

PART III

CURRENT-GENERATED SEDIMENTARY STRUCTURES

CHAPTER 15

DEPOSITION

INTRODUCTION

1 The topic of deposition is an important one, because, obviously, every sedimentary sequence was deposited somehow. This section is meant to serve as background for our consideration of the current-generated physical sedimentary structures in real sedimentary deposits.

2 Let me pose a question for you: **Why does deposition happen?** I 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 does not account for the conditions under which a flow becomes overloaded, and we have to look for a more fundamental answer. (By *overloading* I mean that the flow, at a given time, is transporting a greater sediment load than what it would be transporting if the sediment transport were in equilibrium with the given flow.)

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 (see Chapter 3). Keep in mind, however, that there is 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 why it was that more sediment was falling out of suspension than was being resuspended at the site of deposition. Considerations like this are absolutely critical to a really fundamental understanding of sediment deposition, but in my opinion not nearly enough attention has been given to such matters in the literature on sedimentation, either by hydraulic engineers or by sedimentary geologists. This chapter makes only the barest start on addressing such matters.

MODES OF DEPOSITION

Introduction

4 This section 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.

5 Several distinctive modes of deposition, discussed in the sections 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 are not likely to find them in the published literature on sediment deposition. See Figure 15-1 for cartoons that illustrate the various modes of deposition.

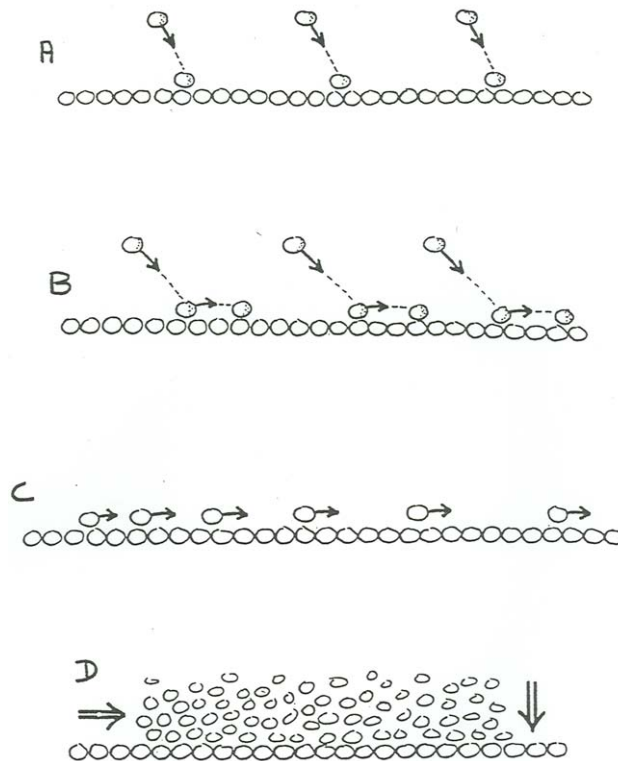


Figure 15-1. Modes of deposition. **A)** Fallout without traction. **B)** Fallout with traction. **C)** Differential transport. **D)** Mass deposition.

Fallout Without Traction

6 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 15-1A). This might be called ***fallout without traction***.

7 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 that is 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.

8 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.

9 In fallout without traction, the thickness of deposit is limited only by the quantity of sediment in suspension above the bed. At first thought this might seem like a severe limitation, but remember that there can be sedimentation systems in which new sediment in suspension is introduced continuously somewhere upcurrent in a steady flow (or, if not steady, episodic but long-continued), like an area offshore of the delta of a river carrying abundant suspended sediment. On the other hand, there is a definite spatial constraint: the downcurrent distance over which such deposition takes place is limited by the downstream loss of sediment from the flow. The finer the suspended sediment and the deeper the flow, the greater the distance over which there is deposition.

Fallout With Traction

10 Sediment particles may settle onto the sediment bed from suspension and then be moved as bed load, or even be resuspended temporarily, before they eventually come to permanent rest and are buried by other particles as the bed builds up (Figure 15-1B). This might be called ***fallout with traction***.

11 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. The spatial and temporal constraints on the mode of deposition are largely the same as for fallout without traction.

Differential Transport

12 To non-geologists (and to some geologists as well!), if you mention deposition, what flashes into their minds is the kind of thing that happens when you suspend some sediment in a vessel of water and let it settle to the bottom. That was called, in the earlier section, fallout without traction. Yes, that is one mode of deposition, and it is important in many natural sedimentary

environments. But there is an equally important mode of deposition that is much less intuitive. 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.

