Chapter 10
DEPOSITIONAL ENVIRONMENTS

PART I: GENERAL

1. INTRODUCTION

1.1 What does a sedimentologist mean by ***environment of deposition***? The concept is not as easy to define as you might think. Basically, *what the conditions were at the site of deposition*. This is usually viewed in terms of *an overall geographical complex or entity that has a characteristic set of conditions*, like a river or a beach—but see below.

1.2 The term environment is really used in two different ways:

THE environment: the aggregate or complex of physical and/or chemical and/or biological conditions that exist or prevail at a given point or in a given local area at a given time or for a period of time.

AN environment: a distinctive kind of geographic setting characterized by a distinctive set of physical and/or chemical and/or biological conditions.

1.3 Important: you can go out and look at all the surface environments in the modern world to help you in your depositional interpretations, but you should keep in mind that *only a small subset of environments (on land, that is) are depositional environments*: most are erosional environments, and they won't help you much (and maybe even mislead you badly) about depositional environments. The somewhat strange word ***actualistic*** is used in geology to describe situations or processes that are represented on the Earth today, as opposed to non-actualistic ones, which are interpreted to have existed at a particular time or times in the past but are not represented on the modern Earth.

1.4 Table 10-1 shows a fairly detailed list of depositional environments. There are various problems with this list:

- There's *lots of overlap* among the different environments.
- It's still *not a complete list*.
- Some of the environments on the list have been much *more common and important in the sedimentary record* than others.
- The divisions are *not entirely natural*.
- The extremely important *effect of tectonic setting* is taken into account to some extent but seriously inadequately.

2. MAKING INTERPRETATIONS

2.1 Here's a seemingly obvious but important point: *interpreting depositional environments involves interpretation*. You take note of objectively observable things in the rocks, and then you use your knowledge, your experience, and your intuition to make interpretations, specific or general. You can be right in your observations and wrong in your interpretations, and you're not doing any great damage. But *if you are wrong in your observations, you are not going to be right in your interpretations*.

2.2 Don't make the mistake of mixing up observation and interpretation. Don't walk up to an outcrop and call the rock a beach sandstone or a point-bar sandstone. First of all, *describe it*, and then *add an interpretation if you want to*.

2.3 At the risk of being too synthetic, I'll point out that *two kinds of interpretation are possible* (although they are not entirely distinct):

Interpret specific conditions at a point in space and time. Example: look at geometry of cross stratification and say something about current velocity.

Interpret general conditions in a local area with time, in the framework of broad kinds of depositional environments you think you understand. Example: Look a sandstone–shale succession and decide that it represents deposits of a large meandering river.

2.4 Here's a list of what you can look for in a sediment rock or a sedimentary bed that might tell you something about depositional environment:

grain size
grain shape
grain surface texture
grain fabric
sedimentary structures
composition (siliciclastic; carbonate, evaporite, coal, chert)
fossils (body fossils, trace fossils)
stratification sequence
sediment-body geometry/architecture

2.5 What are environmental interpretations based on? Three different kinds of things, basically:

- Study of modern environments
- Inferences about the results of known sedimentary processes
- Deductions about the causes of features seen in the ancient

2.6 *It takes a lot of experience to get to be state-of-the-art in environmental interpretation,* and nobody gets really good in all environments, just some. People who are best equipped to interpret ancient depositional environments are those who have experience in modern environments but also experience in dealing with ancient rocks and sequences. It's hard to do a good job without a combination of both.

2.7 A big problem: *things that are easy to study in the modern are hard to study in the ancient, and vice versa*. In the modern, it's fairly easy to observe currents and study areal distributions of sediment types at the sediment–fluid interface, but it's difficult or impossible to study vertical sequences. In the ancient it's impossible to study directly the depositing medium (although inferences can be made), and it's usually difficult or impossible to get an areal view of the depositional surface; on the other hand, it's easy to study the vertical sequence.

3. FACIES AND FACIES MODELS

3.1 You should be familiar with the idea of *facies*. It's a word that has had a long and varied use in sedimentology and stratigraphy, and I won't attempt to review its history here. I'll use the term ***facies*** for a *distinctive kind of sedimentary deposit, which was deposited in a distinctive setting*. Usually a stratigraphic section shows a small to large number of facies, stacked up with some degree of order or succession. This degree of order ranges from seemingly nonexistent to strikingly strong, depending on both the inherent succession of conditions in the depositional environment and the existence of diastems in the record.

3.2 It's your task to recognize or perceive or establish the facies. There is no official list. Usually there are naturally recognizable kinds, with variations on a theme, although commonly what you are inclined to call different facies grade into one another without strong breaks.

3.3 Also, keep in mind that *there are many criteria you could use to recognize facies*, so different people, with different interests, may come up with rather different lists of facies.

3.4 Finally, how many facies you prefer to work with depends on whether you tend to be a "lumper" or a "splitter". There is usually some happy medium: if you are too much of a lumper, you have too few facies to reflect the major aspects of variety in the environment; if you are too much of a splitter, you end up with a confusion of only slightly different facies which do not reveal the major aspects of variety in the environment.

3.5 How do you deal with facies on the outcrop? At the risk of being too prescriptive or "cookbookish", here is a set of steps you might take:

- Cruise up and down the section a few times, slowly, examining it bed by bed.
- Let ideas about facies grow in you mind.
- Develop a tentative list of facies.
- Refine the list by looking at the section again.
- Describe your facies.
- Record the vertical succession of facies in the section, in case that might reveal some characteristic kind of upward transition.
- Think carefully about the environmental significance of the facies and their succession.

3.6 This is a good place to say something about ***facies models*** or ***depositional models*** (and make a warning about their use). Over the years, *various general models of how certain depositional environments work have been developed*. This involves a distillation of the facies and facies successions in a number of related environmental settings into a widely applicable model, which, with variations, helps you to categorize your own section.

3.7 The danger about facies models is that only a few have been well worked out, and you may end up trying to fit your square-peg depositional environment into a round-hole facies model, and doing more harm than good.

4. MARINE OR NONMARINE?

4.1 The broadest, and probably the most important, question of environmental interpretation that confronts you when you look at rocks is this: **Are the rocks marine or nonmarine?** If you don't know that, how can you speculate about specific settings? Below are some guidelines for your consideration. Again I don't want to be too cookbookish about this, but an annotated list seems advisable. *None of the items on this list is infallible* (although the first is about as close to it as you're going to get in sedimentology); consider these items to be pieces of evidence that can sway your opinion, without really proving anything.

Marine fossils

Your best bet is to *find marine fossils*. Of course you might ask: How does one know that fossils considered marine fossils really represent organisms that lived in the ocean? You can safely consider that to be a settled matter. Then it's up to you to identify the fossils. Don't forget that trace fossils are as useful as body fossils in this regard. You usually don't have to worry about marine fossils being reworked from earlier deposits and incorporated into a nonmarine deposit, and vice versa, although it's possible.

Carbonate rocks

There are some fresh-water limestones around (and some fresh-water dolostones, too), but most of the carbonate rocks you are likely to see are marine. This is a suggestive piece of evidence, but clearly it's not definitive.

Red beds

Red beds are rocks (usually sandstone–shale successions) in which at least the finer sediments, if not the coarser, contain a small percentage of hematite, a potent rock pigment that imparts the characteristic red color. The origin of the hematite pigment has been controversial, but it's widely agreed that the iron gets in the sediment at the time of burial detritally as hydrous ferric oxides which later, during early diagenesis, get converted to hematite, provided that there is not so much organic matter to be oxidized that the iron ends up in the ferrous state. That's far more likely to happen in nonmarine, especially fluvial, environments than in marine environments, so red beds are good suggestive evidence of nonmarine deposition. But again there are important exceptions.

Evaporite chemistry

If your succession contains evaporite minerals, you can often make a good case for marine or nonmarine on the basis of the suite of evaporite minerals present. As you learned in the earlier chapter on evaporites, the ionic composition of sea water changes very little, so there's a rigorous regularity in the evaporite minerals formed. On the other hand, evaporites in nonmarine basins, which usually have closed drainage, can vary widely in their chemical composition, because the salt content depends atr least in part on what's weathered out of the particular source rocks and carried into the basin.

5. PALEOFLOW INTERPRETATION

5.1 Probably the most important kind of specific environmental interpretation you can try to make is to figure out the nature of the depositing fluid flow. (Most. but not all, sediments are deposited by flowing fluids.) This deals with some possibilities for making paleoflow interpretations by examining ancient clastic sedimentary sequences. When such interpretations can be made, they serve as guides or constraints in framing a broader picture of the depositional environment. The possibilities for making such interpretations are numerous and varied, but nonetheless they are still limited. Further work is going to reveal a lot of useful interpretive approaches based on features of beds we still don't know how to interpret.

5.2 This section has a practical approach: the focus will be on what you can actually do, or try to do, when you are on the outcrop. The philosophy here is to examine a sedimentary succession bed by bed to try to draw conclusions about water movements, transport modes, and overall sediment budget, to the extent possible. The sedimentary record holds many keys to the interpretation of these aspects of the depositional environment. Sedimentologists have a good understanding of some of these keys, and these will be emphasized here. There must also be many other features of sedimentary beds which have potential for interpretations but we don't yet know how to interpret them.

5.3 Other kinds of interpretive approaches can be brought to bear on sedimentary sequences as well. One can consider the whole complex of sedimentary features and arrangements of a deposit, with the hope of applying or developing a broad depositional model which more or less closely describes the overall depositional environment. (That's what the earlier section of this chapter, on facies models in general, and the last section of this chapter, on specific environments, are about.) Many such models have been developed. Two outstanding examples are the meandering-river model and the submarine-fan model. One danger of such an approach is that a complex and distinctive depositional environment is unnaturally fitted into an inappropriate model.

5.4 My own preference is to try to make small-scale interpretations first, and then use those results as constraints on the choice of a broad depositional model. In a certain sense, to do otherwise is to put the cart before the horse. In some cases, one is forced to conclude or admit that the small-scale results don't add up to any of the standard depositional models. This might be because not enough small-scale information can be obtained, or because we don't understand its significance well enough. But keep in mind that you may be looking at a nonactualistic environment, one that's not even represented on the modern Earth! This is especially true of lower Paleozoic and older deposits, before land plants changed the face of the Earth.

