Chapter 1

THE ENTRAINMENT, TRANSPORT AND SORTING OF HEAVY MINERALS BY WAVES AND CURRENTS

PAUL D. KOMAR

College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA

ABSTRACT

Heavy-mineral grains in a sediment have hydrodynamic properties that are distinct from the particles of quartz and feldspar. Differences also occur within the suite of heavy minerals due to their ranges of densities, diameters and shapes. The contrasting hydrodynamic properties of these sediment grains can give rise to differential rates of transport by flowing fluids that yield distinct patterns of deposition based on the particle attributes. The higher densities and generally finer grain sizes make the heavy minerals more resistant to entrainment by flowing water, and they then experience lower rates of transport when carried as part of the bedload or in suspension where differences in grain settling velocities are important. In the extreme this hydrodynamic sorting can lead to the formation of heavy-mineral concentrates, or a placer when the deposit contains economically valuable minerals. The processes of mineral sorting have been investigated mainly in the context of the formation of placers found in rivers, beaches and in continental shelf sands. That research is reviewed in application to the hydrodynamic sorting of sediment grains in general, with the focus being on the mechanisms of selective entrainment, shear sorting during bedload transport, sorting within the geometry of bedforms such as ripples, and the effects of differences in particle settling velocities on grain sorting during suspension transport and when the sediments are deposited. Each of these mechanisms depends on the particle density, diameter and shape, and collectively account for the observed patterns of mineral sorting found in sediment deposits.

Keywords: beach placers; continental shelf sediments; grain entrainment; grain settling velocities; placers; river placers; sediment sorting; sediment transport

1. INTRODUCTION

The grains of heavy minerals in a sediment can have markedly different hydrodynamic properties compared with the light minerals, quartz and feldspar. Due to

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their contrasting densities as well as grain sizes and shapes, the heavy minerals are generally more difficult to entrain by flowing water than the light minerals, and this can lead to the formation of a lag deposit of concentrated heavy minerals when the light minerals are selectively transported away. This sorting continues for the particles that are under transport; the heavy minerals may have higher settling velocities than the quartz and feldspar, so their transport takes place closer to the bottom where the current velocities are lower.

Selective sorting of particles by differential entrainment and transport can also take place within the suite of heavy minerals due to their ranges of densities, grain sizes and shapes. This sorting may result in problems in the interpretation of ancient sedimentary deposits, for example to establish the sources of the sediment and the paleoenvironment of deposition based on the heavy-mineral content. On the other hand, the separation of the heavy minerals from the light minerals and the sorting within the suite of heavy minerals can produce concentrations having economic significance—placer deposits. Placers can be found in alluvial, marine, aeolian and lacustrian deposits, and have been important sources of metals such as gold, platinum, tin and titanium (Hails, 1976; Komar, 1989).

In spite of the sorting of sediment grains during transport being common and important to the formation of valuable placers, surprisingly little research has focused on the details of the physical processes responsible for this sorting. It is important that this science be improved in order to support a better understanding of the general processes of sediment transport that accounts for the ranges of sizes and densities of particles found in a sediment, to provide a sounder basis for the effective discovery of placer deposits, and in order to improve the interpretation of ancient sedimentary deposits from their heavy-mineral contents.

This chapter reviews the present scientific understanding of the hydraulic behavior of heavy minerals in comparison with the transport of particles of quartz and feldspar, which has been thoroughly investigated over more than a century. The grain sorting mechanisms are first outlined in general, a summary that serves as the basis for the review of research that has attempted to document the roles of those mechanisms through laboratory experiments or in field studies of heavy-mineral concentrates and placers found in various environments.

2. GRAIN DENSITIES, DIAMETERS AND SHAPES

The hydrodynamic properties of sediment grains depend on their densities, sizes and shapes. Emery and Noakes (1968) divided minerals into three groups based on their densities: "heavy–heavy minerals" being those with exceptionally high densities (e.g., gold with a density of 18 g/cm^3), the "light–heavy minerals" which have more moderate densities that fall within the range of common heavy minerals and the "light minerals", mainly quartz and feldspars. Particularly important to their sorting by flowing water is the contrast in densities between the heavy and light minerals, and the large range of densities within the suite of common heavy minerals, especially if one includes particles of gold and platinum important in placer deposits. Even for the common heavy minerals the densities range widely from approximately 7.0 g/cm^3 for cassiterite to 3.2 g/cm^3 for hornblende.

Differences in ranges of available particle sizes and shapes are also important to the hydrodynamic properties. Within their primary source rocks, most heavy minerals occur in sizes comparable to the grains of quartz and feldspar (Feniak, 1944; Kretz, 1966), but it is generally observed that in sediments derived from those rocks the heavy-mineral grains tend to be significantly smaller. This in part is a product of selective sorting by density and size, as will be examined in this chapter, but the abrasion and propensity of the heavy-mineral particles to fracture along cleavage planes during transport must be an important factor as well, since the larger grains commonly disappear entirely from the depositional system. The more resistant grains retain their sizes and even crystal shapes inherited from their primary rock sources; prismatic zircon crystals and euhedral garnet found in sediments are obvious examples. However, it is not well-established how grain properties such as their hardness and cleavability determine the abrasion and thus size and shape changes of the less resistant mineral particles during transport. Most investigators have concluded that grain abrasion and rounding are significantly greater on beaches than in rivers (Kuenen, 1964; Clemens and Komar, 1988), so the degree of change likely depends on the environment. Therefore, abrasion processes can affect the sizes and shapes of the mineral grains, which in turn influences their hydrodynamic properties and ultimately the contents of heavy minerals found in sediment deposits.

The reviews below of grain entrainment and other mechanisms of sorting by flowing water demonstrate the importance of particle density and size, and also their shape although this has been less well-established experimentally. As a result of their controls on particle sorting during transport, the sorting patterns are generally represented by systematic variations in particle densities and grain sizes, which have been interpreted in terms of the "hydraulic equivalence" of the different minerals with the equivalence dependent on the sorting mechanism (Rubey, 1933).

3. PHYSICAL PROCESSES OF MINERAL SORTING

The summary presented here of the sorting mechanisms begins with an examination of the selective entrainment by flowing water of grains from a sediment consisting of different particle sizes and densities. This is the first step in the sorting of heavy and light minerals, and generally turns out in most cases to be the process most important to the formation of heavy-mineral concentrates and placers. The subsequent transport is characterized as being in part a bedload consisting of the coarser (heavier) grains that move along the bed by sliding and bouncing (saltation), and a suspended load of finer grains that are lifted above the bed by the turbulent eddies of the flowing fluid. Grain sorting within the moving bedload can occur as the particles of mixed sizes and densities are sheared to form laminations, or may occur locally within the geometry of bedforms such as ripples and sediment dunes. Most important to the suspended load are the settling velocities of the sediment grains, wherein differences in their densities and diameters can lead to contrasting settling rates that give rise to selective transport and particle sorting. These basic mechanisms are reviewed in this section, while research documenting their roles in various environments are presented later in this chapter.

3.1. Grain Entrainment by Flowing Water

Grain entrainment or the initiation of sediment motion by a flowing fluid has been investigated by a great number of studies spanning more than a century. Nearly all of those investigations focused on the simplest condition that predicts the first movement of grains from a flat bed of nearly uniform particles, uniform in their densities and sizes. Such ideal conditions are not generally found in Nature, but the experiments still have been relied upon to serve as the basis for our standard grain threshold curves. Those results will be reviewed first as they provide the basis for a comparison with grain entrainment from a more natural deposit consisting of a mixture of grain sizes and densities, the condition of interest in this chapter concerned with the selective entrainment of heavy versus light minerals.

The laboratory measurements of the threshold of uniform grains from a flat bed have been compiled by Miller et al. (1977) and Yalin and Karahan (1979) to yield up-dated versions of the threshold curves. Of particular significance is the graphical presentation developed in 1936 by the engineer A. Shields, important in that it offers a non-dimensional analysis which unifies the threshold data and can be employed to evaluate the entrainment of grains of any density by a flowing liquid (but not gases, such as air). It is, therefore, applicable to heavy minerals as well as quartz-density particles. The up-dated Shields curve is given in Fig. 1A, and compares two dimensionless parameters, the Shields entrainment function

$$\theta_t = \frac{\tau_t}{(\rho_s - \rho)gD} \tag{1}$$

and the grain Reynolds number

$$\mathrm{Re}_* = \frac{u_{*\mathrm{t}}D}{\nu} = \frac{\rho u_{*\mathrm{t}}D}{\mu} \tag{2}$$

where τ_t is the threshold mean bed stress exerted by the current (the force per unit bed area), $u_{*\mathrm{t}} = \sqrt{\tau_\mathrm{t}/\rho}$ the corresponding shear velocity, ρ_s and ρ are, respectively, the densities of the sediment grains and fluid, D is the diameter of the grains, g is the acceleration of gravity, and ν and μ are, respectively, the fluid's dynamic and kinematic viscosities ($\nu = \mu/\rho$). The curve shown in Fig. 1A is based on experiments using uniform sediments that individually represent mean grain sizes from silts through pebbles, grain densities from quartz through those of heavy minerals, and employing various liquids that included oils and glycerin as well as water. The agreement of the data for this variety of grain sizes and densities, and for different liquids, on a dimensionless graph illustrates the "universality" of the Shields curve, although it does not extend in application to the case of aeolian grain entrainment. The primary limitation of this threshold curve is that it is based on experiments with uniform grains formed into an artificially smoothed deposits in laboratory flumes, and the potential cohesive effects of clays have also been excluded.

The Shields graph of Fig. 1A can be employed to determine the threshold flow stress τ_t for a grain of density ρ_s and diameter D in a liquid of density ρ and viscosity μ. However, such an evaluation requires an inconvenient convergence approach

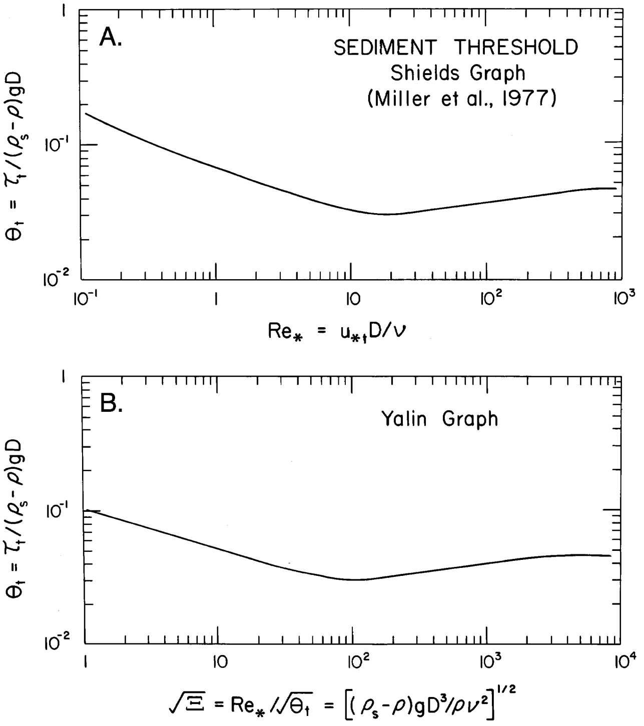

Fig. 1. (A) The standard Shields curve for the threshold of uniform grains. (B) The Yalin (1972) curve which is more convenient for threshold determinations. [After Miller et al. (1977).]

since τ_t is contained in both θ_t and Re_*, the two axes of the Shields graph. This problem induced Yalin (1972) to reformulate the presentation as θ_t versus

$$\Xi = \frac{Re_*^2}{\theta_t} = \frac{(\rho_s - \rho)gD^3}{\rho\nu^2} \tag{3}$$

yielding the curve in Fig. 1B based on the same data that established the Shields curve. The advantage of the Yalin approach is that Ξ can be calculated from known fluid and grain parameters so the threshold θ_t and τ_t can be determined directly without iterative calculations. Examples of derivative curves for the entrainment stress τ_t versus the grain diameter D are presented in Fig. 2 for the threshold of quartz-density grains and representative heavy minerals covering a range of densities. As expected, the curves are arranged in a vertical sequence according to the grain densities, with quartz at the bottom and gold at the top, the gold requiring the greatest entrainment flow stress for a given diameter. The results also demonstrate the significant range of entrainment stresses for the series of common heavy minerals, indicated by the curves for garnet and cassiterite.

The curves of Figs. 1 and 2 are based on experiments with unidirectional currents as found in a river. However, they have been shown to apply as well to grain threshold under the oscillatory water motions of waves. The primary difference is the

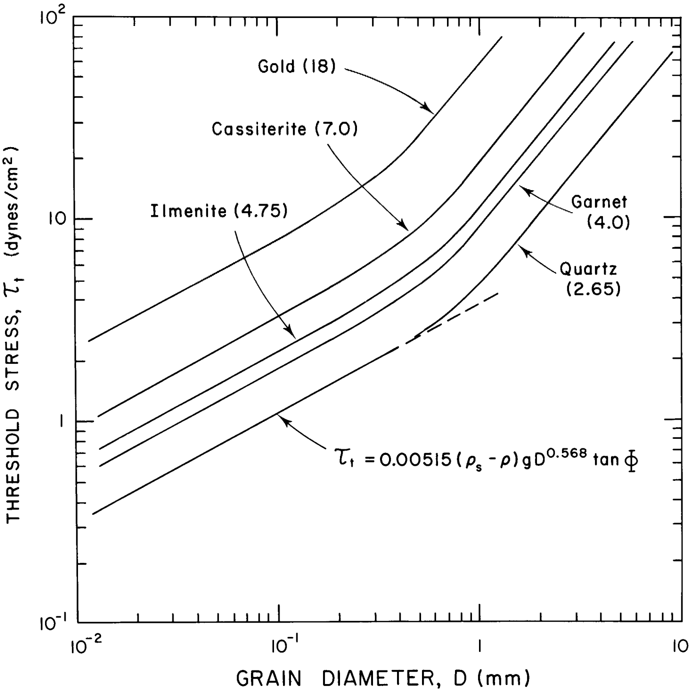

Fig. 2. Curves for the mean entrainment flow stress versus the grain diameter for quartz and representative heavy minerals (specific gravities in parentheses).

way in which the flow stress τ_t is evaluated. For a uniform flow in a river this stress can be calculated with the DuBoys equation $\tau_t = \rho ghS$ where h is the flow depth (or hydraulic radius) and S is the channel slope. For waves the mean stress (averaged over a wave cycle) is calculated with $\tau_t = 0.5fu_m^2$ where u_m is the maximum orbital velocity of the waves at the bed and f is a friction coefficient appropriate for wave motions.

For most analyses of the sorting and concentration of heavy minerals, the threshold curves of Figs. 1 and 2 are not directly applicable since they represent conditions for sediment deposits consisting of only one mineral and effectively one grain size. For example, the curve for ilmenite in Fig. 2 applies strictly only to a deposit consisting of 100% of that mineral, a condition that might conceivably be achieved in a placer but is not relevant to the processes of sorting of the ilmenite mixed with other mineral grains during the concentration process. The curves of Figs. 1 and 2 mainly provide an assessment of the relative stabilities of heavy-mineral concentrates following their formation by the sorting processes.

