3. BED CONFIGURATIONS

3.1 Introduction

3.1.1 A striking characteristic of the transport of granular sediment over a bed of the same material by a turbulent flow of fluid is that *in a wide range of conditions the bed is molded into topographic features, called bed forms, on a scale orders of magnitude larger than the grains*. Little ripples at one's feet at the seashore, or on a dry river bed, or in the desert; gigantic dunes in the desert and (even more common, but not apparent to the casual observer) in large rivers and the shallow ocean—all of these are examples of bed forms. Generations of scientists and engineers have marveled at the rich and confusing variety of these features.

3.1.2 First we'll introduce some terminology. The *overall bed geometry that exists at a given time in response to the flow* (the ***bed configuration***) is composed of *individual topographic elements* (***bed forms***). The *aggregate or ensemble of like bed configurations that can be produced by a given mean flow over a given sediment bed* is the ***bed state***: the bed configuration differs in detail from time to time, and the bed state is a kind of average over the infinity of configurations possible under those conditions. The term ***bed phase*** can be used for *recognizably or qualitatively different kinds of bed configurations that are produced over some range of flow and sediment conditions* and are closely related in geometry and dynamics. Finally, the term ***bedform*** (one word) is widely used, indiscriminately, for *all four aspects of the bed geometry*.

3.1.3 The flows that make bed configurations can be quite complex. Think in terms of two kinds of flow components, unidirectional and oscillatory (Figure 2-40). The simplest cases are *steady unidirectional flow*, with constant flow speed in one direction, and *symmetrical oscillatory flow*, with a regular back-and forth oscillation. But the unidirectional flow can be *unsteady*, and the oscillatory flow can be *asymmetrical* (with the oscillation in one direction slower but of longer duration than the oscillation in the other direction).

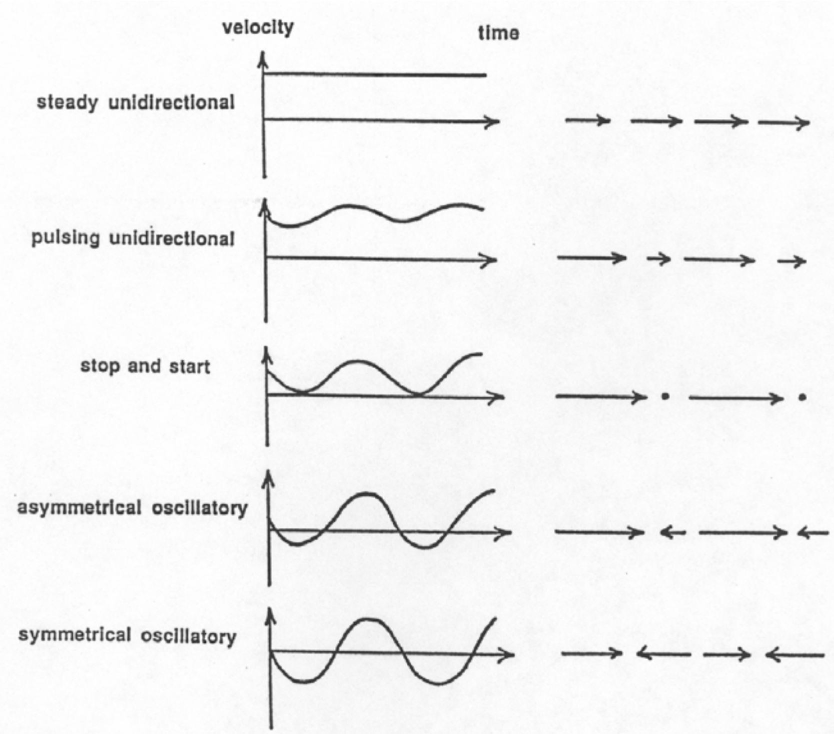


Figure 2-40 Spectrum of kinds of combinations of unidirectional and oscillatory flow components in combined flow

3.1.4 Also, *the unidirectional and oscillatory components can be superimposed* or added together, resulting in what's called ***combined flow***. For an example, think about the shallow sea floor during a storm, with wave-induced oscillatory flow superimposed on a storm-induced unidirectional flow. Also, there can be more than one oscillatory component—in fact, there can be a continuous spectrum of oscillatory components, each with its own period and amplitude. This enormous range of generating flows, together with the complex dynamics of the response of the bed, makes for infinitely varied geometry of the resulting bed forms.

3.1.5 Both engineers and geologists have been making laboratory experiments on bed forms for well over a hundred years, as well as watching their movement in natural flow environments. Our understanding of *unidirectional-flow bed configurations* is pretty good by now, although by no means perfect. Work on *oscillatory-flow bed configurations* is less well advanced: some important ranges of flow and sediment size have been little studied. Finally, *combined-flow bed configurations* are still very poorly known.

3.1.6 *If the flow changes with time, the bed configuration adjusts in response.* In natural flows, equilibrium between the bed and the flow is the exception rather than the rule; usually the bed configuration lags behind the change in the flow. Such disequilibrium is a major element of complexity that makes relationships among bed phases much more difficult to decipher, but its effects are of great importance in natural flow environments.

3.1.7 *Most bed forms are in sands*, but they're produced in silts and gravels as well. Of greatest interest to geologists, oceanographers, and hydraulic engineers are bed forms produced by flows of air or water over mineral sediments, but a far wider range, important in many engineering applications, can be produced by flows of Newtonian fluids with other densities and viscosities over sediments less dense or more dense than the common mineral sediments.

3.1.8 Apart from their intrinsic scientific interest, *bed forms are important in both geology and engineering*. Large subaqueous bed forms many meters high can be obstacles to navigation, and their movement can be a threat to submarine structures. The rugged topography of bed forms in rivers and tidal channels causes flow separation at the crests and therefore large values of form drag; bed forms are thus the most important determinant of resistance to channel flow. The bed state is also closely bound up with the sediment transport rate in unidirectional flows, in that the downcurrent movement of the bed forms largely involves recycling of bed load within bed forms. Sedimentologists have given attention to bed forms mostly because of their role in the development of stratification in sedimentary deposits; bed forms are one of the most useful tools available for interpreting ancient sedimentary environments.

3.1.9 The status of observations on bed configurations leaves much to be desired. It's easy to observe bed configurations in steady unidirectional and bidirectional flows in laboratory channels and tanks, and the major outlines are by now fairly well known, at least for unidirectional flows. But there's a lot of room for further laboratory work, both because the usually small width-to-depth ratios of tanks and flumes tend to inhibit full development of the three-dimensional aspects of the bed geometry, and also because virtually no work has been done with multidirectional oscillatory flows, with or without a unidirectional component. And even the largest of laboratory experiments are restricted to flow depths at the lower end of the range of natural flow depths. In nature, on the other hand, observations on bed configurations are limited by practical and technical difficulties, and the flows that produce them are usually more complicated.

3.2 Unidirectional-Flow Bed Configurations

3.2.1 Introduction

3.2.1.1 Bed configurations made by unidirectional flows have been studied more than those made by oscillatory flows and combined flows. They're what you find in rivers, large and small, and in engineering flows like outdoor canals and channels of various kinds, as well as in pipes and conduits carrying granular materials, whether by design or incidentally.

3.2.1.2 But they're also important in shallow marine environments, especially in areas with strong tidal currents. Even symmetrically reversing tidal currents produce bed forms that look much like those in truly unidirectional flows, presumably because the current in each direction lasts long enough for the bed to respond to what it feels as a unidirectional flow (although there's some debate about this among the experts). In asymmetrical tidal currents, the bed forms show net movement and asymmetry in the direction of the stronger flow, but they suffer interesting modifications by the weaker flow in the other direction.

3.2.1.3 We'll first describe a home experiment to give you *an overall picture of the kinds of bed configurations* made by currents, and then present *a dimensional analysis to organize in more detail what's known about the hydraulic conditions* for the various kinds of configurations. Then we'll tell you some of the most important things about *flow and sediment movement over bed forms*.

3.2.2 A Flume Experiment on Unidirectional-Flow Bed Configurations

3.2.2.1 To get an idea of the bed configurations produced by a steady uniform flow of water over a sand bed, and the succession of different kinds of bed configurations that appear as the flow strength is increased, make a series of exploratory flume experiments on sand with some mean size between about 0.2 mm and 0.5 mm.

3.2.2.2 First of all, you need a flume (Figure 2-41). You could wangle your way into a hydraulics lab, or you could build your own in your backyard (or even, we suppose, in your room.) Mainly you need a long channel that holds water and empties into a tank at the downstream end. Install a pump and some piping to take the water from the downstream tank and recirculate it back up to the head of the channel. You might also mount the whole channel on a set of screw jacks near the upstream end, so that you can change the slope of the channel easily. It would also be nice to make at least one sidewall of the channel out of transparent acrylic plastic, for good viewing.

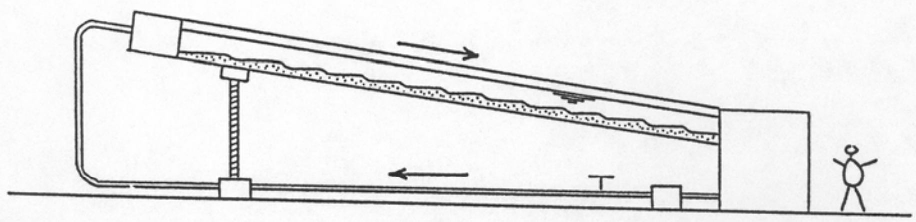


Figure 2-41 A backyard flume

3.2.2.3 Place a thick layer of sand on the bottom of the channel, and then pass a series of steady uniform flows over it. Arrange each run to have the same mean flow depth (as great as the flume will allow, a large fraction of a meter if you're lucky) and increase the mean flow velocity slightly from run to run.

3.2.2.4 In each run, let the flow interact with the bed long enough for the state of the bed to be statistically steady; after that the details of the bed configuration are in constant change but the average state of the bed remains the same. The time required for the flow and the bed to come into a new state of equilibrium might take from as little as a few minutes to as long as several days, depending on the sediment transport rate, the size of the bed forms being developed, and the extent of modification of bed forms left over from the preceding run.

3.2.2.5 You could speed the attainment of equilibrium a little by continually adjusting the slope of the whole channel to maintain uniform flow as the bed roughness changes, but these adjustments are not necessary, because *the flow itself adjusts the bed for uniform flow by erosion at one end and deposition at the other*. For example, if the flume slope is too gentle, you'll end up with the sand bed thinner at the downstream end than at the upstream end, and the slope of the bed and the flow will be greater than the slope of the channel. On the other hand, if the flume slope is too steep, the sand bed will be thicker at the downstream end than at the upstream end. This kind of thing is OK so long as the layer of sand in the channel doesn't taper so sharply that the channel bottom is bare in the upper or lower reaches.

3.2.2.6 If you're impatient for results, the way to make bed forms develop fastest is to start with an irregular sediment bed. But it's more enlightening to start with a planar bed. (You can arrange one fairly easily by passing a straight horizontal scraper blade along the bed. If the blade is mounted on something that slides on the straight upper edges of the flume walls, you get a nice planar result.) Now turn on the pump and gradually increase the flow velocity. The beginning of sediment movement would be in accordance with the threshold curve discussed earlier (Figure 2-42A). Wait a while, and the flow will build very small irregularities at random points on the bed, not more than several grain diameters high, from which small ripples develop spontaneously.

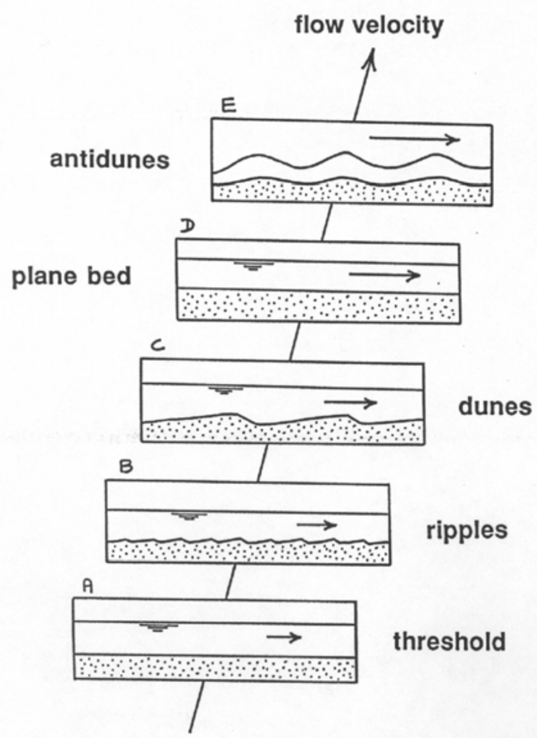


Figure 2-42
Sequence of bed configurations with increasing flow strength

3.2.2.7 You can help things along by poking your finger into the planar bed at some point to localize the first appearance of the ripples. The flow soon transforms the little mound you made with your finger into a flow-molded bed form. The flow disturbance caused by this bed form scours the bed just downstream, and piles up enough sediment for another bed form to be produced, and so on until a beautiful widening train of downstream-growing bed forms is formed (Figure 2-43). Little trains of bed forms like this, starting from various points on the bed, soon join together and pass through a complicated stage of development, finally to become a fully developed bed configuration (Figure 2-42B). The stronger the grain transport, the sooner the bed forms appear, and the faster they approach equilibrium. These bed forms, which we'll later classify as ***ripples***, show generally triangular cross sections.

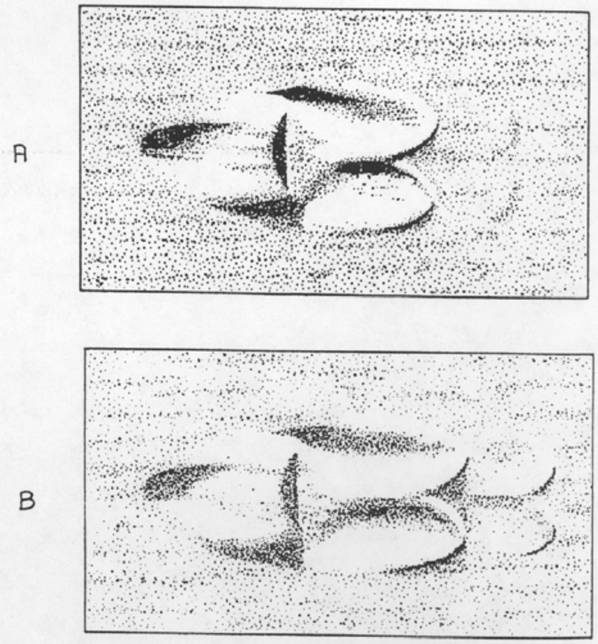


Figure 2-43

A train of ripples developing on an initially planar bed of loose sediment

3.2.2.8 (We'll stop right here and introduce some terms for ripplelike bed forms; see Figure 2-44. *The region around the highest point on the ripple profile* is the ***crest***, and *the region around the lowest point* is the ***trough***. *The upstream-facing surface of the ripple*, extending from a trough to the next crest downstream, is the ***stoss surface***; *the downstream-facing surface*, extending from a crest to the next trough downstream, is the ***lee surface***. A *well defined and nearly planar segment of the lee surface*, called the ***slip face***, is usually a prominent part of the profile. The top of the slip face is marked by *a sharp break in slope* called the ***brink***. There's often but not always a break in slope at the base of the slip face also. The top of the slip face is not always the highest point on the profile, and the base of the slip face is not always the lowest point on the profile.

