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Placer formation in gravel-bedded rivers: A review

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Abstract

The literature on placer formation processes within fluvial systems is widespread and ranges between detailed laboratory studies of the hydrodynamic segregation processes through to the intuitive interpretation of the distribution of minerals within geological sections. However, there are few, if any, comprehensive reviews of the literature. Surprisingly, given the economic importance of placers, the theoretical framework relating to the hydrodynamics of physical grain sorting is not well developed and there are relatively few detailed laboratory hydraulic investigations to inform theory. In this wide-ranging review, the history of the development of principles of placer formation is explored as far as possible in a non-technical fashion. A consideration is given to the hydrodynamics of physical grain sorting above lower-stage and upper-stage bedforms and the typical internal sedimentary structures associated with placer concentrations are detailed. Finally, examples of the depositional environment of diamond, tin and gold placers are considered.

Keywords: Placers; Heavy minerals; Gravel-bed rivers; Bedforms

Contents

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1. Introduction

The concentration of detrital heavy mineral grains in fluvial systems is of economic importance, as mineral placers such as gold and diamonds are often found associated with fluvial sedimentary deposits (Slingerland and Smith, 1986) and fluvial bar-and-channel bedforms in particular (Smith and Minter, 1980; Frimmel and Minter, 2002a). However, placers are often relatively small, diffuse or associated with specific locations within sedimentary depositional systems. Consequently, an understanding of the concentration processes is essential to locate placers and to evaluate the total regional resource. Surprisingly, despite the economic and political importance of some minerals, there have been relatively few detailed theoretical, experimental or field studies of the physical processes that lead to placer development; an understanding of which should aid identification and exploitation (Nami, 1983). The recent restatement that the gold within the Central Rand Group of South Africa is detrital rather than of hydrothermal origin (Frimmel, 2002; Frimmel and Minter, 2002a; Kirk et al., 2002) should provide an impulse to further studies of the hydraulic interpretation of alluvial placers.

Fluid process type and intensity vary in both time and space throughout fluvial systems so that the structure and location of a placer within and between different systems may also vary. In this article the concentration of placers on alluvial fans and within marine deposits is not considered specifically, rather the theory of placer development owing to river mechanics, notably the vertical concentration by meso-scale bedforms in gravel-bed rivers is discussed, with examples drawn from the literature. Although reference is made to some plan-view macro-scale processes, 'channel-scale' concentration processes that occur, for example, in association with confluences, separation-zone bars (e.g., Best and Brayshaw, 1985), push-bars downstream of rapids (Levson and Giles, 1990; Jacob et al., 1999) and density sorting around the margins of lateral (see Carling et al., 2006-this volume) and medial bars (Smith and Beukes, 1983) largely are not addressed here. The review is wide-ranging but not exhaustive. Some examples of bedforms and bedding types associated with concentrations of economic heavy-minerals are given, but a detailed description of sedimentary structures within gravel bedforms is not provided. The interested reader should refer to classic texts on this latter subject (e.g., Harms et al., 1975; Middleton, 1965a; Miall, 1977, 1978; Reineck and Singh, 1975; Rust, 1979) as well as more recent compendia (e.g., Boggs, 1987; Miall, 1996; Reading, 1996).

2. Simple principles of placer formation

Initially, for the later concentration of mineral grains, there is a prerequisite that the mineral grains should survive erosion, weathering and transport. Only minerals that enter the fluvial system in appreciable amounts are likely to form a deposit of economic importance. In situations that are ideal for placer formation, there would be a high degree of connectivity between the source and deposition areas. An example might be the delivery of material to the river across an alluvial debris fan, and the provision of a comparatively low energy environment for deposition, such as a slow flow region or a flow separation zone associated with a river point bar. Linked to this condition of connectivity are enhancing conditions (Best and Brayshaw, 1985): easily accessible heavy mineral grains; competent overland (sheet) flow, and; streamflow with the ability to selectively sort grains. In addition, a degree of repeated reworking of the local sediment deposits will help to concentrate the heavy minerals to form relatively small lenses within larger bodies of less-dense 'host' sediments. Whilst short-term degrading conditions may favour the development of lag concentrations of heavy minerals, longer-term aggrading conditions are required for the preservation of concentrated deposits (e.g. Levson and Giles, 1990). Thus systems with varied flows, variable stream competence and capacity, and high sediment yields are ideally suited to the formation of exploitable placers. Such system characteristics are often obtained in locations proximal to the heavy-mineral source. Specifically, if sediment yields are high then the possibility of large economic placers developing is enhanced. However high sediment yields alone may produce rapid aggradation and so suppress sorting processes, so leading to poor concentration of placers. Rapidly varied flows with concomitant changes in competence can cause concentration of placers even in aggradational environments. In the associated proximal facies, the sediment is usually dominated by coarse sand and gravel which is transported largely as bedload. Bedload transport is often manifest as bedform migration (Allen, 1984) such that proximal placer-rich deposits may be commonly cross-stratified at a variety of scales ranging from fine lamination in sandy ripples through medium and large-scale cross-bedding in dune and bar fronts (Swift et al., 2003).

Once heavy mineral particles (grains, nuggets, flakes and gemstones) enter a stream, various flow mechanisms can then aggregate dispersed particles to form deposits of high concentrations. Heavy minerals can then be sorted into concentrated placer deposits. Morton and Hallsworth (1999) noted that heavy minerals tend to be retained at depositional sites more proximal to their source, in contrast to the lighter minerals present. This is because larger, denser particles are less readily entrained and, when entrained, are not transported far from the sediment source before being permanently deposited. Hence, heavy mineral particles found in downstream reaches are likely to be more dispersed and of smaller grain sizes. These differences in entrainment and transport conditions for heavy minerals of different sizes (and shapes) are considered to be a primary factor in placer formation. The other primary factor is the more ready entrainment and transport of lower density particles (of similar size to the heavy minerals) which leads to physical separation of heavy and light minerals (Reid and Frostick, 1985).

2.1. Hydrodynamics of physical grain sorting

As Slingerland (1984) notes, when the ratio of the settling velocities (between heavy and light particles) increases, the concentration of the heavy mineral grains increases. This is to say that in deposits with greater contrasts between the lighter and heavier particles there is a greater tendency for the formation of layers rich in heavy mineral. This observation reflects the fact that variation in particle transport can be caused by differences in entrainment versus settling conditions, and the factors which control them (particle size, shape and density, hiding effects, turbulence intensity etc).

Developing the simple principles outlined above, in an early study, Rittenhouse (1943) stated three ‘conditions’ for the formation of fluvial placers. These ‘conditions’ are site hydraulics, heavy mineral hydraulics and hydraulic equivalency that, in concert, would determine the concentration of heavy minerals present. Previously, hydraulic equivalency had received attention. Specifically, Rubey (1933) had noted how the density differences between minerals affect a flow’s ability to entrain them. Thus he proposed the principle of ‘settling equivalence’, noting that particle density seemed to be the principle factor for heavy mineral concentration, allowing equivalent particles to accumulate together, be they of large size but low density or of small size and high density. By this process denser, smaller grains are believed to behave in a manner equivalent to larger, less dense grains. The basis of the ‘settling equivalence’ approach assumes either: (a) that it is differential settling in static, laminar or turbulent water which leads to grain concentration or, (b) pragmatically that settling differences are sufficient to explain the presence of spatial concentrations of heavy versus light grains even though the physics of the separation processes might not be so simple. In fact, ‘settling equivalence’ fails to account entirely for the observed differences in particle distributions because grain-shape effects are sometimes ignored and more importantly because factors other than settling are important in the segregation and concentration processes. Nevertheless, the principle is still often cited or utilised because the concept is readily understood and because a primary difference between grains of the same size (i.e., density) is largely accounted for.

More recently, Reid and Frostick (1985) re-emphasised that an understanding of processes which concentrate heavy minerals at the grain scale is required for successful prospecting. They argued that ‘entrainment equivalence’ and not settling equivalence better explains the concentration of heavy minerals in river deposits. The key difference between these two concepts is that very small high-density and low-density particles are ‘hidden’ within a viscous sub-layer adjacent to the riverbed (Fig. 1). In contrast, larger high and low-density particles may protrude into the turbulent boundary layer (which lies above the sub-layer) wherein turbulence can suspend the heavier particles whereas the smaller (low-density or high-density) particles remain unsuspended adjacent to the bed. Further, many high-density fine particles tend to be located between larger less dense particles (granules, pebble and cobbles) and thus are effectively sheltered. Given these dense, smaller particles are confined to moving on (or very close to) the bed, settling equivalence is no longer important, and it is

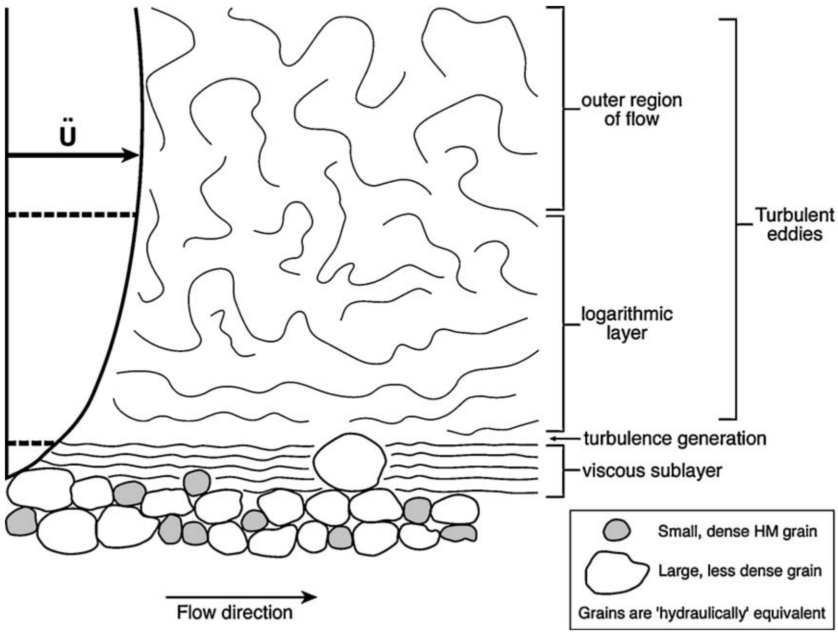

Fig. 1. Definition diagram of turbulent boundary layer.

therefore the entrainment equivalence which controls the sorting of placers from host materials rather than the settling behaviour of the heavy and light fractions. Slingerland (1977) noted that heavy enrichment occurs by a lag mechanism whereby heavy particles remain essentially in situ as light particles are removed downstream, even though the particles may be hydraulically equivalent in Rubey's (1933) terms. Thus settling equivalence and entrainment equivalence can both affect the grain-size of deposits from differing source mixes of sizes. So at a simple level, placer concentration might be viewed as a combination of these two principles. Settling equivalence may be more important in more turbulent situations, and/or with finer grains whilst entrainment equivalence is more important in less turbulent, and/or with coarser heavy mineral grains. Hence Morton and Hallsworth (1999) tend to consider that the entrainment potential of heavy mineral grains is the principle factor in generating economic placer deposits which consist of the larger heavy mineral grains. Detailed hydraulic studies of fine-scale near-bed flow processes (Best and Brayshaw, 1985) noted that grain-by-grain sorting is controlled by small-scale flow conditions, particle non-equivalence being largely owing to differential transport modes of heavy mineral species. Thus, in their view, suites of processes control the eventual deposition of heavy minerals in the fabric of a sediment body. Despite these implicit criticisms of the simple principle of hydraulic equivalence, the concept was until the late 1970's the main tenet of explanation for heavy mineral segregation. Indeed, the relationship between hydraulic equivalence and particle density is still considered by many to be good and of practical utility (e.g., Morton and Hallsworth, 1999).