5.5 The main kinds of features of beds you can study are *stratification, texture, bed thickness, bed geometry, and nature of contacts*. Of these, stratification offers the most valuable possibilities for interpretation. Fundamentally this is because stratification is a fairly direct reflection of the bed configuration that existed at the time of deposition, and, as you learned in an earlier chapter, the bed configuration varies greatly as a function of flow conditions. On the other hand, texture has always been considered to hold great interpretive potential, but we don't yet know very well how to make interpretations from textural features. Bed thickness and bed geometry are more difficult to interpret because they reflect aspects of the depositional environment on a scale which to a great extent is broad or regional rather than local.

5.6 This would be as good point at which to go back to the earlier chapters on particle size and, especially, on bed forms and stratification to review the potential "fodder" for paleoflow interpretations. Below are just two additional matters that you should be aware of.

cross stratification: It is all to easy to walk up to an outcrop with a cross-stratified bed and measure the direction of dip of the cross-strata, and then assume that the result is a good indication of the overall paleoflow direction. The problem is that in most cases the geometry of the cross sets is far from being uniformly dipping planar strata. You saw that in the earlier sections on small-scale trough cross-stratification and large-scale cross stratification generated by the movement of three-dimensional dunes. At the very least, you need to take a large number of dip measurements in a way that is unbiased by the geometry of the outcrop surface itself—commonly an impossible task in practice. Rib and furrow, although uncommon to see in outcrop, is the very best way of obtaining a paleoflow measurement from cross stratification.

parting lineation: Commonly, when a sandstone parts along a stratification plane, there is a subtle (or often not so subtle) "grain" or anisotropy of the parting surface, in the form of irregular steps, all approximately parallel, and usually only a fraction of a millimeter in height, which reflects an anisotropy in rock strength caused by preferential alignment of the sand grains parallel to the paleoflow. It's is often called, alternatively and more accurately, ***parting-step lineation***. Presumably, it's a reflection of upper-regime plane-bed transport.

PART II. SPECIFIC ENVIRONMENTS

1. FLUVIAL ENVIRONMENTS

1.1 Introduction

1.1.1 Rivers are the main routes by which sediment derived from weathering on the continents reaches the ocean. (Remember that this sediment includes dissolved material as well as particulate material; the discussion here deals only with the particulate material.) Most of this sediment indeed reaches the ocean, but a certain smaller percentage is deposited either within the rivers themselves or where rivers end in basins of interior drainage.

1.1.2 In a sense such storage is temporary, in that it eventually is remobilized in a later geologic cycle, but commonly it is stored for geologically long times, tens to hundreds of millions of years and sometimes even billions of years—long enough for it to be deeply buried and lithified, even metamorphosed.

1.1.3 Rivers are enormously varied, in size, geometry, and dynamics. When someone speaks of rivers to you, what image comes to your mind? A rushing mountain stream? The broad and placid Mississippi? These are only two of a great many common manifestations of rivers. So it should not surprise you that fluvial sediments and sedimentary rocks are highly varied as well.

1.1.4 It's usually considered that most rivers are either meandering or braided; straight rivers are not very common. But meandering and braiding are not mutually exclusive tendencies: either or both can be in evidence in a given river, with each with varying degrees of prominence. And both meandering and braiding show great diversity. This should suggest to you that it's not easy to compartmentalize the sedimentological behavior of rivers into a few neat models.

1.1.5 Meandering rivers lend themselves to fairly easy description or characterization, and a widely accepted facies model for the deposits of meandering rivers has been around for a long time. Braided rivers are much more variable and less easy to characterize; there have been attempts to develop facies models for braided rivers, but these have not been nearly as successful or widely used as the meandering model.

1.1.6 This is not the place to present an account of the dynamics and geomorphology of rivers, although I want you to appreciate that understanding of the *geomorphology* of rivers is crucial to understanding and interpretation of fluvial deposits. The major factor in how a fluvial deposit looks is the geomorphology of the river: the arrangement of channels and overbank areas, and how they change with time during slow buildup of the floodplain. All I'll do here is present some basic things about fluvial deposition and fluvial deposits, and then outline the meandering fluvial model, with appropriate caveats on its application.

1.1.7 Keep in mind that the same problem of the modern versus the ancient that holds for marine deposits holds for fluvial deposits as well: It's relatively easy to study sediment movement and disposition in modern rivers, but it's rather difficult to study the vertical sequence of deposits, because of the generally high water table. In ancient rocks, on the other hand, it's easy to study the vertical sequence of deposits, but it's usually impossible to establish the geomorphology of the depositing river itself.

1.2 Why Are There Fluvial Deposits?

1.2.1 It's not obvious why fluvial deposits are an important part of the ancient sedimentary record. After all, rivers drain areas of the continents that are undergoing erosion. It's true that most rivers, except the smallest, are *alluvial* rivers: they have a bed, and a floodplain, composed of their own sediments. But in most cases this alluvial valley sediment isn't very thick. Only in certain cases does the alluvial valley fill become thicker.

1.2.2 Two effects are conducive to deposition in rivers: *progradation* and *crustal subsidence*.

Progradation. As a river wears down the land and delivers sediment to the sea, the mouth of the river builds seaward (Figure 10-1). Because the longitudinal profile of a river is anchored by base level at the mouth, this means that there has to be a slight upbuilding in the lowermost reach of the river. This may not seem like a big effect, but even a hundred meters represents a lot of sediment.

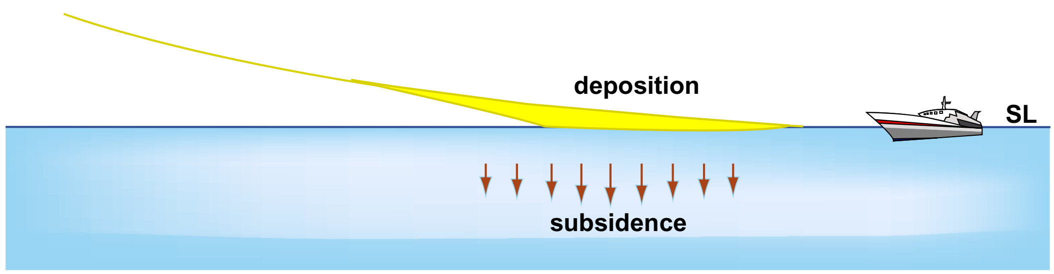

Figure by MIT OCW.

Figure 10-1: Deposition by seaward progradation in the lower reaches of a river system

Crustal subsidence. The only way to get a really thick sequence of fluvial sediment is to drop the crust beneath the river (Figure 10-2). As this happens, slowly, along some reach of the river, there develops a very slight expansion of flow and a decrease in flow velocity and therefore in sediment-moving ability. Just by simple bookkeeping, this must lead to sediment storage along the river: if what comes into a given area of the bed is greater than what goes out, sediment is stored in that area, and the bed builds up. From an anthropomorphic standpoint, the river tries to maintain its longitudinal profile while the bottom drops out from under it, and it does so by leaving a little of the passing sediment to build up its bed.

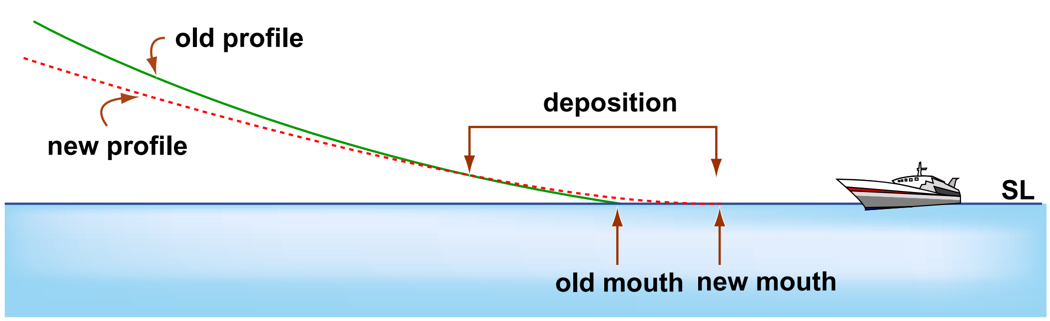

Figure by MIT OCW.

Figure 10-2: Deposition by crustal subsidence in the tower reaches of a river system

1.3 How Do You Know It's Fluvial?

1.3.1 By what criteria might you tell that a sedimentary sequence is fluvial? Here are some, but remember that none is incontrovertible, because each applies to other environments as well.

absence of marine fossils
presence of plant fossils
red beds
scoured channels
unidirectional-flow cross-stratification
broadly unidirectional paleocurrents
paleosols
desiccation cracks
plant fossils

1.4 The Meandering-River Facies Model

1.4.1 Rivers carry mud, sand, and gravel. In meandering rivers, sand (and some gravel) is stored in channel beds and especially in point bars, and mud is stored in floodplains. So *meandering-river deposits end up as large sand bodies, shaped like lenses and shoestrings, partly connected but often mostly isolated from one another, enclosed in mud*. (In braided rivers, sand and gravel in various proportions becomes interbedded very irregularly in lenses, sheets, and channels as the individual anabranches of the stream system shift irregularly and leave bars and islands.) Figure 10-3; Walker, R.G., and Cant, D.J., 1984, Sandy fluvial systems, in Walker, R.G., ed., Facies Models, Second Edition: Geological Association of Canada, Geoscience Canada Reprint Series 1, 317 p. (Figure 1, p. 72); shows a simplified sketch of the plan-view arrangement of a typical meandering river.

1.4.2 With time, an individual meander loop tends to become "loopier" or more accentuated by outward progradation of the point bar and erosion along the concave or outer bank. At the same time the entire meander loop tends to shift downvalley. Often you can see low curving ridges, called ***meander scars*** or ***meander scrolls***, inside the meander loop that record the earlier positions of the point bar.

1.4.3 As time goes one, the meander loop also narrows at its neck. Eventually during some flood the river breaches the neck and straightens itself by establishing a new course across the neck, thereby abandoning the meander loop. This process is called ***neck cutoff***. The ends of the abandoned loop soon become plugged by fine sediment to form an oxbow lake. The floodplains of meandering rivers show a complex pattern of several generations of truncated meander scars and partly or wholly filled oxbow lakes recording a long history of meandering.