The formation of a heavy-mineral concentrate involves the processes of selective entrainment governed by the contrasting densities and sizes of the grains, a condition that departs from the experiments used to establish the Shields and Yalin curves and their derivatives. The studies of Slingerland (1977) and Komar and Wang (1984) have examined the processes of selective entrainment in the formation of placers, with Komar (1989) providing a review. The factors important to the selective

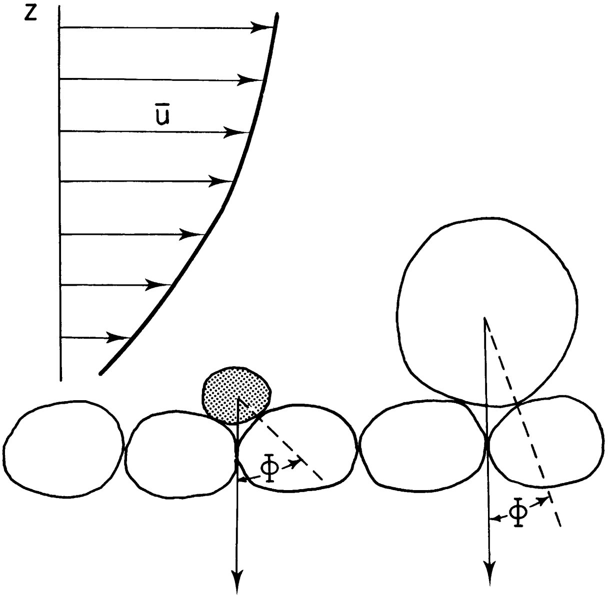

Fig. 3. Effects of relative exposure and variable pivoting angles on the selective entrainment of particles from a deposit of mixed grain sizes and densities, with the smaller heavy-mineral shaded. The velocity $\bar{u}$ is the local time average within the turbulent flow, this average increasing with distance above the sediment to define the flow's boundary layer.

entrainment processes are illustrated in Fig. 3, which contrasts the entrainment of a small heavy-mineral particle (shaded) with a larger quartz grain. The relative weights of the two particles are important to their entrainment, such that the higher density of the heavy mineral tends to offset its smaller size (the two particles illustrated might even have the same immersed weights). The smaller size of the heavy-mineral grain can also be a direct factor in reducing its mobility. Most obvious in Fig. 3 is its limited exposure to the profile of the flowing water, with the water's velocity increasing with distance above the sediment bed, in comparison with that of the larger quartz grain which projects further above the bed and hence experiences greater flow velocities and drag forces. In addition, the entrainment process generally involves the pivoting of the grain out of its resting position, and it is apparent in Fig. 3 that the smaller heavy-mineral particle has a larger pivoting angle Φ than does the quartz grain, a factor that will also increase its resistance to entrainment. Therefore, the increased exposure to the flow and smaller pivoting angles of the larger quartz grain both favor its entrainment in comparison with the heavy-mineral particle. In a deposit of mixed grains, a current may be able to entrain and transport the light minerals, leaving behind a lag of heavy minerals that are more resistant to movement by virtue of their higher densities, lower exposures to the flow and greater pivoting angles.

It is difficult to quantify these processes of selective entrainment, but Slingerland (1977) and Komar and Wang (1984) attempted to do this in connection with the formation of placers. Basic to their analyses are mechanical models that focus on the forces of fluid drag and lift, which act to move the particle but are opposed by the immersed weight of the grain. This type of analysis was first undertaken by White (1940) for deposits of uniform grains, the results of which provide a process-based model that accounts for the success of the empirically based Shields graph (Fig. 1A). θ_t of Eq. (1) was found to be proportional to the ratio of the fluid-drag force responsible for the grain entrainment to the immersed weight of the particle resisting its entrainment, while the Reynolds number Re_* relates to the condition of fluid flow at the bed, its degree of turbulence. Slingerland (1977) and Komar and Wang (1984) expanded the analysis to account for the more natural condition where there is a distribution of grain sizes and densities.

Slingerland (1977) undertook analyses to examine how heavy-mineral enrichment is controlled by the boundary Reynolds number, Re_* of Eq. (2), and the ratio of the grain size in question to the average bottom roughness. He applied his analyses with some success to experiments undertaken in a wave tank and to natural heavy-mineral concentrations in beach sands. In a study of the formation of placers on Oregon beaches, Komar and Wang (1984) employed the threshold relationship

$$\tau_t = 0.00515(\rho_s - \rho)gD^{0.568} \tan \Phi \tag{4}$$

which was obtained empirically by Miller et al. (1977) for the entrainment of uniform grains of diameter $D < 0.1$ cm (see Fig. 2). With uniform grains there is an approximately constant $\Phi = 30^\circ$ [$\tan \Phi \approx 0.6$], but this pivoting angle varies with grain size within a deposit of mixed sizes as illustrated graphically in Fig. 3. Based on the experiments of Miller and Byrne (1966) and established further by Li and Komar (1986), such variations in the pivoting angle can be evaluated with

$$\Phi = e\left(\frac{D}{K}\right)^{-f} \tag{5}$$

where D is the diameter of the grain being entrained while K is the diameter of the grains over which it pivots, generally represented by the median grain size of the sediment. Values of the e and f coefficients are based on experiments, which demonstrated that they depend on grain shape (rollability and angularity) and on packing arrangements such as imbrication. From Eq. (5) it is seen that Φ decreases with increasing D/K as apparent geometrically in Fig. 3, so its use in Eq. (4) accounts in part for the grain sorting processes within a sediment of mixed sizes and densities. This selective grain entrainment model has been tested and verified by Li and Komar (1992a) in a series of laboratory flume experiments that showed excellent agreement between the predicted entrainment stress τ_t from the combined Eqs. (4) and (5) and those measured in the experiments covering a range of D/K from 0.59 to 1.4.

The combined Eqs. (4) and (5) were employed by Komar and Wang (1984) to generate the series of threshold curves given in Fig. 4, the selection of minerals included having been of specific interest to that study of the grain sorting processes leading to the formation of placers on Oregon beaches, to be reviewed later in this chapter. The curve from Eq. (4) with a fixed Φ is included for comparison, and is the same as that in Fig. 2 for uniform quartz grains. The other curves are for the selective entrainment by size and density where Φ varies according to Eq. (5). The selective

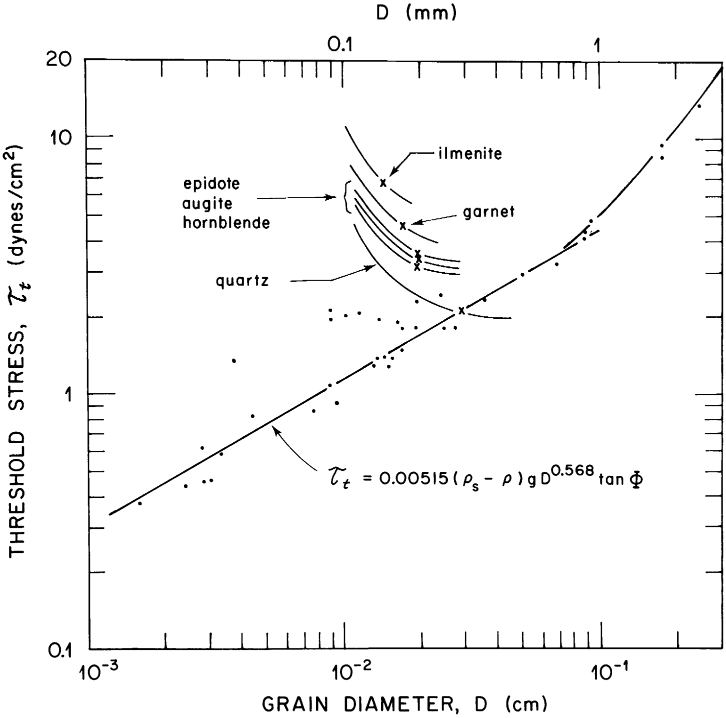

Fig. 4. Curves for the selective entrainment of particles from a deposit of mixed sizes for minerals important to placer formation on an Oregon beach, compared with the standard threshold curve for uniform quartz grains. [After Komar and Wang (1984).]

entrainment curve for quartz within a deposit of mixed sizes is seen to obliquely cross the standard threshold curve for beds of uniform quartz grains, with the crossing point being at the median grain size of the beach sand as a whole (indicated by the *x* on the curve), which initially is determined by the dominant quartz fraction. The curves for the other minerals were calculated on the basis of this same median grain size. Each selective entrainment curve slopes downward to the right; the calculations predict that the stress required for grain entrainment from a bed of mixed sizes of sand decreases with increasing grain diameter within that mixture. Of special interest to the formation of the Oregon beach placer, the series of curves shows that of the several minerals found in the sand, ilmenite would be most difficult to entrain due in part to its having the highest density, but also due to its being the finest grained. Of the several heavy minerals, hornblende is predicted to be most easily entrained, being the least dense and coarsest of the heavy minerals. As will be review in a later section, this predicted order of resistance to entrainment is matched by the degrees of concentration of these minerals in a placer on an Oregon beach, leading to the conclusion that selective entrainment was the primary sorting process important to the formation of that placer.

Analyses of the relative abundances of heavy minerals found in sediments have been presented in terms of their "hydraulic equivalence"—for example, best known is their settling equivalence as advocated by Rubey (1933), which will be discussed below. There could be a comparable condition of "entrainment equivalence" found in sediments, but its development would be more complex. The selective entrainment curves shown in Fig. 4 for minerals found in Oregon beach sands is specific to that mixture, and for the mean grain size of the sand as a whole, dominated initially by the quartz–feldspar fraction. Other mixtures of minerals and grain sizes would yield a different series of entrainment curves. Furthermore, the curves would evolve as the sorting takes place, initially as the quartz and feldspar are preferentially transported away, affecting the mean grain size of the deposit as a whole, and then as the sorting affects the individual heavy minerals and alters their relative abundances. In the end there may be an approximate entrainment equivalence of the series of minerals remaining in the heavy-mineral concentrate, a condition that potentially could be evaluated employing Eqs. (4) and (5). For the minerals to be in entrainment equivalence, that is have the same τ_t entrainment stress, the combination of the two equations yields

$$(\rho_s - \rho)D^{0.568} \tan\left[e\left(\frac{D}{K}\right)^{-f}\right] = \text{constant} \qquad (6)$$

which implies the establishment of an inverse relationship between the densities and grain sizes within the suite of heavy minerals. This relationship for the hydraulic threshold equivalence has not been directly tested employing laboratory or field data.

3.2. Shear Sorting of Mineral Grains

Once grain entrainment has occurred, the flowing fluid produces a transport of the sediment. The moving bedload in part involves the shearing of a thin layer of sand grains across the bed, within which there is a high gradient of the velocity of the concentrated fluid and sediment. This shearing can result in the formation of sediment laminations, which range up to approximately 20 mm in thickness. The laminations are most apparent when accompanied by a sorting of the grains to produce a layer of heavy-mineral concentration overlain by the light minerals, yielding a marked color contrast. Emery and Stevenson (1950), Clifton (1969) and Sallenger (1979) provide measurements of the grain-size and compositional sorting within individual laminations. Fig. 5 obtained by Clifton (1969) from a beach sand shows that a lamination consists of a basal fine layer of dark, heavy minerals and an upper coarser, light-mineral layer. Within an individual lamination the contrast between the heavy mineral and quartz-rich zones is gradual, but the interface between adjacent laminations is sharp.

On beaches the laminated sands are found primarily in the swash zone, produced by the alternating wave-swash runup and backwash across the beach face. The segregation between coarse and fine grains and between light and heavy minerals occurs quickly within the moving bedload layer of sand (Clifton, 1969). Thompson (1937) suggested that the laminations result from variations in the transporting power of the flowing water, the heavy-mineral concentration being produced by their settling out of suspension first to form the bottom of an individual lamination.

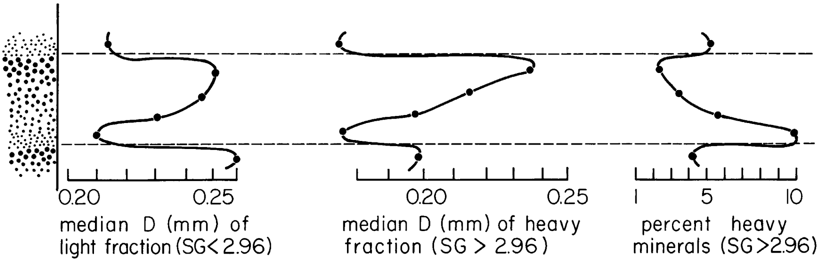

Fig. 5. Variations in grain sizes and heavy-mineral percentages through a single beach laminae. [After Clifton (1969).]

However, that mechanism cannot explain laminations found in coarse sands where there is a sorting by grain size but not necessarily by density, the coarser grains being at the top of each lamination. Most investigators have concluded that the laminations are produced instead by a shearing of the bedload layer and the action of the resulting dispersive pressure between the colliding grains. Bagnold (1954) demonstrated in detailed experiments that this dispersive pressure depends on the diameters and densities of the grains, on the total granular concentration, and on the local velocity gradient (the rate of shear). He went on to hypothesize that when grains of mixed sizes are sheared, the coarser grains tend to migrate upward to zones of lower shear while the finer grains move downward toward the bed where the shear is a maximum. The result is a layer having an inverse grading by size just as seen in Fig. 5, and since the heavy-mineral grains typically are smaller than the quartz, the grading will be accompanied by their concentration toward the base of the layer. Inman et al. (1966) coined the term "shear sorting" for this process, with his analysis having been for laminations formed in the slip face of aeolian sand dunes produced by the same mechanism.

Based on Bagnold's (1954) analyses of grain-dispersive pressures, Sallenger (1979) developed what can be termed the "grain-dispersive equivalence", the hypothesis being that at any single horizon within a sheared concentration particles of equal dispersive pressure will reside together. Employing Bagnold's dispersive-pressure equation, this balance yields

$$\rho_s^{1/2} D = \text{constant} \tag{7}$$

a simple inverse relationship between grain size and density such that a heavy-mineral particle will be smaller than an associated light mineral. Sallenger (1979) tested this relationship and found good agreement with shear laminations generated in the laboratory by subaerial grain flows and with the measurements of McIntyre (1959) of minerals within beach laminations. However, comparisons with other data sets showed poorer agreement.

Alternative hypotheses have been offered to explain the origin of laminations. It may be that some are formed by grain sorting during settling from suspension as suggested by Thompson (1937), even though this process cannot account for most laminated deposits. Middleton (1970) has argued that the sorting is produced by the smaller particles tending to fall into spaces between the larger particles, displacing the larger upward toward the surface. Whatever the mechanism having produced the laminations, the sorting initially results only in a minor separation of heavy and light minerals, amounting to the few millimeters thickness of a single lamination. However, it is possible that by repeatedly shearing the sand as it is transported along a river or when a beach face is cut back by waves during a storm, the heavies will be driven progressively downward and concentrated while the larger quartz and feldspar grains rise to the surface of the shear zone to be transported away. Reid and Frostick (1985a) have emphasized this ancillary relationship between shear sorting and selective grain entrainment, with the shear sorting feeding the larger light minerals to the top of the mobile layer of sediment, where their preferential entrainment as treated above leaves behind a lag of smaller heavy minerals. It is conceivable that grains left behind in the heavy concentrate are dispersive equivalents as given by Eq. (7). This possibility was examined by Komar and Wang (1984) for the placer formed in the swash zone of an Oregon beach, and although it was found that the minerals are not in dispersive equivalence according to Eq. (7), it was still concluded that shear sorting likely played some role in the formation of the placer as suggested by Reid and Frostick (1985a), while being less important than selective entrainment.