Working with synthetic sediments (uniform sediment: $D=3.5$ mm; specific gravities of 1–2.5), Low (1989) stated the following qualitative relationship:

$$Q_s \propto \frac{U^*}{w}$$

where Q_s is the sediment transport rate for a particular mineral type; U^* is the shear velocity and w is the grain fall velocity. The key parameter here is U^*/w, although in essence, minerals with Q_s values lower than that of the host sediment would tend to concentrate.

Slingerland (1984) outlines four mechanisms by which it was considered that the sorting of grains could occur (Fig. 2). These mechanisms are (1) entrainment, (2) suspension, (3) shear and (4) transport sorting, which encapsulate the complexity of the local hydraulic climate noted by Best and Brayshaw (1985).

1. In entrainment sorting, it is the characteristics of the lag deposit (particle properties such as size/shape/density) that will determine the likelihood of the formation of concentrated accumulations of particular grain types. This is because large, light particles tend to protrude more highly into the boundary layer

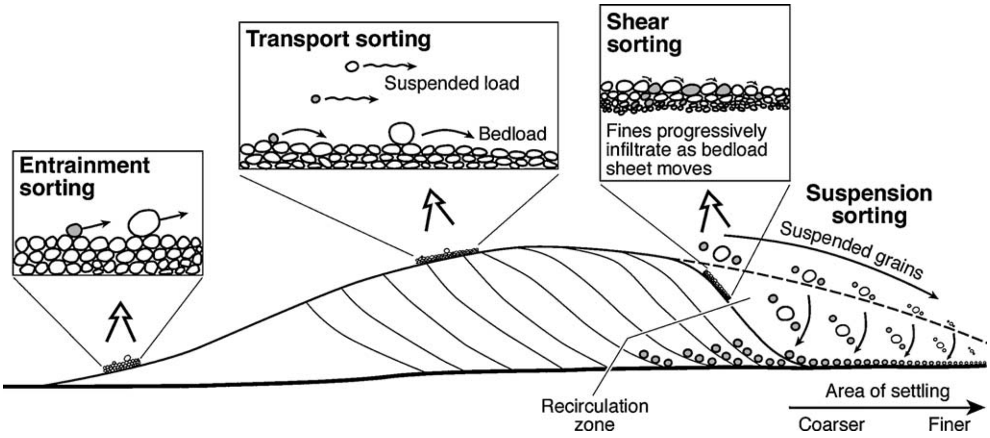

Fig. 2. Modes of heavy and light mineral sorting over a dune.

and have smaller reactive-angles (Fig. 3), and so are more likely to be entrained. Slingerland (1984) notes that in highly turbulent environments it is likely that entrainment sorting will become less important, as critical shear stresses for all types of particles present will be exceeded by the peak stresses.

2. Suspension sorting involves the tendency for lighter, larger grains to stay in suspension for longer (turbulent motion can keep particles suspended for longer). As heavy grains can be suspended for shorter distances, this differential causes more proximal deposition, which can then result in the concentration of a placer deposit consisting of the heaviest grains.
3. Shear sorting expresses the tendency for grains to accumulate in horizons of similar size/density distributions within a "concentrated granular dispersion" (Slingerland, 1984), either due to grain collisions or kinematic sieving (Bagnold, 1954; Middleton, 1965a, 1970). However, considerable debate exists as to the actual mechanisms involved (e.g., Legros, 2002, 2003; Le Roux, 2003).
4. Transport sorting corresponds to differences in the unit transport rates for different fractions of the grains present. Slingerland (1984) considers transport sorting to be the most important factor. As bed roughness increases, the rate equalises for grains of

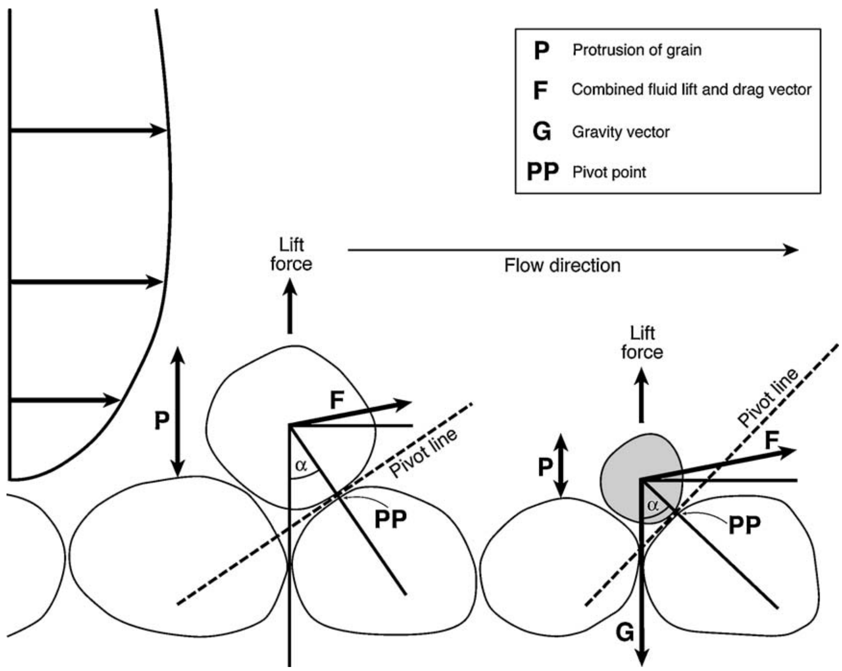

Fig. 3. Definition diagram for initial motion by pivoting of heavy and light minerals.

different densities, largely through the combined effects of 1 and 2.

Jopling (1964) concluded that flow separation behind bedforms was the basic mechanism for (a) the segregation of mineral grains within foreset beds and (b) the reworking of grains in the zone of separation between the toe of the lee of a dune and the reattachment point downstream on the lower stoss of the next downstream dune (Fig. 4). It was clearly shown how the differential particle trajectories vary according to particle mass, with heavier particles being deposited first so they fall onto the foreset beds and lighter particles being carried off, down flow. Again pulses in these particle trajectories were detected, due to the influence of turbulence on the particle transport surface across the stoss side of the dune, with dispersive pressure (Bagnold, 1954) believed to play a role in the sorting of bed layers in the vertical. Best and Brayshaw (1985) pointed out that it is the local flow conditions, such as in the lee of dunes, which control sorting and entrainment, not the settling/hydraulic equivalence concepts. Local sorting is considered more fully below.

3. Theory of placer formation applied to specific gravel bedforms

Many of the arguments developed above have been derived from flume studies of relatively fine sediments, such as fine sand, which are readily studied in hydraulic flumes. There are few detailed investigations of the development of bedding and heavy mineral concentrations in coarser sediments, such as gravels. Nonetheless, Slingerland (1984) notes four key factors for the development of a palaeoplacer. These are:

1. The relative settling velocities (ratio) of the different heavy and light density minerals present;
2. Long term site hydraulics;
3. The average bed roughness;
4. The volume of material processed though time.

To this list we should add:

5. Local flow hydraulics, especially flow separation;
6. High preservation potential.

With respect to (6), the longer-term changes in environmental conditions, including propensity for

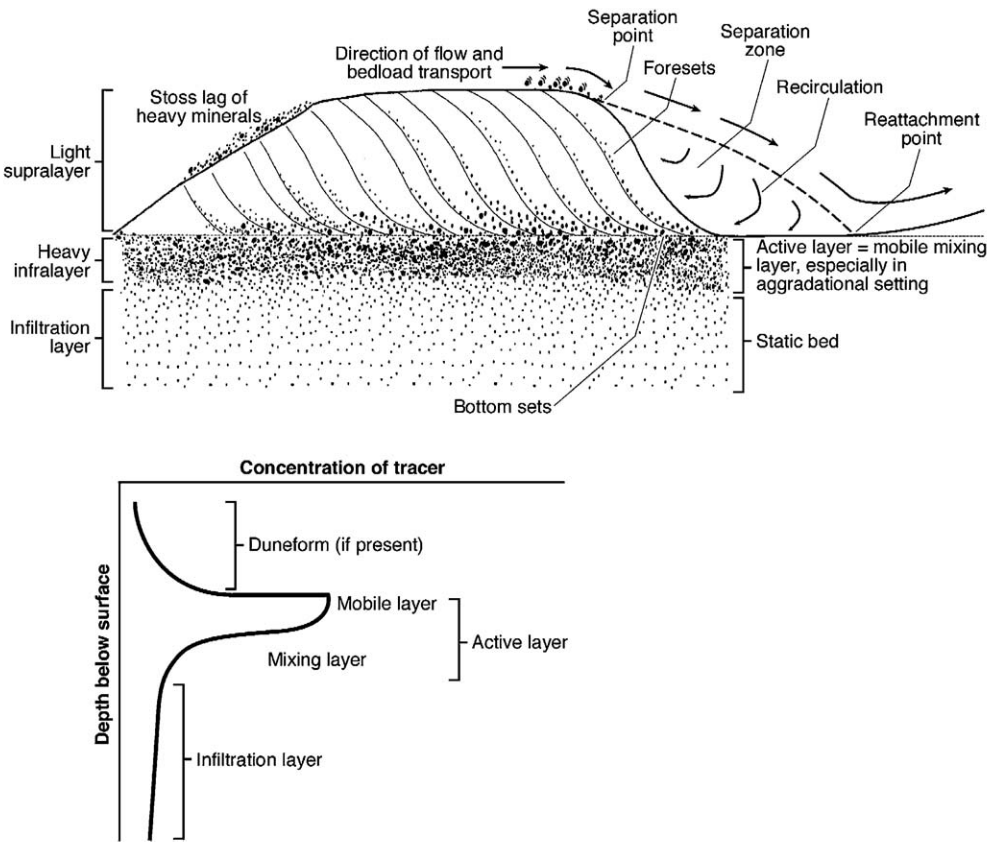

Fig. 4. Typical heavy mineral distribution within and beneath mobile dune.

reworking, are little researched (for exceptions see Sutherland, 1984, 1985; Hall et al., 1985; Thomas and Thorp, 1993). Conditions are required that ensure that the placer is less likely to be dispersed and may be further concentrated.