1.4.4 Every now and then, probably during a really big flood, the river breaks out completely from its meander belt to reestablish its course along some distant lower part of its floodplain, leaving the entire meander belt to be eventually filled and covered by fine floodplain sediment. Such a catastrophic change in course is called ***avulsion***.

1.4.5 In a subsiding reach of a meandering river, the shifting and abandonment of meander loops (and, every now and then, of the whole meander belt) leads to a characteristic vertical arrangement of sand bodies encased in floodplain muds. This is because the sand carried in the main channel is deposited on the sloping surfaces of the point bars as they accrete laterally, and is then left as an irregular but not grossly inequidimensional mass whose thickness is about the same as that of the bankfull depth of the river. Such deposits are called ***lateral-accretion deposits*** (Figure 10-4).

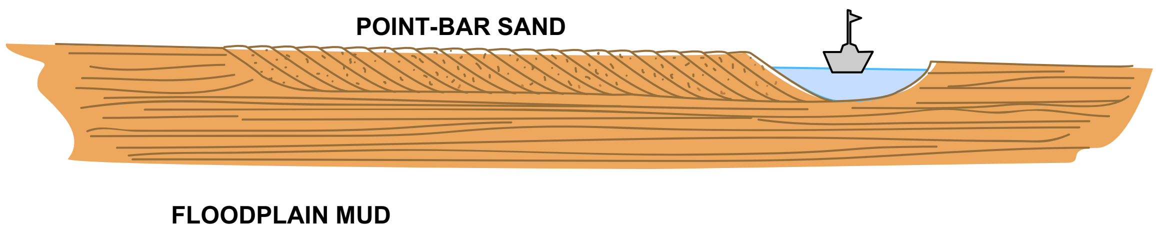

Figure by MIT OCW.

Figure 10-4: Cross section through a point bar, normal to the local course of the river

1.4.6 Sometimes you see a kind of large-scale low-angle cross stratification, reflecting the channelward slope of the point-bar surface, produced by the episodic accretion onto the point bar-surface (it's called, infelicitously, ***epsilon cross stratification***), but usually such cross stratification is masked by the smaller-scale structures (planar lamination and especially large-scale cross stratification) produced by sediment movement on the point-bar surface.

1.4.7 As the channels shift to leave point-bar sand bodies while the floodplain gradually builds up by deposition of muds (called ***vertical-accretion deposits***), a characteristic three-dimensional arrangement of sand bodies surrounded by muds is formed. The geometry of such a fluvial deposit is termed ***alluvial architecture***. Figure 10-5 is a simplified sketch.

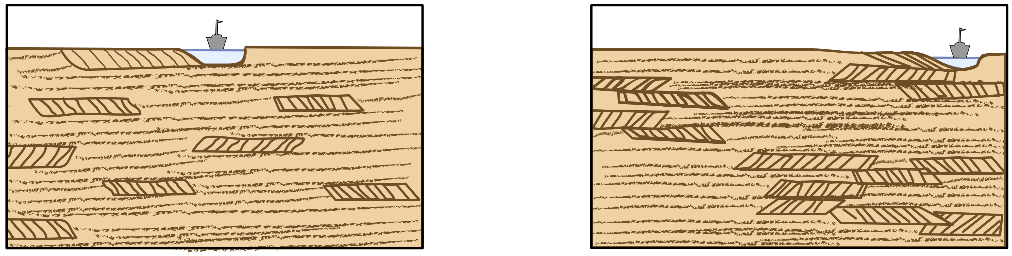

Figure by MIT OCW.

Figure 10-5: Sketch of the disposition of point-bar sand bodies (“alluvial architecture”) in a fluvial deposit left by a meandering river in an aggrading regime. Left: aggradation rate high relative to rater of lateral shifting. Right: aggradation rate low relative to rate of lateral shifting

1.4.8 What you are likely to see in outcrop is one or a few point-bar sand bodies, restricted in lateral extent, interbedded with muds. If you are lucky, you will see some epsilon cross stratification to suggest lateral accretion on a point-bar surface, and/or termination of the point-bar sand body against muds as a record of channel abandonment by cutoff. Only by wider mapping of favorable outcrops, though, can you perceive something of the architecture of the deposit as a whole.

1.4.9 One of the biggest problems in dealing with fluvial deposits that are interbeddings of sands and muds is telling whether a given sand body is the result of lateral accretion of a point-bar surface or widespread deposition of a sand sheet by non-channelized flood water. In the one case, deposition is incremental and local, and in the other case it’s all at once and widespread. The only way to know for sure is to see evidence of lateral accretion, like epsilon cross stratification or channel abandonment, and you are usually not that lucky. Usually you have to fall back on the idea that if the sand body is very thin, less than a meter or two, it was probably a sheet-flood deposit, whereas if it's thicker, it’s likely to be a point-bar deposit.

2. SEDIMENT GRAVITY FLOWS AND THEIR DEPOSITS

2.1 Introduction

2.1.1 ***Sediment gravity flows*** are *turbulent flows of sediment–fluid mixtures which are driven by the downslope component of the excess density of the mixtur*e. This is not an entirely satisfactory definition, and some words of explanation are in order.

2.1.2 The sediment–fluid mixture flows beneath a body of fluid, usually taken to be sediment-free; the density of the sediment–fluid mixture is greater than that of the overlying fluid, and that’s what provides the downslope driving force. One of the intentions of the definition is to exclude rivers from the concept; after all, rivers are downslope flows of sediment–fluid mixtures under gravity, so why aren’t they sediment gravity flows? But rivers flow even if they carry no sediment, whereas the presence of sediment is essential to the existence of sediment gravity flows.

2.1.3 Another sticky point about the definition is that in grain flows, universally considered to be one kind of sediment gravity flow, a sheared dispersion of sediment particles moves downslope under the pull of gravity *without the necessary presence of fluid at all*, either interstitial or supernatant. There can be grain flows even in a vacuum! But for almost all the sediment gravity flows of sedimentological interest, the concept is clear and useful.

2.1.4 Relatively small turbidity currents have been observed and studied in lakes and reservoirs since late in the nineteenth century, but the existence of large marine turbidity currents came to light only by deductions made by geologists about features seen in the ancient sedimentary record. Soon after the existence of large marine turbidity currents was hypothesized, instances of their occurrence in recent times were recognized and studied, and small-scale laboratory experiments (mainly by geologists!) to study their motion and deposits, together with the evidence from the ancient, convinced most geologists of their existence and importance. Interpretation of turbidity-current deposits was well established by the early 1960s.

2.1.5 Recognition of more "exotic" sediment gravity flows, which would generally be classified as *submarine debris flows*, was longer in coming. Although subaerial debris flows were well known, it was not until the 1970s that the concept of submarine debris flows was widely invoked to explain the coarse, poorly sorted, and seemingly deep-marine deposits so common in the sedimentary record. Even now our understanding of the dynamics and depositional effects of debris flows does not match that of turbidity currents. Many important questions, among them the following, remain unresolved:

- What's the nature of flows transitional between turbidity currents and debris flows?
- At what rate do sediment gravity flows lose sediment by deposition as they move?
- How does one distinguish between slowly deposited and rapidly deposited sediment-gravity-flow deposits?
- More generally, how does one interpret the nature of the sediment gravity flow from the record of the deposit?

2.2 Dynamics

2.2.1 This is not the place for detailed consideration of the dynamics of sediment gravity flows; I'll just make some brief comments. Sediment gravity flows are generated, flow for some distance, and eventually dissipate by deposition of the sediment. The origin of sediment gravity flows is their least well understood aspect: one has to appeal to the existence of unstable sediment resting on some slope, and its mobilization by either spontaneous failure or some sudden or cyclic disturbance like shaking by an earthquake or repeated loading and unloading by passage of surface water waves. If the sediment is sufficiently rich in water, liquefaction by rearrangement of grain packing can provide mobility without introduction of additional water, but for the thinner kinds of sediment gravity flows one might have to invoke initial incorporation of water from above as the movement starts.

2.2.2 Sediment gravity flows accelerate and then decelerate again, but for most of their history this acceleration and deceleration is small, and the motion is nearly uniform. There is thus an approximate balance between the driving force, the downslope component of the excess weight per unit volume of the mixture, and a resisting frictional force, exerted mainly by the substrate on the bottom of the flow but also by the overlying fluid on the top of the flow.

2.2.3 The motion of sediment gravity flows, described briefly below, is an outcome of the interplay among three factors: the downslope component of excess weight, which acts throughout the flow; the resisting forces exerted at the upper and lower surfaces; and the local resistive properties of the mixture, which can be characterized, approximately at least, by its viscosity (to the extent that it behaves as a fluid) and its shear strength (to the extent that it behaves as a plastic). Except in a very simplified way, it’s not even possible to write down the governing equations of motion, let alone solve them, largely because of the problem of deciding upon the basic mechanical nature of the material in order to write down what are called the constitutive equations, which relate the deformation to the applied stress. So any treatment of the motions of sediment gravity flows, overall and internal, must still be semiquantitative at best.

2.3 Classification

2.3.1 Classification of sediment gravity flows is based on *the nature of the mechanism or mechanisms by which the sediment is kept supported in the flow*. There are considered to be four such mechanisms:

fluid turbulence
matrix strength
dispersive grain collisions
fluidization

2.3.2 Sediment gravity flows are accordingly classified into four kinds (with various intergradations) on the basis of the dominant support mechanism:

Turbidity currents (mainly *fluid turbulence*; grain dispersion might be important near the base, and fluidization by dewatering of deposits from an earlier part of the same turbidity current is certainly important in many cases)

Debris flows (mainly *matrix strength*; fluid turbulence is presumably important in less concentrated debris flows, and I myself am inclined to think that there is a continuous gradation from turbidity currents to debris flows)

Grain flows (*grain dispersion*; fluid turbulence may contribute to grain support in some grain flows)

Fluidized flows (*fluidization*—that is, the suspension of sediment from uprise of fluid from a source below the flow)

2.3.3 Fluidized flows, except as part of a turbidity current, are not considered to be of great sedimentological importance. Turbidity currents and debris flows are certainly important. The role of grain flows has been controversial: some see them everywhere, whereas others think that except for very local situations, like the avalanche faces of dunes, they are not of great sedimentological importance. No one has yet gotten a good "handle" on grain flows, in the sense that they have developed widely accepted criteria for their recognition in sedimentary deposits.