3.3. Sediment Sorting within Bedforms

The transport of sediment can also give rise to a variety of bedforms such as ripples and dunes, and it has been observed that a local sorting of minerals by density and grain size can develop within their geometry. McQuivey and Keefer (1969) have shown that magnetite grains in a bed of predominantly quartz sand tend to concentrate just upstream of the ripple crests as diagrammed in Fig. 6, and Brady and Jobson (1973) found similar magnetite accumulations on dunes formed in streams.

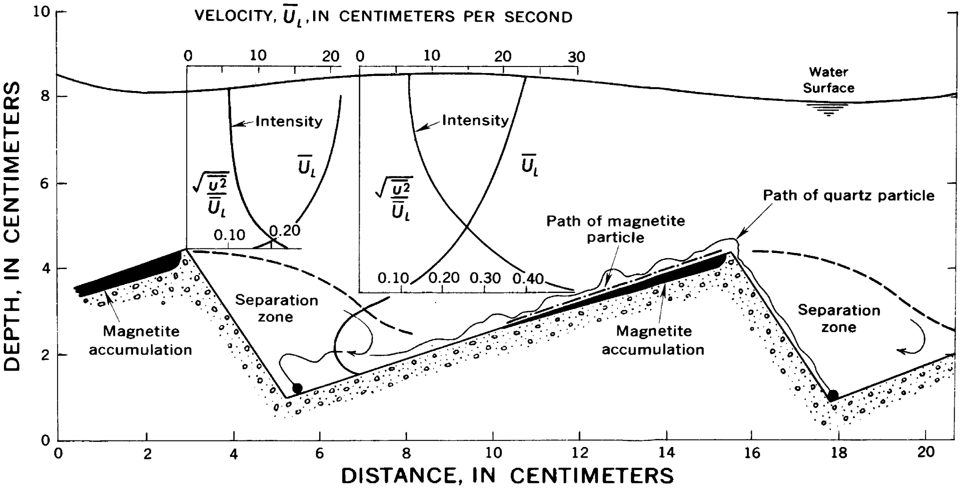

Fig. 6. The concentration of heavy minerals in the crests of ripples due to variations in the flow velocity and intensity of turbulence across the ripple profile. [After McQuivey and Keefer (1969).]

McQuivey and Keefer (1969) explained the pattern in terms of variations in the mean flow velocity and turbulence intensity over the ripple profiles as graphed in Fig. 6. Important is that the variation in the mean velocity is the inverse of the turbulence intensity, the velocity being greatest over the upstream-dipping stoss sides of the ripples, while the turbulence intensity is greatest in the separation zone of the boundary layer immediately downstream of the ripple's slip face. The resulting patterns of movement of the quartz versus magnetite grains are depicted in Fig. 6, with the quartz preferentially being carried over the crest of the ripples and then down the slip face, whereas the magnetite is deposited on top of the ripple.

Important to the resulting pattern of mineral sorting on the ripple, Fig. 6, is the occurrence of a zone of flow separation in the lee of the ripple crest, as it controls the distribution of eddy turbulence and also the pattern of mean bed stresses. The importance of flow separation to the concentration of heavy minerals was examined further by Best and Brayshaw (1985), including having undertaken laboratory flume experiments on the resulting patterns of heavy-mineral concentrations surrounding an isolated hemispherical obstacle clast placed on the bed, and the sorting associated with the confluence of two channels which results in a zone of flow separation that depends on the relative water discharges in the two channels. This points to the potential significance of flow separation to mineral sorting at a range of scales in rivers, including migrating bars, at the points of flow convergence within a braided channel, and at locations where the channel abruptly widens. Examples of sorting at these different scales in rivers will be presented later in this chapter.

3.4. *Settling Velocities of Mineral Grains and their Sorting*

Sediment transport as a suspended load is governed by the irregular motions of the flow, its turbulent eddies, compared with the settling velocities of the grains. If the grain-settling velocity is low then the eddy velocities are able to waft the grains above the bed where they can be carried along at high rates by the mean current. An understanding of grain settling is crucial to the evaluation of sediment transport in general, and can also be a factor in grain sorting where differences in densities and sizes produce contrasting settling rates. Most of the research into the settling behavior of sediment particles has focused on quartz grains of silt and sand, with some consideration given to the effects of their shapes on the rates of settling. The products of that research can be extended to the heavy minerals through known dependencies on the particle density as well as size.

Analyses of particle settling begin with a simple consideration of perfectly spherical grains for which theoretical relationships can be derived. Furthermore, there has been a considerable number of experiments undertaken to measure the forces of drag on a sphere moving relative to a fluid ("relative" in the sense that either the sphere can be moving or the fluid is moving). It has been found experimentally that the frictional force is linearly proportional to the relative velocity so long as the particle is small, the velocity is low, or the viscosity of the fluid is large; more precisely, this condition is met when there is a low value for the dimensionless particle Reynolds number $\mathrm{Re} = \rho u_s D/\mu$, where D is the diameter of the particle, μ_s its relative velocity, and μ the fluid's viscosity. For those conditions, in papers published in 1845 and 1851, Sir George Stokes theoretically derived the relationship

$$F_{\mathrm{d}} = 3\pi\mu D u_{\mathrm{s}} \tag{8}$$

for the drag force F_{d}, demonstrating its linear dependence on the relative velocity as well as the diameter of the sphere and fluid viscosity. His derivation involved a mathematical solution of the Navier–Stokes (momentum) equations, the basic relationships that govern fluid flow, but in order to solve those complex equations Stokes had to assume that the particle Reynolds number is less than approximately 0.5, indicating the limit of applicability of the simple relationship of Eq. (8).

With this relationship for the fluid drag it is simple to derive an equation for a sphere settling in a fluid, a relationship for the case where the grain is settling at a constant velocity, its "terminal velocity". At the terminal velocity there is a balance between the retarding drag force and the immersed weight of the particle that is pulling it downward. If there were no balance then the grain would either speed up or slow down until that balance is achieved. The immersed weight of the spherical particle is the difference between the force of gravity acting downward and the buoyancy force acting upward, and is given by

$$\text{immersed weight} = (\rho_{\mathrm{s}} - \rho)g\left(\frac{1}{6}\pi D^3\right) \tag{9}$$

Equating this to the drag force of Eq. (8) and solving for the settling velocity yields

$$W_{\mathrm{s}} = \frac{1}{18}\frac{1}{\mu}(\rho_{\mathrm{s}} - \rho)gD^2 \tag{10}$$

(W_{s} is used to denote the settling velocity since the descent of the particle occurs in the vertical direction). It is seen that in the Stokes Range the settling velocity of a sphere is dependent on the square of its diameter, the density difference between the grain and fluid, and is inversely proportional to the viscosity of the fluid. This relationship is often referred to as the Stokes Equation for grain settling, in recognition of Stoke's contribution to its derivation. In being limited to the Stokes Range, $\mathrm{Re} < 0.5$, in applications to sediment grains its usefulness is limited to small particles, primarily to silt.

For larger grain sizes experiments have shown that the drag is proportional to the square of the velocity of the sphere relative to the fluid, empirically yielding

$$F_{\mathrm{d}} = \left(\frac{1}{2}C_{\mathrm{d}}\rho u_{\mathrm{s}}^2\right)A \tag{11}$$

where C_{d} is a dimensionless drag coefficient that needs to be determined experimentally, with the measurements showing that it depends on the particle Reynolds number; u_{s} is again the relative velocity of movement between the grain and fluid and A the projected area of the particle in the direction of relative movement (equal to

$\pi D^2/4$ for a spherical grain). The balance between this drag relationship and the immersed weight of Eq. (9) yields

$$W_s = \left[\frac{4}{3}\frac{1}{C_d}\frac{\rho_s - \rho}{\rho} gD\right]^{1/2} \tag{12}$$

which can be applied to coarse grains settling at higher velocities. This relationship is sometimes referred to as the Impact Equation of grain settling in the mistaken impression that the drag is due to the impacts of water molecules against the cross-sectional area of the moving grain. For these coarser grain sizes the prediction is that the settling velocity is proportional to $D^{1/2}$, a weaker dependence than found in the Stokes Range. The application of this relationship is difficult due to the presence of the frictional drag coefficient, C_d that depends on the Reynolds number, which in turn depends on the settling velocity.

Empirical equations have been found that are easier to employ than Eq. (12) in routine computations of grain settling velocities. One in common use is that of Gibbs et al. (1971),

$$W_s = \frac{-3\mu + \sqrt{9\mu^2 + gr^2\rho(\rho_s - \rho)(0.015476 + 0.19841r)}}{\rho(0.011607 + 0.14881r)} \tag{13}$$

where $r = D/2$ is the radius of the spherical grain. This equation is not dimensionally homogeneous (i.e., the units do not balance), and therefore it is necessary that all parameters be in their cgs units ($\mu = \text{g cm/sec}$; $r = \text{cm}$; $g = \text{cm/sec}^2$; ρ and $\rho_s = \text{g/cm}^3$). Gibbs et al. (1971) also provide the inverse relationship whereby the grain size (r) can be calculated for a known settling rate. Although this relationship is messy in appearance, its use is straightforward in that an evaluation of a drag coefficient is not required. Its chief limitation was that it applies only to quartz-density spheres settling in water. However, Komar (1981) found that while there is an increasing systematic error introduced as the density departs from that of quartz, a simple correction factor can be included that reduces the error so the relationship can be applied to the full range of common heavy minerals. As an alternative approach, Warg (1973) has derived empirical equations that accurately cover the full range of grain densities; his relationships are more complex than Eq. (13), but can be included in computer routines to calculate settling velocities of spherical grains having any density.

As well as establishing the expected dependence of the settling velocity on the diameter D of the spherical particle, Eqs. (10) and (12) predict the dependence on the grain's density relative to the density of water. This dependence is seen in the series of curves graphed in Fig. 7 for the settling velocities of spherical grains ranging in diameters from 0.01 to 10 mm (silt, sand and granules), and for grain densities from quartz through a range of heavy minerals to cassiterite (7.0 g/cm^3), and also a curve for gold (18 g/cm^3). In calculating these curves, values $\rho = 1.02\,\text{g/cm}^3$ and $\mu = 0.01\,\text{g}\cdot\text{cm/sec}$ for sea water were used. The Stokes Region is delineated in the graph by the Reynolds number limit $\text{Re} = \rho u_s D/\mu < 0.5$. The curves are seen in Fig. 7 to be steepest for the small particle diameters in the Stokes Range, having a slope of 2 on this log–log graph in conformity with the Stokes settling Eq. (10). Similarly, the

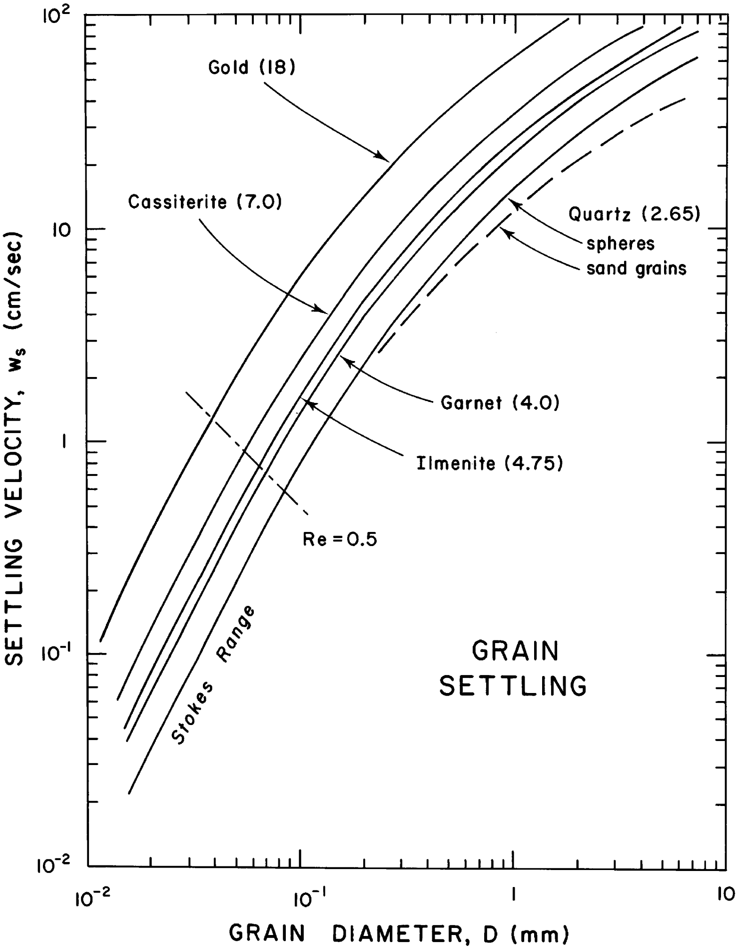

Fig. 7. Curves for the settling velocities of quartz and representative heavy minerals (specific gravities in parentheses). The dashed curve is for the settling velocity of natural quartz sand grains. [After Baba and Komar (1981).]

Impact Eq. (12) predicts a slope of 1/2 once the drag coefficient C_d has become essentially constant for large particle diameters; Fig. 7 indicates that this does not occur until the grains have diameters greater than approximately 5 mm. It is unfortunate that sand-size grains, the range of particular interest, falls between the Stokes and Impact relationships (with a constant C_d), so that direct determinations of the settling velocities of sand are the most difficult.

The primary series of curves in Fig. 7 are for the settling of perfect spheres, and therefore do not account for the irregularities typical of natural sediment particles. It is well established that grain non-sphericity and angularity act to decrease the particle's settling rate from that of a sphere having the same weight and volume (McNown and Malaika, 1950; Albertson, 1953; Williams, 1966; Komar and Reimers, 1978). The dashed curve in Fig. 7 is that obtained by Baba and Komar

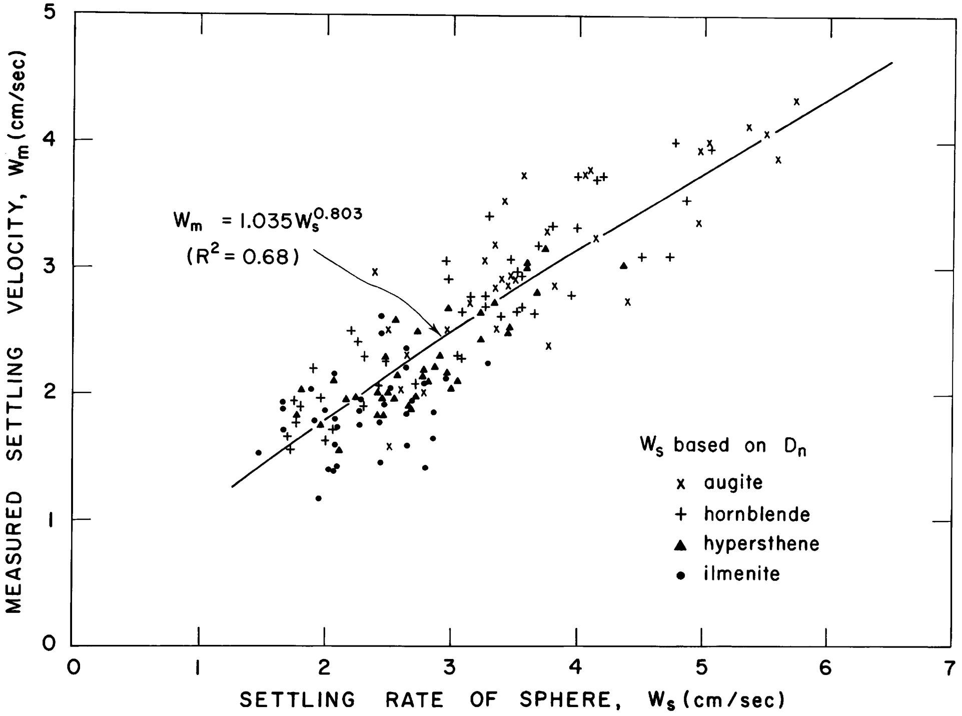

Fig. 8. Measured settling velocities of heavy minerals versus the settling rate of an equivalent spherical grain having the same mass and volume. [After Komar and Wang (1984).]