The processes outlined above are the principle processes responsible for the segregation of heavy minerals in the presence of mobile bedforms. In the following sections consideration is given to how these processes operate for different bedforms and what sedimentary structures are commonly generated. Even though bedforms may only form with small segregations of heavy minerals down foresets and along bedding planes, later reworking may concentrate these thin lenses into thicker and spatially extensive placers. Thus rapid burial in an accumulative setting or rapid draw-down of flood levels may be associated with the preservation of delicate low-concentration placers, whilst thicker extensive placers are indicative of frequent reworking in a non-aggrading system.

3.1. Concentration process on gravel lower stage plane beds (LSPBs)

As flow separation is commonly associated with the development of steep bedforms such as ripples, dunes and bar fronts, it might be expected that placers would form preferentially in environments populated by bedforms with flow separation. This is not always the case, for example planar beds may provide high levels of concentration: Buck (1983) notes this in some sequences in the Archaean Witwatersrand Supergroup, South Africa, and further examples are given below within: Examples of specific placer minerals.

Bridge and Best (1988) detail how flow, over a rising bed level, is forced to converge and this causes an increase in bed friction and shear stress, but at the same time turbulence is suppressed due to the reducing water depth. For flow over a series of large cobbles, this process could result in an enhanced hiding effect, concentrating heavy mineral particles in the lee of the coarse grains. However, to our knowledge, this supposition has not been tested specifically with respect to the development of concentrated placers. Pulses of sediments rich in heavy minerals, in an aggradational setting, lead to the development of ‘heavy infralayers’ separated by ‘light supralayers’ (sensu Kuhnle and Southard, 1990); the latter are composed predominantly of quartz-density sediments. The pulses may be diffuse motions of mixtures of light and heavy minerals or they may be more periodic motions as coherent ‘bedload sheets’ which may only be one or two grains thick (see references within Carling, 1999). Bedload sheets tend to develop coarser fronts with tails consisting of finer grains, and indeed one would also expect to see differential sorting by density. However, to our knowledge, the segregation of lights and heavies by grain size within bedload sheets has not been investigated. Nevertheless, laboratory studies have shown that mixing of tracer grains, in the vertical, through host sediment can occur largely by two processes. If the host sediment bed is static, then finer placer grains moving over the bed surface may infiltrate downwards through the pore space of the coarser bed sediment, if they are fine-enough to enter the gravel pore space (Kolesov, 1975; Beschta and Jackson, 1979; Carling, 1984). Alternatively if the bed sediment is disturbed by sediment transport, tracer grains are physically mixed throughout the active layer (Adams et al., 1978; Kuhnle and Southard, 1990; Brasington et al., 2000). In addition, in accretionary settings, tracers will be trapped over a greater depth than the thickness of the active layer as the bed level progressively increases. In most LSPBs it is probable that both the infiltration and physical mixing processes will operate in concert. This is because very fine heavy minerals, if present, will infiltrate the pore space, whilst coarser grains will concentrate through the bedload transport process (Kuhnle and Southard, 1990). Further consideration of the development of placers on plane beds is provided by Carling et al. (2006-this volume).

3.2. Internal structures within gravel LSPBs

Slingerland (1984) states that the conditions leading to the optimum combination of processes and constraints are poorly understood at the scale of individual grain dynamics. It is noted that, on a plane bed, the roughness of a deposit is determined by the grains in transport as well as by the grain roughness of the immobile substratum, and the combined effect of ‘mobile’ and static roughness is poorly understood. It might be anticipated that the importance of bed grain-roughness for entrapment and formation of placers would be of increasing importance on plane gravel beds in contrast to sandy dune beds. Flume experiments by Slingerland (1984) have shown that, as the roughness of a plane bed is increased, the concentrations of trapped heavy minerals tend to decrease overall, but compared to finer sands a coarser bar surface traps more heavy minerals even at high shear stresses than compared to finer sands. When exposed to high specific grain friction velocities the concentration was then observed to increase, even though the settling velocity ratios between heavy mineral grains and the quartz sand used in the experiments decreased. It appears that an increase in roughness allows for a larger hiding effect in the lower layers of the boundary zone, to a degree that grains become relatively immobile and unable to form concentrated deposits. However for placer formation in gravel beds much further work is needed to clarify these roughness effects.

On a plane gravel bed, the light components move off more easily, due to their smaller mass and pivoting angle (α) (Fig. 3) compared to heavy mineral particles that are hydraulically equivalent (Li and Komar, 1992), and this should act to increase the ability of heavy mineral grains to accumulate in the gravel to form the coarse surface 'infralayers' noted above. In recent unpublished flume experiments using openwork fine gravels (Frostick, pers. comm.), with olivine as the representative heavy mineral, it was recorded that increased 'lift', either an increased Bernoulli lift force, or more likely enhanced upward flow out of the bed, occurred at times when near-entrainment velocities were recorded in the downstream flow near the bed. These effects may have a particularly important role effecting the in-bed concentration of heavy minerals. The results, at first, appear to indicate that lift forces are more important than drag forces on rougher bed surfaces. When the critical entrainment threshold for the static bed was exceeded, tracer started to penetrate the bed. However, it is at this time that bed dilation first occurs by grains rotating from rest (or in some cases through dispersive pressure), and it is this dilation which, in principle, can allow increased interstitial flow up towards the bed surface. However as a particle is rotated out of place, the main stream flow 'hits' an angled surface, and may get deflected downward (reaction effect). Therefore, the water locally also may develop a downward vertical movement induced by dilation. Considered together, the issues noted immediately above should constitute a focus for future research effort.

Pore space dilation allows easier penetration of finer particles towards the base of gravel beds (Middleton et al., 2000; Brasington et al., 2000). This is the mechanical basis for the 'jiggling' effect first proposed by Frostick et al. (1984). Infiltrating fine sand may block the pore space in some regions of the bed but this promotes dilation of the bed elsewhere by the 'rerouted' intensified interstitial flow. This dilation allows successively coarser heavy minerals to settle into the bed. Furthermore more dense particles tended to move down more rapidly and more deeply than less dense particles. Earlier work by Frostick et al. (1984). had shown that it was the pore size of the static surface armour that controlled the infiltration rate of finer particles to the bed. The median pore size of the bed was found to be around 0.41 times the size of the median bedload size. This provides a basic control on which particles can enter the bed, possibly for the formation of a placer. If pore/particle size ratio is not conducive to particle penetration it is unlikely that a high quality placer would form, especially as coarser particles begin to block the pore spaces. Thus a large number of concentrated placers must be associated with dilated finer gravel beds (Allan and Frostick, 1999) or formed in static coarse cobble conglomerates (e.g., Witwatersrand deposits; Els, 1991) in which the pore/particle ratio was favourable. Allan and Frostick (1999) noted that if the shear stresses necessary for the entrainment of gravel were not exceeded then winnowing and over-passing (Slingerland, 1984) would be the dominating processes. This would lead to a fining of particles downstream, possibility leading to local surface lag concentrations of the heavy minerals. Thus Frostick's more recent observations seem to incorporate aspects of Middleton's (1970) 'kinematic sieving' mechanism with other processes such as dispersive pressure (see Legros, 2002). A recent review of surface sediment sorting processes is provided by Julien et al. (1993).

3.3. Concentration processes on ripples

Ripples are small-scale asymmetric bedforms that develop in fine sediments during sub-critical flows with low bed shear stress and their size varies approximately with the grain-size of the bed material. Ripples do not form in gravels i.e., with a $D_{50} > 0.7$ mm. Typical dimensions are heights less than 0.3 m and lengths less than 0.6 m (Carling, 1999). However sandy ripples might be present in the troughs between gravel dunes, on the lower stoss side of dunes and along the lee-toe of dunes. Thus, ripple-derived heavy mineral concentrations may be incorporated locally within gravel dune structures. The processes leading to the concentration of heavy minerals on, and within, ripples have been observed by McQuivey and Keefer (1969) and by Brady and Jobson (1973), who found that magnetite concentrates on the upstream side of these bedforms but close to the trough, extending up the stoss side only as far as a zone of relatively low shear stress permits. As ripples only form from lower stage plane beds, turbulence intensity is often low, but bed shear stress may be at a maximum (Bridge and Best, 1988) on the stoss sides of the ripples. Therefore only the larger, less-dense protruding grains are entrained, leaving a concentration of heavy mineral particles. Turner and Minter (1985) provide an example of this process from the Karoo deposits, NE Swaziland, where concentrated diamond deposits are located within the troughs of large-ripples. Slingerland (1984) also mentions the (rare?) concentration of heavy minerals near the crest of ripples, where lights are preferentially rolled off.

3.4. Concentration processes on gravel dunes

Dunes are large-scale asymmetric bedforms that develop in fine or coarse sediments during sub-critical flows with bed shear stresses greater than those associated with ripples. Dune size varies approximately with water depth and not with the size of the bed-material. Unlike ripples, dunes have been recorded forming in gravels i.e., with a $D_{50}>2.0$ mm. Typical dimensions are heights greater than 0.3 m and lengths in excess of 0.6 m, but incipient dunes can have smaller dimensions and may be confused with ripples (Carling, 1999).

In the lee of dunes flow separation often occurs, proportional to the steepness of the lee slope and the Reynolds number of the flow. Heavy minerals tend to be transported relatively slowly as bedload and consequently tend to concentrate on the dune stoss side, and so in contrast to the lighter, more mobile particles, the heavies migrate downstream as a collective unit with turbulent sweeps supplying the increased shear stress necessary to move these particles over the dune crest (Fig. 5). Before being deposited on the lee side, these heavier grains often accumulate first as a ‘metastable’ wedge at the brinkpoint of the lee slope (Jopling and Richardson, 1966). Then periodic avalanches lead to heavy mineral-enriched laminae within the foreset deposits (Fig. 6), whilst fines continuously fall out of suspension to add to the fabric (Smith and Minter, 1980). When suspension fall-out is sufficiently developed, cross-sets consisting of light minerals will coarsen upwards whilst cross-sets consisting of heavy minerals deposited by avalanching tend to fine upwards. As dunes progress downstream, and sets are eroded and re-deposited, heavy minerals may progressively concentrate at the base of cross-sets along the primary bedding plane.