2.3.4 Figure 10-6 shows the standard diagram, originating with G.V. Middleton in the early 1970s, showing classification of sediment gravity flows.

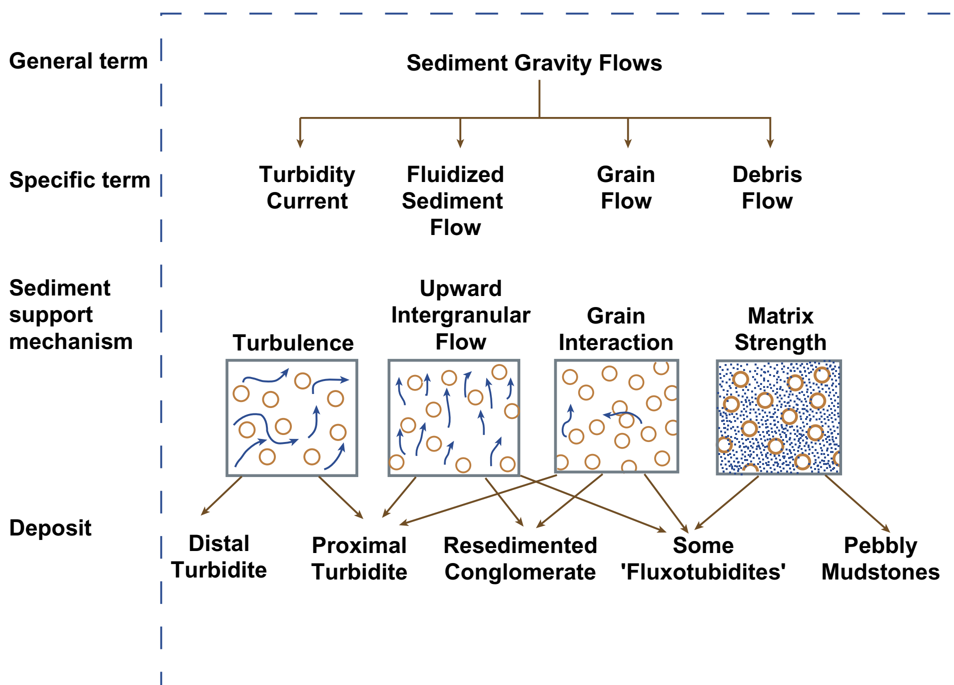

Figure by MIT OCW.

Figure 10-6: Classification of sediment gravity flows

2.4 Motion

2.4.1 All the sediment gravity flows I have seen, or have seen movies of, have a fairly well defined *head* or *front*, where the flow is thickest and where velocities are highest, and a long *body*, and a *tail*, where velocities are lower (Figure 10-7; Walker, R.G., 1984, Turbidites and associated coarse clastic deposits, in Walker, R.G., ed., Facies Models, Second Edition: Geological Association of Canada, Geoscience Canada Reprint Series 1, 317 p. (Figure 1, p. 171)). The implication of this is that sediment gravity flows tend to be dispersive: the head outruns the tail, and the flow stretches out and becomes more diffuse as it flows. Debris flows sometimes show pulses of more active movement along their length: the flow thins and slows or even stops for a while, and then thickens and speeds up again as a pulse from upstream moves by.

2.4.2 Sediment gravity flows may at first incorporate more sediment, by erosion of the substrate, but even if they do (and presumably some are depositional almost from the beginning), when they reach a gentler slope they eventually lose sediment by deposition and therefore weaken. The velocity picture in sediment gravity flows is thus complicated: velocity varies both along the flow at a given time, and with time at any point that's followed along with the flow. Of course, at any point on the bottom the velocity increases and then decreases as the flow passes by.

2.4.3 The state of internal motion in sediment gravity flows is complex and varied. The low-concentration kinds of sediment gravity flows, like turbidity currents, are certainly *turbulent*, whereas the higher-concentration kinds of sediment gravity flows, like debris flows, tend to be *laminar*. Relatively low-concentration sediment gravity flows behave approximately as Newtonian fluids, but relatively high-concentration sediment gravity flows must be non-Newtonian; in fact, very high-concentration flows are thought to have ***matrix strength*** (meaning that *the applied shear stress must reach a certain value before the mixture starts to deform by shearing*), so they may behave as *plastics*.

2.4.4 Matrix strength is significant for the flow behavior of debris flows: in the interior of the flow, where shear is least, there is likely to be a *rigid plug*, and as the flow decelerates and the shear within the flow becomes weaker, the rigid-plug zone expands upward and downward, until the flow grinds to a halt by total rigidification. Many lower-concentration debris flows can be seen to be turbulent, however, so matrix strength must be a much less important effect in them.

2.5 Sediment-Gravity-Flow Deposits

2.5.1 ***Features.***—Most sediment-gravity-flow deposits are ***event beds***: relatively coarse beds, sandstones or conglomerates, underlain and overlain by finer deposits, siltstones and mudstones. They are mostly marine, although lacustrine sediment-gravity-flow deposits are of non-negligible importance.

2.5.2 The lower contacts of sediment-gravity-flow beds are almost always sharp, and often erosional, reflecting the initially very strong current. Upper contacts are usually gradational, although the gradation is often complete over a small thickness, of the order of a centimeter. Normal grading is characteristic of turbidity-current deposits, reflecting temporal decrease in current velocity, and therefore size of sediment carried. Inverse grading is common at the base of both turbidity-current deposits and debris-flow deposits; the mechanics of its development is not clear.

2.5.3 Thickness of sediment-gravity-flow deposits ranges from a few millimeters, in the case of feather-edge distal turbidites, to well over ten meters, in the case of deposits from the largest debris flows or flows intermediate between turbidity currents and debris flows.

2.5.4 Sediment-gravity-flow deposits range from well stratified (as in most turbidity-current deposits), to wholly nonstratified (as in many debris-flow deposits). Structures range from nonstratified through parallel-laminated to cross-stratified, usually but not always on a fairly small scale; soft-sediment deformation is common as well. Because sediment-gravity-flow deposits are deposited rapidly, you might expect them to have rather loose packing and excess pore water; dewatering structures, mainly dish structures and vertical pipelike structures, are common.

2.5.5 ***Interpretation***.—How do you know that you are dealing with a sediment-gravity-flow deposit? Remember that it's always an interpretation, because it's a matter of genesis rather than just description. You have to use some or all of the above features, and more, to make that kind of interpretation on the outcrop. The broader stratigraphic context (what's the overall nature of the section?) is also useful in making such an interpretation. You need practice on the outcrop.

2.5.6 ***The Bouma Sequence.***—Working on turbidites in Spain in the late 1950s, the Dutch (now American) sedimentologist Arnold Bouma perceived *a characteristic vertical sequence of sedimentary structures in turbidites*, which he thought to reflect the temporal sequence of depositional conditions at a point on the bed as the turbidity current flowed by and deposited sediment from a waning current. Since then this sequence has been called the ***Bouma sequence***. (It's unusual for someone to be so immortalized even before one's death!) The distinctive parts of this sequence are called *divisions*; Bouma designated them A through E.

2.5.7 Figure 10-8; Walker, R.G., 1984, Turbidites and associated coarse clastic deposits, in Walker, RG., ed., Facies Models, Second Edition: Geological Association of Canada, Geoscience Canada Reprint Series 1, 317 p. (Figure 4, p. 173); is a sketch of a representative turbidite showing a complete Bouma sequence, followed by a brief account of the genesis of the various divisions, according to modern interpretation.

A division (coarse nonlaminated): rapid deposition of the coarsest sediment, involving sediment accumulation near the bed and then dewatering, as the current first passes; absence of lamination reflects nonexistence of a well defined sediment–fluid interface upon which traction takes place.

B division (parallel-laminated): High-velocity flow over a well defined sediment–fluid interface; abundant fallout of sediment from suspension, followed by active traction; the bed phase is high-velocity plane bed.

C division (rippled): Lower-velocity flow over a well defined sediment fluid interface; abundant fallout of sediment (commonly very fine to fine sand) from suspension, followed by active traction; the bed phase is ripples. Climbing-ripple cross lamination is produced by downcurrent movement of the ripples in the presence of overall aggradation of the bed by sediment fallout.

D division (draped fine sediment): delicate interlamination of very fine sand, silt, and mud draping the underlying tractional deposits; draping of sediment results from fallout while the current is not strong enough to produce traction.

E division (residual mud): deposition of mud brought into the area by the turbidity current and left behind as the turbidity current passed by; deposition is from very slowly moving fluid, and leaves no structures. The turbidite mud passes gradually up into interturbidite "background" mud.

2.5.8 Here's something extremely important to remember about the Bouma sequence: *it's a distillation of observations of a large number of turbidites, and most turbidites show deviations from it*. This is only to be expected, because all three of the factors that govern the vertical sequence of grain size and structure within a turbidite (current velocity, bed aggradation rate, and size of deposited sediment) can vary independently of one another. There's an infinity of possible temporal sequences of variation of these three factors, and each produces a different vertical sequence.

2.5.9 It was recognized long ago that the characteristic sequence (as well as the thickness and mean grain size of the bed) varies as one passes from the *proximal* to the *distal* depositional area. Proximal turbidites are likely to show lots of ABC beds, or AB beds, or even just A beds. More distal beds might be expected to be BC beds, or BC beds or just C beds. (The D and E are left out here, because they are seldom prominent except in sometimes in distal beds.) But even this is too superficial: the mechanics and microenvironments of turbidite deposition are so varied that a great variety of combinations of thickness, grain size, and structure sequence can be found. Some of this variability can be accounted for by what's known about how turbidity currents work in natural environments, but a lot hasn't been rationalized very well.

2.5.10 A particularly important example of the foregoing point is this: one often sees thin but coarse sediment-gravity-flow beds showing evidence of strong traction in the form of planar lamination. The natural assumption is that such beds record passage of strong turbidity currents through channels in the proximal to intermediate environment, with each turbidity current leaving little or even no deposit. In such situations large-scale cross stratification, so uncommon in "classical" turbidites, is not uncommon as well. One assumes that the sediment (presumably abundant) that passed by the given point was deposited as thicker but finer beds downslope.