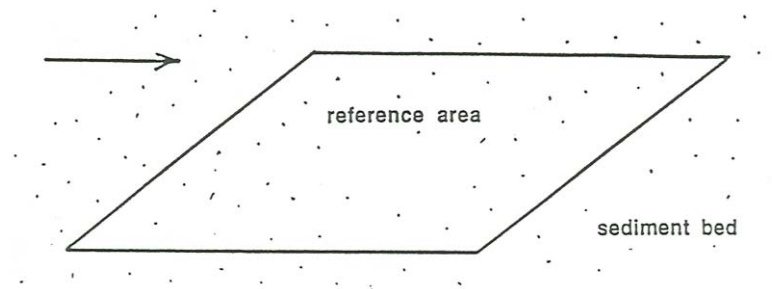


Figure 15-2. A small rectangular reference area on the sediment bed beneath a flow that is transporting sediment over the bed.

13 Look at a small rectangular reference area on the sediment bed beneath a flow that is transporting sediment over the bed (Figure 15-2). The edges of the reference area are parallel to and perpendicular to the flow direction. Because 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.

14 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 15-3A), 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*.

15 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 15-3B), 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 15-1C). Figure 15-4 shows, in cartoon form, the conditions for deposition by differential transport.

16 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 do not change with time. There can be deposition, however, provided that the sediment transport rate is changing *spatially* by decreasing in the downstream direction.

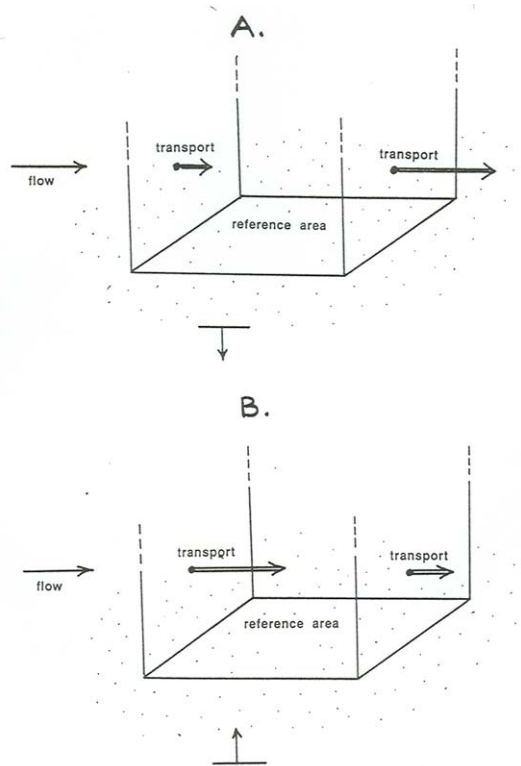


Figure 15-3. Sediment transport over the reference area. A) Sediment is being added to the flow from the bed somehow, resulting in net erosion. B) Sediment is being added to the bed from the flow somehow, resulting in net deposition.

17 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 I will not discuss here), causing the flow velocity and therefore also the bed-load sediment transport rate to decrease in the downstream direction.

18 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 range. Clearly, the coarser the sediment the more likely it is that the process involves differential bed-load transport rather than differential suspended-load transport.

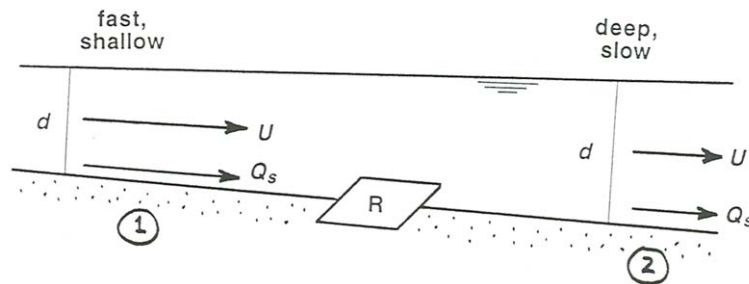


Figure 15-4. The conditions for deposition by differential transport. Sediment transport rate Q_s decreases downstream because mean flow velocity U decreases owing to a downstream deepening of the flow from cross section 1 to cross section 2. The result is aggradation on a reference area R on the sediment bed.