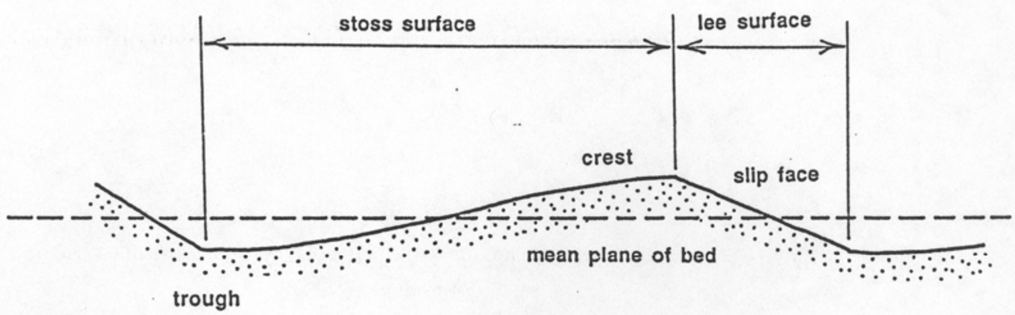


Figure 2-44 Some terminology for ripplelike bed forms

3.2.2.9 The stoss surfaces of ripples are gently sloping, usually less than about 10° relative to the mean plane of the bed, and their lee surfaces are steeper, usually at or close to the angle of repose of the granular material in water. Crests and troughs are oriented dominantly transverse to the mean flow, but are irregular in detail in height and arrangement. The average spacing of ripples is of the order of 10-20 cm, and the average height is a few centimeters. The bed is said to be three-dimensional, rather than two-dimensional as it would be if the ripples were regular and straight-crested. The ripples move downstream (orders of magnitude slower than the flow itself) by erosion of sediment from the stoss surface and deposition of sediment on the lee surface.

3.2.2.10 At a flow velocity that's a middling fraction of a meter per second, ripples are replaced by larger bed forms generally called ***dunes***. Dunes are broadly similar to ripples in geometry and movement, but they are about an order of magnitude larger (Figure 2-42C). The transition from ripples to dunes is complete over a narrow range of only a few centimeters per second in flow velocity. Within this transition the bed geometry is complicated: the ripples become slightly larger, with ill-defined larger forms intermingled, and then abruptly the larger forms become better organized and dominate the smaller forms. With increasing flow velocity, more and more sediment is transported over the dunes as suspended load. If you had a large enough flume at your disposal the dunes would become large enough under some conditions of sand size and current velocity for smaller dunes to be superimposed on larger dunes.

3.2.2.11 With further increase in velocity the dunes become lower and more rounded, over a fairly wide interval of flow velocity, until finally they disappear entirely, giving way to a ***planar bed surface*** over which abundant suspended load as well as bed load is transported (Figure 2-42D). Judging from the appearance of the bed after the flow is abruptly brought to a stop, *the transport surface is strikingly planar: relief is no greater than a few grain diameters*. Since the bed is obscured, it's difficult to observe the mode of grain transport except through the sidewall.

3.2.2.12 As the flow velocity is increased still further, subdued standing waves appear on the water surface, and the resulting pattern of higher and lower near-bed flow velocity causes the bed to be molded correspondingly into a train of waves in phase with the water-surface waves. As the velocity of the mean flow approaches the velocity with which the surface waves can propagate upstream, so that the waves are almost standing still, these coupled bed and surface waves increase in amplitude and become unstable: *they move slowly upstream and at the same time grow in amplitude, until they become so steep that they break abruptly, throwing much sediment into suspension* (Figure 2-42E). The bed and water surface then revert to a planar or nearly planar condition, whereupon the waves build again and the cycle is repeated. Because of their upstream movement these forms are called ***antidunes***.

3.2.2.13 An instructive variant of this experiment would be to increase the flow depth by a factor of two and cover the entire flow with a rigid planar sheet parallel to the mean plane of the bed. The flow structure in the lower half of the closed duct thus formed is not greatly different from that in the original open-channel flow, with some differences caused by the gross difference in roughness of the upper and lower boundaries when bed forms are present on the bed. Make the same sequence of runs with the top cover in place, and you'd find the same succession of bed configurations except for one major difference: *standing waves and antidunes would not appear, and plane-bed transport would be observed up to indefinitely high velocities*. This should tip you off that *the dynamics of antidunes is unrelated to the dynamics of ripples, dunes, and plane bed*. Antidunes are dependent upon the presence of the free surface, whereas ripples and dunes are independent of the presence of the free surface.

3.2.3 Bed-Configuration Regimes

3.2.3.1 *It's extremely useful in physical sedimentology to know something about the conditions of occurrence of the various kinds of bed configurations*, in large part because a lot of the cross-stratification we see in the ancient sedimentary record, probably most, is an outcome of the movement of flow-transverse bed forms like ripples and dunes in flows of water or air in a variety of sedimentary environments.

3.2.3.2 The idea, elaborated in the rest of this section, is that *each bed phase exists or is formed in a certain definite range of the various variables that govern or characterize the development of bed configurations*. The right way to go about doing this is to list all of the variables we think are important and then organize or recast them into a set of dimensionless variables (fewer in number than the original set) that describes the phenomenon in the most useful and the most general way. Doing this would require a considerable detour to lay the background for the technique. But we can take a shortcut at this point, similar to what was done in Section 2 above for describing the threshold of sediment movement, without sacrificing any ultimate usefulness or introducing any serious distortion: eliminate from the list of variables those that don't vary much for quartz-density sand in water-density fluid on planetary surfaces with Earth-like gravity, leaving only a few important variables, and then plot a multidimensional graph (which we hope will be no more than three-dimensional!) in which *the various bed phases occupy contiguous stability fields or existence fields, with boundary curves of surfaces separating the fields*. You could think of these regions as "bed-configuration regimes" of the kind you observed in the backyard experiment. This is a way of systematizing and unifying disparate data on bed states in a wide variety of flows and sediments. Such graphs are closely analogous to the phase diagrams thermodynamicists and petrologists work with.

3.2.3.3 The variables that characterize the development of bed configurations fall naturally into those that characterize *the fluid, the flow, and the sediment*. The sediment might best be described by its mean size, sorting, particle shape, and density. In the interest of a manageable exercise here, let's assume that the most important of these are *mean size* and *density*. The flow can be described by its *mean flow depth* and *mean flow velocity*. (If you find yourself wondering what happened to the bed shear stress, which is what moves the sediment, see below.) The fluid is described by its *density* and *viscosity*. Finally, the *acceleration of gravity* must be included, for two reasons: it helps determine particle weight, and it figures in the behavior of surface gravity waves. That makes for seven variables altogether.

3.2.3.4 Which of the seven variables vary substantially in sediment-moving flows of water on the Earth's surface? Only *four* of them: **flow depth, flow velocity, mean sediment size, and fluid viscosity**. The viscosity of water varies substantially over the natural range of wager temperatures from 0°C to about 30°C, but the effect isn't overwhelming, so you can get most of the picture just by thinking about plotting data on bed configurations in a three-axis graph (which we'll call the ***depth-velocity-size diagram***) with flow depth, flow velocity, and sediment size along the axes. Such a graph shows the bed-configuration regimes in concrete and only slightly fuzzy form.

3.2.3.6 You might be wondering why the bed shear stress τ_o doesn't appear in the foregoing analysis, when after all it's the force of the flow on the bed that moves sediment to mold bed configurations in the first place, right? We can make two comments about that:

θ When ripples or dunes are on the bed, most of τ_o is *form drag* resulting from pressure differences between upstream and downstream faces of the bed forms, and the local bed shear stress (what's usually called *skin friction*)—which is what actually moves the sediment—is only a minor part of τ_o!

θ Using τ_o introduces a kind of double-valuedness that messes up the bed-phase diagrams by making adjacent existence field overlap. Here's why. Keeping in mind the series of runs in your backyard channel, think about what happens to τ_o as U increases over the bed (Figure 2-45). At first τ_o increases with U, as ripples and then dunes develop. But then when the dunes are washed out to plane bed, τ_o decreases, because the form drag disappears. Then with increasing velocity over a plane bed, τ_o increases again. So *there's a range of U for which three different values of τ_o are possible*. If you use τ_o as the flow-strength variable, the bed-phase graph is going to have a serious ambiguity whereby certain fields overlap one another. *This isn't a problem if you use U: there's a nice one-to-one correspondence between bed states and points on the graph.*

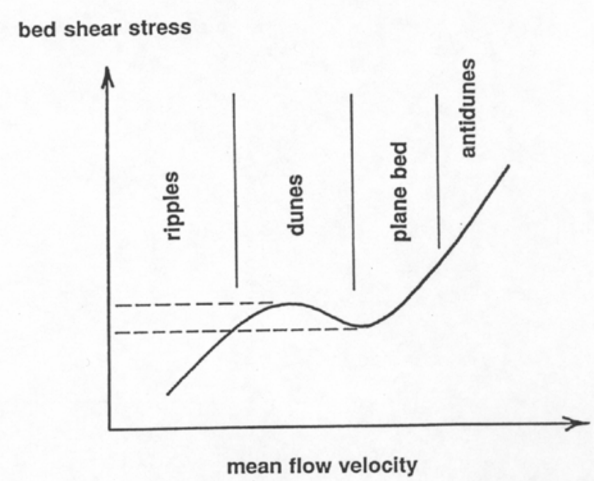


Figure 2-45 Cartoon graph of bed shear stress against mean flow velocity, showing the dip in the curve caused by the decrease in flow resistance in the transition from dunes to plane bed

3.2.3.7 The best way to visualize the depth-velocity-size diagram is to draw two kinds of planar sections through it, in the *depth-velocity plane* and in the *velocity-size* plane (Figure 2-46). Figure 2-47 shows depth-velocity sections for three different sediment sizes, together with cartoon versions, and Figure 2-48 shows a velocity-size section together with a cartoon version. These graphs are based on laboratory experiments mainly at flow depths less than a meter. (It's a lot harder to get data points from deeper natural flows.) These graphs are actually dimensionless graphs, but they've been normalized or standardized to a water temperature of 10°C for comparability and concreteness. If you don't want to worry about dimensionless variables, just think of the axes as real depth, velocity, and size.

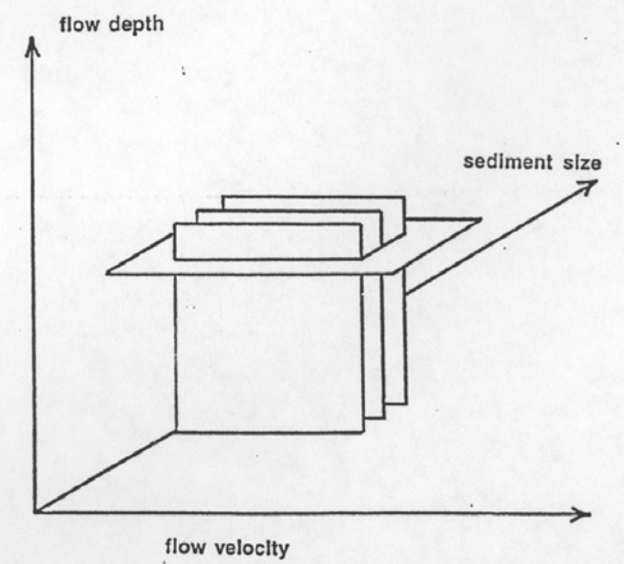


Figure 2-46 Visualizing the depth-velocity-size diagram by means of depth-velocity sections and velocity-size sections

3.2.3.8 The depth-velocity graph for 0.10-0.14 mm sand (Figure 2-47A) shows fields only for ripples, upper-regime plane bed, and antidunes. All the boundaries here and in the other two depth-velocity sections in Figure 2-47 slope upward to the right. The ripple-plane boundary does so because the deeper the flow the greater the velocity needed for a given bed shear stress; the plane-antidune boundary does so because it's closely associated with the condition for which surface waves can propagate upstream about as fast as the flow itself flows downstream, so that the surface waves can interact unstably with the bed to produce antidunes. The latter boundary is shown to truncate the former, because as the condition just mentioned is approached, antidunes develop whatever the preexisting configuration. This relation holds true also, and more clearly, for coarser sediments (Figures 2-47B, 2-47C).