6.5.11 ***Submarine Fans.***—It stands to reason that the deposit formed by repeated sediment-gravity-flow depositional events at the base of a submarine (or lacustrine) slope would be *broadly fan-shaped or cone-shaped*—although outcrop in the ancient is seldom if ever good enough to pin down the three-dimensional geometry of the fan. On the other hand, submarine fans, large and small, are well known in the modern; marine geologists have been studying their geometry and surface sediment for many years. (But it's almost as difficult to study the thick vertical succession of deposits in a modern fan as it is to study the geometry of an ancient fan.) Nowadays, sophisticated seismic reflection techniques allow great insight into the innards of deeply buried submarine fans

2.5.12 During the 1970s, Italian sedimentologists were active in developing a model for the deposition of sediment-gravity-flow deposits as ***submarine fans***. That work drew mainly upon studies in the ancient, but other sedimentologists later integrated that model with what's known about modern fans.

2.5.13 Keep in mind that, as with any depositional models, application of the submarine-fan model involves a certain leap of faith, because there's nothing from the outcrop that tells you directly that you are dealing with a fan, only indirectly.

2.5.14 How do submarine fans operate? There is good evidence from the modern that the sediment gravity flows are usually carried by *a* network of distributary channels, which change and shift irregularly with time (Figure 10-9; Stow, D.A.V., Reading, H.G., and Collinson, J.D.,, Deep Seas, in Reading, H.G., ed., Sedimentary Envbironments; Processes, Facies and Stratigraphy, Third Edition: Blackwell Science, 688 p. (Figure 10.46, p. 430, and Figure 10.51, p. 432)). Some aspects of this change are closely analogous to meandering of surface rivers, and some aspects are closely analogous to braiding of surface rivers. The essential similarity between alluvial fans and submarine fans is that upbuilding is localized on one part of the fan for a long while, until the channelized flow breaks out at some point to seek a lower elevation on some other part of the fan that hasn't been active for a long time.

2.5.15 The irregular shifting of distributary channels on a fan surface gives rise to a signal in the event-bed succession, whereby some parts of the section consist mostly or entirely of coarse event beds (this represents the active upbuilding of the fan by the channelized flow) and other parts of the section consist mostly of finer background deposits (this represents interchannel or overbank deposition away from the areas of active upbuilding by channelized flow).

2.5.16 Packets of event beds in the submarine-fan setting often show a tendency, subtle or pronounced, for thickening and coarsening upward, or thinning and fining upward. Such packets are typically several meters to a few tens of meters thick. The model accounts for this by assuming that as a new area of the fan is being constructed, the event beds become thicker and coarser for two reasons: the new distributary channel gathers discharge slowly, and the local environment becomes more proximal as the deposit progrades. On the other hand, if flow in a given distributary channel is gradually choked off, the sequence of event beds would show a tendency to be thinner and finer upward.

2.5.17 The submarine fan model has been refined to the point where many sub-environments are recognized. I won't elaborate except to mention three such sub-environments;

• **The basin plain**, the most distal environment, where the waning sediment gravity flows are no longer strongly channelized but can spread widely to the side, to leave beds that are traceable for long distances in two lateral directions, not just one.

• **Throughput channels**, where strong sediment gravity flows in fairly proximal positions transport large quantities of sediment past a given reach but leave little or no thickness of sediment. It's in such environments that thin, coarse, and amalgamated sediment-gravity-flow deposits are common.

• **Overbank areas** lying adjacent to active distributary channels, where especially large flow events spill over the channel banks to deposit finer suspended sediment (silts and fine sands) from currents of moderate velocities to build broad natural levees.

3. OPEN SHALLOW MARINE DEPOSITS

3.1 Introduction

3.1.1 Today several percent of the area of the world's oceans is floored by the ***continental shelves***: *the submerged shallow margins of the continents*. Water depths are seldom greater than about 200 m even at the shelf edge, and relief is subdued, except where submarine canyons cut into the shelf. Widths range up to a few hundred kilometers. Average bottom slopes are so small that if they drained the ocean and parachuted you blindfolded onto the middle of the continental shelf, you wouldn't know which way to walk to get back home, just from the lay of the land.

3.1.2 The total area of continental shelves in the world is a very sensitive function of world sea level, because along tectonically stable, passive-margin coasts at least, the inland area is usually a gently sloping coastal plain. Sea level today is not as low as it has been in the geologic past, but not as high, either: at certain times of high eustatic sea level stand, a much larger percentage of the continents was flooded by shallow seas, giving rise to what are called ***epeiric seas*** or ***epicontinental seas***. For example, during the Cretaceous, the greater part of the area of North America was covered with water! Today we have no models for such vast shallow seas—so reconstruction and interpretation of depositional environments is hindered by the impossibility of studying them in the modern.

3.1.3 It stands to reason that shelf deposits are generally coarser than deep marine deposits, because coarse sediments (sands and gravels) delivered to the shoreline by rivers, or derived by coastal erosion, need strong currents for dispersal, and such strong currents are generally restricted to shallow water, where the tides and the winds can cause strong water movements throughout the water column. (Sediment gravity flows, are a notable exception to this generalization.)

3.2 Hydrodynamic Classification of Coasts

3.2.1 Coasts can usefully be classified in many ways, but one way that's especially useful for sedimentology is by the dominant hydrodynamic effects that give rise to sediment-moving currents. Here's a list of types of coasts by hydrodynamics:

Tide-dominated coasts. Along coasts with a large tidal range of a few meters of more, strong tidal currents, often exceeding a meter per second near the bed, move sands and even gravels along complex transport paths governed by coastal and sea-floor topography. Thick accumulations of sand can be deposited even on the outer shelf.

Storm-dominated coasts. Along coasts exposed to passage of intense storms (hurricanes and migratory extratropical cyclones), combinations of strong currents and powerful wave motions affect the sea floor now and then.

Current-dominated coasts. Some coasts lie in the path of the margins of major deep-ocean currents, which produce steady movement of coastal sediment parallel to the coastline.

Wave-dominated coasts. Along some coasts, the strongest water movements are nothing more than oscillatory flows produced by impingement of swell from distant ocean storms. This has a strong effect on beaches, where the large waves finally break, but much less effect on offshore areas of the shelf.

Of these four types, the first two, tide-dominated and storm-dominated, are the most important in the sediment record.

3.3 Deposits of Tide-Dominated Coasts

3.3.1 Two things you should know about tidal currents are that:

- in nearshore areas (and in offshore areas too, if there's any large-scale relief) tidal currents tend to be channelized into largely bidirectional currents rather than rotary, as tidal dynamics would predict, and
- such bidirectional tidal currents almost always show some degree of asymmetry, in that the flow in one direction is stronger than the flow in the other direction during the tidal cycle.

3.3.2 These two facts together imply that sand deposits shaped by tidal currents tend to show one-way cross-stratification—especially because sediment transport rate is such a steeply increasing function of current strength. The moderately high current velocities, together with the fairly deep water depths, lead to large-scale cross stratification, ranging from planar-tabular (resulting from movement of 2D dunes) to trough (resulting from movement of 3D dunes). Dunes in modern tidal currents can be up to tens of meters high; set thickness in ancient sands thought to be of tidal origin are usually less, but in some cases can be up to several meters, or even more.

3.3.3 Several special features of cross stratification produced by tidal currents are characteristic:

Herringbone cross stratification (Figure 10-10): It seems logical that if currents reverse, then the cross stratification produced by bed forms moving under the influence of the reversing current should show vertical sequences with cross sets dipping opposite each other. And that's true, especially on fairly small scales of up to a few decimeters within the deposits of larger bed forms that on average move in one direction. But beware of making such an interpretation just on the basis of an outcrop face that seems to show 180° reversal of current direction: usually in such cases, the angular difference is much less, and the visual effect is caused by the section view.

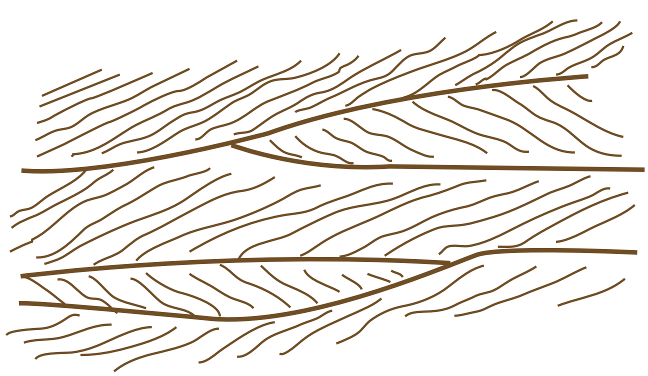

Figure by MIT OCW.

Figure 10-10: Herringbone cross stratification

Reactivation surfaces (Figure 10-11): the time-varying flow strength can cause periodic degradation and then reconstruction of the crests of large bed forms, resulting in characteristic internal truncation surfaces called ***reactivation surfaces***. Beware of automatically making a tidal interpretation, however, because similar reactivation surface can be produced by changes in bed-form geometry in a flow that's steady in the large, probably because of the mutual interactions among neighboring bed forms in a train of inherently changeable bed forms.

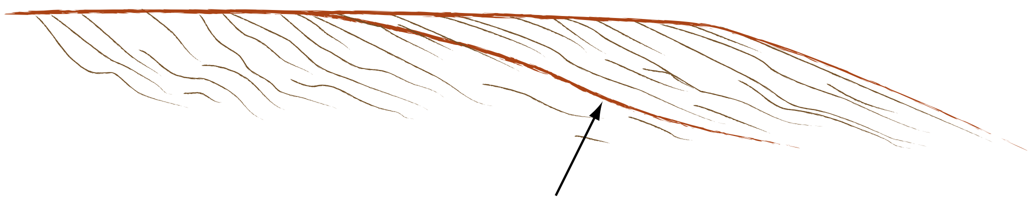

Figure by MIT OCW.