Jopling and Richardson (1966) also considered accumulation of heavy minerals at the crest of dunes and

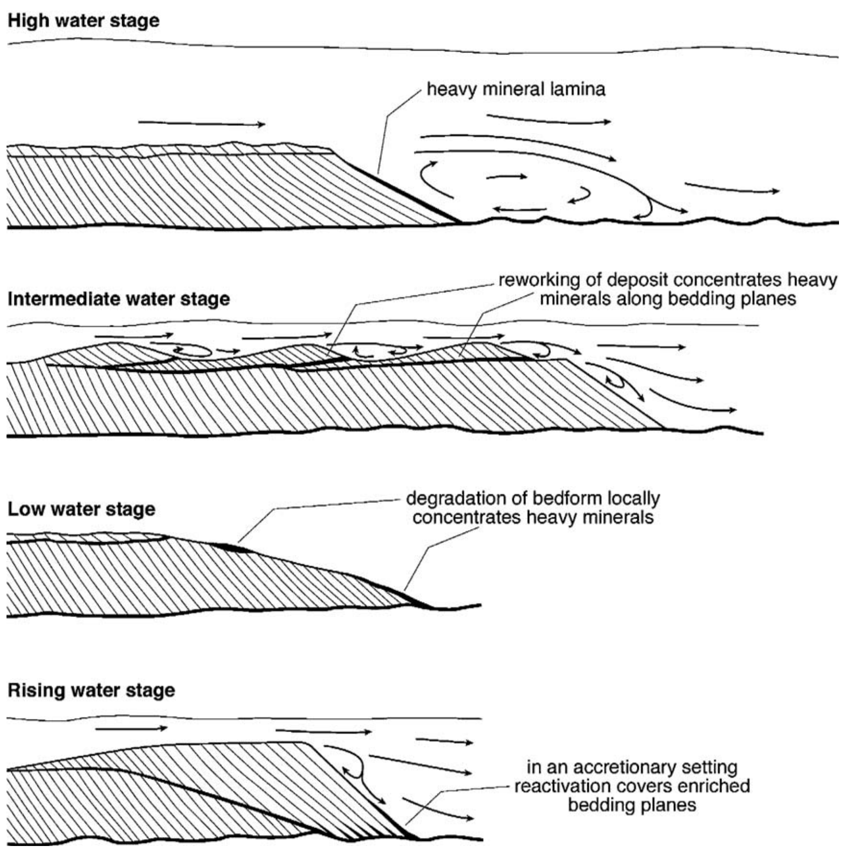

Fig. 5. Distribution and redistribution of heavy mineral concentrations within dune or gravel bar front.

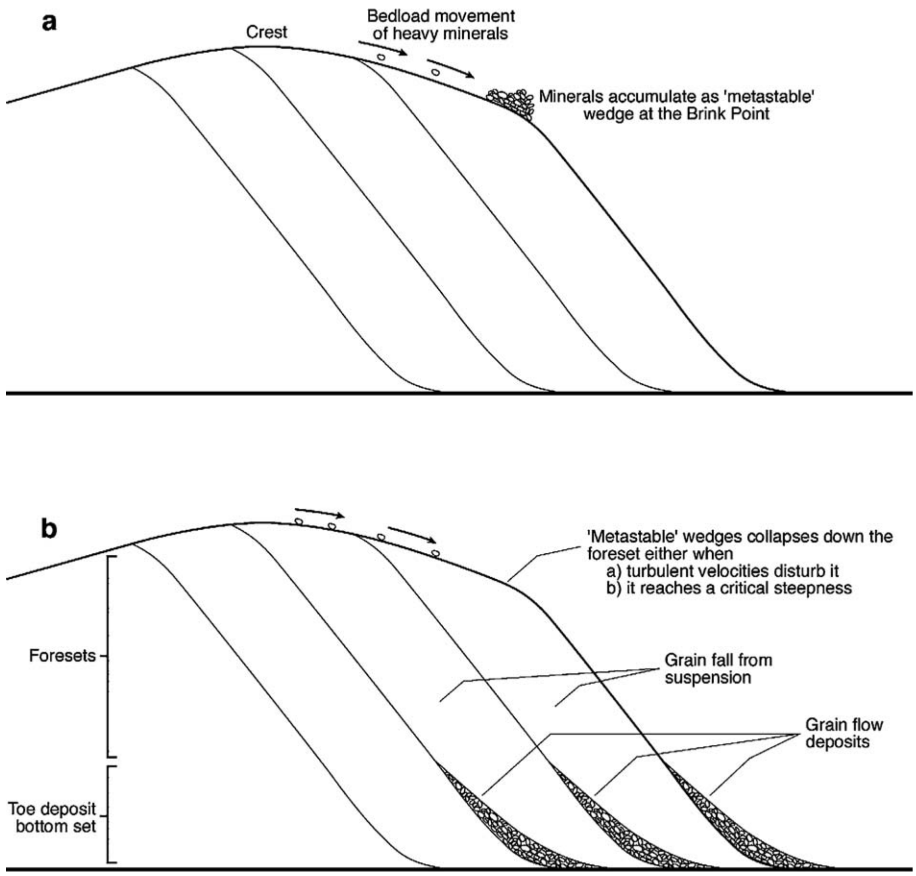

Fig. 6. (a) Development of 'metastable' wedge of heavy minerals at brinkpoint of dune. (b) Collapse of 'metastable' wedge and subsequent grain flow lead to enhanced heavy mineral concentration within toe sets.

on the foresets; the latter is due to the shear sorting of grains during avalanching. On the crest, finer and lighter grains readily go into suspension above the lee slope, leaving coarser and heavier grains as bedload. Denser grains suspended above, or within the separation zone, will settle first, with fines carried further downstream. Grains are reworked in the separation zone by turbulence especially at the point of reattachment; minimum shear stress here allows further concentration of heavy mineral particles towards the base of the stoss-slope of the next dune downstream. Best and Brayshaw (1985) demonstrated that significant concentrations of heavy minerals within the troughs of dunes, some eight times more concentrated than within the surrounding environment, can result from flow separation. In part this enrichment process is probably enhanced by the preferential resuspension of finer bed sediment from the dune troughs (as noted above) which leaves a coarser, openwork bed layer in the dune troughs (Blom et al., 2003) which should trap heavy minerals effectively. White and Williams (1967) also considered suspension induced by flow separation over the foreset slope to be one of the primary factors in the dispersion and sorting of various grains, but further factors noted were selective transport within the bedload, and dispersive pressure within avalanching sediments. White and Williams (1967) found that the bottom set originated from suspension, whilst the foreset originated from both suspension and traction. Thus dune troughs in a sand and gravel deposit were found to be good accumulation sites; in this case tourmaline was the main heavy mineral present.

As dunes over-ride each other in aggradational settings, the topsets of coarse material developed over the crests of successive dunes are also preserved as distinctive laminae (Fig. 5). Consequently discrete bedding units develop which Jopling and Richardson (1966) termed "sporadic residues of coarser/finer sediment preserved as a regular to irregular; wavy, lenticular, trough shaped or tabular deposit". Jopling and Richardson (1966) also noted that stripping of the top layers occurred by the passage of periodic turbulent pulses and, more particularly, by draw-down in water level on falling stage. In either case faster flows caused a coarsening of the top of the dunes following which coarser sediments later avalanched down the lee-side, resulting in localized much coarser foresets. Finally, it was shown that rapid changes in the size of material delivered to the lee-side favour the formation of well-defined bedding. In this manner, and considering the issues of settling equivalence and entrainment equivalence noted above, it is likely that heavy minerals will tend to be segregated from lights and be concentrated on the stoss (McQuivey and Keefer, 1969) of dunes, and then moved down to form laminae within the foresets of bedforms (Buck, 1983).

Grading of grains down the foresets of dunes has been noted by Allen (1984) amongst many others. In the case of tangential grading on the foreset, two cases may be found: reverse, where grains increase in size down the foreset, and normal, where grains decrease in size down the foreset (Fig. 7). Further it is noted that the reverse form of this grading is most commonly found in coarse (gravel/sand) cross-strata, normal grading occurring typically in finer grained fabrics. Reverse grading occurs when near-bed velocity is at a level that will allow a range of grains the potential to settle out, but only occurs when the grains present on the bed are relatively coarse and ideally where a large range of grain sizes are present. The implication of these different sorting mechanisms depends on size of the heavy mineral grains relative to the host sediment. Grains can move down the foreset slope by two processes: avalanching and over-passing (Carling and Glaister, 1987). In the case of avalanching, Allen (1984) notes that the roughness of the foreset controls grain positioning, the slope being proportionately less rough to larger grain sizes, which are then less likely to be retained in mid-slope. For over-passing, larger bedload grains sit proud on the bed and thus experience less roughness but experience more drag and are transported in contact with the bed over the dune crest. In contrast, finer particles are trapped within the interstices of the surface gravel and then infiltrate into the bed upstream of the crest. Therefore heavy minerals may not necessarily concentrate at the base of the dune foreset, if they are fine grained, whereas coarser grained heavy mineral grains should. Thus process is relevant to preservation potential, in that often only the dune bases are preserved, upper parts being eroded, so reverse grading may provide better conditions for deposits of economic value to be preserved.

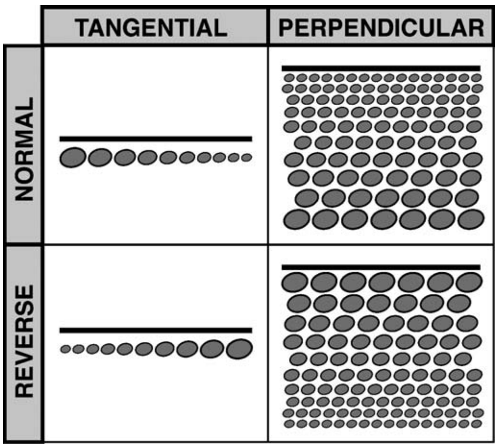

Fig. 7. Definition diagram of normal and reverse grading of grain size within bed foresets.