19 As with deposition by fallout, there are constraints on both the thickness and the downstream extent of deposition by differential transport, but they are not exactly the same as for deposition by fallout. For a given value of “input” transport rate (that is, at the upstream end of the reach of flow that is experiencing downstream-decreasing transport rate), there must be an inverse relationship between the distance along which there is deposition and the rate of deposition at points along the transport path—basically because deposition is everywhere using up the stock of sediment that is in transport. This will have application to the geometry and interpretation of cross-stratification produced by bed forms in unidirectional and combined flows; see Chapter 16.

20 Keep in mind also that deposition can be by a combination of fallout and differential transport. These two cases are only end members of a continuous spectrum of possibilities, depending upon the particular depositional setting (that is, the nature of the sediment supply and the nature of the current).

Mass Deposition

21 In many flows, the concentration of sediment is so high that there is no strong distinction, in sediment concentration or particle fabric, between the flow and the underlying immobile bed. In such cases it is common for deposition to take place by sudden or gradual freezing or immobilization of the flow. I will call this mode of deposition *mass deposition* (Figure 15-1D). This is in contrast to

deposition by gradual buildup of the sediment bed when there is a well defined sediment-water interface. Mass deposition, discussed in this section, can therefore be counterposed to what might be called *interfacial deposition*, discussed in the preceding three sections. Treatment of the various processes involved in mass deposition, and the sedimentary textures and structures of the resulting deposits, are outside the scope of these course notes. The following brief comments will have to suffice.

22 Conditions during mass deposition are difficult to observe, because 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.

23 It is my belief that mass deposition is important in two different but closely related depositional settings, both associated with sediment gravity flows:

- mass deposition *at the base of a heavily laden turbidity current*
- mass deposition by *freezing of a classical debris flow*, from the top down

Here are some brief comments about each of these settings.

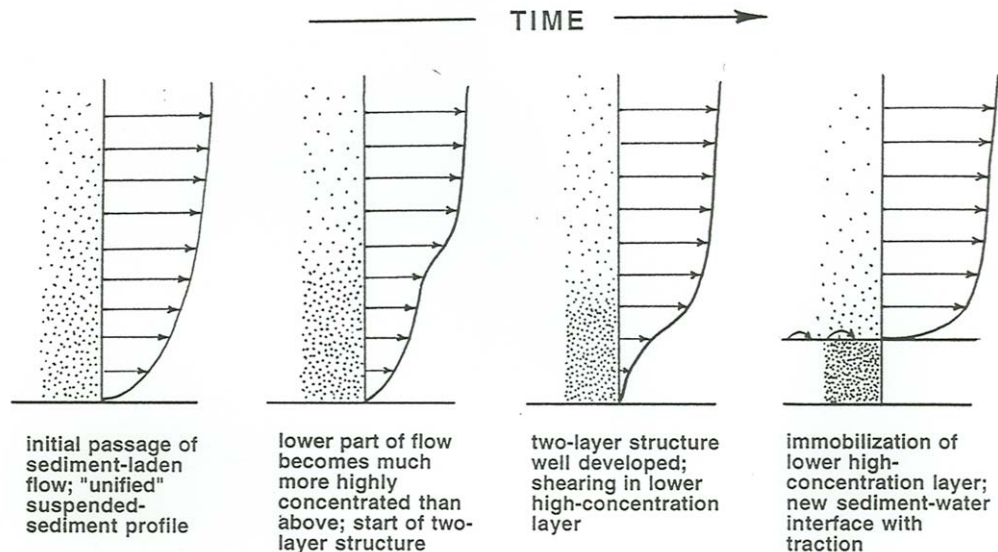


Figure 15-5. Development and immobilization of a lowermost higher-concentration layer at the base of a strong, high-concentration turbidity current.

24 When the region of the flow near the bed is overloaded with a high concentration of suspended sediment, as near the base of a large and powerful **turbidity current** carrying a high concentration of sediment both coarse and fine, the sediment settles to the bed with little space between adjacent sediment particles. 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 15-5).