Figure 10-11: Streamwise cross section through a subaqueous dune, showing a reactivation surface

Tidal bundles (Figure 10-12): The two-week spring–neap cycle causes substantial periodic changes in tidal current velocities, and, *a fortiori*, sediment transport rates. A large tidal dune that feels effectively one-way flow and sand movement might therefore be expected to show different surface features at different times in the spring–neap cycle. This spring–neap inequality is great enough in many cases that sand movement is strong during the spring part of the cycle but ceases entirely during the neap part of the cycle, causing the dune to be draped or mantled with finer sediment, most but not necessarily all of which is stripped from the dune surface during the spring part of the cycle. The resulting cyclic interbedding of sand and mud, especially on the lower and middle parts of the lee sides of the dunes, is called ***tidal bundling***, and is considered to be definitive evidence of tidal origin.

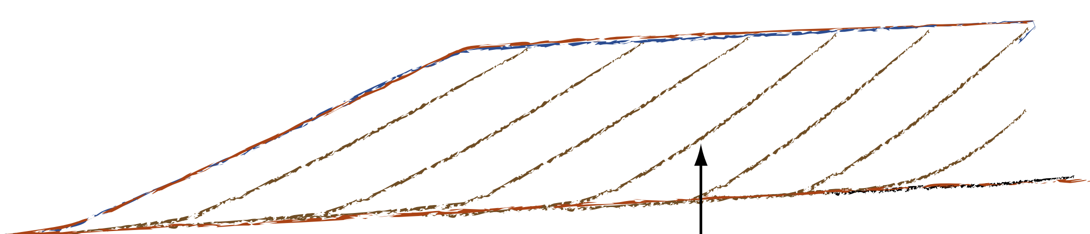

Figure by MIT OCW.

Figure 10-12: Cross section through a subaqueous dune in a tidal environment, showing tidal bundles

3.3.4 Tidal deposition is just as important, and probably more so, in protected nearshore environments than on the open shelf. There will be more to say in a later section about tidal deposits in protected environments.

3.4 Deposits of Storm-Dominated Coasts

3.4.1 On shelves unaffected by really strong water movements except during occasional strong storms, one might expect that most areas, except fairly near shore, would be floored by *mud*. Think of that mud as the *normal quiet-water deposit*, building up very slowly by fallout from suspension during long periods between unusually large storms. Many deposits interpreted as offshore shelf deposits show only such muds. The sediment may be *well stratified*, or it may be partly or entirely *homogenized by bioturbation*.

3.4.2 Many shelf sequences show an *interbedding of quiet-water muds and sand beds* interpreted to be event beds deposited by major, even catastrophic storm-generated flow events in which enormous quantities of sand, usually very fine to fine, are transported from sites nearer shore and spread as an extensive mantle over shelf muds. These sand beds characteristically *show hummocky cross stratification*, suggesting strong and complex oscillatory flows. The sand beds may be *amalgamated*, especially in areas nearer shore, where the frequency of strong bottom water movements is greater than farther offshore.

3.4.3 The nature of the sand-transporting currents and the mechanisms and site of sand entrainment by the current are still controversial:

• Some people are believers in **shelf turbidity currents**. In this view, great masses of sediment and water are mobilized at the shoreline during certain major storms, perhaps by liquefaction caused by cyclic loading by storm waves, and then move offshore as a density underflow.

• Other people deny the existence of such shelf turbidity currents, and appeal instead to a kind of current that might be called a **storm-surge-relaxation current**, whereby water piled against the coast by strong winds tries to flow seaward, only to be turned parallel to shore by the Coriolis force. Such shore-parallel currents, which are in the nature of geostrophic currents, are commonly observed along modern shelves, and can attain speeds in excess of a meter per second.

3.4.4 Various problems remain unresolved. Here are what we consider three of the most difficult problems:

- How is the sand moved offshore?
- How can the currents carry enough sand to deposit extensive beds that are in some cases over a meter thick?

- How can the necessary unidirectional delivery of the sand be reconciled with the existence of sedimentary structures that seem to be produced by dominantly oscillatory flows?

4. TIDAL FLATS

4.1 ***Tidal flats*** occur on open coasts of low relief and relatively low energy and in protected areas of high-energy coasts associated with estuaries, lagoons, bays, and other areas lying behind barrier islands. The conditions necessary for development of tidal flats include *an effective tidal range* and the *absence of strong wave-induced currents.*

4.2 The extent of tidal flats along modern coastlines varies greatly and includes small, locally restricted areas of several hundred square meters or regional features extending over hundreds of square kilometers. One of the best studied siliciclastic depositional environments that has extensive tidal flats is the coastline of the Netherlands, Denmark, and Germany. In the case of carbonates, the best developed tidal flats occur along the coast of the western Persian Gulf and on the western, leeward flank of Andros Island in the Bahamas.

4.3 Some confusion in terminology occurs because tidal flats may carry local geographic names such as lagoon, bay, or salt marsh. Studies of tidal flats became very popular in the late 1950s and early 1960s and helped to clarify this confusion. It is clear that there is great variability in tidal flats, depending on sediment types and availability, presence or absence of vegetation, tidal range, and coastal energy and morphology.

4.4 Tidal flats are subdivided into ***intertidal*** and ***subtidal*** environments which control facies distribution. Parts of the tidal flat lying between high and low tide range, the intertidal zone, make up the major areal extent of the tidal flat. If a noticeable variation in sediment type is present throughout the flat, for example muds and sands, the intertidal area commonly possesses alternating layers of both textures. Where sand forms lenses in mud, the texture is called ***lenticular bedding***, and where mud forms lenses in sand, the texture is called ***flaser bedding***. Most tidal flats have a third zone, developed above the intertidal zone, called the ***supratidal zone***. Supratidal sediments are deposited above normal or mean high tide and exposed to subaerial conditions most of the time because they are flooded only by spring and storm tides; spring tides occur twice each month, and ***storm tides***, the largest of all, occur occasionally during certain seasons.

4.5 Subtidal areas are important to the understanding of this environment because they are the part of the tidal flat most likely to be preserved. Most tidal-flat deposition results from lateral accretion in association with progradation of the flat and the point bar associated with meandering tidal channels. Therefore, a major part of the sedimentary record for most tidal-flat successions includes features associated with *channel fills* and *tidal point bars*.

4.6 Animals and plants play a significant role in tidal-flat environments. They are influential in trapping sediment, forming sediment particles as fecal pellets, and generating biogenic sedimentary structures as a result of the processes of feeding, dwelling, and moving. Tidal flats commonly preserve the details of sedimentary structures owing to the alternation of sand and mud layers.

4.7 Intertidal and subtidal parts of tidal flats are continuously affected by tidal currents as well as wind-induced wave currents. Current velocity can be highly variable in different settings of in the same area under different conditions. Regional and local geomorphology, tide range, and strength and direction of local winds are factors controlling waves and currents. For example, consider the difference between the U.S. Gulf Coast, where the tidal range is less than 0.5 m (***microtidal***) and the Bay of Fundy, where a normal tide may range greater than 10 m (***macrotidal***). ***Mesotidal*** ranges are intermediate, and range from one meter to a few meters.

4.8 Tidal flats that developed under progradational conditions, as in the case of shallowing upward cycles in carbonates, are characterized by a ***fining-upward succession***, consisting of coarse sediments at the base and progressively finer sediments toward the top in an uninterrupted vertical sequence. This common relationship reflects decreasing energy in a progression from subtidal to intertidal parts of the tidal flats. Tidal channels are commonly substantially coarser than laterally equivalent parts of the tidal flat system. Where best developed, facies progression in a vertical sequence can be represented by: (1) a dominantly sandy subtidal zone of channel-fill, point-bar, and shoal sediments; (2) a mixed sand and mud intertidal flat deposit; (3) a muddy upper intertidal flat or salt-marsh deposit.

4.9 Certain sedimentary structures are characteristic of tidal-flat environments: desiccation cracks, thin lamination, commonly disrupted to some extent by bioturbation, and microbial laminites, often with fenestrae (owing to the exclusion of grazing snails in the tidal zone, microbial communities are free to flourish), and intraclasts.

5. BARRIER ISLAND, BEACH, AND LAGOON ENVIRONMENTS

5.1 Introduction

5.1.1 Wave-dominated sandy shorelines in interdeltaic and nondeltaic coastal regions are characterized by elongate, shore-parallel sand deposits**.** Barriers and beaches are prominent depositional features of modern coasts, and sandstone bodies of similar origin are represented in the stratigraphic record. In contrast to rivers and deltas, the geometry of barrier islands is molded almost entirely by marine processes.

5.1.2 For our purposes, ***barriers*** are defined as *sandy islands or peninsulas elongate parallel with the shore and separated from the mainland by lagoons or marshes*. Some major environments associated with barrier island systems are: (1) **beach and shoreface** environments on the seaward side of barriers and strand plains, (2) **inlet channels and tidal deltas**, separating barriers laterally, and (3) **washover fans** on the landward or lagoonward side of barriers. Seaward or longshore migration of these environments results in facies successions constituting much of the volume of many coastal sand bodies. For example, the emergent parts of many barrier-island successions are often underlain by progradational beach and shoreface facies.

5.2 *Beach and Shoreface Deposits*

5.2.1 Successions formed by the seaward progradation of beach and shoreface (nearshore) deposits account for a major part of the volume of Holocene barriers and strandplains. One famous example is Galveston Island, located along the Texas portion of the U.S. Gulf Coast.

5.2.2 The beach is commonly divided into a ***backshore***, which consists of a nearly level ***berm***, and a ***foreshore***, which slopes seaward from the berm edge or crest. The foreshore includes the ***beachface*** and, on some beaches, one or more elongate bars and intervening troughs called ***ridge-and-runnel systems***. The shoreface, as is commonly thought of, extends from the beach offshore to a depth of 5 to 20 m, where there is commonly a change of gradient from the gently sloping shoreface to the nearly level shelf.

5.2.3 Sediment transport on the beach and shoreface is dominated by waves and wave-induced currents, although tidal currents may be locally important near tidal inlets and estuaries. As waves move toward the shore they begin to “feel bottom” on the seafloor near the base of the shoreface, become progressively oversteepened, and collapse to form ***breakers*** on the upper shoreface. As the surf runs up the beach, it forms a thin rush of water called the ***swash***, followed by an even thinner return flow called the ***backwash***. When waves approach the shoreline with an oblique orientation, one direction of longshore current predominates. Sand is transported very rapidly along shore under such conditions, a situation which no jetty can help remedy.