3.5. Internal structures within gravel dunes

The systematic steady downstream migration of gravel dunes or bars tends to result in the development of characteristic internal layering within deposits. Models have been developed linking dune behaviour to the development of internal structures (e.g., Raudkivi and de Witte, 1990; Paola and Borgman, 1991; Leclair and Bridge, 2001). These models consider the influence of the passage of different sizes of bedforms but do not consider sediment mixtures per se. In the case of gravel, the layering is primarily developed at the front of the dune on the lee-side by periodic avalanching of coarser grains which tend to accumulate at the top of the lee slope until the local lee-side slope becomes over-steepened and collapses (e.g., Hunter, 1985; Kleinhans, 2002). Alternatively, bedload moving over the crest of the dunes may be unsteady (Kleinhans, 2002), moving as temporally and spatially discrete 'bedload sheets' (see references in Carling, 1999). These sheets become differentiated by size, such that the fronts of the sheets consist of grains coarser than those within the tails of the sheets. In either case layering known as cross-bedding is formed on the dune lee slope which meets the surface over which the dunes are moving either tangentially at steep angles or asymptotically at gentle angles (Hunter, 1985). Asymptotic contacts tend to reflect an abundance of finer sediment largely deposited from suspension as well as from bedload transport (Blatt et al., 1980) and the cross-beds may be weakly sigmoidal (Carling et al., 2006-this volume, their Fig. 9). If most of the sediment is moving as bedload then the contact angle tends to be acute and the foreset bedding is quasi-parallel and straight (Fig. 8). A thin bottom-set lamina of fines settled from suspension in the lee of the dunes may be present but often this is

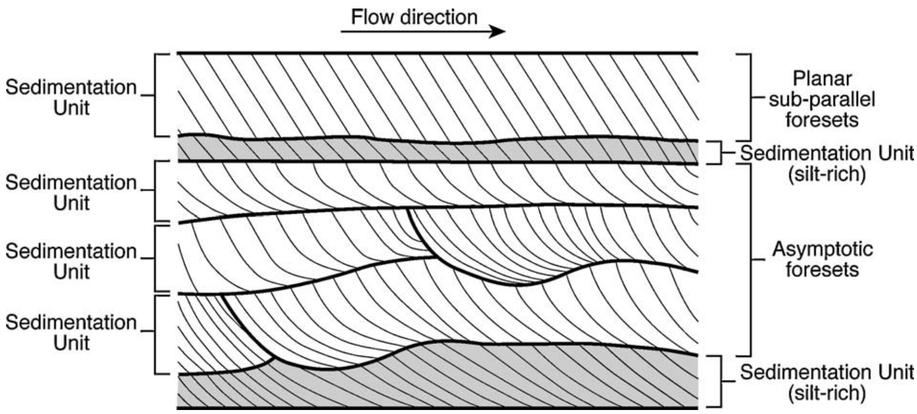

Fig. 8. Typical stylised sedimentation sequence in an accretionary setting whereby suspension dominated deposition (asymptotic foresets) alternates with bedload dominated deposition (planar sub-parallel foresets). Heavy minerals concentrate primarily along the primary bedding planes which are depicted by heavier lines.

indistinct and is manifest as a fines-rich horizon at the base of individual foresets. In the coarsest of sediments, individual cross-beds may be difficult to discern but usually alternating coarser and finer cross-beds are present which are amalgamated to various degrees. This coarser–fine alternating of cross-beds is due to the differential sorting of the avalanching grains (see below) or to be due to the deposition of the coarser fronts of bedload sheets before the finer tails over-run the resultant coarser cross-bed. In some cases, the cross-beds may be sub-parallel, of similar thickness and extend the full height of the bedform. More usually, as the angle of the lee slope might vary somewhat during dune progression, and the balance between local erosion and deposition can also change, then some variation in the angle of the individual cross-beds is normally apparent. The result is that some cross-beds are truncated and do not extend the full height of the bedform. A corollary of the formation processes of cross-beds is that grading in size and density of the gravel particles and finer sediments are usually present within the cross-beds (Carling and Glaister, 1987; Carling, 1990; and see Fig. 9 in Carling et al., 2006-this volume). In accretionary settings, cross-beds tend to occur in sets (bedsets) with distinct or indistinct bedding planes separating each set. It is along these bedding planes (also called bounding surfaces or bedding surfaces) that heavy minerals tend to be concentrated as 'false-bottom' placers. A simple scheme (e.g., Boggs, 1987) identifies two forms of cross-bedded units. Tabular cross-bedding is most commonly associated with gravel dunes and consists of cross-bedded units which are laterally extensive in contrast to a limited vertical expression but notably the bedding planes tend to be planar. Trough cross-bedding consists of cross-bedded units in which the bedding planes are curved or undular. In the latter case the foresets tend to have the tangential contacts and may be sigmoidal in form (Fig. 8). In the case of planar bedding planes, any placer is likely to be laterally continuous, whilst undular planes might be associated with discontinuous series of placer lenses (Frimmel and Minter, 2002b).

Small sections opened in well-preserved 2-D gravel dunes tend to display planar cross-bedding whilst in 3-D dunes, trough cross-strata are common (Bretz, 1959; Baker, 1973; Maizels, 1989; Carling, 1996). Some dunes show progressive coarsening down the cross-beds (Baker, 1973) or only at the toes of the cross-beds (Carling, 1996). Heavy mineral particle size and concentration tend to increase progressively down the cross-bed as well as along the bounding surface (Carling et al., 2006-this volume). However, ground-penetrating radar surveys (Huggenberger et al., 1998) of predominately 2-D gravel dunes show that the internal structure is often more complex than is revealed within small sections (Fig. 9). In sections parallel to the flow, these surveys show clearly the large-scale 2-D tabular cross-beds which formed at the front of largely straight-crested dunes, as well as primary bedding planes between individual sets of cross-beds. These latter interfaces are often reactivation surfaces. That is, the lower side of the bedding plane is usually a set of cross-beds which have been partially eroded and reworked as a further set is deposited by a dune progressing over the underlying sets. Also present are presumed backsets developed on the stoss sides of the dunes and inclined upstream. However in sections normal to the flow, beneath the crestline of the dunes, as well as the parallel bedding to be expected, inclined sets of cross-beds are

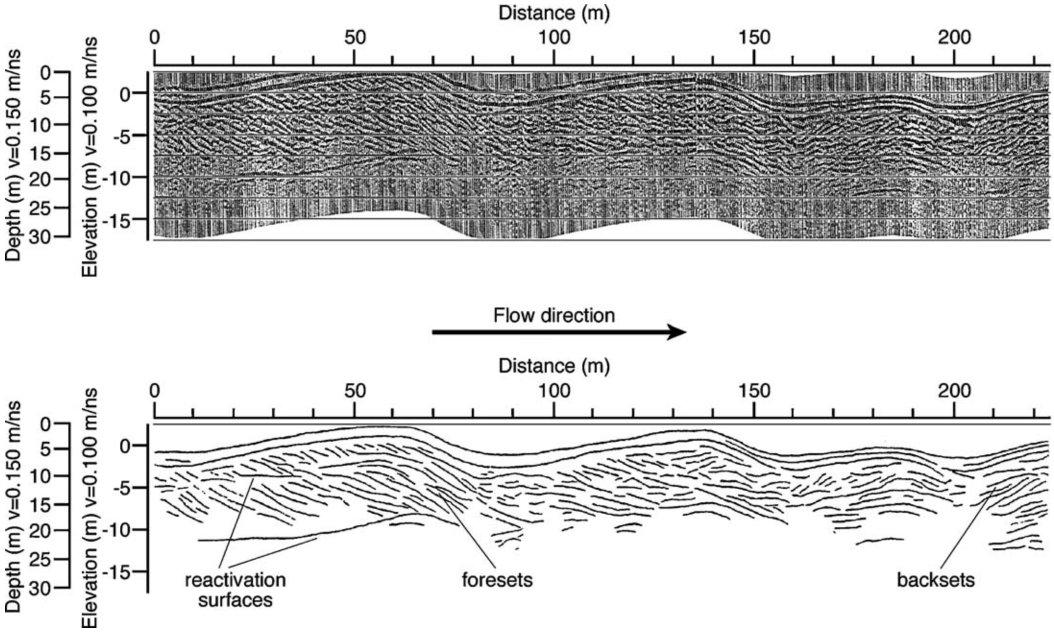

Fig. 9. Ground-penetrating radar profile parallel to flow direction through 'fossil' Pleistocene gravel dunes (redrawn after Huggenberger et al., 1998). Note presence of foreset and backset units. Heavy mineral accumulations (if present) would be expected along the reactivation surfaces, at the base of the foresets and possibly within the lower stoss portions of the backsets.

evident. The latter are interpreted as representing the flow-normal inclined slopes which develop on the lateral margins of elevated lobes and depressed saddles along undulating crestlines. These undulations in the crestlines are evident in the surface morphology of these 'straight-crested' dunes (Carling, 1996). Thus locally the 2-D tabular structure is replaced by strongly curvilinear cross-beds producing trough cross-bedding.

3.6. Concentration processes on gravel antidunes and within hydraulic jumps

Antidunes are bedforms that develop under transitional and supercritical flow conditions, such as during large flood events in rivers and within shallow fast flowing overland sheet flows. At these times there may be a large amount of material available for transportation, and this may be segregated by size and density within the sedimentary structures constituting the body of the bedform. In most cases antidunes migrate upstream short distances before collapsing and washing-out. Flow over upstream-migrating antidunes is characterised by decelerating flow on the up-channel side of the bedform which causes net deposition to occur, whilst on the down-channel side, flow acceleration causes net erosion. The standing waves developed above antidunes grow in amplitude and then collapse, at which time the antidune itself has maximum amplitude. When collapse occurs, the body of the antidune is rapidly eroded by high-velocity highly turbulent flow. During this process, larger and denser grains which are more resistant to entrainment tend to accumulate on the upstream side of the antidune to form lenses of coarser, denser sediments. This should mean that although high-density coarse grains may concentrate here, some of the finer sized heavy mineral particles should also be selectively entrapped here amongst larger low-density grains due to hiding effects. Further, the greater submerged weight of heavy mineral particles and the high pivoting angle of finer particles add to their stability within the bed, such that only the largest, less dense particles which protrude further into the flow may remain mobile (Hand, 1969). This is especially so on the decelerating flow on the upstream side of the antidune where the downslope component to grain force balance makes re-entrainment less likely (Kennedy, 1963). In concert, these processes lead to the formation of drop-out armour, as gravel collects on the upstream side of an antidune (Foley, 1977). The initial coarseness of these gravel lags is important, allowing smaller heavy mineral deposits of lower mobility to collect in the interstices. Foley (1977) noted that this process of lag accumulation was most pronounced when antidune amplitude was at the maximum. Thereby heavier particles are progressively concentrated, as finer fractions move downstream upon the collapse of an antidune, potentially to form a finer grade lag in a downstream antidune. Thus, selective sediment transport effectively allows these deposits to form as a series of downstream fining lags (Komar and Wang, 1984).