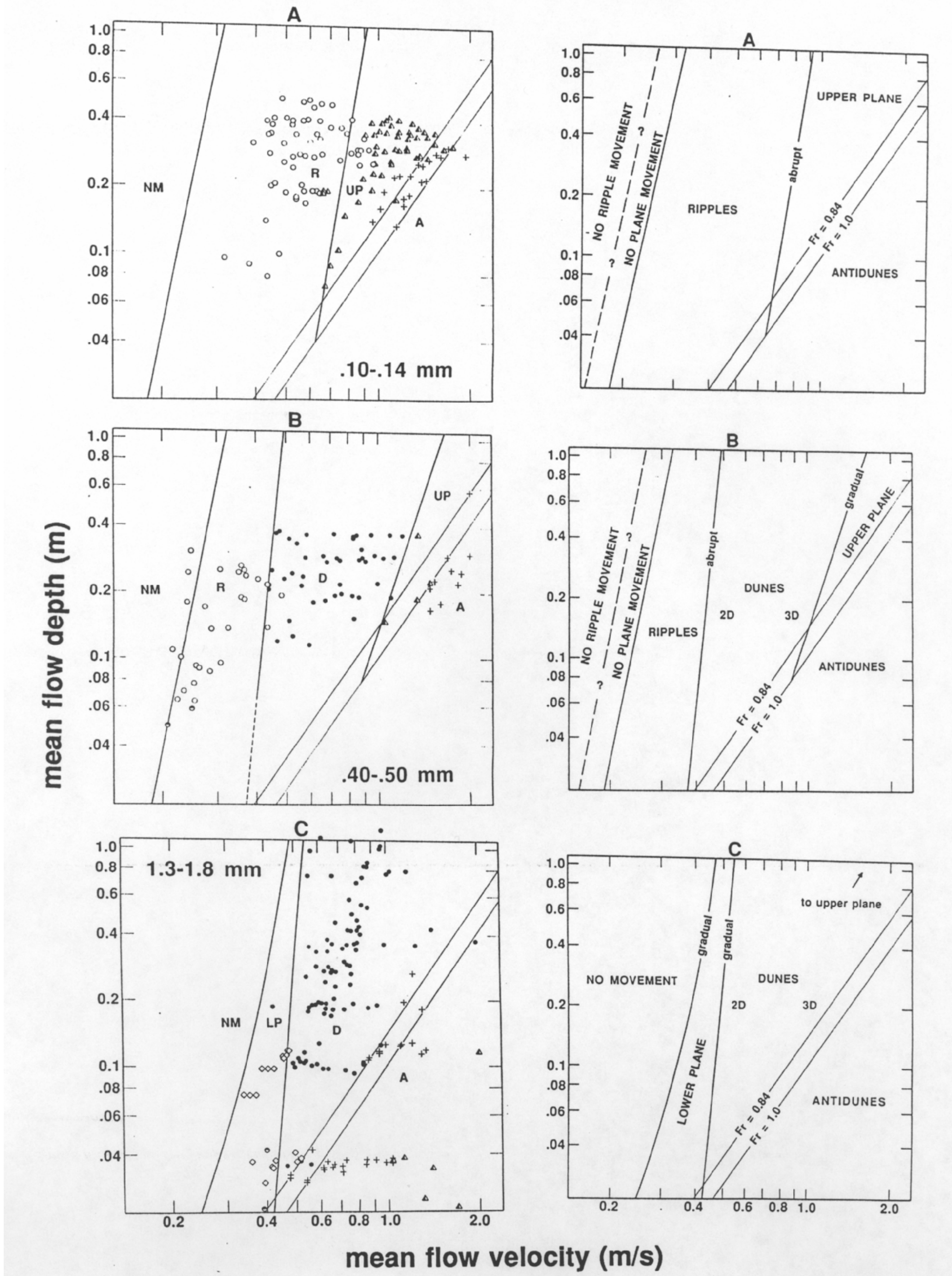


Figure 2-47

Three depth-velocity sections through the depth-velocity-size diagram for bed phases in unidirectional flow, for three different sand sizes, along with cartoon versions. NM, no movement; R, ripples; D, dunes; LP, lower plane bed; UP, upper plane bed; A, antidunes. Open circles, ripples; solid circles, dunes; open diamonds, lower plane bed; half-open triangles, upper plane bed; plus signs, antidunes.

3.2.3.9 In Figure 2-47A (and in Figure 2-47B, for medium sands, as well) there are two kinds of boundary between movement and no movement. To the right is a modification of the threshold curve for incipient movement on a plane bed, appropriately transformed into this depth-velocity graph. To the left is the ripple-maintenance boundary, which defines the minimum velocity needed to maintain preexisting ripples at equilibrium. The ripple-maintenance boundary is not well constrained by data, so it's shown only in the cartoon, but it clearly lies at lower flow velocities than the plane-bed threshold curve.

3.2.3.10 The depth-velocity graph for 0.40-0.50 mm sand (Figure 2-47B) shows an additional field for dunes between those for ripples and plane bed, with its high-velocity boundary clearly sloping less steeply than the low-velocity boundary. For depths less than about 0.05 m it's difficult to differentiate between ripples and dunes, because dunes become severely limited in size by the shallow flow depth. The appearance and expansion of the dune field with increasing sediment size pushes the lower termination of the plane-bed field to greater depths and velocities, nearly out of the range of most flume work (but not of natural flows!). The antidune field truncates not only the ripple field, as with finer sands, but the dune field as well.

3.2.3.11 In the depth-velocity graph for 1.30-1.80 mm sand (Figure 2-47C), a lower-regime plane bed replaces ripples at low flow velocities. Upper-regime plane bed is still present in the upper right but few flume data are available. Upper-regime plane beds succeed antidunes with increasing flow velocity and decreasing flow depth in the lower right. (This passage from plane bed to antidunes and back into plane bed is sort of analogous to breaking the sound barrier: once you get past the condition wherein surface waves have the same speed as the flow, the coupling that leads to antidunes disappears again.) The boundary between no movement and lower plane bed is shown as the threshold curve for incipient movement on a plane bed. Sections for even greater sediment sizes are qualitatively similar to that in Figure 2-47C.

3.2.3.12 In the velocity-size graph for flow depths of 0.25-0.40 m (Figure 2-48), ripples are stable for sediments finer than about 0.8 mm. The range of velocities for ripples narrows with increasing sediment size to terminate against the fields for plane beds with or without movement. Relationships in this region are difficult to study because in these sand sizes and flow speeds it takes a long time for the bed to attain equilibrium. In medium sands ripples give way abruptly to dunes with increasing flow velocity, but in finer sediment, ripples give way (also abruptly) to plane bed. Although not well constrained, the ripple-plane boundary rises to higher velocities with decreasing sediment size.

3.2.3.13 Dunes are stable over a wide range of flow velocities in sediments from medium sand to indefinitely coarse gravel. Both the lower and upper boundaries of the dune field rise with increasing velocity, and both are gradual transitions rather than sharp breaks. For sediments coarser than about 0.8 mm there's a narrow field below the dune field for lower-regime plane bed; the lower boundary of this field is represented by the curve for threshold of sediment movement on a plane bed.

3.2.3.14 There's one triple point among ripples, dunes, and upper plane bed at a sediment size of about 0.2 mm, and another among ripples, dunes and lower plane bed at a sediment size of about 0.8 mm. The coverage of data around these two triple points constrains the bed-phase relationships fairly closely. Between these two triple points the dune field forms a kind of indented salient pointing toward finer sediment sizes. The boundary between ripples and upper plane bed seems to pass beneath the dune field at the upper left triple point to emerge again at coarser sizes and lower velocities as the boundary between ripples and lower plane bed at the lower right triple point. We might speculate that the ripple-plane boundary is eclipsed by development of dunes on the bed over a certain range of flow velocities and sediment sizes. This interpretation has some experimental support: when the development of dunes is suppressed in very short channels, ripples persist to higher velocities. The stability fields for ripples and dunes thus seem to be controlled by dynamically separate effects, and the position of the boundary is mediated by the interaction between the two competing effects.

3.2.3.15 The depth-velocity-size diagram shown in Figures 2-47 and 2-48 spans a depth range of more than an order of magnitude, from less than a tenth of a meter to almost a meter, with good coverage of data. Figure 2-49 shows schematic velocity-size sections, superimposed on the same plot, for flow depths of 0.3 m, 1 m, and 3 m. The 0.3 m and 1 m boundaries are well tied down by flume data, but the 3 m boundary is just an extrapolation from shallower depths. But the field boundaries are constrained well enough in the 0.1-1.0 m depth range that extrapolation by even another order of magnitude to about ten meters, to cover much of the range of natural flow depths in rivers and tidal currents, shouldn't introduce any gross distortions in velocity estimates for the various fields and their boundaries. You can see from Figure 2-49 that with increasing flow depth, all phase boundaries shift upward, the antidune boundary the most rapidly, and the dune field spans a greater range of velocities. The sediment sizes associated with the two triple points seem to change little with flow depth. You can compare this extrapolation with the "Rubin diagram" (Figure 2-50), assembled by Rubin and McCulloch (1980), which shows the depth-velocity-size diagram for deeper natural flows.

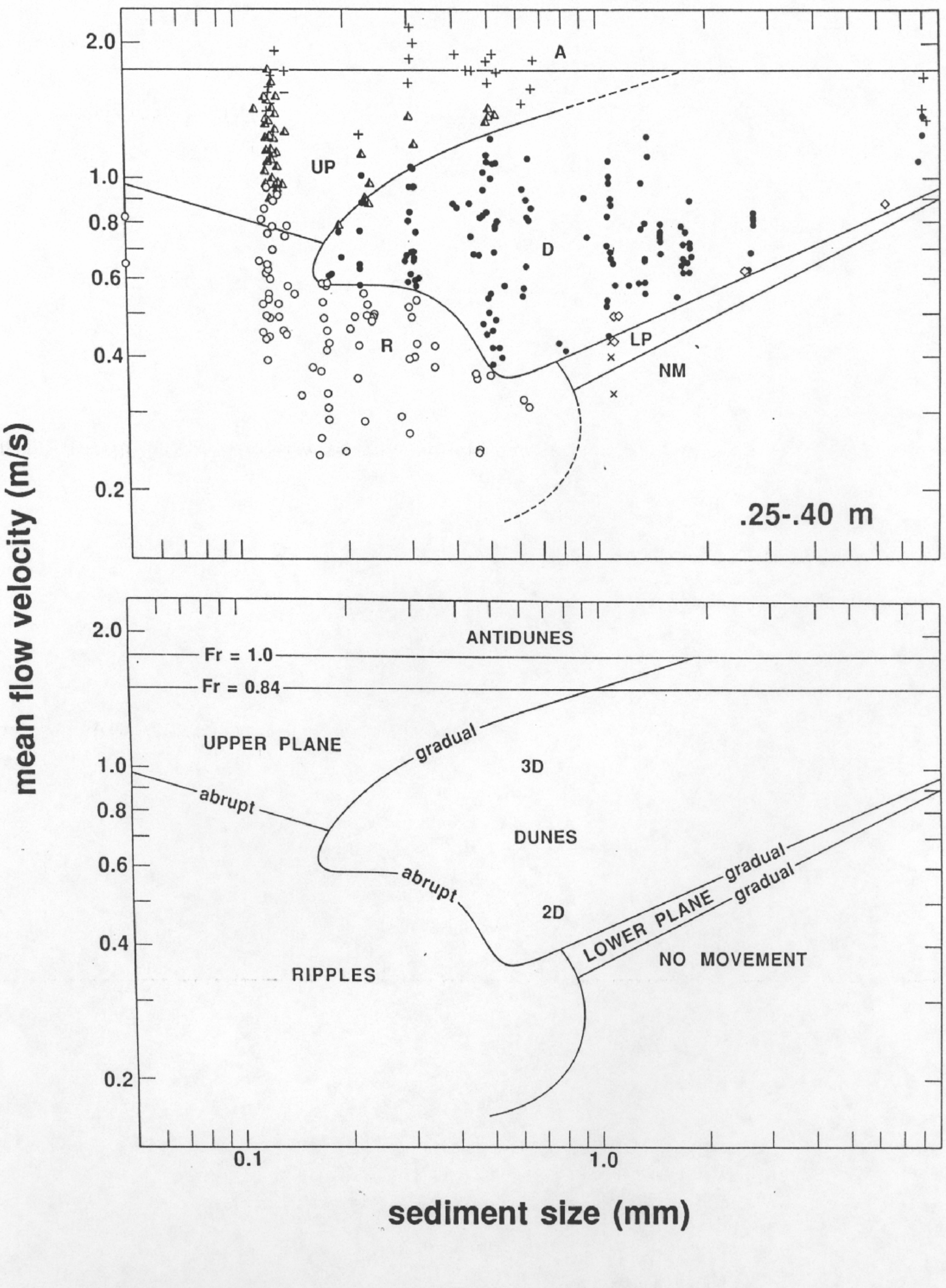


Figure 2-48 Velocity-size section for a flow depth of 0.25-0.40 m through the depth-velocity-size diagram for bed phases in unidirectional flow. Symbols are the same as in Figure 2-47.

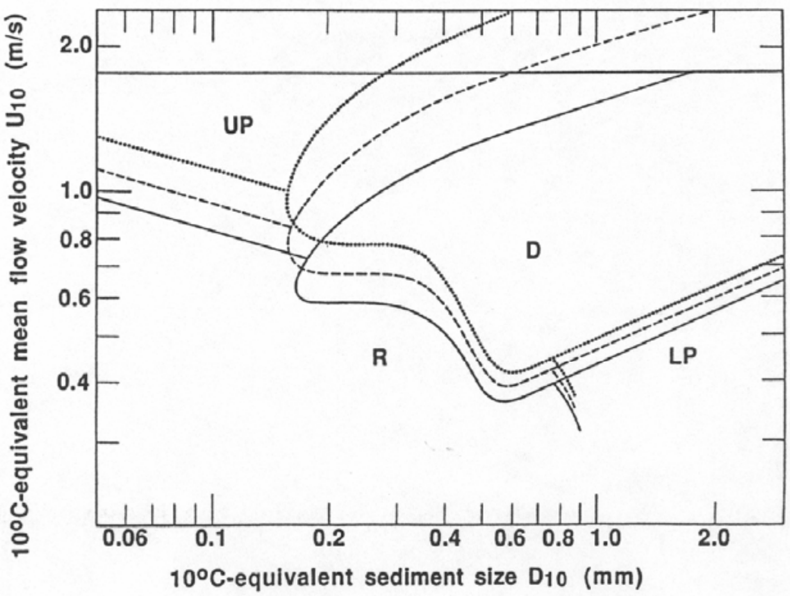


Figure 2-49 Schematic velocity-size sections, superimposed on the same plot, for flow depths of 0.3 m, 1 m, and 3 m

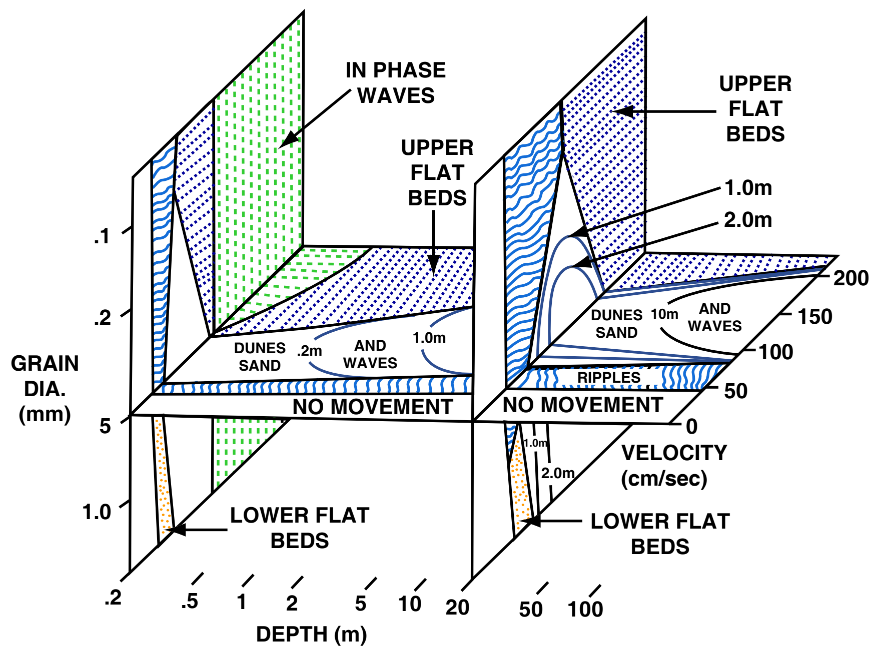


Figure by MIT OCW.