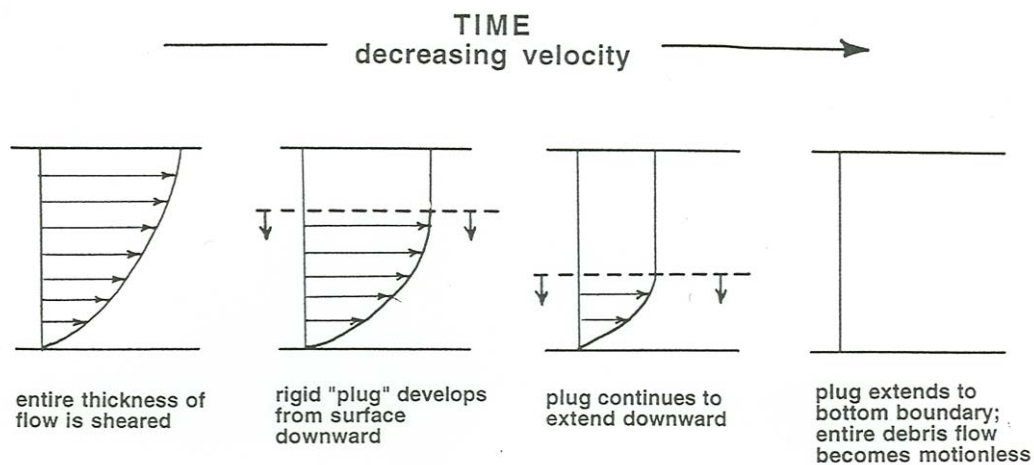


Figure 15-6. Freezing of a debris flow from the top downward, ending in complete cessation of movement.

25 During such mass deposition there is no well defined sediment–water interface; instead there is 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.

26 The other setting for mass deposition is that of a high-concentration **debris flow**, in which the sediment concentration is near the “choke point” (the maximum possible for which the sediment–water mixture can still undergo shearing without the particles locking together). The mechanical properties of a debris flow are very different from those of clear water, but the velocity profile is qualitatively the same, in that the rate of shearing increases from zero at the free surface to a maximum at the base. Note that the velocity profile is perpendicular to

the bottom boundary at the surface and becomes more and more nearly parallel to the bottom boundary with depth in the flow. This is because at deeper and deeper levels in the flow, there is a greater and greater weight of overlying fluid that drives the fluid overlying the shear plane at that level in the downchannel direction. Also, highly concentrated mixtures of sediment and water are different from clear water also by having shear strength: it takes a certain nonzero shear stress acting across the shear planes for shearing movement to take place. The consequence for thick and highly concentrated debris flows is that as the flow decelerates it freezes from the top down, and when the freezing reaches the base, the flow comes to a halt (Figure 15-6), whereafter it sits motionless and slowly dewateres.

WHY DEPOSITION OR EROSION?

Introduction

27 This section provides some background on the basic nature of deposition and erosion. Some of it might seem elementary to you, but a clear understanding of it is fundamental to a productive view of the nature of sediment deposition and erosion. In this section, I will use the terms *aggradation* for increase in bed-surface elevation during deposition, and *degradation* for decrease in bed-surface elevation during erosion.

A Broad View of Sediment Deposition

28 Take as broad a view of sediment deposition as possible (Figure 15-7): sediment is derived from a *source*, mobilized, transported along a transport path, and deposited somewhere, which you could think of a *sink*. This is simple and elegant—but there is much more here than you might assume, at first thought.

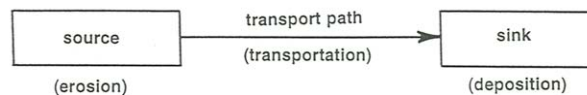


Figure 15-7. A broad view of sediment transport and deposition.

29 Sometimes the deposition is abrupt, as in the case of a Gilbert-style delta where a stream debouches into a lake (Figure 15-8A). More commonly, deposition is gradual, in a spatial sense: it is spread out over a long distance. Figure 15-8B shows a common and important example.

The Relationship Between the Load and the Deposit

30 This subsection makes some fundamental points about the relationship between the sediment load and the deposit in a depositing flow. In my opinion, this material is fundamental to understanding the texture of a deposit, although it is not likely to tell you anything really practical.

31 Obviously (but importantly), 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, as with certain kinds of debris flows. Just for convenience, I will call this ratio—unofficially—the *deposition ratio*. (Do not worry about how this ratio could be defined quantitatively.) Although you cannot read the value of the deposition ratio directly from beds in an outcrop, I think that it is one more of those things that are useful to think about as an aid in framing your interpretations.