(1981) based on measured settling velocities of natural quartz grains obtained from beaches. Its departure from the curve for quartz-density spheres is small in the Stokes Range, but increases for the coarser grain sizes, a departure that Baba and Komar (1981) demonstrated was due primarily to the non-sphericity of the grains, with some reduction also due to the particle angularity. A similar decrease in the settling rates of heavy-mineral grains occurs due to their irregular shapes. Figure 8 shows the curve of measured settling velocities obtained for the placer minerals in the study of Komar and Wang (1984), compared with the settling rate of an equivalent sphere with the same density, calculated using the nominal diameter $D_n = \sqrt[3]{D_a D_b D_c}$, assuming that the heavy mineral is a triaxial ellipsoid having the measured axial diameters D_a, D_b and D_c of the actual particle (a similar correlation, but with somewhat greater scatter, is found if the settling velocity of the equivalent sphere is based only on the grain's intermediate diameter). Briggs et al. (1962) have undertaken the most extensive measurement study of the grain settling velocities of 15 common heavy minerals, demonstrating that the C_d drag coefficient in Eq. (12) depends on the grain's sphericity, the value of C_d increasing as the sphericity decreases, thereby in part accounting for the decrease in settling velocity.

The most extreme case of the effect of particle shape on grain settling is that of flat mica plates (Komar et al., 1984). Several investigators have stressed the importance of the effects of the flattened shapes of gold particles on their settling velocities, and hence on the sorting processes responsible for its accumulation in a placer (Tourtelot and Riley, 1973; Kolesov, 1975a, b; Saks, 1976). Calculations indicate that with the flatness values typically found for gold particles, their settling rates would be decreased by some 30–50% from the rates they would have as spheres (Komar, 1989), an estimate that is supported by the limited measurements of gold settling velocities obtained by Shumilov and Shumovskiy (1975). Such a reduction in settling rates for gold particles yields values that are comparable to those of other heavy minerals, so shape effects may act to reduce the contrast in settling-equivalent sizes between gold and the lower density minerals.

Settling rates of individual grains in a suspension can also be reduced by the overall volumetric concentration of particles (Richardson and Zaki, 1954). Slingerland and Smith (1986) suggested that hindered settling may play a role in the separation of light and heavy minerals. Suspension concentrations would have to exceed roughly 5% in order for the settling rates of individual grains to be hindered by grain-to-grain interactions and by the generation of an upward counterflow of suspending fluid. Slingerland and Smith (1986) base their hypothesis on experiments undertaken by Richardson and Meikle (1961) where mixtures of equal volumes of two species of sand-sized spheres having contrasting densities and diameters were settled together. The densities and sizes were off-setting such that the two species of spheres had equal unhindered settling velocities. It was found that if the total concentration is less than 8%, the two species settled with equal (but reduced) velocities and produced a single mixed layer. If the total concentration was increased to between 8 and 10%, settling was found to produce three layers of sediment, the lower consisting solely of the denser grains, the upper entirely of the lighter grains, with the intermediate layer being a mixture. At concentrations above 10% settling produced two layers with complete segregation of the separate species. Richardson and Meikle (1961) explained these results in terms of the buoyant forces on the large light grains created by the mixture of fluid and small dense grains. As pointed out by Slingerland and Smith (1986), such a process might occur where natural flows rapidly decelerate and drop their suspended sediments at high concentrations. They suggested that this could occur in overwash flows on beaches or points of flow expansion in streams.

While such effects of sorting might occur locally due to differences in grain settling, a large-scale cumulative sorting could take place during prolonged transport. As noted above, the coarser particles with high settling velocities remain on the bed and are transported along as a bedload, while the smaller grains with low settling velocities are carried up into the water and are transported more rapidly in suspension. This division between bedload and suspension transport is generally defined by the limit $W_{sc}/u_* \approx 0.8$ to 1.5 where W_{sc} is the critical particle settling velocity for this division and u_* is the shear velocity of the flow that indirectly governs the intensities of the irregular velocities within the turbulent eddies that are actually responsible for suspending the grains. For a fixed u_* determined by the flow, grains having settling velocities greater than this W_{sc} cut-off are part of the bedload while grains having lower settling velocities are in the suspended load. The division is somewhat arbitrary, and this accounts for the range of values that have been used by various investigators.

Important to grain sorting is that within the suspended load particles having lower settling velocities tend to be carried higher above the bottom and at higher concentrations, up into the region of flow experiencing greater current velocities

(Brush, 1965). This vertical distribution of suspended grains is predicted by the Rouse equation

$$C \propto C_a z^{-w_s/u_*} \tag{14}$$

where C is the concentration of grains at the distance z above the bed and C_a a reference concentration of that particle size in close proximity to the bed. This relationship shows that the concentration decreases exponentially with distance z upward into the flow, with the rate of decrease depending on the ratio W_s/u_*; for a fixed value of u_* as might occur for example in a stretch of river, the higher the settling velocity of the particles the more rapid their decrease in concentration above the bed. The grain sorting itself is produced by the action of the current on this vertical distribution of suspension concentrations, being given by $C\bar{u}$ where $\bar{u}$ is the mean velocity of the flow at the elevation z where the grain concentration C occurs. Since this local flow velocity $\bar{u}$ increases with distance above the bed, the grains having lower settling velocities will be transported at greater rates than those having higher settling rates that remain close to the bed.

With the moving suspended load being finer grained than the sediments generally found on the bed, there is the potential for entrapment of some suspended grains within a coarser and largely immobile bed deposit. In this manner the heavy minerals having higher settling velocities might preferentially be trapped, reducing further their rates of transport. Such a process has been offered as an explanation for the presence of fine gold particles found within the matrix of gravels, a common association in both streams and gravel beaches (Smith and Minter, 1980; Vorob'yev, 1979). Kolesov (1975b) has analyzed the process of small grains "subsiding" through the pore spaces of an otherwise stationary bed of coarser grains. In a series of flume experiments, Minter and Toens (1970) demonstrated that gold can move into the interstices of a simulated river gravel. Frostick et al. (1984) experimented with compartments containing different simulated armor frameworks placed within a stream, while Reid and Frostick (1985a) discuss the results in the context of gold placer formation. They concluded that there is greater potential for placer development by entrapment where gravels fine upward, since the pore spaces tend to become uniformly packed. With a coarsening-up sequence the sub-surface pores are smaller than those of the armor layer, and this can lead to clogging the upper pores while leaving a considerable amount of unfilled space below the matrix plug. Although such processes have not been examined in the context of the preferential entrapment of heavy minerals other than gold, in some instances this might be significant to their selective sorting and concentration.

While there is a considerable potential for the extensive sorting of heavy and light mineral grains during transport and deposition due to their contrasting settling velocities, geologists and sedimentologists have been interested primarily in the relationship between the minerals in terms of their potential equivalence once the sediment has been deposited. This interest appeared early as the concept of a settling equivalence as formulated and advocated by Rubey (1933). His concept of hydraulic settling equivalence was stated as: "…whatever the conditions may have been which permitted the deposition of quartz grains of a certain size, these conditions would also permit the deposition of magnetite grains that had the same settling velocity"

(Rubey, 1933, p. 5). According to this concept, in a given sample the dominant size (mean grain size) of the magnetite grains would be smaller than the mean size of the quartz grains since the denser but smaller magnetite particles would have the same settling rate as the larger but low-density quartz. If one applies the Stokes Eq. (10) to examine this equivalence, the respective densities of magnetite (5.1 g/cm^3) and quartz (2.65 g/cm^3) require that the ratio of their diameters be 1.6 in order to have the same settling rates—the quartz must be a factor 1.6 larger in diameter.

Settling equivalence can be established in Fig. 7 by any horizontal line of constant settling velocity, crossing the series of curves for the several minerals at what would be their respective mean diameters found in a sediment deposited on that basis. The curves diverge somewhat as their grain sizes and settling velocities increase, so differences in sizes of settling-equivalent grains would be greater for coarser sands than for silts in the Stokes Range. Hyperdense gold has such an extreme density that its curve is displaced from those of other minerals, so it would be considerably finer grained if deposited in a condition of settling equivalence. The grain-settling Eqs. (10) and (12), respectively for the Stokes and Impact Regions, yield the following settling-equivalence relationships based on the condition $W_s = \text{constant}$:

$$\text{Stokes settling equivalence } (\rho_s - \rho)D^2 = \text{constant} \tag{15a}$$

$$\text{Impact settling equivalence } (\rho_s - \rho)D = \text{constant} \tag{15b}$$

Both show the expected inverse relationship such that an increase in particle density requires a decrease in grain diameter for the minerals to have the same settling velocities. Since sand is intermediate between the Stokes and Impact Ranges, the exponent for the grain diameter might be expected to be somewhere between 1 and 2.

Although seemingly sound in principle, the proposal by Rubey (1933) of the equivalence of settling velocities of simultaneously deposited grains has not generally been found in sediments according to measurements of actual distributions of heavy minerals and quartz grains (von Engelhardt, 1940; Rittenhouse, 1943; Briggs, 1965; Hand, 1967; Lowright et al., 1972; Slingerland, 1977; Komar et al., 1984). Explanations for this deviation from settling equivalence have followed two lines: (1) the distributions are affected by the inherited size restrictions from the source rocks, or (2) differential transport of the various minerals in a sand governs their relative size distributions. This second explanation involves grain sorting by the other processes discussed here, for example, that the equivalence has been controlled by selective entrainment rather than by settling equivalence. Although it appears that grains found together in close association within sediments rarely have equivalent settling velocities, it does not follow that settling velocities play little or no role in the sorting of sediments during transport and deposition, at times leading to the formation of heavy-mineral concentrates and placers. As will become apparent in the following section, multiple processes generally act to bring about the sorting of mineral grains according to their contrasting densities and diameters, with grain shape at times also being a factor.

4. ENVIRONMENTS OF MINERAL SORTING

The previous section presented a summary of the principal mechanisms involved in the sorting of sediments leading to concentrations of heavy minerals. Only passing reference was given to research that has examined the importance of those processes in various environments. The objective of this section is to more closely examine studies that have either undertaken direct experiments in the laboratory to test the grain-sorting models, or have documented sorting patterns found in rivers and marine environments, analyzing them in terms of the sorting processes. Here I have had to be selective in deciding which studies to review, not having the space to produce a full summary; other chapters of this volume fortunately provide additional coverage.

This presentation is organized into research undertaken with unidirectional currents as occur in rivers and ocean currents (including tides), versus the short-period oscillatory motions of waves which dominate sediment transport on beaches and offshore to water depths of 100 m or more on most continental shelves. In each case the research has involved both the controlled conditions of laboratory flumes or wave tanks, and the more complex conditions found in the natural environments of rivers and the ocean.

4.1. Mineral Sorting by Unidirectional Currents

Research of sediment sorting by unidirectional currents has included experiments in laboratory flumes, permitting an idealization and simplification of the processes in contrast to rivers, which can be exceedingly complex. The idealized conditions of the laboratory flume are illustrated in experiments undertaken by Meland and Norrman (1966, 1969) and Steidtmann (1982).

The experiments of Meland and Norrman (1966) examined the transport velocities of glass spheres measured over fixed beds of ideally packed, uniform spheres. Diameters of both the transported spheres and those in the fixed bed (which determine the boundary roughness) were varied to examine the effects of the relative roughness on the transport rates. For a fixed roughness size, larger grains moved faster than smaller ones, likely a result of the larger particles projecting higher into the velocity profile of the flowing water, and because the larger transported grains roll more easily over the comparatively small bed roughness, factors discussed earlier in the context of selective grain entrainment and depicted in Fig. 3. Meland and Norrman (1966) did not vary grain densities in their experiments, but Steidtmann (1982) did in experiments that were otherwise similar. Results from two experiments with different u_* shear-stress values are shown in Fig. 9 where the grain's transport velocity is related to both its diameter D and to the ratio D/K where $K = 0.35$ mm is the diameter of the grains forming the fixed bed in Steidtmann's experiments. The limit of grain movement occurred at approximately $D/K = 0.6$, apparently in response to the high pivoting angles and limited exposure of the particles to the flow. Transport velocities of the grains are seen in Fig. 9 to increase with D/K for a fixed u_*, and with increasing u_* for a fixed D/K. Transport velocities of the light minerals (L) are greater than the heavy minerals (H), the difference being small for low values of D/K but increasing for higher D/K.

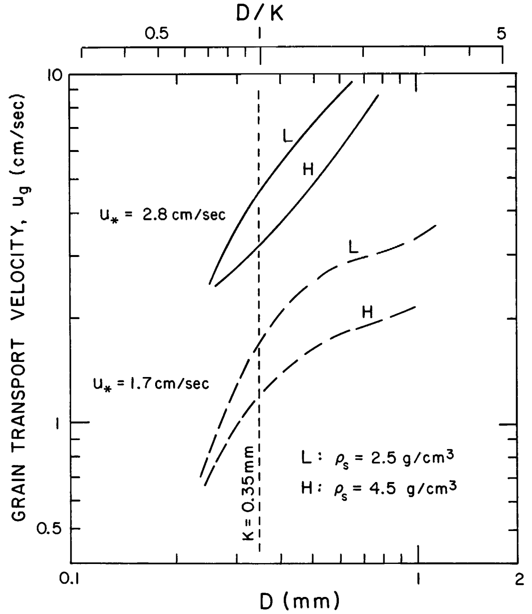

Fig. 9. Selective transport measurements of Steidtmann (1982) in a flume, showing that the relative transport rates of heavy (H) versus light minerals (L) depend on the shear velocity of the flow and the diameter *D* of the transported grain relative to the fixed bottom roughness *K*. [After Steidtmann (1982).]

Meland and Norrman (1969) and Steidtmann (1982) also undertook experiments with mobile beds, the moving sediment defining its own mean bed roughness. Meland and Norrman (1969) used glass beads and natural sand in different experiment series. They found that the maximum transport velocities occurred for intermediate sizes within the distributions, the smallest grains having lower rates just as found in the fixed-bed experiments, but there also was some reduction in transport velocities for the coarsest grains in the size distribution. They explained this reduced transport of the largest particles as resulting from their tendency to roll to the lowest positions on the lee surfaces of transverse bed forms as found by McQuivey and Keefer (1969) and illustrated in Fig. 6. Steidtmann (1982) experimented with a mixture of spherical glass beads having densities of 2.5 and 4.5 g/cm^3, the denser grains forming 5% of the mixture but having the same size range as the low-density grains. With plane-bed conditions he obtained results that are similar to those for a fixed bed, but for rippled beds no systematic difference could be found in transport rates of the heavy versus the light grains.