Thus the sediment sorting processes associated with the hydrodynamics of antidunes may concentrate heavy minerals within antidune stratigraphy (Bridge, 2003). Although the preservation of antidune sedimentary structures in the geological record is rare (e.g., Collinson, 1966), placers can be found within these structures. Flume experiments considering antidune formation (Yokokawa et al., 1999), using silicon carbide ($\rho_s = 3.2$: a black powder) as a tracer for heavy mineral, showed that the tracer concentrated within distinctive lenses and laminae within the antidune structure. In particular, the tracer concentrated in thin discontinuous layers along the bedding planes between individual lenses so as to highlight them. Thus although the distinctive topography of these upper regime bedforms may not survive waning flow, thin, wispy, accumulations of heavy minerals may be preserved in the stratigraphic record (Cheel, 1984, 1990).

In a field study of antidune stratigraphy, Langford and Bracken (1987) found partially preserved lenses (0.06 m thick and 0.7 m long) as well as rarely preserved complete lenses with thin (2–6 mm thick) laminae consisting of alternating coarser and finer grains. Other lenses either fined upwards or downwards. Similarly, Bridge and Best (1997) found laminae that showed, at the base, an upward-coarsening trend, followed by an upward-fining trend, due to the deposition of finer materials that had apparently infiltrated into the coarser sediments of the bedwave. This infiltration process could be a means by which diffuse placers develop within gravel beds (Frostick et al., 1984). Bridge and Best (1997) noted that periodic flow separation on the lee side, with its associated turbulence, would tend to rework sediment to reduce any degree of sorting and laminae preservation; this process may however lead to further concentration of heavy minerals, the lights being entrained and winnowed off by reworking (Cheel, 1990).

Jopling and Richardson (1966) conducted flume experiments with a hydraulic jump whereby initially supercritical flow transforms into a sub-critical flow where deposition may occur. Downstream of the transition a sedimentary accumulation is produced, with foreset bedding on the downstream face and backsets with symmetric undular antidune-like bedding on the upstream face. The upstream side tends to consist of coarser material — a lag deposit, from which lighter particles are removed. This crudely stratified backset bedding, dipping in the upstream direction is readily preserved if the prevalent conditions are aggrading (Russell, 2001). Jopling and Richardson (1966) showed that magnetite grains are deposited in both the backset and foreset beds. However, within the backsets, distinctive upstream-dipping heavy-mineral laminae are formed (Jopling and Richardson, 1966). On the downstream side of the deposit, the same method of aggradation occurred as was previously outlines for dunes — periodic avalanching of heavy minerals accumulated in a wedge at the top of the bedform crest form laminae in the foresets. Better interpretation of the sedimentary structures (Alexander et al., 2001) may be accomplished when there is a better understanding of the hydraulic structure of breaking standing waves such as is now reported for hydraulic jumps (Long et al., 1990, 1991).

3.7. Internal structures within gravel antidunes

Normal grading (i.e., fining upwards) is sometimes seen as indicative of super-critical flows with antidunes present (Harms and Fahnstock, 1965; Walker, 1967) whereas in sub-critical flows reverse grading is prominent due to the development of surface armour in LSPB conditions. However this distinction is by no means robust. The structures in antidune deposits in sand-sized sediments are well-documented from laboratory studies (e.g., Allen, 1966; Middleton, 1965b; Jopling and Richardson (1966); Yagishita and Taira, 1989; Prave and Duke, 1990; Yagishita, 1994; Yokokawa et al., 1999; Alexander et al., 2001; Araya and Masuda, 2001). However, there are few descriptions of the internal structure of fluvial gravel antidunes (Shaw and Kellerhals, 1977; Alexander and Fielding, 1997) and thus reasoning by analogy from other environments of deposition is required.

A useful discussion and illustrations of antidune structures within sandy or granule-rich sediments are provided by Allen (1984; p. 422–430). This consideration mainly is related to the identification of flow regime within pyroclastic flows. Nevertheless, with caution it is possible to use these structures, and those observed in sandy fluvial systems, as analogues to those that might develop in fluvial gravels. Examples of structures present in downstream-migrating, stationary and upstream-migrating bedforms are presented, although Allen (1984, p. 430) cautioned that the presence of upstream-dipping structures, although common in antidune bedding, does not guarantee that supercritical flow conditions pertained, nor that the bedforms progressed upstream. Whereas dunes might display steep angle of repose cross-sets, upstream migrating and stationary antidunes are characterised by lower-angle bedding and symmetrical lenses. Bedding is inclined predominantly upstream (Power, 1961) but massive ungraded wedges and near-horizontal laminated lenses may also occur (Harms and Fahnstock, 1965; Middleton, 1965b; Hand et al., 1969; Foley, 1977; Massari, 1996). Blair and McPherson (1994) attribute bipartite layering (couplets) of open-work and close-work gravels to the build up and collapse of antidunes, and this issue is further addressed by Russell (2001) and Russell and Arnott (2003). However it should be noted that similar couplets form within dunes. Further details of internal structures are provided by Carling (1999) and Bridge (2003). Presumed antidune structures in the geological record indicative of downstream migrating antidunes are described by Crowe and Fisher (1973), Mattson and Alvarez (1973) and Schmincke et al. (1973), but this identification is not necessarily robust. Similarly, models linking the hydraulics of standing-waves to the antidune morphology and sedimentary structures are poorly developed (Hand et al., 1972; Hand, 1974; Langford and Bracken, 1987; Normark et al., 1980; Pantin, 1989; Prave, 1990; Morris et al., 1998; Blair, 1999; Fralick, 1999; Kubo and Yokokawa, 2001).

3.8. Concentration processes on gravel upper stage plane beds (USPBs)

Upper stage plane beds occur in supercritical flows and concentration processes have largely been studied for sand beds rather than gravel. Cheel (1984) considered the movement of concentrated bedsheets of heavy minerals. The sheets tend to be spatially periodic, being separated by areas of the bed containing low levels of heavy minerals. The initial concentration of heavy minerals was associated with small standing waves of a very low amplitude (length = 0.5 m, height = 1.5 mm), beneath which low-amplitude bedforms of similar scale developed. The minerals became concentrated at the crests of the structures. Cheel and Middleton (1986a) noted that these heavy mineral-rich laminae initially accumulated in areas of lesser entrainment potential which further reduced entrainment potential. This spatially selective mechanism effectively is equivalent to the concept of the development of a differential transport rate as a requirement for a concentrated deposit to form (Komar and Wang, 1984).

Cheel and Middleton (1986a) concluded that the quasi-periodic uplift and ejection of a low speed fluid away from the boundary (bursting), alternating with the inrush of high speed fluid toward the boundary from the outer region of flow (sweep), are the mechanism for development of these laminae. A turbulent sweep involves the inrush of water towards the bed and an increase in the shear stress at that local point. In contrast, a burst is an ejection of (sediment-rich) water away from the bed. Although occurring over very short temporal and spatial scales, the repeated action of this process concentrates heavy mineral grains. This mechanism was considered more fully by Bridge and Best (1988), who outlined the way in which an increase in suspended sediment transport depressed the upwards motion of turbulence, therefore allowing greater turbulence to occur above coarsening-upward sequences. Again, millimetre-thick laminae on an USPB were attributed to turbulent bursting. However it was concluded that the prediction of initial growth and formation of these structures will require an accurate description of the way in which local sediment transport lags behind the fluid phase.

Later work by Paola et al. (1989) on parallel lamination found thin laminae only a few millimetres thick, these forms were traceable over an area of approximately 0.3×1.5 m. Again, like Cheel (1984), the presence of extremely low amplitude bedforms of a very subtle nature was detected, even on this flat upper stage bed, and these features were considered to be related to the formation of the laminae. Deposition of a layer of coarse material due to shear stress excesses from turbulent fluctuations was followed by the deposition of finer material. With this latter formation of a smooth bed, turbulent scour is reduced and the development of fining-upwards sequences is suppressed. Thus vertical sequences of parting lineations were considered a product of the near bed turbulence (Paola et al., 1989). This conclusion accords well with Bridge (1978), who considered that the burst-sweep mechanism alone could not explain the formation of coarsening-upward and fining-upward sequences.

3.9. Internal structures within gravel USPBs

Work by Cheel and Middleton (1986b, 1987) on the Whirlpool Sandstone of Silurian age, near Georgetown, Ontario found laterally extensive sheets of heavy minerals. These structures had a scale of around 10–100 m in lateral extent, but were only 2–3 grains thick. Further analysis of the facies here revealed the existence of textural laminae, with coarsening-upwards and fining-upwards sequences. These sequences tended to occur in a random order, but as the frequency of each was similar, they were interpreted as being associated with turbulent action on the bed. The proposed mechanism for this is that coarsening-upwards sequences formed when the dispersive pressure of a turbulent sweep removed fine grains, and the fining-upwards sequences formed by the fallout of progressively finer particles carried upwards by a turbulent burst. Within these sequences heavy mineral grains were found to exist as coarse lags left by migrating patches of heavy minerals, where high levels of average shear stress associated with large flow eddies could concentrate them. As heavy grains are more resistant to sweep, heavy minerals effectively formed an armour on the bed. These heavy mineral sheets are associated with coarsening upward sequences and are generally found at the base of such sequences (Cheel and Middleton, 1986b).