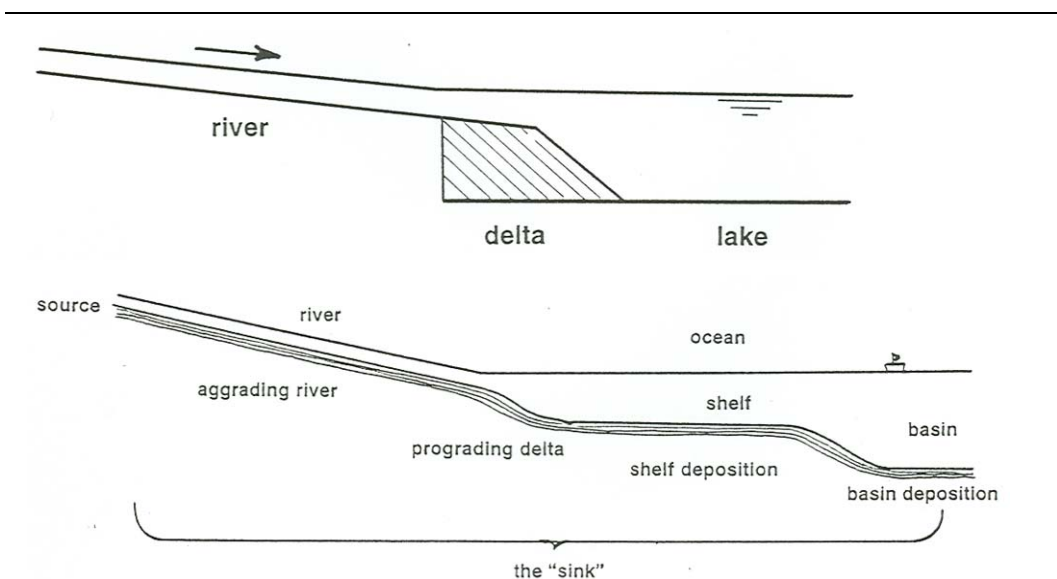


Figure 15-8. **(upper)** A river enters and lake and builds a delta. **(lower)** Spatially gradual sediment deposition along a typical transport path.

32 This section deals with the relationship between the characteristics of the sediment load and the characteristics of the deposit left by the flow. As you learned back in Chapter 13, the sediment—whether in the substrate, in the active layer, on the bed surface, or in the sediment load—always has some joint probability distribution of particle size, particle shape, and particle density. 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 is nonetheless real, and important.

33 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 is what I consider to be the most fundamental question of sediment deposition: *How does the nature of the deposit depend upon the characteristics of 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 that question first.

The Active Layer

34 There is more to the selection process than might seem to you at first thought. First I would like to divide the sediment bed into two depth zones (Figure 15-9). 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 re-entrainment by the flow as the bed elevation at any given point rises and falls as a result of local erosion and deposition that is 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 is recycled by the flow at least once by the flow before it is permanently buried. Below the active layer is the substrate, which might be called 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. (You thus have to take the word “permanent” to apply to a time that extends into the future only as far as the flow conditions remain fairly constant.)

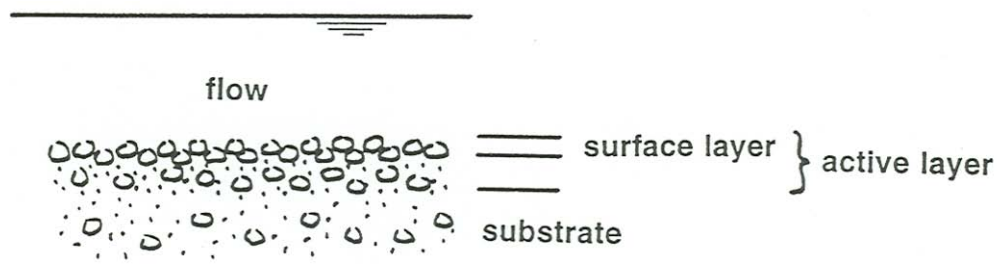


Figure 15-9. The surface layer, the active layer, and the substrate (the permanent deposit).

35 The thickness of the active layer may range from just several 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 re-erode sediment as they move downstream.

36 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, whereupon they become part of the permanent deposit. During long-term aggradation at a point on the sediment bed, the active layer rises vertically, relative to some datum buried deeply in the substrate. Sediment particles are added to the active layer from the sediment load, by way of resting at least briefly on the bed surface, and at the same time the base of the active layer rises upward through the deposit, as particles at the base of the active layer pass beyond the reach of the flow (or, in other words, as the probability of eventual re-entrainment by the flow becomes zero).