Figure 2-50: The Rubin diagram: the depth-velocity-size diagram for a wide range of flow depths in flumes and natural flow environments

3.2.3.16 It's important to know not just the conditions for existence of the various bed phases, but also something about *how their size and shape varies within those fields*. This is a more demanding task, because you have to measure the bed forms rather than just discover their existence. Even in flumes that's difficult, to say nothing about natural flow environments. This boils down to knowing *how the height and spacing of dunes varies with flow depth, flow velocity, and sand size*, because *ripples don't vary much in size or shape over most of their range of existence*. Figure 2-51 shows crude contours of dune spacing (Figure 2-51A) and dune height (Figure 2-51B) in a depth-velocity graph, and Figure 2-52 shows crude contours of dune spacing (Figure 2-52A) and dune height (Figure 2-52B) in a velocity-size graph. Data are from the USGS flume program in the 1950s and 1960s (Guy et al., 1966).

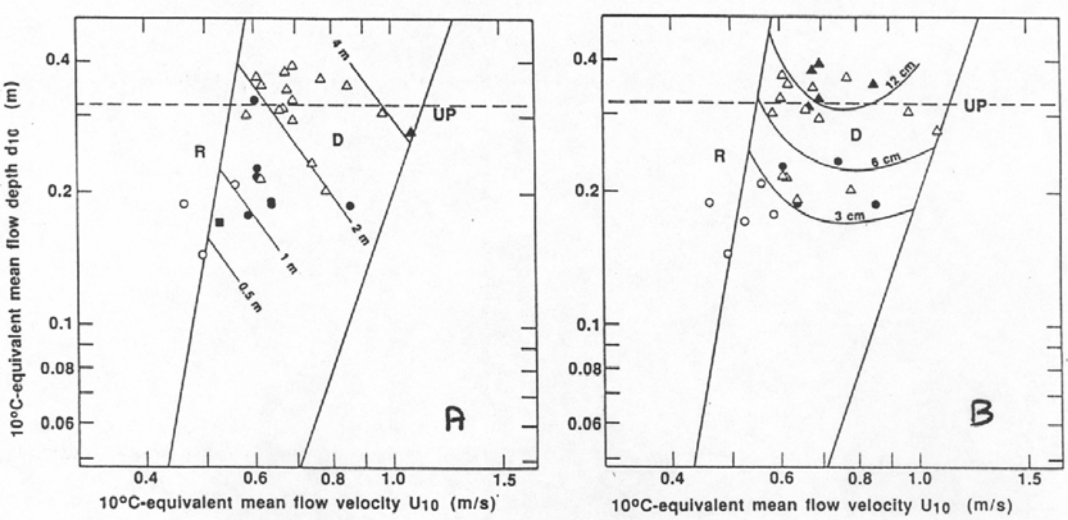


Figure 2-51 Crude contours of dune spacing (A) and dune height (B) in a depth-velocity section. Symbols for dune spacing: solid squares, <0.5 m; open circles, 0.5-1 m; solid circles, 1-2 m; open triangles, 2-4 m; solid triangles, >4 m. Symbols for dune height: open circles, <3 cm; solid circles, 3-6 cm; open triangles, 6-12 cm; solid triangles, >12 cm.

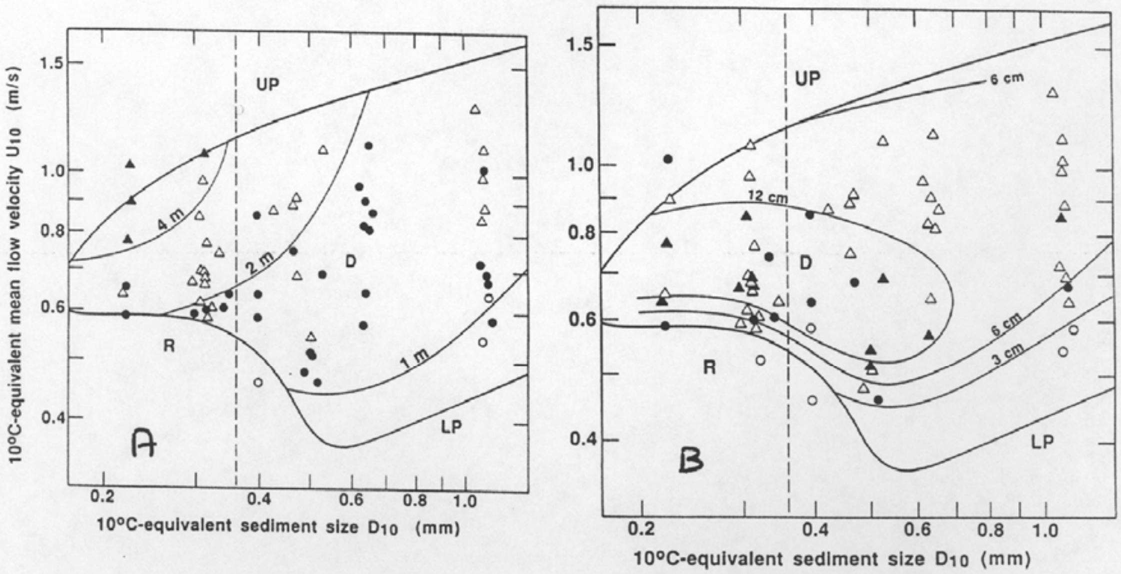


Figure 2-52 Crude contours of dune spacing (A) and dune height (B) in a velocity-size section. Symbols as in Figure 2-52.

3.2.3.18 In the depth-velocity section (Figure 2-51A), dune spacing increases from lower left to upper right, with increasing depth and velocity, although the extent of the data points does not constrain the slopes of the contours well. In the velocity-size section (Figure 2-52A), dune spacing increases from lower right to upper left with increasing velocity and decreasing sediment size; the greatest spacings are at the upper-plane-bed boundary and a sediment size of between 0.2 and 0.3 mm. Dune height shows a different and more complicated behavior. In the depth-velocity section (Figure 2-51B), dune height increases monotonically with increasing depth but shows an increase and then a decrease with increasing flow velocity at constant depth. In the velocity-size section (Figure 2-52B), there is an elongated core of greatest heights extending from near the left-hand extremity of the dune field, at the finest sizes of about 0.2 mm, rightward to sizes of 0.5 to 0.6 mm. Heights seem to decrease in all directions from that core, most rapidly with decreasing flow velocity.

3.2.4 Flow and Sediment Movement over Ripples and Dunes

3.2.4.1 Flow over ripples and dunes is dominated by ***flow separation***, a phenomenon whereby the flow separates from the solid boundary in the region where the boundary curves away from the general upstream flow direction. The general picture of separated flow over a ripple or a dune is shown in Figure 2-53, and in more cartoonlike form in Figure 2-54. When the flow reaches the crest it continues to move in the same direction rather than bending downward to follow the contour of the bed. Strong turbulence develops along the surface of strong shear, called the ***shear layer***, which represents the contrast between the high velocity in the separated flow and the low velocity in the shelter of the bed form. This turbulence expands both upward and downward, and at some position downstream of the crest the turbulent shear layer meets the sediment bed. The flow is said to ***reattach*** to the bed at that point. Downstream of reattachment, the flow near the bed is directed downstream once again. Upstream of reattachment, in what is called the ***separation vortex***, the bed feels a weak flow in the reverse direction.

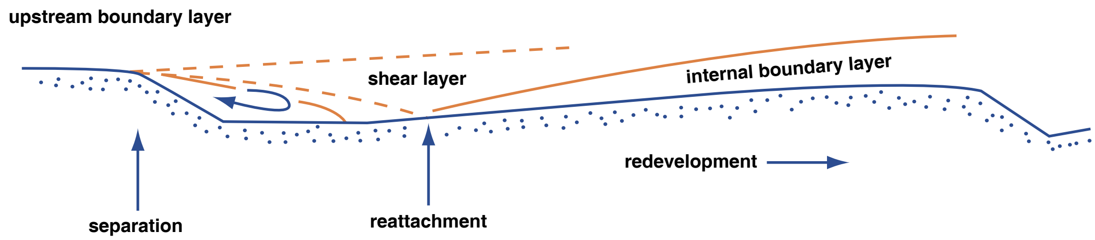


Figure by MIT OCW.

Figure 2-53: General structure of separated flow over a ripple or a dune

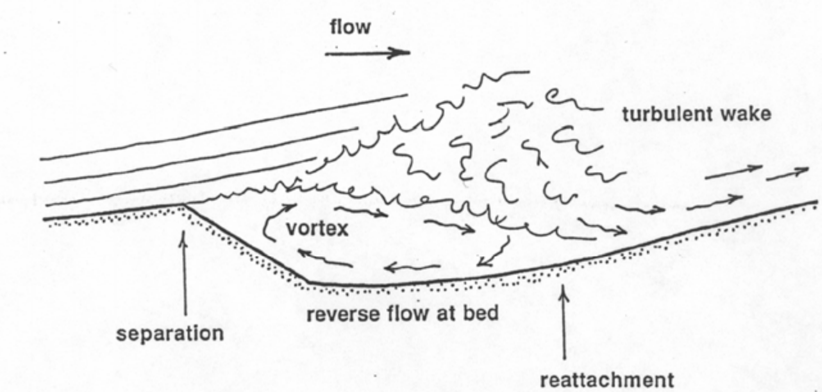
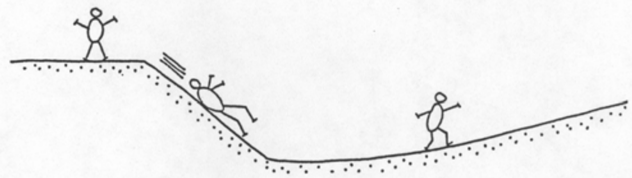


Figure 2-54 More cartoonlike version of Figure 2-53 showing the general structure of separated flow over a ripple or a dune

3.2.4.2 Take a tour of a ripple or dune profile by starting at a crest, sliding down the slip face, and then walking across the trough and up the stoss surface downstream (Figure 2-55). The flow you'd sense would differ greatly along the profile. You could actually do this on a big dune in a river or a tidal current, or on a subaerial dune. Refer to Figures 2-53 and 2-54 as you read on.

Figure 2-55

Taking a tour of a ripple or dune



3.2.4.3 Turbulence rapidly develops on the shear surface extending downstream from the separation point at the ripple crest. The turbulent shear layer grows upward into the now-separated boundary layer above, and also downward. The streamline (defined only in a time-average sense) that extends downstream from the point of separation at the crest, called the ***dividing streamline***, descends gently toward the trough, as the overall flow tries to follow the ripple profile.

3.2.4.4 At about ten step heights or a little less downstream, the shear layer meets the bed at a moderate angle at a *stagnation point* (also well defined only in a time-average sense). The shear layer is said to ***reattach*** to the boundary at that point. (Technically it's a stagnation *line* rather than a stagnation *point*.) At reattachment the flow in the shear layer divides: some is diverted upchannel, but most continues downchannel, now in contact with the bed.

3.2.4.5 The space below the shear layer and upstream of the reattachment line is called the ***separation bubble*** (although it has nothing to do with bubbles *sensu stricto*). Turbulent mixing of fluid from the top of the separation bubble into the lower part of the shear layer, together with the upchannel diversion of a part of the shear layer at reattachment, combine to produce *a weak vortex or roller*, with sense of circulation shown in Figure 2-54. As you moved down the lee face and out onto the trough you'd feel a weak, irregular, eddying current in the opposite direction.

3.2.4.6 Near the reattachment line you'd feel the full effect of the turbulence in the shear layer. *In the reattachment zone the strong eddies generated in the shear layer impinge upon the bed and flatten out against it to cause temporarily very high local shear stresses.* You'd feel strong puffs of flow trying to push you this way and that. But even though the shear stress is high at certain points and certain times, it's nearly zero on the average; the time-average component of velocity parallel to the bed is zero at the reattachment line, by definition, so the time-average local boundary shear stress is just about zero there also. Both the near-bed velocity and the average boundary shear stress increase sharply downstream from reattachment, but the magnitudes of the fluctuations decrease.

3.2.4.7 The flow a short distance downstream of reattachment has a very complex structure. There are three layers:

θ *The shear layer developed by separation* is now flowing in contact with the bed.

θ Above the reattached shear layer is *the original boundary-layer flow from upstream*, which maintains its identity for a long distance downstream of separation even as it's consumed from below.

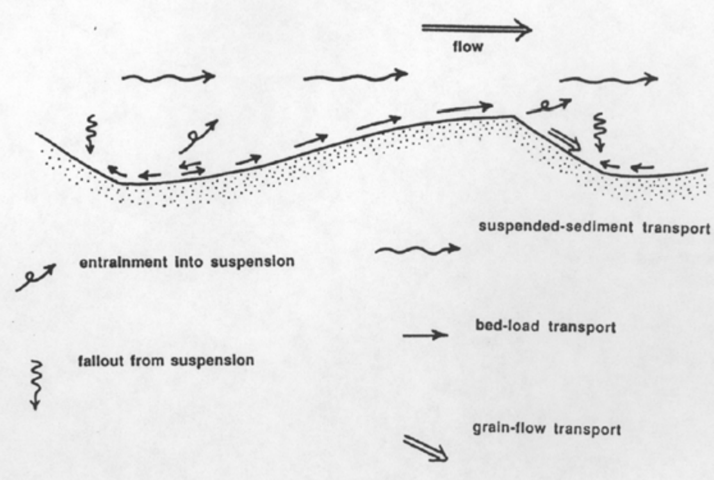
θ As it moves up the stoss surface, the flow in the reattached shear layer has to adjust itself to the presence of the boundary by development of *a new boundary layer* (an example of an internal boundary layer) upward from the bed. In this way the presence of the boundary eventually alters the structure of the turbulence in both of the other two layers above; the disturbed boundary layer is said to ***relax*** toward the new equilibrium state.