5.2.4 Beachface and foreshore deposits commonly consist of low-angle, seaward dipping, planar lamination, formed by the swash–backwash process, which occur as wedge-shaped sets (Figure 10-13). Upper-shoreface deposits are commonly highly variable, owing to the extremely complex hydraulic environment of the surf zone. Such a regime gives rise to a complex sequence of multidirectional sedimentary structures and variable sediment textures characteristic of these deposits. Gravels are often concentrated in this zone, because of winnowing of finer-grained deposits. Trough cross bedding is also developed, but low-angle bidirectional planar cross-bedded sets and subhorizontal plane beds may also occur. The lower shoreface may include abundant plane beds, wave-oscillation ripples, intercalated with finer silty or muddy layers. However, structures are commonly obliterated by bioturbation.

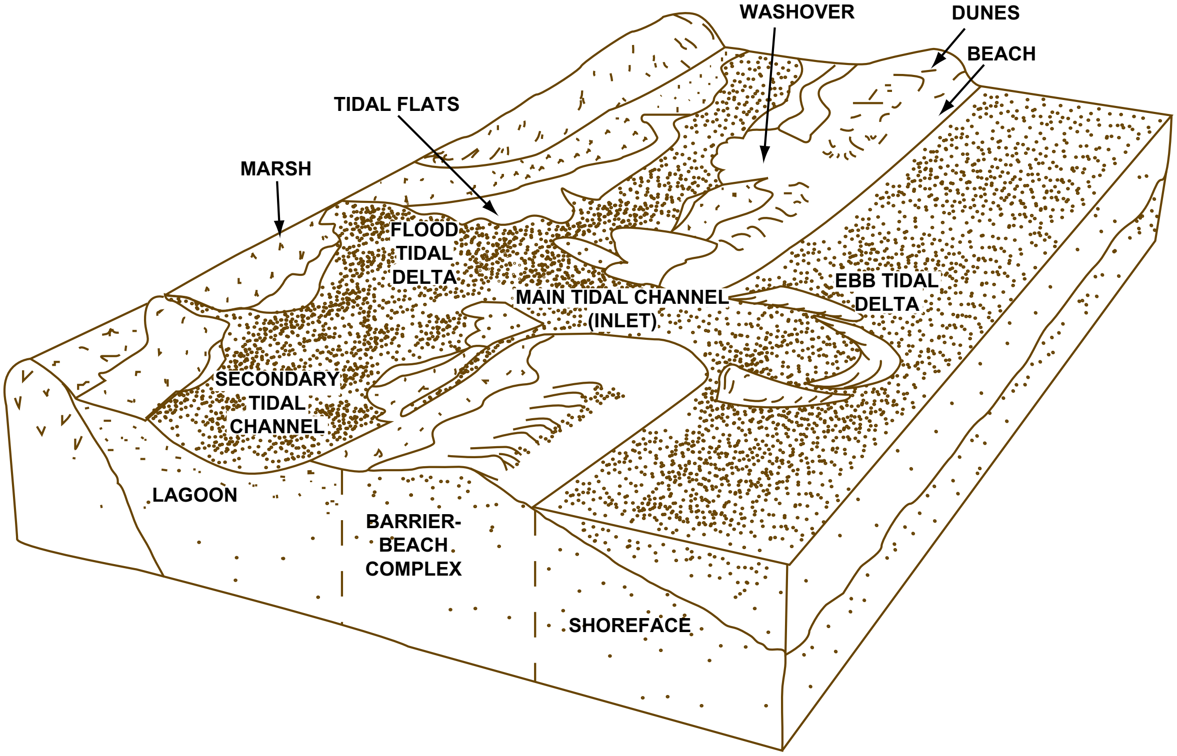

Figure by MIT OCW.

Figure 10-13: Block diagram showing typical morphology of a barrier and tidal inlet system

5.3 *Tidal-Inlet Deposits*

5.4.1 Tidal inlets are more or less permanent passages between barrier islands that allow tidal exchange between the open sea and lagoons, bays, and tidal marshes behind the islands. Inlet channels are generally deepest between the tips of the islands and shallow into tidal deltas both lagoonward (***flood delta***) and seaward (***ebb delta***). The length of barrier is commonly increased by accretion along the tip of one island and erosion of the tip of the adjacent island. Lateral accretion results in growth of ***spits***.

5.4.2 The spacing of tidal inlets is closely correlated with tidal range. As you might expect, macrotidal zones produce barrier-island systems with many inlets, whereas microtidal regimes generate very continuous barriers, as along the U.S. Gulf Coast. Also, the wave energy of the coastline determines whether or not ebb tidal deltas are as well developed as flood tidal deltas. The higher the energy, the more destructive the system, and the less likely that an ebb tidal delta projecting out into the open ocean is developed.

5.4.3 Tidal inlets migrate laterally as the spit on the end of a barrier island grows. The thickness of sediments deposited by migration of tidal inlets and associated environments may be as great as the depth of the tidal channel itself (Figure 10-14).

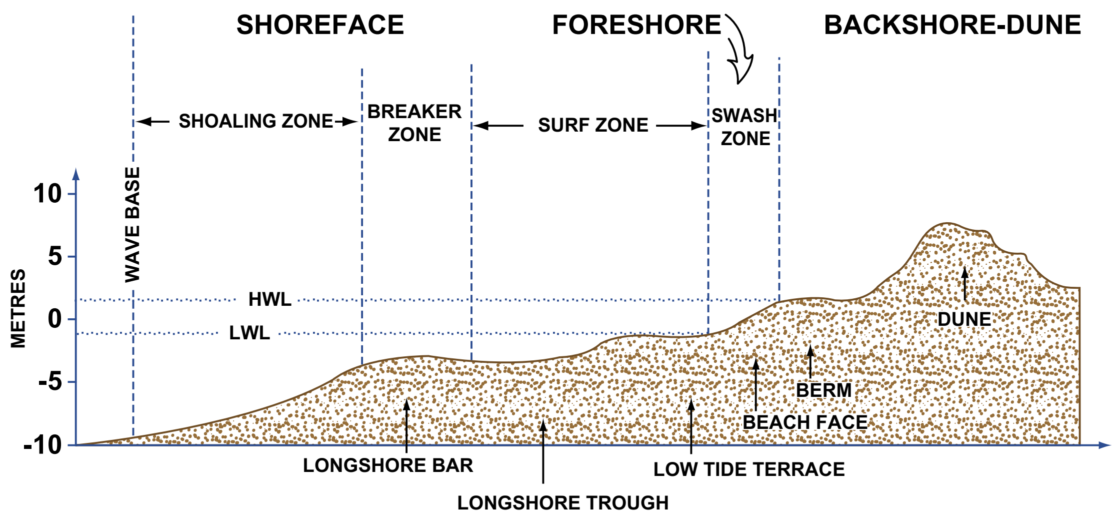

Figure by MIT OCW.

Figure 10-14: Terminology for beach morphology, shown in a cross section normal to the beach

5.4.4 Sedimentary structures in tidal inlets are often very complex, owing to the alternating flow directions created during one tidal cycle (Figure 10-15). There is much variability among different tidal channel complexes that have been studied. However, there is some evidence that in the deeper parts of channels, say below about 4–5 m, sands are coarsest and characterized by mainly ebb-oriented, tabular, planar cross strata, with reactivation surfaces formed by flood-oriented tidal currents. Sands of the channel margin have trough-shaped sets of cross strata formed by both flood-oriented and ebb-oriented dunes, as well as large foresets formed by the lateral migration of the spit. The uppermost part of the channel profile is flattest and exhibits swash stratification, similar to the beachface, but oriented generally along the longshore dip direction.

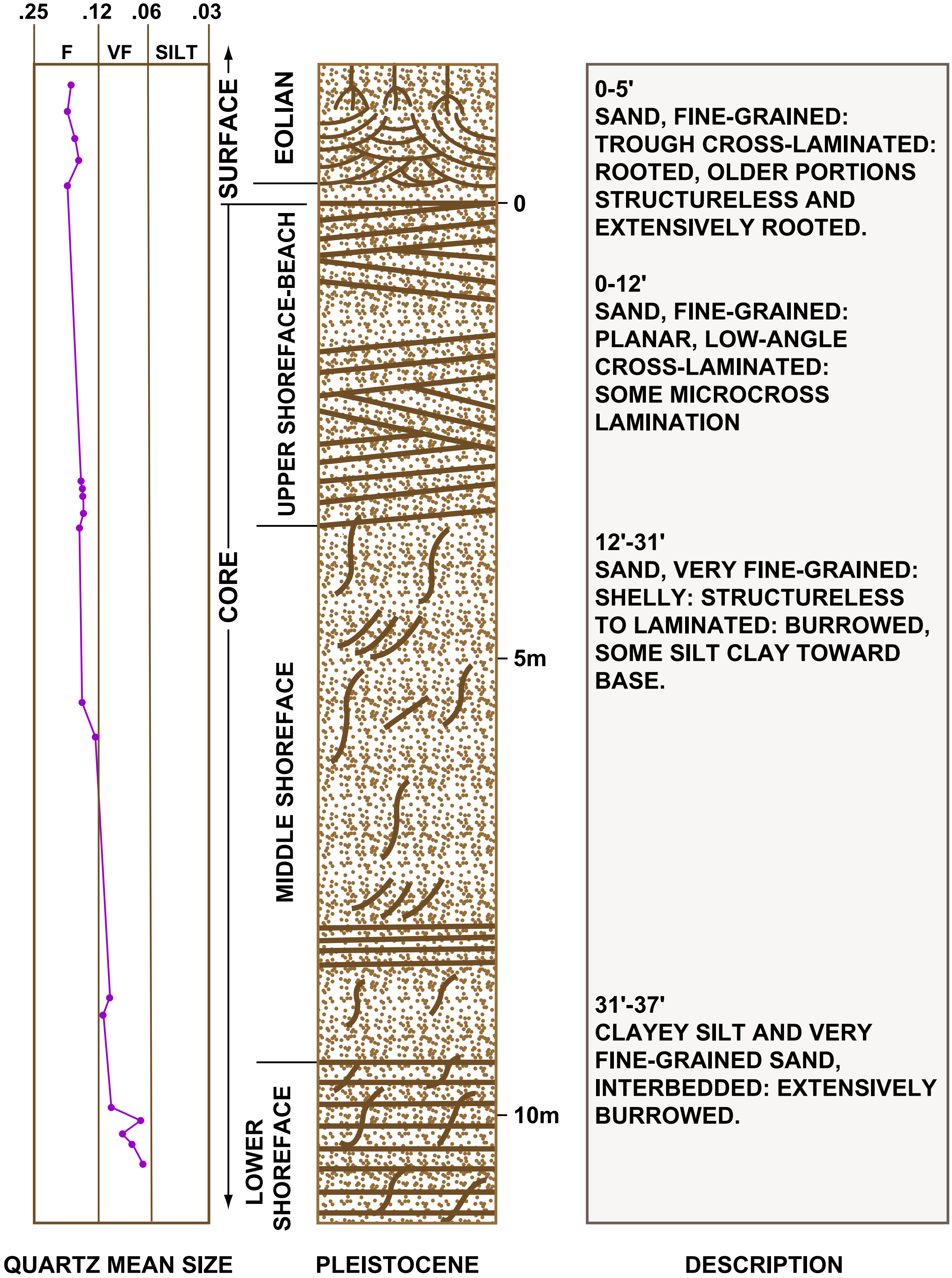

Figure by MIT OCW.