By having idealized the transport conditions to varying degrees, the flume experiments of Meland and Norrman (1966, 1969) and Steidtmann (1982) were able to reveal some of the grain-sorting mechanisms discussed earlier, but even under those simplified conditions it is apparent that multiple mechanisms are involved so the results are already becoming complex. The transport of bedload includes the repeated entrainment of grains, causing them to roll and saltate with the grains making repeated contacts with the bed, and in the case of completely mobile sediments the grains are organized into ripples with their accompanying sorting. The grain sorting found in those studies, therefore, resulted from the mechanisms of grain entrainment and bedload transport, but did not extend to sufficiently intense flows to have included sorting during suspension transport. The dependence of the transport and sorting on D/K, the diameter of the moving grain D relative to the bed roughness or mean grain size of the sediment over which the movement occurs, in part verifies the significance of selective entrainment as illustrated in Fig. 3 and contained in Eqs. (4) and (5) derived for the entrainment model. However, the dependence on D/K in the flume experiments also resulted from the subsequent rollability of the grains during transport, with the grains rolling faster and probably for greater distances if D/K is large. This would enhance the transport of quartz grains relative to the smaller heavy minerals, the light minerals being more easily entrained and then rolling at faster rates once they become part of the bedload. The density difference itself is also important, apparent in Fig. 9 for the higher transport rates of the low-density grains (L) versus the high-density grains (H) for the same grain size D. Finally, the experiments documented the tendency of the largest particles to roll to the lowest positions on the lee surfaces of transverse bed forms. While that sorting tended to offset the higher rates of transport of the larger grains by rolling, decreasing the degree of size sorting, in application to the sorting of light versus heavy minerals where the heavy minerals generally have smaller diameters, this sorting within the bedforms would concur with that found by McQuivey and Keefer (1969) as depicted in Fig. 6, contributing to the lag of the heavy minerals during transport.

The observations and conclusions based on these laboratory flume experiments agree with the application of general sediment transport calculations based on formulations that include many of the grain sorting mechanisms. This is shown by analyses undertaken by Slingerland (1984) in his study of placer formation. He employed the bedload evaluation approach of Einstein, a model that simultaneously considers processes of selective entrainment and transport, and permits considerations of grain-sheltering effects. Similar to his 1977 study, which focused only on entrainment, Slingerland (1984) examined the effects of Re_* and the boundary roughness on the differential movement and segregation of minerals. Fig. 10 shows his results for a hypothetical mixture of 90% quartz and 10% magnetite sand with initial size distributions having nearly equal settling velocities. Slingerland (1984) found that for a given u_*, transport rates for all sizes and both minerals decrease with increasing bed roughness (which can be considered as being proportional to the coarseness of the average bed material). Also seen in Fig. 10 is that Slingerland (1984) determined that the relative proportion of magnetite in the moving bedload increases with increasing u_* for a certain bed roughness, and decreases with increasing roughness for a given flow u_*.

More advanced and generalized sediment transport formulations are being developed that include the conditions of dealing with a natural sediment having a mixture of grain sizes and densities. Vogel et al. (1992) in particular developed analysis procedures that include most of the grain sorting mechanisms discussed here, and tested their model versus several data sets of measured transport rates and their grain-size distributions measured in both flumes and streams. Of particular interest here, they also simulated the formation of a gold bearing placer deposit

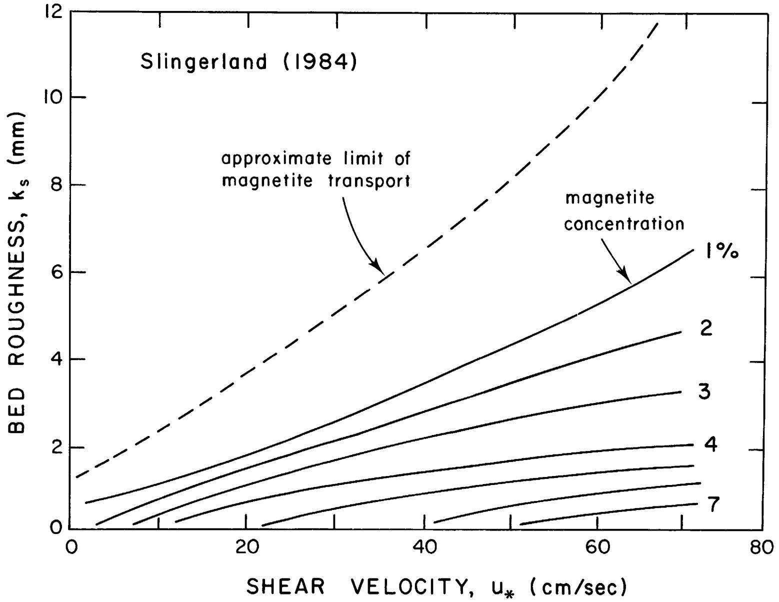

Fig. 10. Theoretical transport curves from Slingerland (1984) showing the effects of the bed roughness and shear velocity on the resulting concentration of magnetite in a deposit with quartz sand. [After Slingerland (1984).]

found in the Precambrian Witwatersrand of South Africa, with their model yielding reasonable results.

Beyond the highly idealized flume experiments like those of Meland and Norrman (1966, 1969) and Steidtmann (1982), flume studies by various investigators have attempted to simulate more realistically the transport and mineral sorting in what amounts to a small stream, the laboratory permitting controls of the flow discharge and sediment characteristics. One of the earliest studies of this type was that of Wertz (1949), who undertook experiments using a mixture of quartz and magnetite with the objective of improving the understanding of placer distributions found in South African rivers. While small scale and rather crude by modern standards, his experiments demonstrated the coincidence of the heavy-mineral concentrations with localized areas of erosion, while the barren zones corresponded to the areas of bulk sand accumulation. From the spatial distributions of mineral concentrations produced in his experiments and his discussions of the concentrations related to eddies, it is apparent that the patterns were associated with small-scale fluid motions and associated bedforms. Although he attempted to do so, his flume results should not be extrapolated to the large-scale sorting patterns of placer concentrations found in the South African rivers, which appear to be associated with pool-and-riffle sequences, with flow convergence zones in meander bends, and with sites where tributaries join the main channel (Wertz, 1949, Fig. 15).

Shepherd and Schumm (1974) undertook a series of flume experiments of channel incision into resistant "bedrock" materials (a mixture of kaolinite and sand), which also yielded information pertinent to mineral sorting found in natural rivers.

A sediment containing a small percentage of magnetite was transported along the experimental channel to simulate the erosion followed by aggradation during a major flood. It was found that the coarsest particles plus the magnetite formed a lag on the channel floor, that is, atop the “bedrock”. As the post-flood aggradation continued, the magnetite was buried and preserved. The experiments, therefore, explained the common occurrence of heavy-mineral concentrations found atop or near bedrock in natural rivers, first documented by Cheney and Patton (1967). The concentrations of magnetite found in the experiments of Shepherd and Schumm (1974) were not uniformly distributed over the bedrock floor, but instead achieved maxima on both low and high points of the irregular topography. In the pools the heavy minerals were trapped within the voids of the coarsest material, while on the highs in reaches where the channel widths were also the greatest, the locally reduced flow velocities resulted in the deposition of heavy minerals.

Mosley and Schumm (1977) expanded the flume experiments of Shepherd and Schumm (1974) to examine heavy-mineral concentrations and placer occurrences at stream junctions, where the combined discharges and sediment inputs led to mineral sorting and accumulation. Their experiment series included variations in the tributary confluence angles, the ratio of their discharges, tributary widths and sediment loads. Important to the mineral concentration was the development of a localized scour hole within the zone of otherwise general sediment deposition. Dye injections demonstrated the existence of complex flow patterns in the convergence zone, but important was the shear along the boundary between the two converging flows that set up vertical vortices. Similar experiments with tributary channels were conducted by Best and Brayshaw (1985) in their documentation of the significance of flow separation and mineral sorting, with their study providing greater details of the patterns of heavy-mineral concentration percentages under different flow conditions.

Field studies of heavy-mineral sorting in rivers have focused primarily on recording occurrences of concentrated deposits related to the channel hydraulics and morphology. While this has included sorting within ripples and dunes, discussed above as one of the mineral sorting mechanisms, it has included large-scale sorting as observed with respect to the migrations of bars, concentrations found at points of flow convergence in channel junctions, and at locations where the channel abruptly widens. Much of this research concerns the formation and occurrence of gold-bearing deposits, generally within gravel bed material, but the results are relevant to the general patterns of heavy-mineral sorting in rivers and in most cases actually involved a documentation of easily sampled minerals such as magnetite.

Smith and Beukes (1983) investigated the occurrence of heavy-mineral concentrates within three flow reaches of two mixed sand and gravel rivers in South Africa, the interest being to document modern counterparts to gold-bearing sands found in the Witwatersrand Leader reef of that country. Of special interest were deposits extending for tens of meters along the length of the channel, formed in the convergent zones of sluiceways confined between a stable bank and a parallel margin of a bar that was migrating toward the bank. The patterns of mineral concentration were based on the magnetite contents, the primary heavy mineral in those rivers and easily extracted from bed sediments collected spatially through the channel reach. One example is shown in Fig. 11, a map view of the sampling locations and

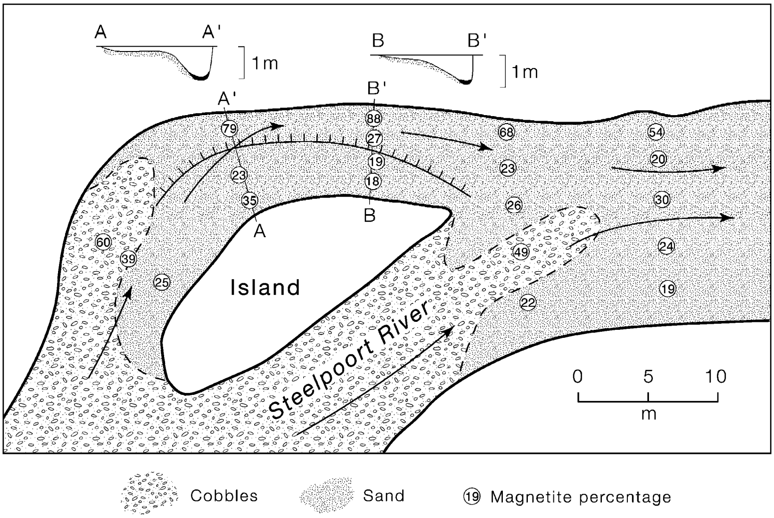

Fig. 11. Concentrations of magnetite grains as percentages of the sand fraction bed material, sampled in the Steelpoort River of South Africa, showing the highest concentrations in the zone of flow convergence in a sluiceway. [After Smith and Beukes (1983).]

magnetite percentages of the sand fractions in the Steelpoort River. The vectors included in the diagram depict the flow paths, with the convergence zone located along the stable outer bank of the river. The highest magnetite contents, reaching 88% of the sand, were found where the sluiceway currents were strongest, close to the outer bank. Five-fold magnetite enrichments were found in two of the three sluiceways investigated, those that had achieved an equilibrium geometry so the bars were no longer migrating toward the opposite bank, while sand was still being transported by oblique currents flowing across the bar toward the sluiceway; this provided a continuous supply of sand to be "processed" by the strong currents within the sluiceway. Enhanced concentrations of magnetite were not found in the third sluiceway studied, one that had not reached an equilibrium width so the bar was still migrating toward the opposite bank; the sand crossing the bar was instead deposited in bulk as foresets, without the processing that leads to the concentration of the magnetite. A small degree of magnetite concentration was found in the convergent zone immediately downstream from the island, corresponding to the sorting investigated by Mosley and Schumm (1977) and Best and Brayshaw (1985) in flume experiments. However, the degree of concentration found by Smith and Beukes (1983) in the South African river was relatively minor and varied in position with time as flow discharges and the bed morphologies changed, such that significant volumes of heavy minerals could not accumulate.

Smith and Beukes (1983) did not investigate in detail the actual mechanisms important to the concentration of the magnetite in the suiceway convergent zones, though it was clearly related to the locally increased intensity of the flow and the selective removal of the light minerals, leaving the magnetite as a lag. They did document that the settling velocities of the magnetite grains differ from the associated feldspar, so the concentration did not produce a grain-settling equivalence.

They suggested instead that selective particle entrainment was the most important sorting mechanism, a reasonable conclusion.

As seen in Fig. 11, much of the channel in the Steelpoort River studied by Smith and Beukes (1983) consisted of a cobble pavement (armor layer). They noted the enhanced accumulation of magnetite sand captured in the voids between the cobbles, achieving 60% magnetite in one sample, but this occurrence was not the focus of their study. Day and Fletcher (1989, 1991) investigated the sorting and distributions of magnetite and gold particles, compared with quartz, along a 5-km stretch of Harris Creek, a gravel-bed stream in British Columbia, Canada, where heavy-mineral entrapment within the pavement was shown to be important. Harris Creek has a pool and riffle sequence typical of many gravel-bed streams, and on a larger scale the creek changes from meandering to braided within their study area. The mean annual flood is approximately 19 m^3/sec, determined by the seasonal snowmelt. Following the peak of the spring-melt flood in 1986, bed sediment samples were collected along the study reach, at positions related to channel bars/riffles and low-energy eddy zones. With the sampling having occurred immediately after the spring flood, it recorded the deposits following the movement of the gravel bed material and its re-establishment as a pavement (armor) layer, and then the entrapment of the sand containing the magnetite and gold within the gravel voids and in the eddy zones where the deposits were entirely sand.

Following the classification of Slingerland (1984) developed for placer deposits at different scales, Day and Fletcher (1991) identified magnetite and gold concentrations in Harris Creek at three scales: the <1 m scale where the heavy mineral deposits formed by entrapment by the pavement voids; at the 10–100 m scale related to the preferential accumulation of heavies in the bar-head gravels of riffle-pool sequences; and at the >1000 m scale related to the average channel slope, with the highest concentrations found where the slope reduced from 0.04 to 0.02. The primary interest of their study was relating these observed variations in mineral concentrations, contrasting those of magnetite versus gold, to a model based on the processes of erosion and redeposition of the bed following a flood event. The model analyses employed applications of Einstein's bedload transport function, extending those of Slingerland (1984), with the flow and channel parameters chosen to represent the study reach of Harris Creek. In the model analyses the transported sediments included mixtures of magnetite, gold and quartz sand, with the series of model runs varying the diameter of the bed roughness (ranging from a 10-mm pavement to a sand bed) and for bottom slopes of 0.01, 0.02 and 0.04. In each model run the analysis yielded the ratio of the transport rate of quartz to the transport rate of magnetite or gold. The model results were compared with those measured in Harris Creek, showing good agreement. Both the model and field data demonstrated the importance of the pavement voids to the preferential entrapment of the heavy minerals, influenced by the particle size and density as this determined the frequency with which the minerals contacted the bottom permitting their capture within the voids, increasing the concentration of the gold relative to the magnetite, with both significantly increased relative to the quartz sand. The decrease in channel slope similarly led to the accumulation of sand-sized sediment, again with the preferential deposition of the high-density minerals, magnetite and gold. On the other hand, both the model and field data demonstrated that the sandy sediments in back-bar and counter-current eddy pools are unfavorable sites for the preferential accumulation of the heavy minerals, their concentrations instead reflecting the bulk composition of sediments being transported along the river.

The research of mineral sorting by unidirectional currents undertaken in laboratory flumes and in natural rivers has led to a better understanding of the concentrating mechanisms and the resulting patterns of heavy-mineral concentrations and placer occurrences in rivers. The research products are being integrated into sediment transport models, which can serve in the quantitative analysis of mineral sorting that includes the major mechanisms, tools that will be useful in the interpretation of heavy-mineral deposits found in rivers, in both modern and ancient fluvial deposits.