Fractionation

37 If we lived in a world of unisize (and “unishape” and “unidensity”) sediment (a boring world, for sedimentationists!), then what has gone before in this section would be all that there is to it. In the real world, however, every sediment contains a range of particle sizes, shapes, and densities, as you have seen earlier in these notes. (Here, for convenience, I will refer to fractions in the three-dimensional joint frequency distribution of size, shape, and density as “SSD fractions”.) This opens up the possibility of *fractionation*: the spatial segregation of different SSD fractions during transport and deposition.

38 The simplest kind of fractionation to understand is *lateral*: different SSD fractions can be deposited, or stored, along the “sides” of the transport path—as, for example, in overbank deposition in a river system. As a consequence, the SSF distribution of the transported sediment, which we might call the “throughput”, evolves in the downstream direction.

39 Because only a subset of the particles of the load end up becoming part of the permanent deposit, there is the possibility of *fractionation* of the various SSD fractions between the load and the deposit. Obviously, such fractionation can take place only if there is 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.

40 The fractionation can be viewed as a multi-step process, from the load, to the bed surface, to the active layer, and finally to the permanent deposit.

Figure 15-10 shows some general things about the course of this fractionation during deposition. The first step is fractionation between the load and the bed surface. As you saw in Chapter 13, most tractional flows the bed surface is coarser than the load, although that effect is most striking at weak transport rates and becomes much less at higher transport rates. The rest of the active layer, below the bed surface, is finer than the bed surface, but it can be either finer or coarser than the load. Although more work needs to be done, it seems clear that in weak flows the active layer as well as the bed surface is coarser than the load, but in strong flows carrying coarse sediment the active layer is actually finer than the load! The relationship between the active layer and the permanent deposit is still not well understood, but it does not represent the major effect in fractionation.

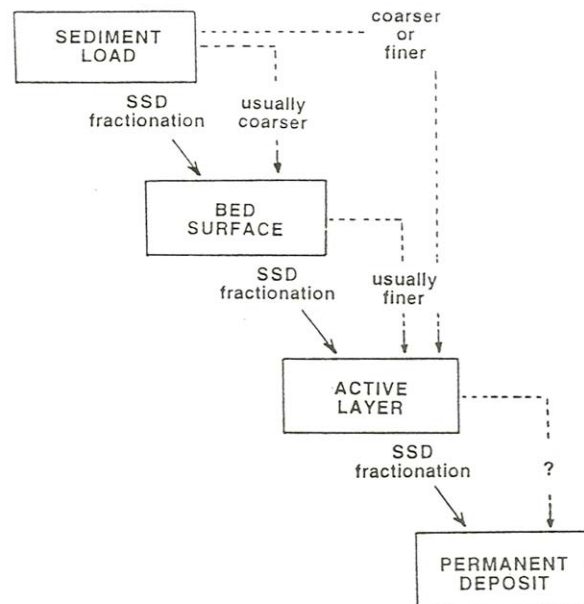


Figure 15-10 Steps in fractionation, from the sediment load to the permanent deposit.

41 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 greater than the mean size of the load. One's first reaction is that the stronger the flow, the coarser the deposit. But just the opposite is true! (The qualification here is that we are considering a

given supply of sediment that flows with a range of flow strength are constrained to carry.) Here is yet another example of how deduction or intuition can mislead us when it comes to the dynamics of sediment transport by turbulent flows.

A NOTE ON DEGRADATION

42 Up to now in this chapter the focus has been on aggradation. Degradation is also important to consider, because in a succession of deposited sediment there might be thin intervals that represent periods of temporary degradation, and the nature of the SSD distribution in those intervals can be greatly different from the rest of the succession. In particular, density fractions that are more difficult for the flow to transport might become concentrated to form an economically important placer.

43 In the context of differential transport (see the earlier section on modes of deposition), if for whatever reason the sediment transport rate *increases* downstream in a given reach of the flow the bed elevation *decreases*, causing degradation. If the flow is able to transport all of the sediment that it encounters as it eats into the substrate, then the process can continue indefinitely, for as long as the large-scale changes that cause the degradation—like base-level lowering in a river—continue to operate. If the coarsest of the transported fractions are in the gravel size range, the bed is likely to be paved (see Chapter 13), but the coarser particles that constitute the pavement can be transported by the flow, and so, although the exact nature of the pavement might change with time, degradation can continue. If, however, during degradation the flow encounters size fractions that are so coarse that it cannot transport them, then the pavement evolves into armor, and degradation ceases.