3.2.4.8 If a planar boundary extended far enough downstream, the new boundary layer would eventually develop through the entire flow depth, and the velocity gradient and therefore the bed shear stress would decrease gradually from a maximum just downstream of reattachment to equilibrium values far downstream. But in flow over a ripple, redevelopment is still incomplete where the flow reaches the crest, so the flow well above the crest senses little of the profound changes in near-bed flow. The flow throughout the growing boundary layer and the degrading shear layer above it is accelerated as it's crowded upward over the upsloping stoss surface. It doesn't take much of a slope for this acceleration to cause an increase in both boundary shear stress and near-bed velocity up the stoss surface, so the near-bed flow is strongest as it reaches the crest to separate again.

3.2.4.9 The mode of sediment transport varies greatly from place to place over the ripple or dune profile. A repetition of your traverse, just to watch the sediment movement, would be good. See Figure 2-56 for a key to what's discussed below. Start at the reattachment zone, where time-average bed-load transport rate is near zero. Strong eddies in the reattaching shear layer impinge upon the bed to cause strong but sporadic grain transport. At low mean-flow velocities sediment is shifted this way and that on the bed in local pulses that strike seemingly at random. This is the site of first suspension of sediment as flow velocity gradually increases: swirls of sediment are put into suspension in puffs and gusts, and then the grains either settle directly back to the bed or are dispersed up into the flow.

Figure 2-56

Sediment movement over a ripple or dune



3.2.4.10 Downchannel from reattachment the pulses of movement are directed more and more consistently downchannel and gradually give way to more uniform grain movement up the stoss slope. In the other direction they cease to be important just a short distance upchannel from reattachment, because flow in the separation vortex is relatively weak.

3.2.4.11 Grain movement up the stoss surface is much like that on a planar sediment bed: as isolated puffs at low mean-flow velocities, and as a continuous sheet at higher velocities. With increasing velocity the bed-load movement is obscured by sediment suspended from the trough or from upstream ripples. Dunes often have ripples or even smaller dunes superimposed on their stoss slopes; this shouldn't surprise you, because such bed forms are very opportunistic, and will develop wherever they have enough space and the right flow conditions.

3.2.4.12 At low flow velocities all the sediment transported as bed load to the brink is dumped there, tending to build the stoss surface forward over the top of the lee surface. The sediment slips down the lee surface as a kind of grain flow to try to restore a stable angle of repose. Grain flow is localized and sporadic when the rate of delivery is slow, but widespread and continuous at higher flow velocities. The result is *a nearly planar lee surface*, the ***slip face***, with a break in slope not only at the top but also at the base, where the slip face builds forward onto the surface of the trough downstream.

3.2.4.13 At higher flow velocities some fraction of the transported grains are carried beyond the crest above the separation surface, to settle through the complicated turbulent flow field in the wake of the ripple and land at various points (Figure 2-57): on the slip face, in the trough, on the stoss surface of the next ripple downstream, or even on some ripple much farther downstream. Where the grains land depends on several things: the flow velocity, the settling velocity, the height of the grains above the bed as they pass over the brink, and just which eddies the grains happen to fall through.

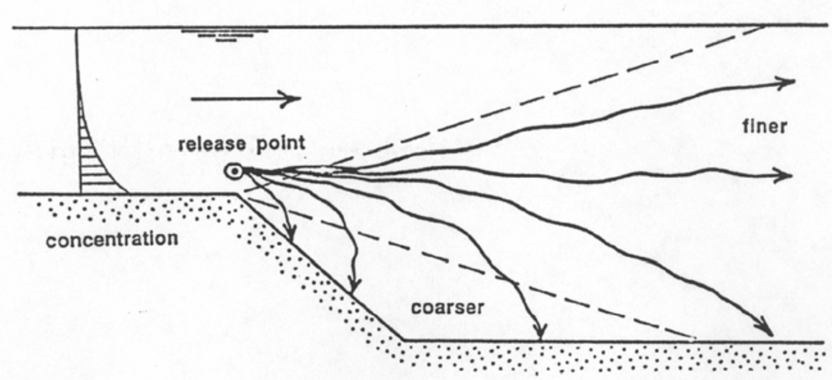


Figure 2-57 Some fraction of the transported grains are carried beyond the crest above the separation surface, to settle through the complicated turbulent flow field in the wake of the ripple and land at various points

3.2.4.14 When the ripple geometry is three-dimensional many troughs show no well defined separation vortex, and patterns of flow and sediment transport are not as simple as outlined above. The bed surface near the base of the lee slope nonetheless usually feels flows that are much weaker than over the stoss slope, although these flows may have a substantial cross-stream component. Transverse flow in the lee of the dunes often makes ripples in troughs and on lee slopes, with crests oriented at a large and variable angle to the dune crests.

3.2.4.15 Ripples and dunes move downstream, at speeds orders of magnitude slower than the flow speed, by erosion on the stoss surface and deposition on the lee. It's surprisingly difficult to characterize this downstream movement, partly because the bed forms change their profiles with time, but even more importantly because any given bed form has a finite lifetime: it's formed, it moves, and it eventually dies, usually within a travel distance equal to only a small multiple of the bed-form spacing, something like 5-10 spacings. A good way to apprehend the transitory existence of individual bed forms is to take a time-lapse movie of a moving train of ripples in your flume. When you viewed the film at normal speed you'd see the ripples doing all sorts of crazy things that are hard to appreciate by real-time viewing; the moderately regular arrangement of ripples in still life is deceiving.

3.3 Oscillatory-Flow and Combined-Flow Bed Configurations

3.3.1 Introduction

3.3.1.1 Remember from the discussion of gravity waves that shallow-water waves propagating in water much shallower than the wavelength cause a back-and-forth motion of the water at the bottom. *If the maximum speed of the water (which is attained in the middle of the oscillation) exceeds the threshold for sediment movement, oscillatory-flow bed forms develop.* This is common in the shallow ocean, where swell from distant storms causes bottom oscillatory motion even though the weather is fine and calm locally. Bottom-water motions under large storm waves cause bed forms too, but then there's likely to be a nonnegligible current running as well; we'll have something to say about such combined-flow bed forms in a later section.

3.3.1.2 The treatment of oscillatory-flow bed configurations here will be the same as that for unidirectional flow bed configurations above, although not as lengthy: after describing an exploratory flume experiment, we'll present what's known about the existence fields of the various kinds of bed configuration.

3.3.2 A Tank Experiment on Oscillatory-Flow Bed Configurations

3.3.2.1 There are three different ways to make oscillatory-flow bed configurations in the home or laboratory. One is to build a big long tank and make waves in it by putting a wave generator at one end and a wave absorber at the other end (Figure 2-58). The generator doesn't have to be anything more than a flap hinged at the bottom and rocked back and forth in the direction of the tank axis at the desired period. This arrangement makes nice bed forms, but the trouble is that you're limited to short oscillation periods.

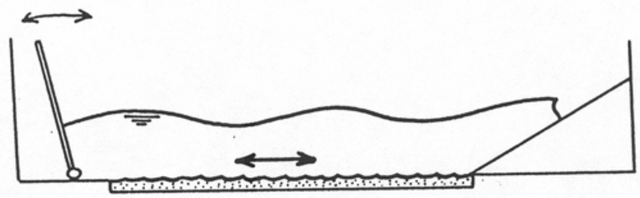


Figure 2-58 Oscillatory flow in a wave tank

3.3.2.2 Another good way to make oscillatory-flow bed configurations is to build a horizontal closed duct that connects smoothly with reservoir tanks at both ends, fill the whole thing with water, and then put a piston in contact with the water surface in one of the reservoir tanks and oscillate it up and down at the period you want (Figure 2-59). This lets you work with much longer-period oscillations, but there's the practical problem that the apparatus has its own natural oscillation period, and if you try to make oscillations at a much different period you have to fight against what the duct wants to do, and that means big forces.

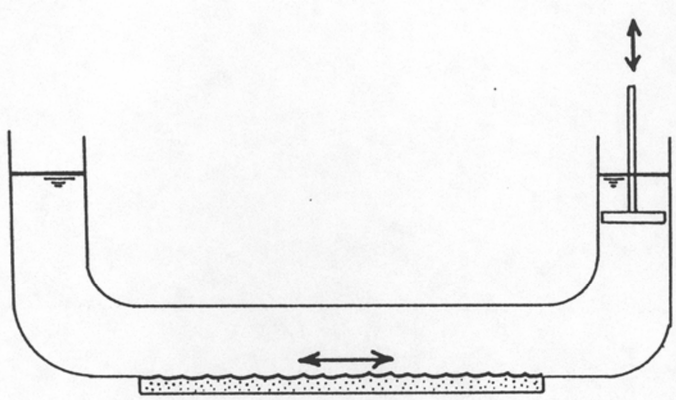


Figure 2-59 Oscillatory flow in a closed duct

3.3.2.3 The third way should seem elegant and ingenious to you: place a sand-covered horizontal tray at the bottom of a big tank of water, and oscillate the tray back and forth underneath the water (Figure 2-60). The problem is that the details of particle and fluid accelerations are subtly different from the other two devices, and it turns out that the bed configurations don't correspond well with those produced in the other two ways.

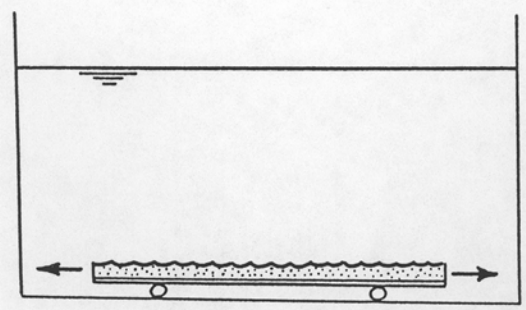


Figure 2-60 Oscillatory flow in an oscillating-bed tank

3.3.2.4 We suggest that you build the horizontal closed duct apparatus, if you still have room left in your back yard. The only problem, aside from fighting leaks, is the mechanical arrangement to make the up-and-down oscillation. Have you ever seen those weird-looking pump jacks in oilfields? One of those would be just right for the job.

3.3.2.5 Then you can make an exploratory series of runs to get a general idea of the nature of oscillatory-flow bed configurations. Work at just one oscillation period, in the range from three to five seconds. Start at a low velocity and increase it in steps. Here's the sequence of bed configurations you'd see (Figure 2-61).

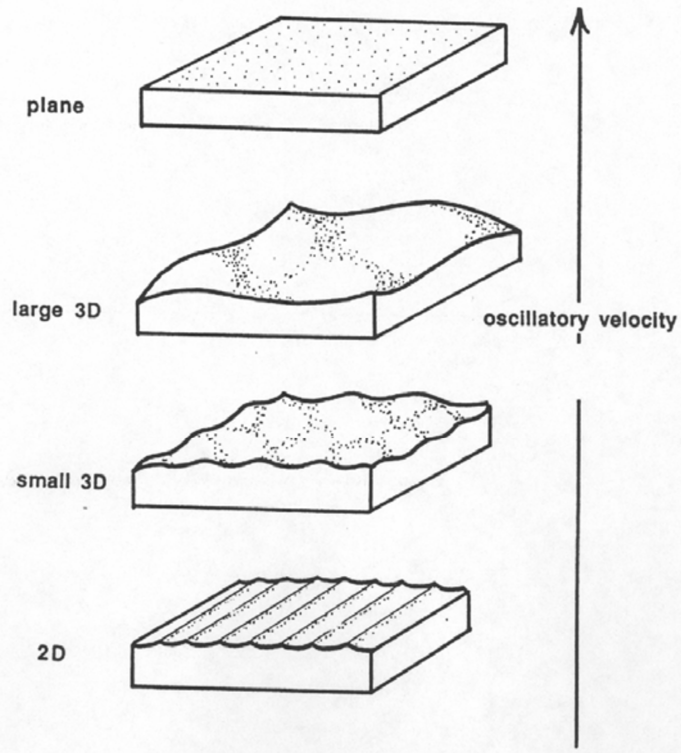


Figure 2-61 Sequence of oscillatory-flow bed configurations with increasing flow strength at a moderate to long oscillation period

3.3.2.6 Once the movement threshold is reached, a pattern of *extremely regular and straight-crested ripples* develops on a previously planar bed. The ripples are symmetrical in cross section, with sharp crests and broad troughs. In striking contrast to unidirectional-flow bed configurations, the plan pattern is strikingly regular: ripple size varies little from ripple to ripple. At fairly low velocities the ripples are relatively small, with spacings of no more than several centimeters, but with increasing velocity they get bigger and bigger.

3.3.2.7 In a certain range of moderate velocities, the ripples become noticeably less regular and more three-dimensional, although they still are oriented dominantly across the oscillatory flow. These 3D ripples continue to grow in size with increasing velocity, until eventually they become flattened and are finally washed out to a planar bed. So, just as is true in unidirectional flows, rugged bed configurations pass over into a stable plane-bed mode of transport with increasing velocity.

3.3.2.8 We want to make a distinction here between what we'll call ***oscillatory-current ripples*** and ***reversing-current ripples***. Although the terminology is somewhat infelicitous, the distinction is significant. Oscillatory-current ripples are dynamically related to the oscillatory current itself. These are the ripples that start small and grow much larger as oscillation speed and period are increased, and are coupled in some not-well-understood way to the orbital diameter. Reversing-current ripples, on the other hand, are dynamically akin to unidirectional-flow ripples, in that they are formed and maintained by the one-way flow during each part of the oscillation. The reversal of the current merely flips their symmetry, and also inhibits their full development. They live stunted lives in which they can develop no further than incipient unidirectional-flow ripples. Significantly, their size is almost independent of the oscillation period and velocity.

3.3.3 Bed-Configuration Regimes

3.3.3.1 Let's assume again that the sediment is described well enough by its density ρ_s and average size D. The oscillatory flow is specified by any two of the following three variables: oscillation period T, orbital diameter d_o, and maximum orbital velocity U_m; let's use T and U_m. As with unidirectional-flow bed configurations, we also need to include ρ, μ, and g. That makes seven variables. Let's take exactly the same approach as for unidirectional flow: the only variables of the seven that vary much in water flows transporting quartz-density sediment on Earth are sediment size, oscillation period, maximum orbital velocity, and water viscosity, and we can safely neglect the viscosity with only minor fuzziness of the results. So *we can examine relationships among bed phases in a three-dimensional size-velocity-period graph*.

3.3.3.2 The most convenient and revealing way of looking at the size-velocity-period graph is by means of several *velocity-period sections* for different sediment sizes (Figure 2-62). Figure 2-63 shows two such sections, one for fine to very fine sands, with average size in a narrow range of 0.1-0.2 mm (Figure 2-63A), and the other for coarser sands, with average size in the narrow range 0.50-0.65 mm (Figure 2-63B). As with unidirectional flows, the axes are labeled with the 10°C values of orbital velocity and oscillation period corresponding to the actual dimensionless variables, but you don't need to concern yourselves with that.