4.2. Mineral Sorting by Waves (Beaches and Continental Shelves)

Concentrations of heavy minerals on sandy beaches are readily apparent, ranging in scale from the local sorting in backwash ripples and laminations to profile-scale sorting where the heavy minerals have accumulated in large volumes at the landward edge of the beach, the light minerals having been preferentially transported offshore. In the extreme the backshore deposit may consist of effectively a 100% black-sand mineral concentrate, potentially containing valuable placer minerals such as ilmenite, chromite, rutile and sometimes gold and platinum. Being readily visible, the heavy-mineral concentrates on beaches have received significant research attention, with a few studies having had the objective to establish which of the grain-sorting mechanisms were important to their formation.

Within the beach environment, the foreshore or swash zone is most conducive to the processes of heavy-mineral enrichment leading to black sand deposits and placers. Such occurrences has been documented by a number of studies, with the investigations by Rao (1957), Cordes (1966), Woolsey et al. (1975) and Komar and Wang (1984) having examined the conditions under which the heavy minerals were concentrated. Each study pointed to the importance of beach erosion, either a brief episode of recession leaving a thin layer or lens of black sand, or continued erosion over a long period forming an extensive deposit. Fig. 12 from Rao (1957) illustrates the role of beach erosion on the coast of India during a typhoon on the Bay of Bengal, the erosion having produced an extensive concentration of heavy minerals. The observations by Woolsey et al. (1975) on a Georgia beach and by

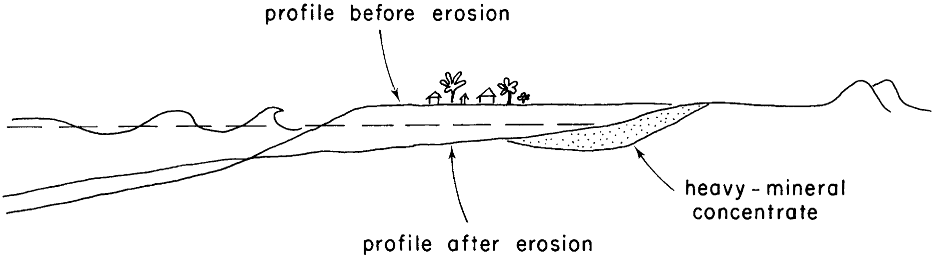

Fig. 12. The formation of a black-sand placer due to beach recession on the east coast of India during a typhoon. [After Rao (1957).]

Komar and Wang (1984) on the Oregon coast documented the development of smaller black-sand deposits during single storm events, the concentrating processes taking place within the zone of wave swash on the beach face. The heavy-mineral deposit investigated by Cordes (1966) at Skagen, Denmark, was unusual in that it formed in an area of erosion downdrift from harbor jetties.

Swash zone processes are ideal for the development of heavy-mineral concentrates by the selective winnowing of low-density quartz and feldspar, leaving behind the heavy minerals. The action of the swash is similar to the water motions induced by a prospector panning for gold. Measurements of the swash runup on the beach face have yielded the surprising result that when a storm occurs and breaking wave heights increase, the runup of the wave bores themselves at the shore do not necessarily increase. This unexpected result is attributed to the fact that doubling the offshore wave height doubles the depth at which the waves break, and the bores must then travel roughly twice as far from the breaker zone to the swash zone. However, there is a marked enhancement of swash motions having periods >20 sec, the approximate upper limit of wave periods directly attributable to the storm. This long-period swash action, referred to as the "infragravity motions", must obtain its energy indirectly from the storm since it does increase with storm intensity and offshore wave heights. These long-period swash motions are a major factor in producing erosion of the beach face, and with the motion being comparable to the water oscillations in panning for gold, this increase in the long-period infragravity swash on beaches during storms is ideal for carrying away the quartz and feldspar, while leaving behind the concentrated heavy minerals.

The grain-sorting mechanisms that actually occur on the beach face have been investigated by Hand (1967), Trask and Hand (1985) and Komar and Wang (1984). Hand (1967) found that heavy minerals in beach sands settle more slowly than predicted by settling equivalence with the associated quartz. He attributed this difference to the difficulty of entraining the small heavy minerals in comparison with the larger quartz grains. Trask and Hand (1985) investigated sorting patterns on a beach along the eastern shore of Lake Ontario where the predominant direction of the waves resulted in a net northward longshore transport of the beach sand. From each sample they separated a fraction of grains, which had the same settling velocity, and then examined the longshore sorting of the minerals within that settling-equivalent fraction. It was found that the heavy minerals decrease in abundance in the direction of transport, and Trask and Hand (1985) were able to establish that the degree to which any mineral lags behind another lighter mineral is a function of the ratio of their effective densities. The sorting itself was attributed to differential entrainment and transport, the sampling procedure having eliminated sorting due to differences in settling velocities.

A more direct assessment of the roles of the potential sorting mechanisms was provided by the study of Komar and Wang (1984) of a heavy-mineral black sand on an Oregon beach. A series of sand samples was collected along a profile across the beach during an erosion event, at a time when the wave swash was removing sand from the beach face in the swash zone and transporting it offshore. This permitted a documentation of the minerals that were preferentially being left behind to form the black-sand concentrate, versus those that were selectively transported offshore, and permitted detailed analyses of which sorting processes were responsible. It was found

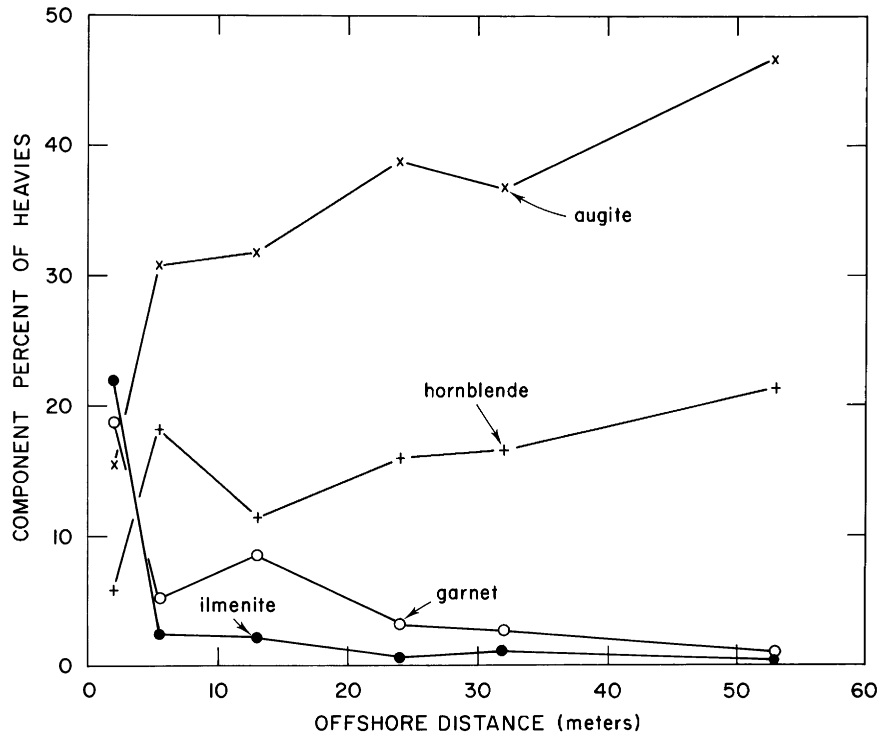

Fig. 13. Along-profile variations in heavy-mineral percentages in the swash zone of an Oregon beach. [After Komar and Wang (1984).]

that the overall concentration of heavy minerals systematically decreased across the width of the swash zone, being 96% heavies in the landward-most sample while 54 m down the beach face (but still within the swash zone) the sample contained only 6% heavies. Cross-shore changes in percentages within the heavy fraction of four of the principal minerals are graphed in Fig. 13, demonstrating that the efficiencies of the concentrating processes were not the same for each mineral. Nearly all of the ilmenite and garnet remained at the back of the beach in the most concentrated heavy-mineral deposit, while a greater proportion of the hornblende and augite moved offshore along with the quartz and feldspar. These cross-shore trends are clearer if expressed as a concentration factor for each mineral, its percentage in the accumulated black sand divided by its percentage in the offshore sample—here the light minerals were included so the ratio became a direct evaluation of the degree to which a mineral had been concentrated in the placer as opposed to having moved offshore with the quartz and feldspar. The results are shown in Fig. 14 as a graph of mineral densities versus their median diameters, the concentration factors being printed adjacent to the data symbols. The highest concentration factor is that of ilmenite (1 4 0 3) with zircon a close second (1 1 7 5), signifying that both remained in the concentrated deposit at the top of the beach and virtually none was carried offshore. Of the heavy minerals, hornblende has the lowest concentration factor (5), indicating that it did tend to remain in the placer but the concentrating processes

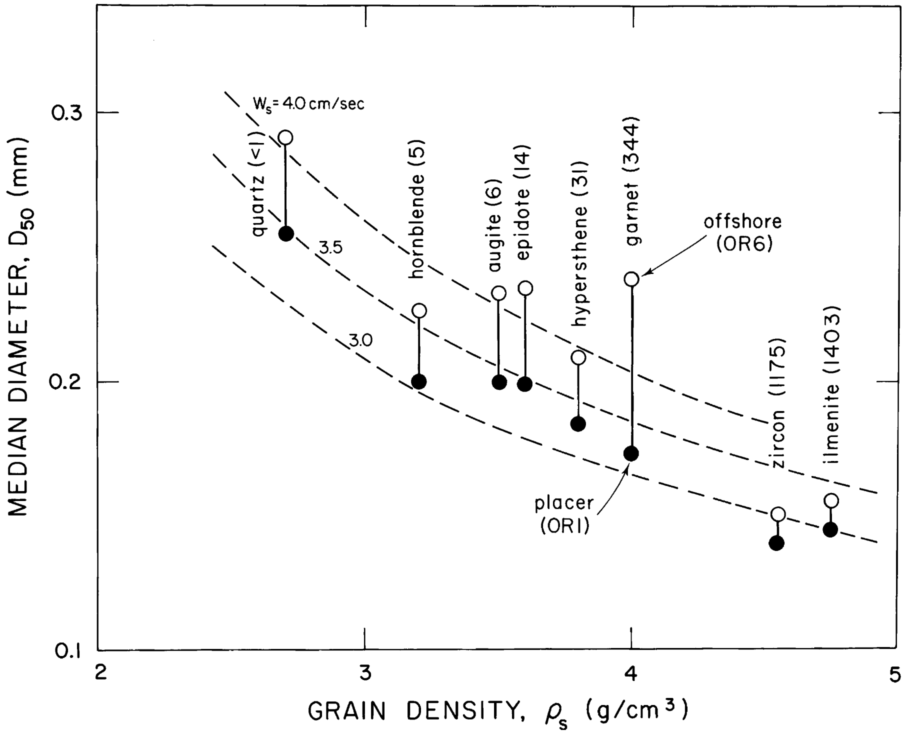

Fig. 14. The median grain diameters versus densities of the minerals in an Oregon beach, with the closed data symbols being for the concentrated black sand formed at the back of the beach while the open symbols are for a sample obtained 53 m down the beach face. The ratios of the mineral concentrations in the black sand to the offshore sample are shown in parentheses. The dashed lines represent constant grain settling velocities. [After Komar and Wang (1984).]

were less efficient so much of it moved offshore. Quartz has a concentration factor less than 1 since it preferentially moved offshore rather than remaining in the black sand.

The data of Komar and Wang (1984) in Fig. 14 demonstrate that for the several minerals found in the Oregon beach sand, the higher the density of the mineral the lower its median grain size within both the concentrated black sand and in the offshore sample. The concentration factor of the mineral in the black sand accordingly increased with increasing grain density and decreasing diameter. Ilmenite was most efficiently concentrated in the black sand because it is the densest of the minerals and is the finest grained, while the processes were least efficient in concentrating the hornblende because it has the lowest density and the largest diameter within the suite of heavy minerals. The graph of Fig. 14 also shows that for any given mineral, the median diameter is greater in the offshore sample than in the black sand. The pattern of sorting leading to the formation of the placer is, therefore, one where the processes have selectively removed the grains of lower density and coarser size, leaving grains of high density and small diameters in the black sand.

This inverse relationship between grain density and diameter suggested that there might be a settling equivalence between the several minerals (Komar and Wang, 1984). Direct measurements of their settling velocities demonstrated such a near equivalence, and this is also indicated in Fig. 14 where the dashed curves are for constant settling velocities depending on the combinations of grain diameter and density; a settling velocity of 3.5 cm/sec yields the curve most central to the minerals. It is apparent from this that no relationship can be found between the grain settling velocity and the respective concentration factors for the individual minerals. It was concluded that over the thousands of years of beach development, the waves and currents had sorted the minerals so the sediment particles have a relatively narrow range of settling velocities. However, this settling equivalence of all minerals in the beach sand largely precluded any further role of that parameter in producing grain sorting, leading to the formation of the black-sand concentrate. The analyses instead led to the conclusion that selective grain entrainment and transport were responsible for the sorting and mineral concentration. Fig. 4 presented earlier in the context of mineral sorting is from the study of Komar and Wang (1984), and includes curves for the entrainment stresses of the several heavy minerals present in the Oregon beach sand. In that graph it is seen that ilmenite is most difficult to entrain due to its high density and smaller diameters, while hornblende is most easily entrained of the heavy minerals. The sequence of curves given in Fig. 4 corresponds exactly to the order of concentration factors for the minerals, with the values being directly compared in Fig. 15. The uniform trend suggests that selective entrainment has been the

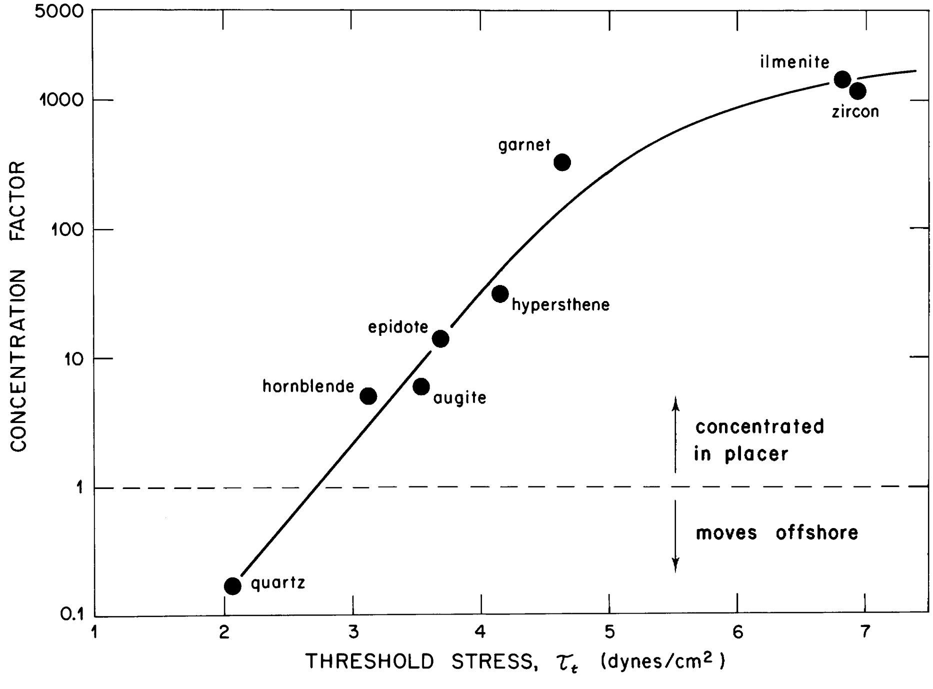

Fig. 15. Concentration factors of minerals in the Oregon-beach black sand versus the flow stresses required for their entrainment. [After Komar and Wang (1954).]

most important sorting process leading to the black-sand concentration on that Oregon beach. Both the high density and small diameters of the ilmenite grains increased their entrainment stress, and this accounted for its extreme concentration within the deposit. Hornblende is the other extreme in the suite of heavy minerals, it having the lowest density and largest median grain size, and therefore has the lowest entrainment stress so it tended to be carried away into the offshore with the light minerals. Quartz continues this trend, Fig. 15, being most easily entrained so it was readily transported offshore, leaving almost no quartz in the black sand deposit.

