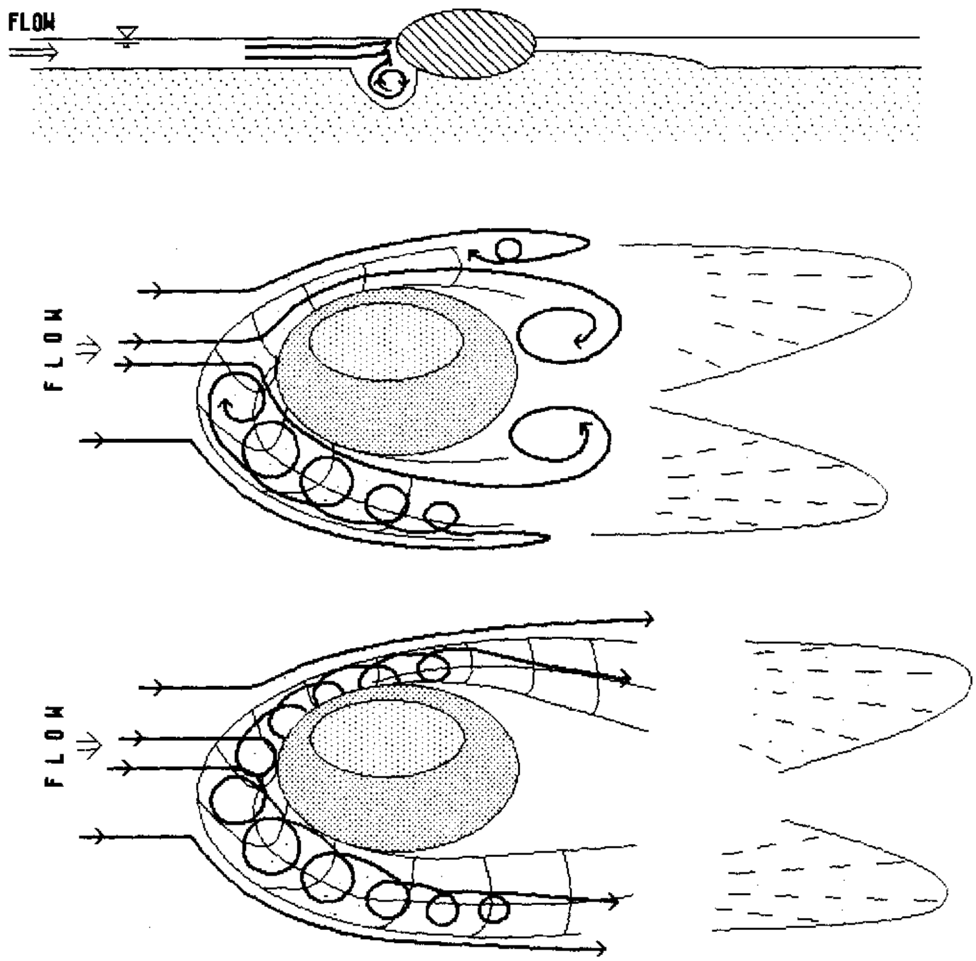

Fig. 3.20: Horseshoe vortex scour around a pebble in a sandy matrix: profile view and moderate flow intensity (top); plan view and moderate flow intensity (center); plan view and high flow intensity (bottom). (Reprinted from Bunte and Poesen (1994), by permission of John Wiley and Sons, Ltd.).

The sizes of particles in wake deposits are affected by the intensity of the local hydraulics around the obstacle. Sand transported over the bed during low flows may be deposited in the boulder wake, whereas during higher flows the material scoured in the vortex is deposited.

3.4.5 Cobble embeddedness and protrusion

Embeddedness refers to the position of a large particle relative to the plane of the bed. A large particle that is partially buried in finer sediment is said to be embedded. The degree to which a particle is embedded is called embeddedness. Embeddedness is a parameter used particularly by fisheries biologists to quantify the abundance of fine sediment in a streambed. The particle sizes that constitute large and fine sediment depend on the study objective and the channelbed conditions. According to Burns and

Edwards (1985), embedded particles typically have *a*-axes lengths of 45 to 300 mm, whereas the size of the finer sediment in which large particles are embedded is smaller than 6.3 mm. Embeddedness can occur throughout a reach of concern or be restricted to areas where local hydraulics lead to local deposition of fines.