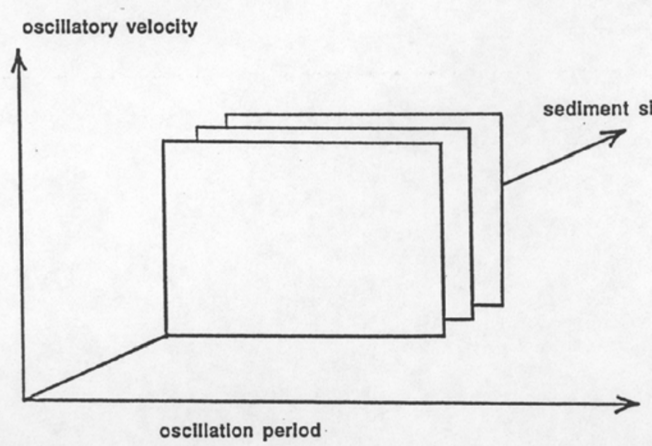


Figure 2-62 Visualizing the velocity-period-size diagram by means of velocity-period sections

3.3.3.3 In both parts of Figure 2-63 a broad field of ripples of various sizes and shapes is bounded below by a field where the flow is too weak to maintain equilibrium ripples and above by a field for transport over a planar bed. The boundary between ripples and plane bed is clear-cut, but because of the scarcity of official plane-bed data points (not shown), is fairly well constrained only at intermediate oscillation periods. The boundary between ripples and no ripple maintenance is less well defined, owing to a lack of well documented runs. This boundary is drawn arbitrarily to be horizontal. As in the unidirectional case, there actually are two boundaries in this region of the graph, one for development of ripples on a planar bed and the other for maintenance of preexisting ripples with slowly decreasing velocity. The ripple field clearly broadens rightward. The minimum period for generation of ripples seems not to have been studied, but in any case is unimportant for natural sedimentary environments.

3.3.3.4 In Figure 2-63A, for very fine to fine sand, ripple spacings increase from about 0.05 m at periods of less than 2 s to well over a meter at periods approaching 10 s. Crude contours of spacing, drawn where possible, are nearly parallel to lines of equal orbital diameter d_o, reflecting the well known tendency for oscillatory-flow ripples to scale with orbital diameter, but there seems to be a tendency for these contours to be steeper than the lines of constant d_o. The outstanding feature of this graph is a transition from regular and straight-crested ripples (two-dimensional ripples) at low oscillatory speeds and small periods to irregular (three-dimensional ripples) at high oscillatory speeds and long periods. This transition has been reported in several studies but hasn't been studied in detail. Ripple spacings in some of these three-dimensional ripple runs were not reported even approximately. At the longest oscillation periods typical of shallow marine environments, in the range 8-20 s, large three-dimensional ripples are the stable configuration at oscillation speeds up to about one meter per second.

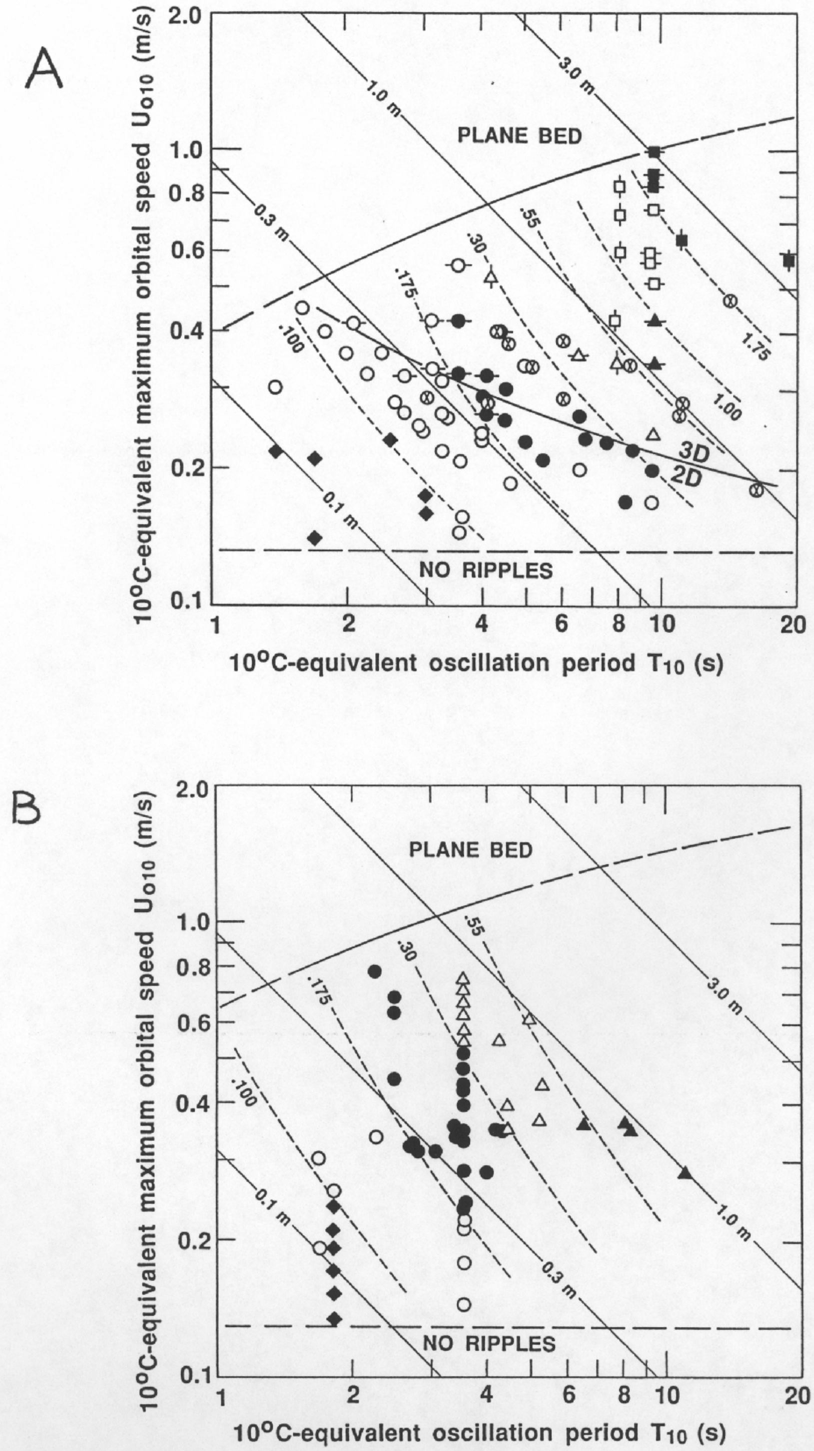


Figure 2-63

Velocity-period sections for sand sizes of (A) 0.01-0.02 mm and (B) 0.50-0.65 mm sand. Symbols for ripple spacing: solid diamonds, < 0.100 m; open circles, 0.100-0.175 m; solid circles, 0.175-0.30 m; open triangles, 0.30-0.55 m, solid triangles, 0.55-1.00 m; open squares, 1.00-1.75 m; solid squares, > 1.75 m. Horizontal tick marks indicate a three-dimensional configuration. Symbols without tick marks indicate a two-dimensional configuration, except that circles with enclosed X's represent a three-dimensional configuration for which a characteristic ripple spacing was not measured. Vertical tick marks indicate ripples whose spacing is much greater than the duct width, so that the three-dimensional geometry of the ripples could not be observed.

3.3.3.5 It's clear that all of the two-dimensional ripples, at relatively small orbital velocities are oscillatory-current ripples, as defined earlier. The onset of three-dimensional geometry with increasing orbital velocity at any given oscillation period seems to reflect the development of reversing-current ripples (which are dynamically akin to current ripples in unidirectional flows, and vary little in spacing) and their increasingly strong interaction with the oscillatory-current ripples. At longer oscillation periods and even greater orbital velocities the oscillatory-current ripples grow to be much larger than the reversing-current ripples, thus eliminating the strong interaction between the two; the reversing-current ripples are only passively superimposed upon these larger oscillatory-current ripples. We want to emphasize that a lot more work has to be done at relatively large orbital velocities and oscillation periods before these speculative relationships can be confirmed.

3.3.3.6 Careful observations of oscillation ripples in the shallow oceans have revealed the existence at moderate to large oscillation speeds and long oscillation periods, in the upper right of Figure 2-63A, of only small 2D ripples, with spacings almost without exception in the range 0.07-0.08 m, rather than large three-dimensional ripples. These small ripples are almost certainly reversing-current ripples, described above. Why were large three-dimensional ripples not observed? Was not enough time available as the oscillatory flow waned from plane-bed conditions? Or is there something inherent in oscillatory flow in a closed flow duct that is conducive to their development? The ancient sedimentary record of shallow-marine environments gives incontrovertible evidence of large-scale three-dimensional oscillation ripples in fine sands, but we have no way of knowing whether the oscillatory flow was dominated by a single component or was composed of a range of components with different periods, directions, and amplitudes. Only observations of the bed configuration in the shallow ocean during storms can resolve this question.

3.3.3.7 Relationships of ripples in coarse sands, shown in Figure 2-63B, are simpler than in fine sands. Ripple spacing again increases upward to the right, scaled closely to orbital diameter. Again the crude contours of equal ripple spacing seem to slope a little more steeply than the lines of constant orbital diameter. Somewhat surprisingly, the lower boundary of the ripple field seems to be in about the same position as for the much finer sands. All the ripples are two-dimensional oscillatory-current ripples; for reasons unclear, the instability leading to three-dimensional geometry in fine sands is not manifested in coarse sands. Neither are large three-dimensional oscillation ripples represented in the ancient sedimentary record.

3.3.4 Combined-Flow Bed Configurations

3.3.4.1 So far we've looked at just the two "end-member cases" of flows that make bed configurations. Even aside from the importance of time-varying unidirectional and oscillatory flows, and of purely oscillatory flows with more than just one back-and-forth oscillation component, there's a whole world of combined flows out there making their own bed configurations. Observations in the natural environment have been scarce, and systematic laboratory work is only now beginning.

3.3.4.2 Observations of combined-flow bed configurations are not yet at the stage where we can draw well organized graphs for you. Theoretically, we should be dealing with a five-dimensional graph, made up with the variables sediment size, unidirectional-flow velocity component, flow depth, oscillatory-flow velocity component, and oscillation period. We would have great envy of anyone who can visualize a four-dimensional graph as well as a three-dimensional graph, but we don't know anybody who can. But matters are not as bad as they seem. For oscillation-dominated flow we should be able to neglect the flow depth, because everything happens in an oscillatory-flow boundary layer within a meter or so above the bottom whose thickness is limited (in ways we can't discuss here) by the nature of the oscillation itself. And in unidirectional-dominated flow we might be able to neglect the oscillation period.

3.3.4.3 What little we know about combined-flow bed configurations is mostly from oscillation-dominated combined flow. We can handle the four variables by trying to plot a series of three-dimensional graphs for various values of the fourth variable. At this stage, which one we choose as the fourth variable is irrelevant, because there's data only for one sediment size and one oscillation period! Figure 2-64, from experiments by Arnott and Southard in a combined-flow duct, shows a graph of oscillatory velocity component against unidirectional velocity component for a sand size of about 0.1 mm and an oscillation period of about 9 s.

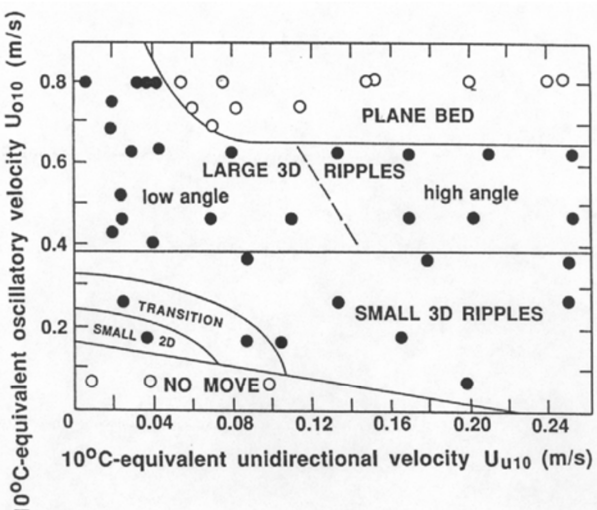


Figure 2-64 Combined-flow bed-configurations in a graph of oscillatory velocity component against unidirectional velocity component for a sand size of about 0.1 mm and an oscillation period of about 9 s. Solid circles, combined-flow ripples; open circles, sediment movement on a plane bed (above the ripple field) or no sediment movement on a plane bed (below the ripple field).

3.3.4.4 The plot in Figure 2-64 is partitioned into fields for various intergradational bed phases. In the range of flows studied (oscillatory velocity 0-0.80 m/s; unidirectional velocity 0-0.25 m/s) these bed phases are: no movement; small two-dimensional ripples; small three-dimensional ripples; large three-dimensional ripples; and plane bed. The transitions among these bed phases are gradual; the partitioning is only an attempt to identify regions with distinctive bed geometry, and is not meant to imply sharp distinctions among the various phases. But the differences in bed configuration from region to region in Figure 2-64 are real and substantial. In particular, the transition from small ripples to large ripples seems to represent a region of accelerated change in bed-form scale compared to regions above and below, where changes are slower although not negligible.

3.3.4.5 The sequence of bed phases along the oscillatory axis is known from earlier work in the same flow duct using the same sediment size and oscillation period: no movement, small two-dimensional ripples, small three-dimensional ripples, large three-dimensional ripples, plane bed. Likewise the sequence of bed phases along the unidirectional axis is well known from many studies in unidirectional flow: no movement, unidirectional-flow ripples, plane bed. In the interior of the graph, the boundary between no movement and combined-flow ripples is not well constrained, and is shown arbitrarily as a straight line. The boundary between combined-flow ripples and plane bed, on the other hand, is fairly well constrained: within the range of unidirectional flow velocities attainable, it falls sharply with increasing unidirectional velocity at first and then becomes nearly horizontal.

3.3.4.6 Over a narrow range of oscillatory velocities above threshold and for very small unidirectional velocities, less than a few centimeters per second, the bed configuration consists of regular ripples with straight and laterally continuous sharp crests and broad troughs oriented perpendicular to the flow. Ripple profiles are only slightly asymmetrical. With only slight increase in either velocity component the ripples become increasingly irregular in plan geometry. Rightward from the oscillatory axis, over the entire range of unidirectional velocities studied, the configuration consists of relatively small ripples with more or less sinuous although fairly continuous crest lines and with more or less pronounced local lows or scour pits in troughs. Dips on the upstream and downstream ripple flanks are not greatly different, but the lamination within the ripples always dips downstream, because the ripples move slowly in the direction of the unidirectional component. Even at small values of oscillatory velocity the overall appearance of the ripples is not grossly different from those in purely unidirectional flows.