Further analyses indicated that relative transport rates of the different minerals also played a role in the formation of the black sand on that Oregon beach (Komar and Wang, 1984). The significance of different transport rates of the minerals toward the offshore was readily apparent thanks to the contrasting colors of the minerals. During offshore transport across the beach profile it is common to see the tan-colored quartz and feldspar move at the fastest rates and outdistance the other minerals, followed by the green augite, in turn followed by pink garnet, leaving the black ilmenite as a lag. Following the analysis approach of Slingerland (1984), Komar and Wang (1984) used the relationships of Einstein to calculate the relative transport rates of the different minerals, with the results providing further confirmation.

It is well-established that heavy-mineral concentrates tend to form in the swash zone of beaches during erosion events with offshore transport, and the dominant processes appear to have been identified. The interesting experiments by Saks (1978) indicate that sorting can also occur as a result of differential rates of transport in the onshore direction. He injected steel shot and lead filings into the mid-swash zone of a beach, and 45 min later measured concentrations along a cross-shore profile. Concentrations shoreward of the injection site were found to be 10 times those of an equivalent distance seaward, demonstrating that there was an active shoreward transport of those high-density grains, presumably due to the asymmetry of the swash motions with the landward uprush being stronger than the backwash.

When waves break at an angle to the shore they produce a longshore transport of the beach sand, and this can result in the sorting of mineral grains spanning many kilometers of shoreline length. A study comparable to that of Komar and Wang (1984), but of mineral sorting in the longshore direction, was undertaken by Li and Komar (1992b) adjacent to the mouth of the Columbia River. Beach-face sand samples were collected along a 70-km length of shore both to the north and south of the river mouth, and as graphed in Fig. 16 a marked longshore variation in the concentration of heavy minerals was found, the highest concentrations reaching 60–70% in the summer beach closest to the river mouth (approximately 100% in the eroded winter beach). There is a rapid decrease in concentrations both to the north and south, reduced to $<2\%$ after approximately 20 km of longshore transport away from the river source. The median grain sizes of the sand also varied with distance from the river, Fig. 16, initially decreasing to the north, the predominant direction of sand movement, but with a coarsening beyond the 25-km distance north of the river. Important to the development of this black-sand beach deposit was the construction of the jetties at the mouth of the Columbia River beginning in 1885 and extending into the early 20th century (Komar and Li, 1991). Their construction initially resulted in the formation of Peacock Beach to the immediate north of the jetties, and the small Clatsop Spit to the south (Fig. 16). However, the subsequent erosion of

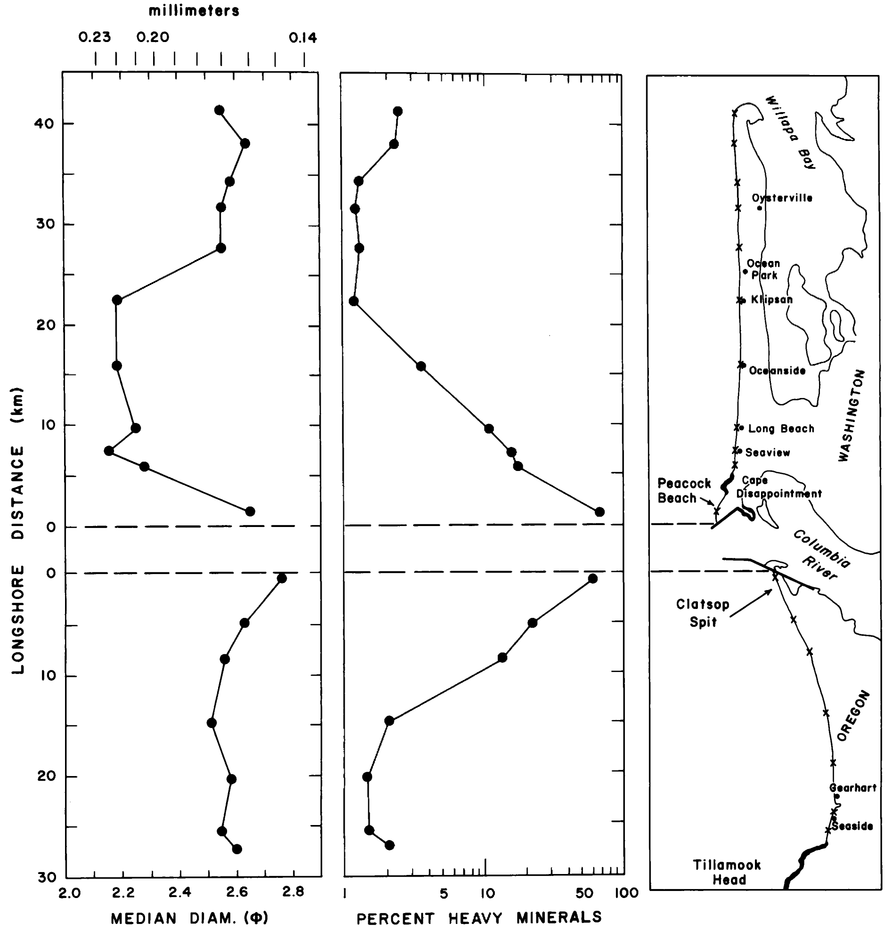

Fig. 16. Longshore variations in beach sand median diameters and percentages of heavy minerals north and south of the Columbia River. [After Li and Komar (1992b).]

these beaches, continuing up to the present, has led to the development of the concentrated black-sand placers in those areas and their progressive expansion alongshore to the north and south.

The objectives and analyses of the Li and Komar (1992b) study at the Columbia River mouth were much the same as those of Komar and Wang (1984), only directed along the length of shore rather than in the cross-shore direction along a beach profile. The mineralogies of the sands in the two studies differed due to having had significantly different sources. The study of Li and Komar (1992b) focused on the opaques (mainly magnetite), hypersthene, augite and hornblende, derived mainly from the volcanics that dominate the Columbia River watershed. An inverse relationship was again found between the grain densities and their sizes, with the concentrations in the placers adjacent to the river being greatest for the opaques and least for the hornblende, the same pattern found by Komar and Wang (1984) with the highest density and smallest diameter grains preferentially remaining in the heavy-mineral deposit. The longshore decreases in mineral concentrations also depended systematically on the grain density and diameter, shown in Fig. 17 which contrasts the northward decrease of hornblende and the opaques, with the rates of decrease reflected in their respective exponents $k = -0.117$ and -0.205 in the relationship $C = C_o e^{kd}$, where C_o is the mineral concentration at the river mouth and C its concentration at the longshore distance d. The lower graph in Fig. 17 plots

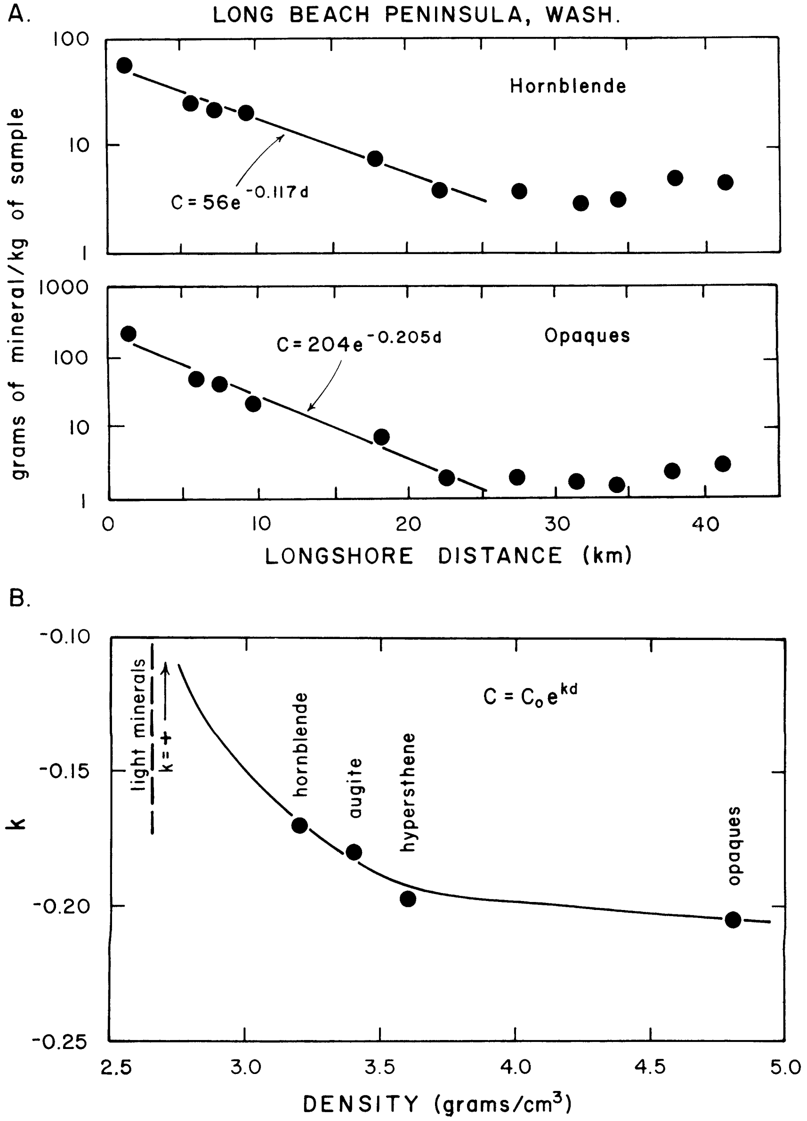

Fig. 17. The decreases in concentrations of hornblende and the opaque minerals in beach sands along the Long Beach Peninsula north of the Columbia River. The value of k reflects the exponential rate of mineral concentration decrease to the north as a function of the mineral's density. [After Li and Komar (1992b).]

the values of the k exponent as a function of mineral density for the five minerals (including quartz, which has a positive exponent since it increases in concentration with longshore distance). Measurements of grain settling velocities indicated that sorting by that mechanism may again explain the bulk characteristics of the beach sand, but cannot account for the enrichment of the dense minerals in the concentrated placer. Instead, minerals requiring higher selective entrainment stresses and having lower bedload transport rates were again found to be those most concentrated in the placer. This was the case for settling-equivalent fractions within the deposits, as well as for the entire samples. This is shown by the comparisons in Fig. 18, with the two graphs, respectively, comparing the mineral concentration factors with their entrainment stresses and calculated transport rates.

From this review it is seen that heavy-mineral concentrates commonly form in the swash zones of beaches, and based on the studies reviewed a reasonable understanding of the sorting mechanisms has been achieved. There is less evidence for similar processes operating within the surf and breaker zones, on the offshore bars and in the troughs eroded by longshore currents and rip currents. Black sands are sometimes found in those environments, but it is unclear whether they formed in situ

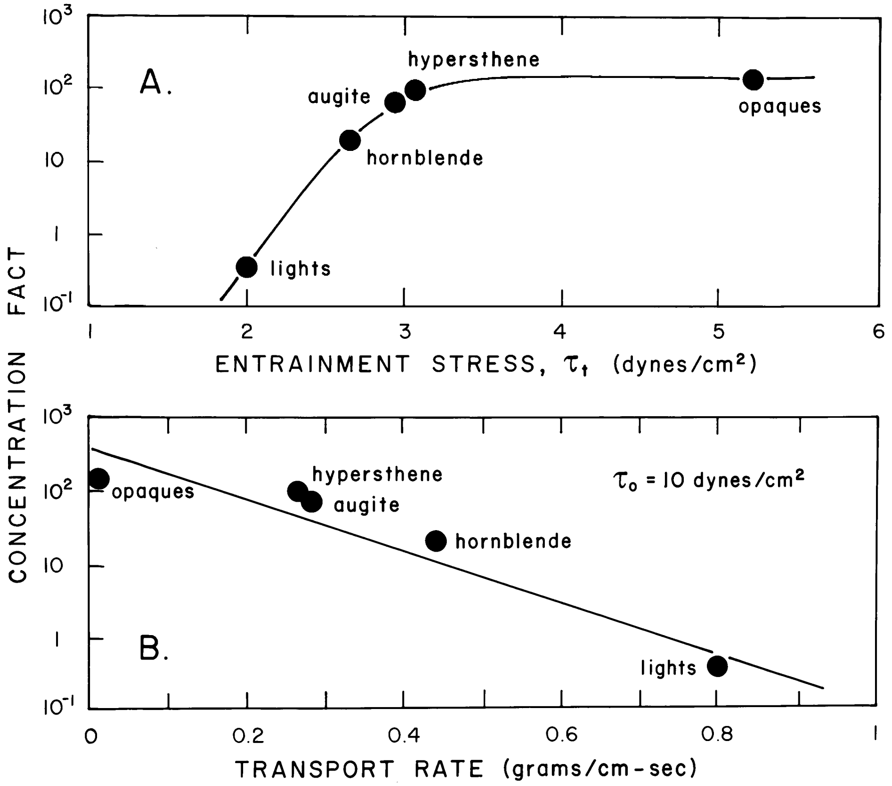

Fig. 18. The concentration factors of minerals in the black sand placer immediately north of the Columbia River versus (A) the flow stresses required for their entrainment and (B) their subsequent transport rates. [After Li and Komar (1992b).]

or resulted from processes operating in the swash zone followed by the offshore dispersal of the concentrated heavy minerals. The waves and currents in the outer portions of beaches are not as conducive to mineral sorting as in the swash zone. The breaker zone is characterized by high levels of turbulence, which carry sand in suspension, this having the effect of mixing of the sediments rather than sorting them according to their densities. Particles having low settling rates will tend to drift offshore from the breaker zone, and this may result in some degree of concentration of heavy minerals on the beach as a whole. This sorting would narrow the range of settling velocities of grains remaining on the beach, as found by Komar and Wang (1984) on Oregon beaches.

Reid and Frostick (1985b) documented the formation of heavy-mineral (ilmenite) concentrates on sand bars of beaches in Lake Turkana, Kenya. However, these were not submerged bars typical of breaker zones, but instead were swash bars that actively migrate onshore during rising lake levels and come under the action of the wave swash. The processes of mineral concentration were therefore likely similar to those discussed above for deposits formed in the swash zone. Two types of bars were recognized by Reid and Frostick (1985b) that differed in their cross-sectional shapes, their occurrence depending on the wave periods and energy levels. The bar shapes were in turn found to be important to the concentrating processes, with higher concentrations found on swash bars that have significant vertical reliefs, limiting the degree of overtopping by the waves. A pattern of increasing concentrations of heavy minerals from the break point up the swash slope was found, with peak concentrations occurring at and just over the bar crest. With lower wave periods and energies dune-like bars formed, their crests being approximately at the water level so wave overwash was frequent. Reid and Frostick (1985b) provided sedimentological evidence that grain suspension was more important on the dune-like bars, resulting in a less effective concentration of the heavy minerals.