Several methods may be employed to describe the degree of cobble embeddedness (MacDonald et al. 1991). *Embeddedness* (E) is the ratio of total vertical extent of a particle D_t to the vertical extent of the particle below the bed surface, i.e., the embedded portion of the particle D_e, so that $E = D_t/D_e$ (Fig. 3.21 a).

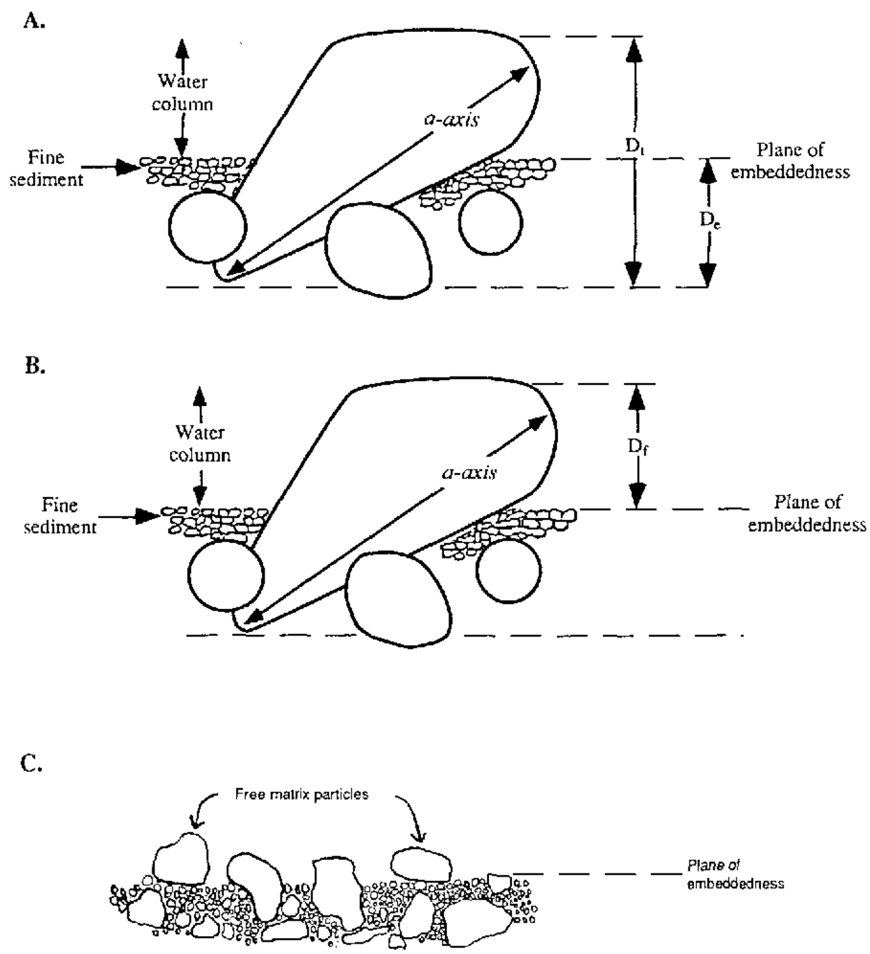

Fig. 3.21 a-c: Three methods of quantifying cobble embeddedness: **Embeddedness** $E = D_t/D_e$ where D_t = total vertical extent of a particle, and D_e = embedded vertical extent of a particle (a); **Free particle space** where D_f is the height of particle protrusion above the bed (b); **Percentage of free matrix particles** (c). (Slightly modified from MacDonald et al. (1991); source: Burns and Edwards (1985)).