Figure 10-15: Vertical section through a typical beach deposit

5.4 *Lagoonal Deposits*

5.5.1 Lagoonal successions commonly contain interbedded sandstone, shale, siltstone, and coal facies characteristic of a number of overlapping depositional environments. Sand facies include washover sheet deposits and sheet and channel-fill deposits of flood-tidal-delta origin. Fine-grained sediments include those of the lagoon and tidal flats**,** which are situated adjacent to the barrier or on the landward side of the lagoon abutting the hinterland marsh and swamp flatlands.

5.5.2 Generally the lagoon is fed with marine waters that run through the numerous channels in the barrier-island system. However, where lagoons are developed adjacent to rivers and estuaries, lagoonal waters may often be brackish to nearly fresh.

5.5.3 Because of the inherent low energy of most lagoons (little current activity of any kind), fine-grained sediments are common. Often lagoons are the site of prolific production of plants and burrowing organisms that feed on the decaying organic matter. As a result, lagoonal sediments are rich in organics, are highly bioturbated, and may form coal seams in the geologic record.

5.5.4 Other than the sands that are swept into the lagoon adjacent to ebb tidal deltas, the only dominant source of sand is from the growth of ***washover fans*** (Figure 10-16). These form during storms, when water is piled up against the beachface on the oceanic side of the barrier island. Commonly, the barrier island is breached at low points between the dune fields that form the top of the island, the water pours through and entrains abundant sand en route to flushing it through to the lagoon. Over the course of several storms, washover fans may actually prograde out into the lagoon.

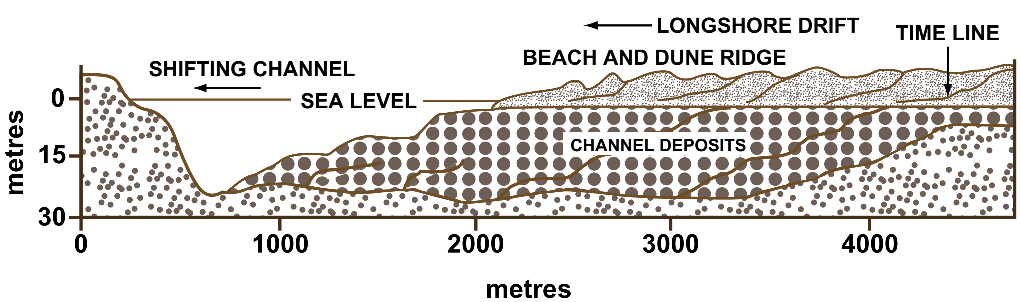

Figure by MIT OCW.

Figure 10-16: Cross section parallel to the shoreline, showing deposits left by lateral migration of a tidal inlet

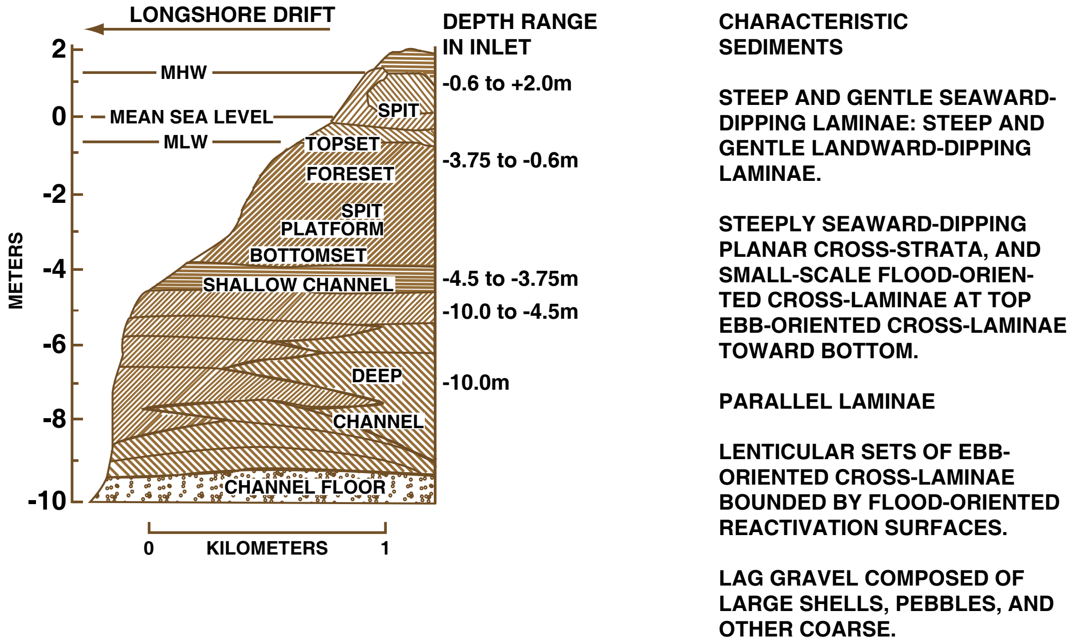

Figure by MIT OCW.

Figure 10-17: Vertical section through a typical tidal-inlet deposit

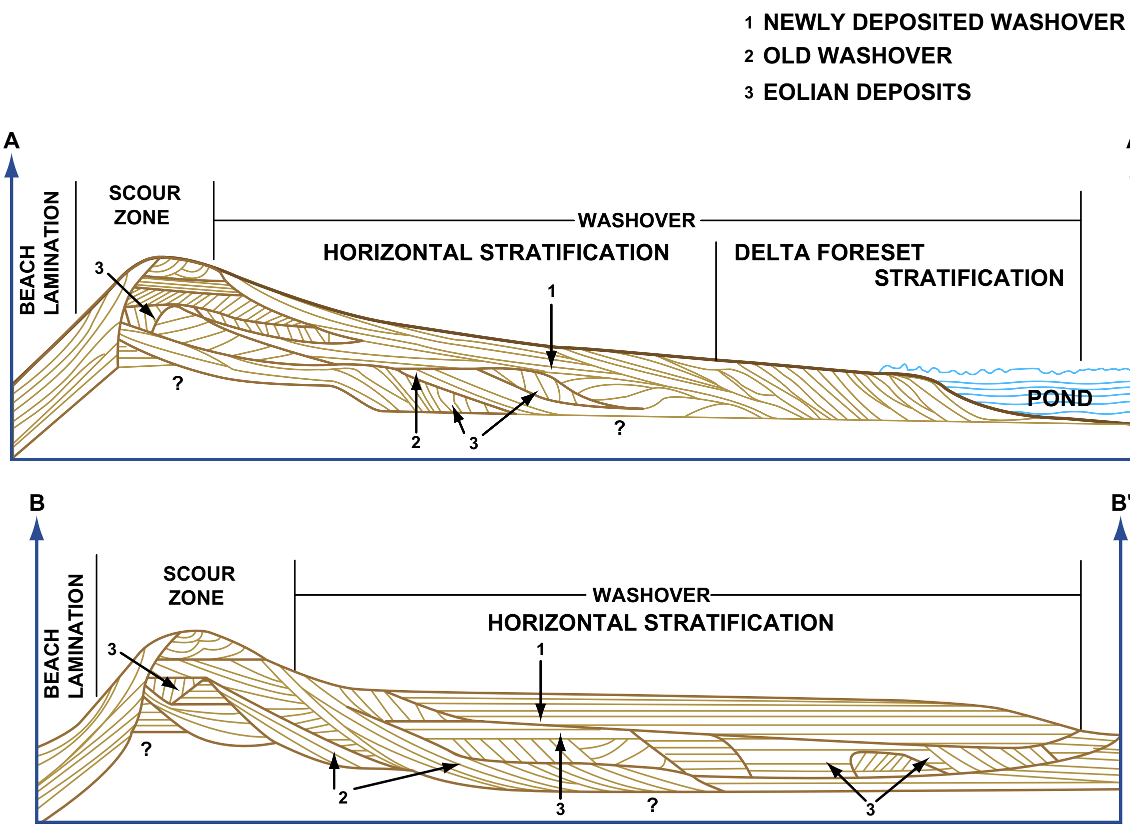

Figure by MIT OCW.

Figure 10-18: Vertical section normal to the beach, showing typical washover deposits

Table 10-1. List of Depositional Environments

- nonmarine
  - terrestrial
    - desert
    - loessial
  - subaqueous
    - fluvial
    - lacustrine
    - paludal
    - spelean
  - glacial
    - subglacial
    - glacier-terminus
    - proglacial
- transitional
  - deltaic
  - lagoonal
  - estuarine
- marine
  - coastal
    - beach
    - tidal-flat
    - muddy shoreline
    - reefy shoreline
    - prodelta
  - shelf
    - siliciclastic shelf
    - carbonate shelf
  - abyssal
    - continental slope
    - submarine canyon/fan/abyssal plain
    - open deep ocean