4. Examples of specific placer minerals

4.1. Diamonds

A recent study by Jacob et al. (1999) of diamond placers in the Orange River, South Africa detailed the importance of irregular bedrock contacts and large irregular, oversize clasts in allowing concentrated zones of diamond deposition to form. These locations are stable over time, despite high energy flows and turbulence which may disturb finer material, allowing a particularly prolonged period for diamond placer formation. Indeed Spaggiari and De Wit (1999) believe that sites within the lee of oversize (static) bedrock clasts provide a quasi-permanent environment for the development of diamond placers. As a further example, Youngson and Craw (1999), examining New Zealand gold deposits, again note that gold is found in coarse conglomerates but often at the sedimentary base as lag accumulations in bedrock hollows, where it is concentrated by flood events. Thus it would seem that openwork cobble beds that are stable over extended periods of time would be good repositories for diamonds. In this vein, Hall et al.'s (1985) interpretation of the Birim diamond placer in Ghana is consistent with the flume studies of Allan and Frostick (1999). Hall and colleagues state that diamonds are found with pebbles and cobbles, and consider the trapping of diamonds by these to be one process in the formation of this diamond placer. These coarse gravels appear to be a particularly good location for placer formation as they provide protected storage in which prolonged diamond concentration can occur with minimal reworking. The 'kinetic sorting' (Middleton, 1965a, 1970) or 'jiggling' of Frostick et al. (1984) associated with high levels of bed shear stress is again cited as a major aid to the ingress and concentration of these particles. A slightly different example is provided by Turner and Minter (1985). These authors detail the presence of diamonds in deposits in the Karoo rocks, NE Swaziland. The diamonds appear to be associated with dune trough cross-bedding, these areas being laterally extensive due to progressive channel migration over the floodplain. Turner and Minter argue that the sinuous-crested dunes were present at all flow stages. Turner and Minter concluded that the diamonds are concentrated within a thin, laterally extensive sand body deposited by a brief rapidly decelerating, overloaded, ephemeral flood flow. Turner and Minter (1985) observe that diamonds and garnets were also concentrated at the base of this sandstone on disconformities, at the base of fluvial upward-fining sequences, this being the normal position for hydraulic bedload concentration (Tuck, 1968) during degradation, later to be buried by aggradation.

4.2. Tin (cassiterite)

Aleva (1985) noted that the main concentration of Malaysian tin deposits occurs in static lag gravels. It was argued that the presence of these static gravel beds is important as they can entrap and retain all the economic grain sizes (defined as $D_{50}>0.07$ mm) of the cassiterite grains. Nevertheless, in concurrence with Frostick et al. (1984), Aleva states that the development of a mobile bed layer at high shear levels is invaluable for the incorporation of heavy minerals, and the expulsion of light, finer grains. In addition it is considered that beds of finer sediments are not efficient in entrapping mobile cassiterite grains, so placers forming here will be of a lower concentration. In the case of the coarse lag gravels, the transport distance was only around 500 m from the cassiterite source before a substantial incipient placer could develop. Fletcher and Loh (1997) observed that repeated grain settling, entrainment and motion are most effective in concentrating heavy minerals that are sufficiently fine ($D<0.180$ mm) to be hidden on the bed. Fletcher and Loh (1997) found that upon the onset of bedload motion, fine cassiterite particles could be entrained from the bed and introduced to the bedload or suspension load. They considered that suspension sorting was the most important factor segregating the finest heavy minerals as more dense particles settle more quickly. However for the coarsest heavy minerals, bed roughness was found to be an important factor in determining the concentration of placers, as the coarser beds were best at catching larger amounts of heavy minerals, as even large heavy mineral grains could penetrate into the void space.

4.3. Gold

With specific reference to gold deposits, Wang (1994) created a scale model of a section of the Yangtze River, to study the movement of gold particles. He concluded that gold particles tended to saltate within the gravel bedload. However there was a tendency for the particles to follow narrow paths along the deepest parts of the streambed (see Nami, 1983), unlike the suspended load and the rest of the lighter bedload. Deep pools were found to be the favoured location of deposition (see also Levson and Giles, 1990). Particles moved throughout each part of the flood cycle. Movement was controlled by the greater drag force and bottom velocity in the deepest part of the channel. Results showed that a tracer for fine gold (magnetite) tended to deposit with the coarser bed sediment fractions, mainly in braided sections on the heads of bars. In addition, at abrupt changes in the bed geometry, where helical flow was well established, the finer sediments were winnowed out. This action often left a concentration of gold particles amid a coarser gravel lag, usually in the distal portion of an upstream pool (Wang, 1994). Similarly, Smith and Beukes (1983) found that in the case of placers forming in zones of flow convergence between a mid-river bar and the outer bank that heavy minerals concentrated in the deepest part of the channel. They found that as the flow converges in this section of channel that concentration of up to four or five times background levels could collect in the bedload and within the matrix of cobble beds in these sections. This only occurred in the convergence zone, with concentration levels returning to normal once flow had re-entered an un-constricted section of the main channel. These field results compare well with the heavy mineral concentrations noted by Best and Brayshaw (1985) in flume studies of heavy mineral concentrations at confluences. Best and Brayshaw found that heavy minerals tended to be concentrated along the separation zone occurring between the two flows, this area being in the central part of the channel, just downstream from the confluence and associated with the turbulence at these sites. Thus these examples highlight macro-scale (channel-scale) concentration processes which require further consideration in both field and experimental conditions.

At the meso-scale, Coetzee (1966) compared the distribution of heavy minerals in the Vaal Reef gold placer in the Witwatersrand Basin, South Africa. A sympathetic relationship existed between gold, uraninite and pyrite minerals in each placer. Similarly to Jopling and Richardson (1966), Minter (1976), in the case of the Vaal Reef Placer, concluded that medium-grained pyrite concentrations and other detrital heavy minerals were probably sorted from the host sand during avalanching on the foreset slopes of dunes. Deposits of these were present in trough-type structures, and this type of cross-bedding was exclusively found in the thicker channelway deposits. Flow depth was estimated as 0.45 m, using the method of Allen (1970), based on the grain size and the scale of cross-bedding. Heavy minerals such as gold and uraninite are present in smaller quantities alongside nodular pyrite, zircon, chromite and leuoxene; these were found to be hydraulically equivalent to the sand-sized mode in the Witwatersrand ore bodies. It was found that pyrite was concentrated on the basal contact, on cross-bedded foreset planes and trough bases and indeed on all the sedimentary partings in the placer, as it tends to be the lighter grains that can move with the bedload (Minter, 1976). For security reasons only a limited discussion of gold and uraninite deposits is given but up to a 20-fold concentration in the basal centimetre can occur. In fact, between half and three-quarters of all gold was confined to the basal contact. Minter (1976) found only a 60% correlation between gold and uraninite concentrations, which, as Coetzee (1966) states, is only a sympathetic relationship. This would seem to suggest that differing mechanisms are responsible for the concentration of these two heavy minerals. Indeed, Minter found that total gold content was not dependent on the thickness of the ore bodies, whilst uraninite content was. The logical interpretation of this is that gold is found on the basal contacts and at the toe of foresets, whilst uraninite is spread within the foreset structures (see also Pretorius, 1981). It seems reasonable to assume this is owing to (unspecified) differences in the grain properties such that uraninite is readily transported within the dune bedload, whilst gold is left as a scour and lag residual. Given the differences in the specific gravity of the two minerals (Table 1) it must be concluded that the uranite particles in the above example were probably substantially finer than the gold particles, although shape effects could also play a role in the observed sorting and concentration. Minter (1976) suggested that initial deposition took place in a high energy braided system, which later underwent reworking by dunes allowing the concentration of gold at the foreset toes on the basal contact. However, braided systems contain many different types of depositional niche and further investigation of channel- and bar-scale concentration

Table 1
Specific gravity of placer minerals

Mineral	Specific gravity
'Quartz' sediment	2.65–2.75
Gold	19.3
Diamond	3.5
Cassiterite	6.4–7
Magnetite	5.2
Tungsten	19.3
Lead	11.4
Uraninite	10 un-oxidized (>7 depending on oxidation level)
Silicon carbide	3.2
Olivine	3.3–4.3

processes such as those at channel bifurcations and around medial bars could identify specific niches and clarify the initial concentration process. Minter and Toens' (1970) later work on gold bearing conglomerates showed that the heavy minerals present are hydraulically equivalent to the sand-sized fraction and suggested that the high density heavy minerals were deposited in the open-framework of clast-supported immobile gravels. Flume experiments showed that pebbles 19-times the diameter of the sand fraction should be best at concentrating the gold particles. Magnetite particles used initially to represent detrital gold did not infiltrate the bed, but instead concentrated in the bedload. In contrast, actual gold particles introduced to the flume readily were entrapped to form concentrated placers in the matrix of the cobble beds. Minter and Toens (1970) conclude that openwork gravels do not necessarily separate heavy minerals from the bedload efficiently. Rather, as the interstices of the gravel bed within a given area are progressively filled by trapped heavy minerals, then the trapping efficiency reduces. Thus the content of heavy minerals in the bedload passing over the 'trap' area increases and is available for entrapment in openwork gravels further downstream (Kuhnle and Southard, 1990). Smith and Minter (1980), again with respect to the Witwatersrand, showed that although there are good sympathetic correlations between the occurrence of gold and uraninite heavy minerals, the ratios are inconsistent — a symptom perhaps indicative of the effects of provenance and/or sorting mechanisms. Gold was concentrated on scour surfaces, and as the matrix in conglomerates, with moderate values of gold existing in foreset laminae, in scour troughs and at the base of constricted channelways. Uraninite was concentrated onto scour surfaces, and along bedding planes but concentrations here were not significantly greater than the concentrations spread throughout deposits. This is because the finer uraninite particles are easily suspended, in contrast to gold, and thus do not readily concentrate as lag deposits on bedding planes but are frequently deposited and re-entrained in association with dune progression.

Smith and Minter (1980) argue that upstream sourcing and hydrodynamics control the concentration and dispersion of heavy minerals from local point sources. They propose a hierarchy of processes, stating that the optimum set of processes only emerges after a great deal of field sampling. For example, coarse conglomerates may result from rapidly varying flows such as within high energy braided systems, where initial gravel deposits can consist of both coarse and fine particles, only to be later winnowed, leaving a coarse gravel deposit. Compound bars also provide an ideal location for the concentration of heavy minerals; these deposits are reworked by floods such that the concentration of heavy minerals is increased locally within the compound bedform as individual gravel sheets, while small bed forms and small bars progressively are amalgamated both laterally and vertically (Kuhnle and Southard, 1990). Although foreset and trough concentrations may occur in dunes, often dune aggradation and deposition are too rapid, and lack the degree of reworking necessary to increase the concentration of heavy minerals significantly (e.g., LeBarge et al., 2002). Smith and Minter (1980) considered sand dunes forming on a gravel bar top. Here fine and light particles were swept away as the dunes avalanche into the main channel adjacent to the bar, allowing gold to concentrate onto the bed of the bar, and be trapped within the gravel interstitial space. In this way, areas of very local high concentration were produced and this mechanism may lead in time to the formation of deposits of high concentration. It was noted that aggrading conditions must ultimately prevail to preserve these deposits.