Many beaches are characterized by having a longshore trough between the breaker zone and swash zone, an area of complex sediment transport brought about by the interplay of shoreward-moving wave bores and currents flowing in the longshore direction. Erosion can be significant in the troughs, at times leading to the development of a gravel lag. There may be some entrapment of heavy minerals and gold in the trough gravel, as well as in the gravel of the swash zone. The nearshore currents become strongest where they turn seaward to form rip currents, which transport sand offshore and deposit it beyond the breaker zone, often eroding embayments into the beach face. Bogdanov et al. (1986) found localized concentrations of heavy minerals on beaches along the Baltic Sea coast, which corresponded to the rhythmic topography of the beach produced by nearshore currents. The concentrations at the sediment surface were greatest over the tops of bars, and may represent erosional lags. There were also concentrations within seaward-trending troughs, but these were buried beneath several centimetres of overburden; it may have been that the troughs were eroded by strong rips at the time of a major storm, concentrating the heavy minerals, but later were buried during post-storm beach accretion.

Bogdanov et al. (1986) also found that when waves break obliquely to the beach and produce a longshore sand transport, the patterns of localized mineral concentrations tend to be erased. Under such conditions it is likely that the rip currents would migrate alongshore or disappear altogether, accounting for the disappearance or burial of the local mineral concentrations they had produced. However, the longshore directed currents then become more important in the transport of sand, so it is possible that the processes of heavy-mineral concentration within longshore troughs are enhanced. This is speculation, and needs to be examined by field studies. There are cases where along-coast variations in placer development have been attributed to large-scale longshore sand movements. On the beaches of the east coast of Australia the net sand transport is to the north, and it has been found that the highest mineral concentrations are located to the south of headlands (Hails, 1976), an occurrence that has been attributed to the enhanced erosion caused by the deflection of northward flowing longshore currents to form a seaward flow similar to a very strong rip current. The heavy-mineral concentrates on the Oregon coast achieve their maximum developments to the south of headlands, but those beaches form isolated pockets with headlands at each end, within which seasonal reversals in the directions of longshore sand movement occur but with a long-term net zero transport. Peterson et al. (1986) formulated a model to explain this mineral concentration south of headlands, suggesting that strong winter storms from the southwest cause the northward transport of all minerals and grain sizes, whereas the weaker summer waves from the northwest preferentially return the light minerals to the south, leaving behind the heavies concentrated at the north ends of the beaches, that is to the south of the headlands. Furthermore, the northward movement of the sand during the winter occurs when the beach face is cut back exposing the concentrated heavy minerals, while the southward movement of the summer occurs when the black-sand concentrates are covered by quartz-rich sand.

Numerous exploration studies have been undertaken in the search for placer deposits offshore in continental shelf sands, but only limited research has been devoted to analyzing the processes of waves and currents at those depths that potentially could concentrate the heavy minerals. The long glacial period of lowered sea levels permitted the transport of river sands and their reworking as beach deposits in areas that are now covered by the sea. Following the depletion of high-grade mineral reserves on beaches, attention shifted to the adjacent offshore with the expectation that there would be a continuation of the placer deposits in sands of the continental shelf. However, in most cases this search has been disappointing. For example, the beaches of southeast Australia have been a rich source of rutile, zircon, monazite and ilmenite, but are now largely exhausted with mining activities continuing only in the low-grade accumulations of coastal dunes (Komar, 1989). This induced explorations of the adjacent continental shelf (Jones et al., 1982; Riech et al., 1982; Kudrass, 1987), but comparable offshore placers have not been found. The modern beaches contain some 10 times more heavy minerals than the offshore sands, and as shown in Fig. 19, there is a trend of decreasing percentages of heavy minerals with depth across the continental shelf.

This trend of decreasing concentrations offshore continues that found on beaches, as seen in Fig. 13 from the Oregon beach studied by Komar and Wang (1984). This suggests that the shelf trends are an extension of the sorting processes and patterns found in the nearshore. High-density minerals such as ilmenite and magnetite are concentrated within placers of the swash zone, whereas less-dense minerals such as augite are not as efficiently concentrated and tend to follow the quartz offshore during beach-erosion events. This makes the less-dense heavy minerals better

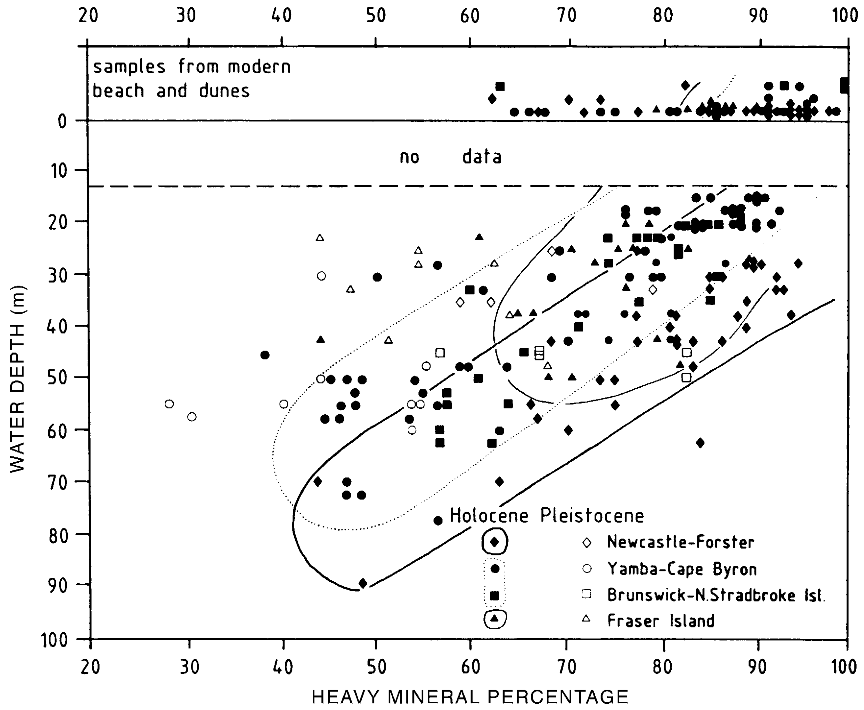

Fig. 19. The offshore decrease in the denser heavy minerals (rutile, ilmenite, zircon, magnetite and tourmaline) in the total heavy-mineral fractions found in various areas of the Australian continental shelf. Open symbols are for Holocene surface sediments, closed symbols for Pleistocene deposits in cores. [After Kudrass (1987).]

represented in the shelf sands. Jones and Davies (1979) and Jones et al. (1982) have invoked such sorting processes, together with considerations of sea-level transgressions, to explain the enrichment of heavy minerals in Australian beaches and their depletion in the adjacent shelf sands. Kudrass (1987) used this explanation as the basis of his "Australian model" for the search of shelf placers. Accordingly, with a rise in sea level the valuable minerals (ilmenite, magnetite, etc.) were progressively carried landward, remaining within the nearshore to accumulate in the modern beaches, whereas the low-density minerals were predominantly deposited in the trailing sand sheet left behind on the shelf.

Kudrass (1987) indicated that his "Australian model" applies mainly to high wave-energy coasts with narrow shelves and a low to moderate supply of terrigenous material. He also proposed a "Zambezi model" for coasts having a broad shelf and moderate to high terrigenous supply, based on the Mozambique shelf off the Zambezi Delta studied by Beiersdorf et al. (1980). In the Zambezi model the placers are envisioned to form along the delta during lowered sea levels, but the large quantities of sediment prevented complete reworking during the subsequent transgression. The result is a disseminated placer deposit like that found on the middle Zambezi shelf, rather than the depletion of the shelf sand of heavy minerals as off the coast of Australia.

The models proposed by Kudrass (1987) invoke something of a "sweeping" action of the waves, selectively pushing the heavy-minerals landward to concentrate them in the beach sands, depleting their concentrations in the offshore shelf sands. Part of this sweeping action may result from the orbital motions of the waves acting on the seafloor sand in the offshore. At intermediate to shallow water depths, ocean waves are characterized by crests that are narrow compared with the broad intervening troughs as depicted in Fig. 20. This asymmetry in the surface form of the waves is reflected in the orbital water motions at the bottom, also shown in the diagram. The water movement under a wave crest is directed shoreward and achieves a high velocity but with a short duration, whereas the offshore return flow under a trough is slower and of longer duration. This asymmetry can result in sediment sorting in the cross-shore direction, with the heavier grains being entrained during the higher velocities under the wave crests and thus moved onshore, but not by the lower velocities under the troughs that would return them to the offshore. At the same time, low-weight grains would readily move under both the landward and seaward orbital velocities, and so would not experience a net displacement unless simultaneously acted upon by a superimposed unidirectional current. The waves themselves can induce a net shoreward current, the Stokes Drift, but in general other ocean currents will be stronger so the low-weight grains would generally follow different transport paths than the heavier grains which tend to move onshore.

There are dramatic examples of the onshore transport of coarse debris that can be attributed to asymmetries in the wave-orbital velocities. Ballast dropped offshore by ships has washed up on beaches, and there is even a case where pig iron from a wrecked ship migrated 2 km to a beach. A number of field studies have established that offshore sources can contribute sediments to beaches, but few controlled experiments have been performed to test this mechanism of onshore sediment transport and sorting by wave orbit asymmetries. Of most direct interest, May (1973) performed a series of wave-tank tests on the relative shoreward movements of heavy versus light minerals, finding that under certain wave conditions the heavy minerals moved shoreward at faster rates than the light minerals, which he attributed to the asymmetries in the wave-orbital motions as depicted in Fig. 20.

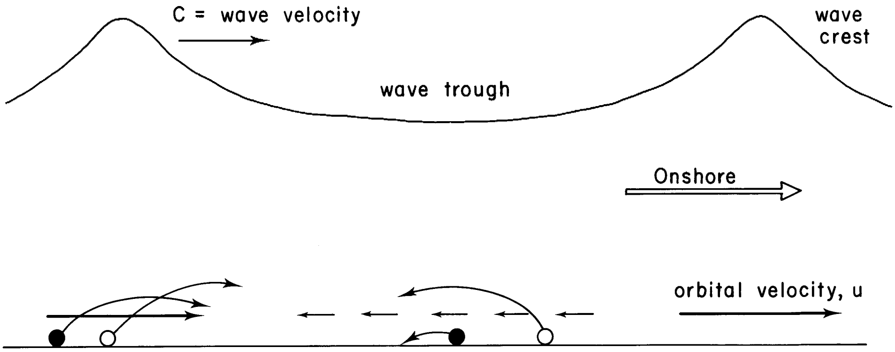

Fig. 20. The selective grain transport under the asymmetrical orbital motions of waves, the heavier grains (dark) moving shoreward a greater distance under the wave crests than seaward under the troughs, while the low-weight grains (light) move equal distances.

5. SUMMARY AND DISCUSSION

The flow of water in a river or the oscillatory motions of waves can bring about a sorting of sediment grains due to their contrasting densities, grain sizes and shapes. This hydrodynamic sorting visibly separates the heavy minerals from the light, producing heavy-mineral black-sand concentrates and in some cases valuable placers. Sorting can also occur within the suite of heavy minerals due to their differences in hydrodynamic properties. This chapter has reviewed the various processes or mechanisms through which this sorting can occur: this included differences in flow velocities and stresses required to entrain grains from a deposit of mixed sizes and densities; their further separation when transported as a bedload with the grain-dispersive pressure (shear sorting) forming laminations or with local sorting occurring in bedforms such as ripples and dunes; and the potential for large-scale sorting in the suspended load due to differences in grain setting velocities.

When one turns to an examination of the roles of these mechanisms in the sorting of mineral grains in rivers, beaches and in continental shelf sands, it is found in general that more than one mechanism is involved so it is difficult to establish any hydraulic equivalence of the deposited grains based on a single process such as an equality of their settling velocities. However, in more general terms an understanding of the grain-sorting processes provides explanations for the observed sorting patterns of minerals in natural environments. In the case of rivers researchers have investigated the occurrence of heavy-mineral concentrates in migrating bars, at points of flow convergence in channel junctions, and at locations where the channel abruptly widens. Particular attention has been given to the entrapment of transported heavy-mineral grains in the matrix of gravel-bed material, this being important to the formation of fluvial gold placers. Significant advances have been made in understanding the formation of black-sand mineral concentrates on beaches, demonstrating that occurrences in the swash zone are due primarily to selective entrainment and bedload transport, while grain suspension by the surf and breaking waves can have a counter effect of acting to homogenize the different minerals. The processes of waves and currents in these marine environments can also account for large-scale sorting patterns, as where the longshore transport of the sand leads to a concentration of heavy minerals adjacent to a river-mouth source or next to a headland, or the tendency for the waves to "sweep" the heavy minerals from continental shelf sands and concentrate them in landward beaches.

A practical product of this research into the processes of mineral sorting has been an improved understanding of the origin of placers, a scientific understanding that aids in the search for those valuable deposits, complementing the guidance previously based on the cumulative experience of prospectors and mining engineers. For example, we now know that the existence of valuable heavy-mineral sands found on a modern beach may not represent evidence that similar deposits exist on the adjacent shelf—to the contrary, the abundance of minerals in the beach may indicate that the shelf sands have been depleted. The improved understanding of mineral sorting may also assist in the analysis and interpretation of ancient sedimentary deposits based on their contents of heavy minerals. The dependence of the sorting patterns on processes of waves and currents can support an interpretation of the paleoenvironment of deposition, and provide an explanation for the patterns of large-scale sediment movements where there are areas of erosion versus accretion. This is illustrated in modern environments, for example along the shores of river deltas. Deltas are conducive to the formation of heavy-mineral concentrates because they provide a major source of terrigenous sand and may undergo episodes of shore retreat and mineral concentration when attacked by storms or when the river mouth shifts position. In contrast, the stretches of shore experiencing accretion tend to be enriched in the light minerals. Such patterns related to shoreline erosion versus accretion are well-illustrated by the Nile Delta, reviewed in the following chapter.

A better understanding of the mineral-sorting processes can also assist in interpretations of analyses of the heavy-mineral contents of sediments, modern or ancient, to determine their sources. As an example, Clemens and Komar (1988) applied factor analysis to the heavy-mineral contents of beach sands collected along the Oregon coast, yielding three factors which established that the beach sands are mixtures of metamorphic minerals derived from the Klamath Mountains in southern Oregon and northern California, a limited suite of minerals from volcanic rocks in the Coast Range mountains, and from the Columbia River to the north. The proportions of minerals in the beach sand derived from these three sources depended on the relative proximity of the beach to those three sources. The Oregon beach containing the black-sand deposit whose origin was investigated by Komar and Wang (1984) consists mainly of Coast Range derived sand, but with a significant contribution from the Klamath Mountains. The multiple sand samples collected by that study from a single beach were subjected to a factor analysis which yielded two dominant factors (Komar et al., 1989), one containing the densest heavy minerals (mainly garnet and zircon), while the second included the lower density minerals (hornblende, augite and epidote). These two factors obviously reflected the cross-shore mineral sorting patterns found by Komar and Wang (1984), providing direct evidence that grain sorting can affect factor analyses and interpretations of sediment sources from their heavy-mineral contents.

In spite of the sorting of sediment grains during transport being of common occurrence and important to applications such as those noted above, relatively little research has focused on the details of the physical processes that actually bring about the sorting. It is important that this science be further improved in order to support the many applications of heavy-mineral analyses discussed in the other chapters of this volume.

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