3.3.4.7 As oscillatory velocity increases beyond about 0.4 m/s, the three-dimensional ripples become much larger. The transition is gradual, but the rate of change with increasing oscillatory velocity is greater than at smaller oscillatory velocities. Bed-form crests become less continuous and more rounded, resulting in forms whose geometry could be described as hummocky. As spacing continues to increase to over 2 m at the highest values of oscillatory velocity, detailed information on plan geometry is lost owing to the narrowness of the flow duct used, although the ripples are still substantially three-dimensional. Except at the greatest oscillatory velocities, small reversing-current ripples are prominently superimposed. With increasing unidirectional velocity the flow-parallel profiles of the three-dimensional ripples become more asymmetrical, eventually attaining lee-side angles of up to 25°. A unidirectional component of only a few centimeters per second is need to make the profiles noticeably asymmetrical. Heights first increase with oscillatory velocity and then decrease in the transition to plane bed. Spacings are a large percentage of the orbital diameter, suggesting that these large three-dimensional ripples are analogues of the oscillatory-current ripples well known from oscillatory flows.

3.3.4.8 These large three-dimensional combined-flow ripples must somehow disappear with increasing unidirectional velocity, because in purely unidirectional flow small three-dimensional ripples pass into plane bed with increasing velocity, and the upper boundary of combined-flow ripples must connect with that transition point on the unidirectional axis, as shown in Figure 2-65, which is a rather speculative extrapolation of Figure 2-64 to greater values of unidirectional velocity. Also to be ascertained is the relationship between large combined-flow ripples in very fine sand, like those described above, and dunes in purely unidirectional flow in sands coarser than about 0.2 mm. A whole series of intermediate "sections" in the four-dimensional graph of oscillatory velocity, unidirectional velocity, oscillation period, and sediment size must be explored to establish this relationship, even for the simplest case of combined flow, in which the oscillatory and unidirectional components are parallel.

3.3.4.9 To summarize the first-order things about the combined-flow bed configurations shown in Figures 2-64 and 2-65, it's clear that *it takes only a small unidirectional flow component to make oscillatory-flow bed forms noticeably asymmetrical*, and that *even a substantial (but subordinate) oscillatory flow doesn't change unidirectional-flow bed forms very much*. Also, there's clearly *a continuous spectrum of small ripplelike bed configurations that stretches from unidirectional-flow ripples to small oscillatory-flow vortex ripples*. The major problems revolve around how (if in fact at all!) unidirectional-flow dunes connect with the large 3D vortex ripples known to be produced by strong oscillatory flows at long oscillation periods.

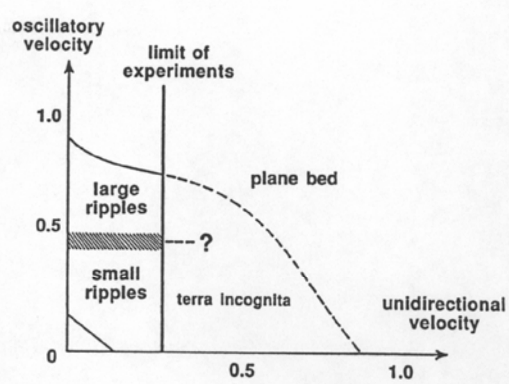


Figure 2-65 Extrapolation of the combined-flow bed-configuration graph of Figure 2-64 to greater unidirectional velocities

3.4 Eolian Bed Configurations

3.4.1 So far we've addressed only bed configurations formed in water flows. Bed configurations produced by the wind are a prominent feature of the Earth's modern surface, and by good evidence have been important at various times in the geologic past.

3.4.2 If we take the most general view in the context of the kinds of existence diagrams described in the earlier sections of this chapter, we might imagine trying to obtain the data to construct *a four-dimensional graph with axes unidirectional flow velocity, flow depth, sediment size, and density ratio ρ_s/ρ*, where remember ρ_s is the density of the sediment and ρ is the density of the fluid. Probably the best way to deal with such a four-dimensional graph is to picture it as a series or continuum of three dimensional depth-velocity-size graphs as ρ_s/ρ varies. Only two graphs out of this continuum are of very much interest to us, though: those for quartz-density sand in water and for quartz-density sand in air. You also have to sort of look past the awkwardness of not having a well defined flow depth to deal with in the first place in the case of sand in air.

3.4.3 Everyone knows that there are two important eolian bed phases: *ripples* and *dunes*. But be on your guard against assuming that, just because we use the same terminology for these features as for ripples and dunes in unidirectional water flows, the two sets of features are dynamically related! Unless someone comes up with an incontrovertible theory for the existence and dynamics of dunes, the only way we'll ever know this is to make a whole series of observations at intermediate values of the density ratio. (That would make a great thesis project for somebody, wouldn't it?) Our own suspicion is that we would be able to *trace the continuous existence of dunes but not of ripples through the intermediate range*.

3.4.4 The trouble with the organizedly empirical approach (which works so fruitfully for sand in water) in the case of sand in air is that *we just don't know very much about the existence fields for eolian bed configurations*, let alone *how the size and geometry of dunes varies within the existence field for dunes*. Maybe some of our eolian colleagues would take exception to that statement, but we think we can defend it pretty well. Here are two factors we think are significant:

θ *Nowhere on Earth does the wind blow steadily for nearly a long enough time to bring the bed configuration into equilibrium with the steady wind*. There are, however, places like the Arabian Peninsula where the sand-moving winds blow mainly from the same direction but with time-varying velocity.

θ *There aren't many places on Earth where eolian bed configurations aren't starved*. (By *starved* we mean that the thickness of wind-movable sand is not great enough to prevent exposure of immovable substrate in the troughs of the bed forms.) Actually, that's true only of the larger bed forms, which are always called dunes; full-bed wind ripples are of course common, although starved wind ripples are important too.

3.4.5 As far as we can tell, we don't even know whether eolian dunes are *self-limiting in size* or whether they would *continue to grow in size given a long enough reach of full sand bed exposed to the wind*. But we think that in practice this is not a big issue, because in most situations dune size is limited either by starvation or by limited reach length.

3.4.6 Has it ever struck you that subaerial types never make duct experiments on subaerial dunes the way the subaqueous types like us make flume experiments on subaqueous dunes? What would we find if we built a gigantic quonset-hut racetrack duct on a full sand surface in the desert and ran a steady wind over the sand surface with an aircraft engine? we suspect that no matter how big we built the duct, *the dunes would grow to the point where further growth is impeded by their feeling the roof*. We could indeed make some interesting observations on:

- θ dune development
- θ how the fully grown dunes vary in shape as a function of wind velocity
- θ the wind velocity needed to smooth out the dunes to a plane bed (not very relevant to the Earth's surface, we suppose!)

3.4.7 We think the bottom line here is that most of the emphasis we gave to the existence, size, and geometry under steady, full-bed conditions in water flows is irrelevant to the real world of eolian bed forms and stratification. The geometry if not the scale of most real eolian dunes (which is what mainly determines the nature of eolian cross-stratification) is shaped mainly by *the time history of wind speed and direction in the dune field*, which as we pointed out earlier ranges all over the place. This is what occupies a lot of the efforts of eolian researchers. We won't try to summarize here what's known in this regard, partly because the possibilities are so varied but mainly because we're not an expert on such matters. Eventually, though, we'll have to return to this difficulty when we deal with the

3.5 A Note on Bed-Configuration Dynamics

3.5.1 At first thought it might seem that the natural mode of transport would be over a planar bed. In certain ranges of flow a planar transport surface is indeed the stable bed configuration. Only in laminar flows, however, is this invariably so. You've seen that in turbulent flows, plane-bed transport is the stable configuration under certain conditions, but bed forms are the dominant transport surface in both oscillatory and unidirectional flows. This must mean that *over a wide range of flows and sediment sizes a planar transport surface is unstable to small perturbations*, and otherwise insignificant geometrical irregularities, either preexisting or flow-generated, are amplified to become bed forms.

3.5.2 Can theories be developed to account for the existence and range of occurrence of the bed configurations we observe? A time-honored way of developing theories for such phenomena is to make a ***stability analysis***: write down what you think is the governing equation of motion (or, in the case of sediment-transporting turbulent flows, some workable approximation thereto), and then introduce a small-amplitude perturbation to the planar bed and see whether the perturbation is *damped out with time* (indicating that *the plane bed is the stable configuration*) or whether the perturbation is *amplified with time* (indicating that *rugged bed forms are destined to develop*). In the latter case, you can also try to see which wavelength of disturbance grows the fastest, thus presumably indicating the *scale* of the resulting bed forms.

3.5.3 There's been some modest success with such stability analyses, but there are lots of difficulties. As the flow molds the bed by erosion and deposition, the bed geometry thus generated changes the structure of the flow itself in fundamental ways that are difficult to build into mathematical models. There is thus *a strong interaction or feedback between the bed and the flow*; this essential element of complexity has hindered the development of theory. Another problem is that even if the stability analysis is successful, it says nothing about *the finite-amplitude effects that are really important in shaping the growing bed forms*.

4. DEPOSITION

4.1 Introduction

4.1.1 The topic of deposition is obviously an important one, because *every sedimentary sequence was deposited somehow*. This section is meant to serve as a framework for trying to make interpretations about deposition from the evidence of beds in a sedimentary section in the final section.

4.1.2 Let us pose a question for you: *"Why does deposition happen?"* We wonder whether this strikes you as a trivial question or as a difficult question. In one sense, we can supply a simple answer: sediment is carried by a flow, and *when the conditions are such that the flow becomes overloaded, the sediment is deposited*. But in another sense, *this is a superficial answer, because it doesn't account for the conditions under which a flow becomes overloaded*, and we have to look for a more fundamental answer.

4.1.3 The most straightforward process involved in deposition is ***settling***: *the downward fall of sediment particles through the surrounding fluid by the pull of gravity*. But keep in mind that there's far more to deposition than just settling of sediment particles: you have to worry about *where the sediment came from, how it got to the site of deposition, and how it was deposited at the site of deposition*.

4.2 Modes of Deposition

4.2.1 Introduction

4.2.1.1 This subsection examines local modes of sediment deposition. Some of these modes may be observable in laboratory experiments or in field studies. Others may be difficult or impossible to observe with present technology, and we can only make deductions or speculations about them. (Keep in mind that *deductions can be very dangerous in physical sedimentology*, because the physics of the phenomena are so complex that we can easily fool ourselves into thinking that an unimportant process is important or that an important process is unimportant.) The treatment will be entirely qualitative.

4.2.1.2 Several distinctive modes of deposition, discussed in the subsections below, can be recognized. *These modes grade into one another*; there are no sharp boundaries among the various processes involved. Keep in mind also that the terms used for these modes are only *unofficial*; you won't find them in the published literature on sediment deposition. See Figure 2-66 for cartoons that illustrate the various modes of deposition.

4.2.2 Fallout Without Traction

4.2.2.1 In the simplest of depositional modes, *sediment particles suspended in a flow by some earlier process or event settle to the bed and are not transported thereafter, either by traction or by suspension* (Figure 2-66A). This might be called ***fallout without traction***.

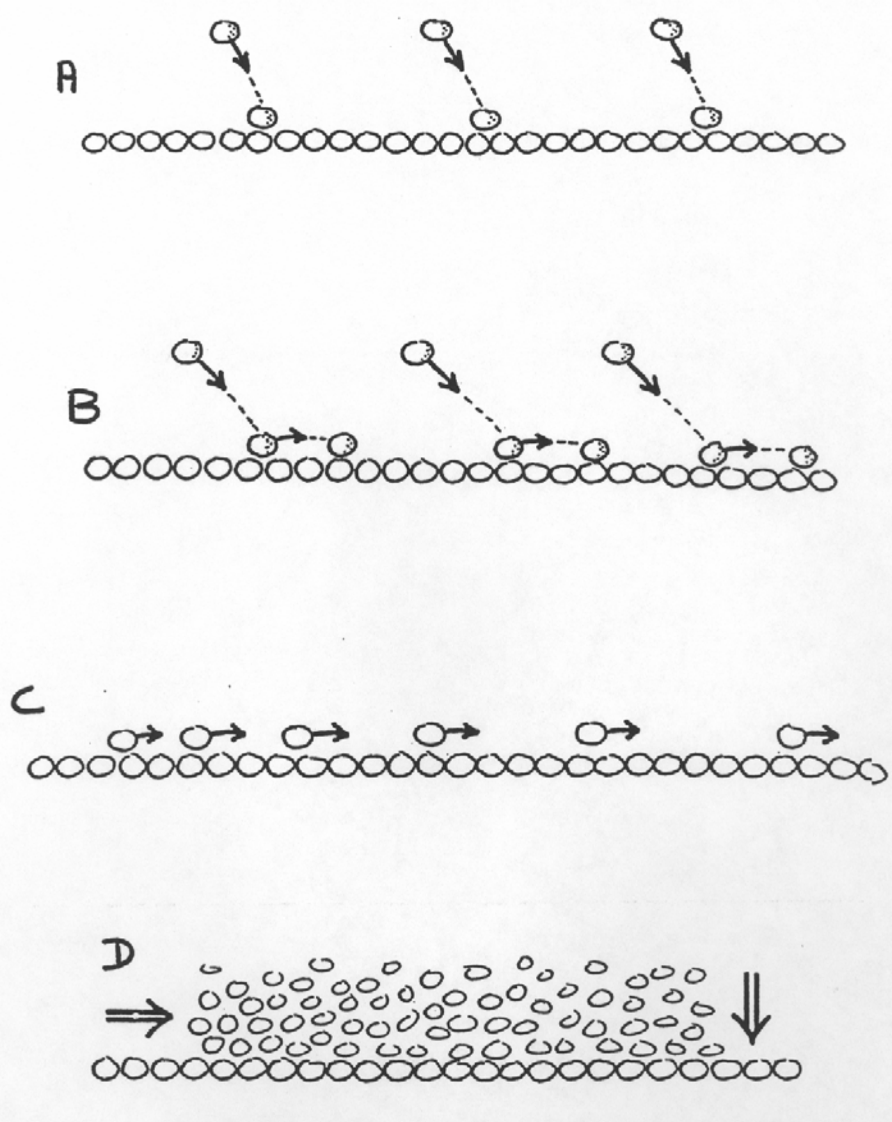


Figure 2-66 Modes of deposition. A: fallout without traction. B: fallout with traction. C: differential transport. D: mass deposition.