Slingerland (1984) states that uraninite is often found further down slope than gold due to its lesser density and hence being more easily entrained. So it is found further from source and further down the slopes of the Witwatersrand depositories, perhaps explaining Coetzee's (1966) sympathetic relationship. Minter et al. (1990) investigated gold deposits in Minas Gerais, Brazil. Again like the Witwatersrand, the gold-bearing placers here are conglomerates with heavy minerals particularly concentrated in the matrix of cobble conglomerates. Emphasis is placed upon the linkage of an actively eroding upland source area to provide high inputs of debris to a fan or braided system for deposition within bars and sheets. At Minas Gerais, the conglomerates fine upwards, which Minter et al. (1990) considered to be indicative of a waning flood flow depositing them. Again it was found that these conglomerates were often placed on an erosional channel base (unconformity), this being taken as evidence of channel degradation and later aggradation (see also Levson and Giles, 1990; Els, 1991). It was found that heavy minerals were either present at the base of a conglomerate (highest gold concentrations commonly found here on the basal contact), or as a surface lag in the conglomerate due to winnowing/over-passing as discussed earlier. For this reason Minter et al. (1990) classed the deposit as a degrading deposit, which they considered to be the richest type of gold deposit. Minter et al. (1990) cite Slingerland and Smith (1986) in that gold concentration processes operate most effectively on degrading bed surfaces, when lighter particles are selectively entrained and the finer grained heavy gold particles are concentrated. Further degradation only leads to further concentration. Minter et al. (1988) noted that, in the Welkom Gold Field of South Africa, concentrates of heavy minerals were deposited in shallow palaeochannels (see also Wang, 1994). Buck and Minter (1985), again in the Witwatersrand gold deposits, noted a high concentration due to the scouring and winnowing of a coarse conglomerates surface. This study also helps to elucidate the relationship between uranium and gold deposition, averring that: "hydrodynamically larger gold particles accumulate under more turbulent flow conditions than uranium". This corresponds well to the assertion made by Roscoe and Minter (1993) of the miss-match in hydraulic equivalence between gold and uraninite particles, hence the differing concentrations. Buck and Minter (1985) also noted that placers form as a lag filling in erosional 'etches', and that more powerful braided streams are coarser-grained, and thus should contain more gold. Youngson and Craw (1999) note that flattened gold particles are more easily entrained (flattened surface areas increase drag and reduce the settling velocity), and so these particles are preferentially moved further down the system. However as particles progressively thin, they eventually become folded. Folding reduces the surface area making them less-readily entrained. The malleability of gold is much in excess of other heavy minerals present in most systems such that entrainment potential can be related to a flatness index. Overall the consideration is that nuggets have a high residence time, whilst recycled placers (allochthonous gold) tend to have a higher flatness, and may be more easily removed from the system. In contrast, Minter (1999) notes that the toroidal shape of the majority (75%) of the gold particles found in the Witwatersrand is of aeolian origin. Vogel et al. (1992) conducted numerical experiments to determine the position of gold particles in a placer depository using the computational code: MIDAS (Model Investigating Density And Size sorting; Niekerk et al., 1992). The model predicted that, for heterogeneous sediment (a gravel/sand mixture) under non-uniform and quasi-unsteady flow conditions (similar to reality), the grain size of heavy minerals was the main controlling factor influencing dispersion. It asserted that coarse gold particles would be distributed in the proximal part of the system, whilst fine-grained gold would be depleted in proximal locations but would be concentrated further downstream. The results of the model reflect sample distributions well, and further may explain, for example, why gold deposits are not absolutely related to uraninite concentrations. Vogel and colleagues conclude that it is the shear stresses within the flow that control the deposition of gold, as finer particles are deposited in the more distal portions of the depository where lower channel slopes induce lower shear stresses. In a flume study of the Witwatersrand deposits, James and Minter (1999) considered the effects of sourcing of the material, the local hydraulics and the effects of particle size and density. The finer heavy mineral grains were transported preferentially. In their experiment, tungsten (specific gravity equivalent to gold) was used as a surrogate for gold nuggets whilst magnetite was considered to represent well the toroidal gold of the Witwatersrand depositories. The tungsten moved as a traction load, whilst magnetite either saltated or was suspended during high flows. The concentration of the deposit was also found to be proportional to the supply concentration and to the coarseness and hence roughness of the bed. In relatively fine bed materials only fine heavy mineral grains were caught, the coarser particles continued to move downstream. These two different types of movement could well be important in the modelling of gold placer formation.

Nonsheet-like deposits are less well understood due to their lateral discontinuity (Buck, 1983). Individual primary sedimentary structures in gravel-bed rivers are therefore an area of interest, as Buck (1983) notes with respect to the Saaiplaas Quartzite Member in the Witwatersrand depository. Here complex sedimentary structures are abundant and well-preserved. Gold concentrations seem to be particularly high, whilst uraninite deposits are more distributed albeit within the same bodies as gold. Gold and uraninite seem to be particularly concentrated on the basal scour contact of cross-bedded structures, among over-size clasts (lag deposits), within conglomerates generally and along any horizontal erosive bedding planes (Buck, 1983; Nami, 1983). As noted elsewhere (Nami, 1983), low-to-zero concentrations were found in cross-bedding unless the cross-bedded surface had been scoured when concentrations could be elevated. Buck (1983) concluded that the trough cross-bedding is due to dunes and the horizontal bedding is due to upper stage plane beds. Buck (1983) also notes that variations in shear stress and turbulence over a bedform would be the major mechanism for the segregation of gold from uraninite and lighter minerals. He concluded that the rough surfaces of the stable lag conglomerates would have produced large variations in the turbulence intensity of the stream flow, providing ideal conditions for the concentration of heavy minerals with no further likelihood of re-entrainment (see also Frimmel and Minter, 2002a). The dunes in contrast were often reworked, so that foreset placers are not concentrated except at the toe of the foresets where they merge with, and become indistinguishable from bedding plane concentrations (see also Carling et al., 2006-this volume). The bedding planes often survive extensive reworking as dunes pass over them, and this becomes more likely as heavy minerals concentrate at the surface.

The flume experiments of Kuhnle and Southard (1990) clarify the behaviour of the particles in the coarse grained systems studied by Buck (1983), Stavrakis (1980) and, in part, in the systems reported by Nami (1983). Experiments indicated that heavy mineral grains tend to become concentrated beneath low-amplitude dunes as a heavy 'infralayer' often of nearly 100% heavy mineral composition, beneath a light 'supralayer' containing lower density sediment particles moved within the dunes. The results showed that heavy mineral grains did not progress further downstream until a heavy mineral layer had become fully developed at that point. Interestingly Kuhnle and Southard used lead and tungsten particles (as well as magnetite), with larger diameters and densities than the magnetite. Tungsten has a specific gravity of 19.3 which is similar to gold, compared to the specific gravity of magnetite, of around five, which is often used to illustrate gold movement. The emphasis of the experiment was on the vertical and stream-wise segregation of heavy minerals in the active layer, related to the discharge and sediment discharge, hence the results are particularly relevant here. In their experiments flow was varied, as uniform flow is not normally found in river systems, and the variation caused by this non-uniform flow is important in terms of providing aggrading and degrading bed conditions to concentrate heavy minerals. The importance of flow variability was noted early in this review and the importance of scour-fill cycles in concentrating placers is emphasised here as a topic that requires further experimental investigation. The dunes which developed had no appreciable tungsten and lead present and only low levels of magnetite. The heavy infralayers observed were largely formed due to extended periods of degradation. During degradation, finer lighter particles were removed to leave a coarser lag in which the heavier mineral particles move down through the interstices to accumulate as a fining-upwards infralayer. Under aggrading conditions, heavy minerals were buried in several superimposed infralayers, each of limited downstream extent. This produced a laterally non-extensive area of many heavy mineral-rich infralayers. Each infralayer graded from nearly 100% heavy mineral upstream to 0% over a short distance downstream, as another infralayer began to form on top. In contrast to fluvial systems, the flow was provided in the flume with a ready supply of heavy minerals. However the similarity of the Kuhnle and Southard (1990) experimental beds with the beds recorded in the field by Buck (1983) and by Stavrakis (1980) leads to the inference that similar processes occurred in the field, especially when beds were degrading and consequently concentrating relatively dispersed heavy minerals. Thus flume studies may supply powerful analogies for interpreting placer processes within outcrops.

5. Conclusions

Within the geological community the theory of heavy mineral segregation and concentration by turbulent flow processes is not well developed. Better understanding of turbulent flow processes and grain sorting processes are emerging, largely within the literature developed by hydrodynamic specialists. To date this literature has largely considered particle size segregation and to a lesser extent grain-shape sorting. However, given the emergent understanding of small-scale hydraulic processes (largely mediated by advances in instrumentation) there is now a major opportunity to advance this understanding to include density-sorting, and so further the understanding of economic placer formation.

Although reference has been made to some plan-view macro-scale processes (such as 'channel-scale' concentration processes) for reasons of brevity these largely have not been addressed herein. Examples are processes associated with the development of large-scale flow-shear zones, flow separation and large-scale eddies that might occur at flow-expansions, flow divergence and convergence around river islands and medial bars as well as at main-channel confluences.

Push-bars downstream of rapids and waterfalls have received little attention, as have the more local effects of density sorting around the margins of lateral and medial bars which must be intimately associated with concentration processes at bar heads and within bar-associated separation zones. These kinds of environments are frequently proposed as sites of placer development within the geological record. However, there is little substantive (analogue) evidence from process studies to support these suppositions. Thus concentration mechanisms at this scale of channel environments require experimental, computer-simulation or full-scale field study of modern fluvial systems.

At the meso-scale, the recent interest in concentration of heavy minerals owing to flow separation downstream of bedforms such as dunes has resulted in an inadvertent neglect of mineral sorting mechanism over lower-stage plane beds, especially rougher ones associated with stable cobbles and which often are major repositories for economic placers. To our knowledge, the segregation of lights and heavies by grain size within bedload sheets has not been investigated and for flow over a series of large cobbles, this process could result in an enhanced hiding effect of heavy mineral particles in the lee of the coarse grains. The behaviour of mixed-density fine sediments, deposited and sorted within the void space of stable boulder-beds, has never been considered in any detail. For placer formation in gravel beds, generally, much further work is needed to clarify these roughness effects. Within more frequently mobile pebble and cobble beds, a large number of concentrated placers must have formed, in part, owing to the dilation that can occur in the surface of the beds for conditions of initial bed motion or partial transport. Experimental-flow visualization studies have a lot to offer in this respect.

High preservation potential is predicated upon the appropriate environmental conditions pertaining over extended time-periods. Conditions are required that ensure that the placer is less likely to be dispersed and may be further concentrated. The propensity for reworking, the associated long-term conditions and the structures that may develop owing to repeated cut-and-fill are poorly researched.

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