Alternatively, *free particle space, or protrusion* D_f is the height by which a particle extends above the bed surface. Embeddedness and free particle space are related by D_f =

D_t - D_e (Fig. 3.21 b). Free particle space can also be expressed as an *interstitial space index* by computing $\Sigma D_f/A$, where A is the sampling area. To account for the high variability of individual measurements, the index can be computed by summing measured protrusion heights D_f and dividing by the sampled area, which is typically a circle with a diameter of 60 cm. The *percentage free matrix particles* for a given area is the ratio of the number of particles n_{exp} freely exposed on top of the bed to the number of particles of similar sizes n_{emb} that are embedded (Fig. 3.21 c). The percentage of free matrix particles $n_{\%\,exp} = 100 \cdot n_{exp}/n_{emb}$ closely corresponds to percent embeddedness $E_{\%}$.

Besides direct measurements of free particle space, the degree of protrusion by a particle with the size D can also be expressed by the ratio of D/D_{50}. A particle is protruding above the median particle size of the bed if $D/D_{50} > 1$, and hiding if $D/D_{50} <1$.

To characterize a streambed, particle embeddedness should be measured on at least 100 particles. A sample size equation (Section 5.2.1) should be consulted to determine the exact relation between sample size and error for a specific sample site. A more intensive sampling scheme is to measure embeddedness within circles of 60 cm in diameter outlined by hoops. Percent cobble embeddedness $E_{\%}$ for each hoop is $100 \cdot \Sigma D_e/\Sigma D_t$. Approximately 25 - 35 particles are measured within each hoop, and approximately 20 hoops (with a total of 500 - 700 particles) are needed to characterize $E_{\%}$ for a reach.

3.4.6 Gravel sheltered in pockets

In contrast to horseshoe vortex erosion that increases gravel mobility, gravel particles hidden in pockets between immobile boulders or other obstacles are sheltered from flow and have a pronouncedly lower mobility. Barta et al. (1993) suggested that pocket gravel is mobilized during flood events with a two-year recurrence interval. Mobilization of pocket gravel required total shear stresses 2 to 20 times larger than those needed if boulders were not present, and the required total shear stress increased with the height of obstructions (Barta et al. 1994). Thus, when sampling bed material for a flow competence analysis in boulder-bed streams, the population of transportable gravel needs to be analyzed separately from immobile boulders.

3.4.7 Implications of bed-surface structures for bed-material sampling

Bed-surface structures affect the mobility of particles on the bed. Imbricated, embedded, wedged, sheltered, and clustered particles have higher erosion thresholds than particles of the same size not contained in these surface structures (Brayshaw et al. 1983; Brayshaw 1985, Naden and Brayshaw 1987). Conversely, particles subjected to horseshoe vortex scour are moved by flows much lower than the threshold flow needed for particle motion from a plane bed without obstacles (Bunte and Poesen 1993, 1994). Thus, if bed material is sampled for analysis of forces exerted onto the streambed, initial motion studies, flow competence and bedload transport prediction, it is important to recognize and note particle packing and the presence of structures (Dunkerley 1994). Bed-surface structures also affect the hydraulic roughness of the stream. Imbricated beds and embedded particle structures have a lower roughness than one would assume from particle size alone, whereas the presence of clusters increases bed roughness beyond that expected for large particle sizes.

Surface structures may cause difficulties when sampling bed material. The presence of clusters or horseshoe vortex erosion requires that the spacing between sample points exceeds the size of the bed-structure. Taking more than one particle from local accumulations of coarse or fine particles (clusters or wakes) causes serial correlation in the sample and should be avoided (Section 4.1.1.4). Similarly, clusters or wakes should be avoided when trying to estimate the average particle size within the sample area. Avoiding bed-material structures is important when collecting all particles contained within a small sampling area (areal sample, Section 4.1.3).

Imbricated and embedded bed surfaces may also cause problems for visual particle-size analysis or when measuring the size of surface particles from a photograph. Imbrication and embeddedness does not pose so much a problem for measurements of the *b*-axis, but for measurements of the *a*- and *c*-axes which are partially hidden from view (Section 4.1.2.2 and 4.1.3.3). Photographs of the streambed surface, however, are quite suitable to map bed-surface structures. The orientation of individual particles can be analyzed from large-scale photographs that cover 0.1 –1 m^2 of streambed. Areal overview photographs that cover 100 m^2 or more can be taken from a camera suspended 10 - 30 m above ground by a crane or helium balloon and are suitable to analyze the spatial distribution of bed-surface structures within a reach (Section 4.1.3.4).