4.2.2.2 Flows that deposit sediment by fallout without traction have velocities below the threshold for bed-load transport, which ranges from slightly less than 0.2 m/s to well over 0.3 m/s, depending on the depth of the flow and the size of the sediment particles. In general, the weaker the flow, the finer the sediment being carried and deposited in this mode. The flow may even be nonexistent; in that case, the sediment must be supplied directly from above, as for example by fallout of eolian sediment into a standing body of water.

4.2.2.3 The size of the sediment deposited by fallout without traction is usually very fine, seldom coarser than very fine sand. The reason is that the flow would need to be much stronger to carry coarser sediment in suspension, and such flows would be strong enough to move the deposited sediment as bed load after the sediment lands on the bed.

4.2.3 Fallout With Traction

4.2.3.1 *Sediment particles may settle onto the sediment bed from suspension and then be moved as bed load, or even resuspended temporarily, before they eventually come to permanent rest and are buried by other particles as the bed builds up* (Figure 2-66B). This might be called ***fallout with traction***.

4.2.3.2 Flows that deposit sediment by fallout with traction can have a wide range of velocities, from a small fraction of a meter per second to much greater than a few meters per second. Sediment size can range from silts to gravels. The only condition is that the flow is not so overloaded with suspended sediment that a well defined sediment-water interface cannot be maintained.

4.2.4 Differential Transport

4.2.4.1 A sediment deposit can be formed without any fallout from suspension. At first thought this might seem strange, so we need to spend a little more time discussing this mode of deposition. Think about the consequences of *a downstream change in sediment transport rate in a steady flow*.

4.2.4.2 Look at a small rectangular reference area on the sediment bed beneath a flow that's transporting sediment over the bed (Figure 2-67). The edges of the reference area are parallel to and perpendicular to the flow direction. Since volume of sediment is neither created nor destroyed on the short time scales associated with sediment transport by traction or suspension, we can invoke the ***principle of conservation of sediment volume*** in accounting for what happens to the sediment.

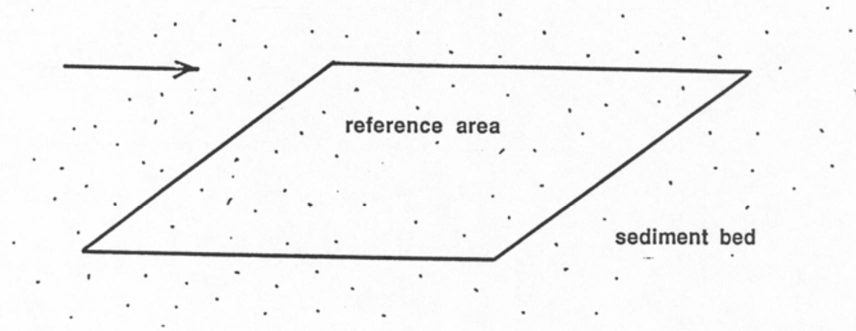


Figure 2-67 A small rectangular reference area on the sediment bed beneath a flow that's transporting sediment over the bed

4.2.4.3 If the total volume of sediment in traction and suspension passing across the plane extending upward from the upstream edge of the reference area is *less* than the total volume of sediment passing across the plane extending upward from the downstream edge of the reference area (Figure 2-68A), then *sediment is somehow being added to the flow in the space above the reference area*. The only place where that added sediment can come from is from the bed, and the only place where it can go is into the flow. So there must be *net erosion of the bed*.

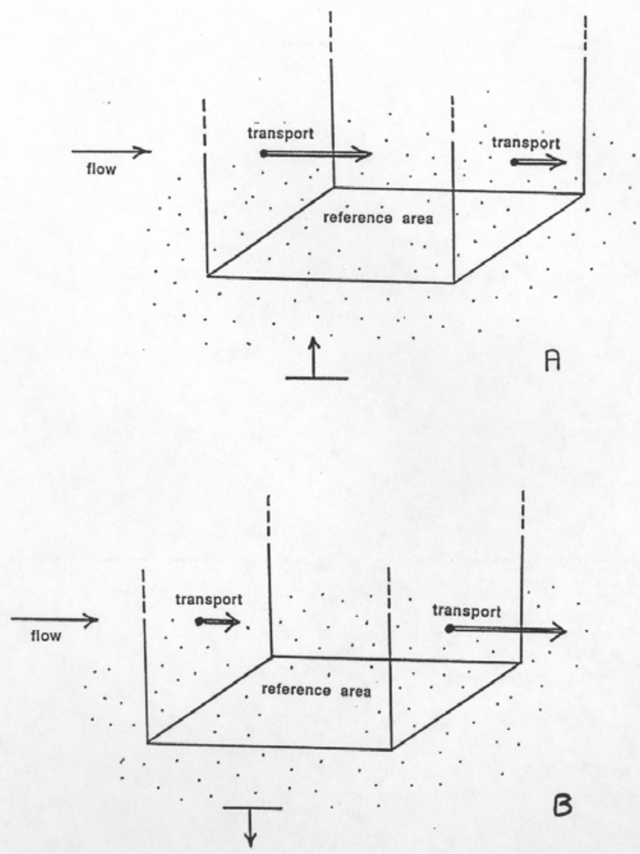


Figure 2-68 Sediment transport over the reference area. A: Sediment is being added to the flow from the bed somehow, so there's net erosion. B: Sediment is being added to the bed from the flow somehow, so there's net deposition.

4.2.4.4 On the other hand, if the total volume of sediment in traction and suspension passing across the upstream plane is *greater* than the total volume passing across the downstream plane (Figure 2-68B), then *sediment is somehow being extracted from the flow in the space over the reference area*. The only place where that extracted sediment can go is onto the bed, so there has to be *net deposition on the bed*. This mode of deposition might be called deposition by ***differential transport*** (Figure 2-66C).

4.2.4.5 The consequence of the reasoning presented above is that *there can be deposition on a sediment bed without any temporal change in the picture of sediment transport*: the flow is steady, and the load and the sediment transport rate at every point does not change with time. There can be deposition, however, provided that the sediment transport rate is changing *spatially* by decreasing in the downstream direction.

4.2.4.6 Deposition by differential transport can take place entirely by downstream decrease in bed-load transport rate, even without any suspended sediment in the flow. This happens wherever the flow deepens slightly in the downstream direction (for any one or more of several reasons, which we won't discuss here), causing the flow velocity and therefore also the bed-load sediment transport rate to decrease in the downstream direction.

4.2.4.7 Flows that deposit sediment by differential transport range widely in flow velocity, from a few tenths of a meter per second to well over two meters per second. Sediment size ranges from finer than sand size to well into the gravel size. Clearly, the coarser the sediment the more likely it is that the process involves differential bed-load transport rather than differential suspended-load transport.

4.2.5 Mass Deposition

4.2.5.1 When the region of the flow near the bed is overloaded with a high concentration of suspended sediment, the sediment settles to the bed with little space between adjacent sediment particles, and a layer of the flow with a thickness that's orders of magnitude greater than the particle size becomes immobilized almost simultaneously as the shearing of the highly concentrated sediment-water mixture ceases (Figure 2-66D). Such a mode of deposition might be called ***mass deposition***.

4.2.5.2 During mass deposition there's no well defined sediment-water interface; instead there's a gradual transition between the underlying already-deposited bed and the sheared, highly concentrated suspension above. Another way of looking at this is that the pore-water content of the mixture varies continuously upward from the already-deposited sediment bed into the still-moving sediment-water mixture.

4.2.5.3 Conditions during mass deposition are difficult to observe, because the sediment concentrations are high and deposition is rapid. Also, the flows from which mass deposition occurs tend to be more powerful and on much larger scales than is the case with the other modes of deposition discussed above. Mass deposition is characteristic of strong sediment gravity flows, especially in their earlier stages.

4.3 The Relationship between the Load and the Deposit

4.3.1 This subsection makes some fundamental points about *the relationship between the sediment load and the deposit in a depositing flow*. We think this material is fundamental to understanding the texture of a deposit, although it won't tell you anything really practical.

4.3.2 Obviously, whenever a deposit is being formed by a sediment-transporting flow, some percentage of the sediment load is being extracted from the flow and added to the bed, by one or more of the various processes discussed in the previous section. The ratio of sediment extraction to sediment passage or throughput can range from nearly zero, in the case of an almost uniform flow carrying fairly high concentrations of sediment in an almost nondepositional regime, to one hundred percent, when a flow dumps all its sediment in one place, like certain kinds of debris flows. Just for convenience, we'll unofficially call this ratio the ***deposition ratio***. (Don't worry about how this ratio could be defined quantitatively.) Although you can't read the value of the deposition ratio directly from beds in an outcrop, we think it's one more of those things that are useful to think about as an aid in framing your interpretations.

4.3.3 This section deals with *the relationship between the characteristics of the sediment load and the characteristics of the deposit left by the flow*. The sediment load always has some joint probability distribution of particle size, particle shape, and particle density (Figure 2-69). You can never really characterize this distribution fully, even when you can obtain a good representative sample of the load, mainly because of the problem of the infinite variations in particle shape, but it's nonetheless real and important. When deposition takes place, *some subset of the passing particles are selected from the flow to become part of the permanent deposit left behind by the flow*. Here's what we consider to be the most fundamental question of sediment deposition: **How does the nature of the deposit depend upon the flow and the nature of the load?** If sedimentologists are ever going to be able to make interpretations about depositional conditions by examining the texture of the deposit, they are going to have to answer this question first.

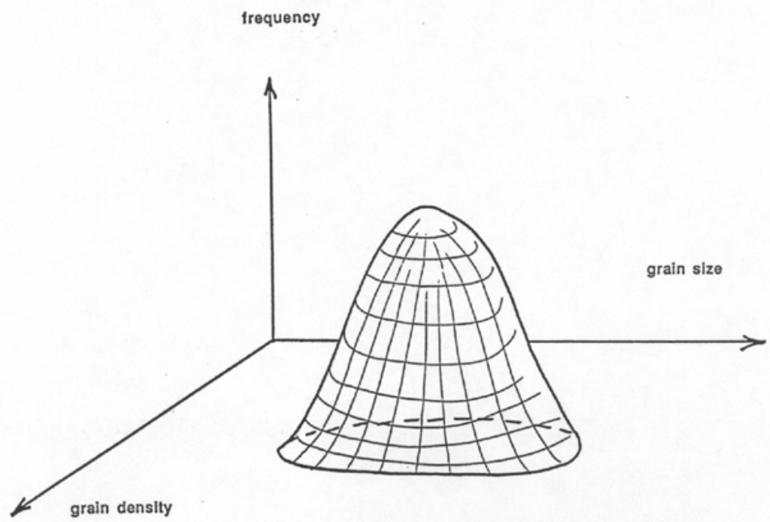


Figure 2-69 The sediment load always has some joint probability distribution of particle size, particle shape, and particle density

4.3.4 There's more to the selection process than might seem to you at first thought. First we'd like to divide the sediment bed into two depth zones (Figure 2-70). The uppermost zone, extending some distance down from the bed surface, is called the ***active layer***. The sediment in the active layer is subjected to repeated reentrainment by the flow as the bed elevation at any given point rises and falls as a result of local erosion and deposition that's superimposed on the long-term net deposition. A good example of such temporary changes in bed elevation are those associated with the passage of bed forms. *All the sediment within the active layer will be recycled by the flow at least once by the flow before it's permanently buried.* Below the active layer is the ***permanent deposit***. The sediment in the permanent deposit is *below the reach of the local erosional processes of the flow, and it will never again be entrained by the flow* (unless the overall depositional regime changes into an overall erosional regime at some later time).

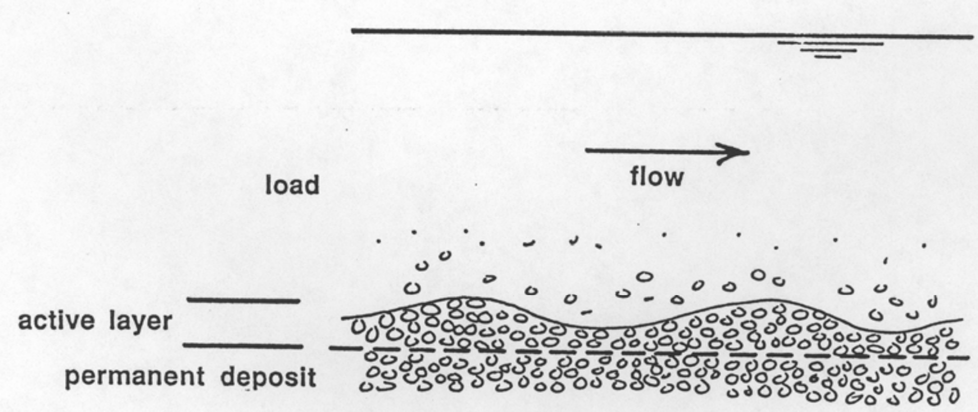


Figure 2-70 The active layer above the permanent deposit

4.3.5 The thickness of the active layer may range from just one or two grain diameters, on an approximately planar bed undergoing aggradation, to many meters, when the bed is covered with very large bed forms that deposit and reerode sediment as they move downstream.

4.3.6 When viewed in terms of the active layer, *deposition therefore involves the burial of certain particles deeply enough within the active layer so that they are no longer moved by the flow again*, so that they become part of the permanent deposit.

4.3.7 Since only a subset of the particles of the load end up becoming part of the permanent deposit, there's the possibility of *fractionation* of the various size, shape, and density fractions between the load and the deposit. Obviously, such fractionation can take place only if there's some range of sizes, shapes, or densities in the load in the first place. But all natural sediments show at least some variation in size and shape.

4.3.8 Here's an important question for you. Think about the ratio between the mean size of the load and the mean size of the deposit. As the flow strength increases, does this ratio increase or decrease? In other words, **if other factors remain the same, does the deposit become coarser or finer as the flow strength increases?** We expect to fool you with this question! We fooled *ourselves* recently when we did a laboratory research project on deposition from strong flows carrying coarse and poorly sorted sediments. One's first reaction is that the stronger the flow, the coarser the deposit. But just the opposite is true!

4.3.9 In the strongest flows, with high concentrations of sediment traveling both as bed load and suspended load, the coarser particles less commonly find permanent resting places on the bed, so the deposit is much finer than the load. In weaker flows, on the other hand, under conditions not far above the threshold for particle transport, the mean size of the deposit is about the same as the mean size of the load. Here's yet another example of how deduction or intuition can mislead you when it comes to the dynamics of sediment transport by turbulent flows.

4.3.10 We think it's premature for us to try to draw useful conclusions for you about the relationship between the load, the flow, and the deposit. But we want you to be aware of the importance of such knowledge. As more work is done on deposition of mixed-size sediment, there's a good chance of obtaining some results that will be really useful in paleoflow interpretations.