Chapter 3
SEDIMENTARY STRUCTURES

1. INTRODUCTION

1.1 You might have heard us define ***structure*** in rocks as *rock geometry on a scale much larger than grains*. This is a singularly unilluminating definition, because it doesn't conjure up in the mind of the uninitiated any of *the great variety of interesting and significant geometries* that get produced by the physical, chemical, and biological processes that operate on sediments during and after their deposition.

1.2 One qualification to the foregoing definition is that *the term structure is used in two different senses*:

- θ For features, on the scale of hand specimens to large outcrops, *produced within a depositional environment*, during or (usually) not long after deposition. These are usually prefaced by the adjective *sedimentary*.
- θ For features, on the scale of hand specimens to whole regions, produced by *deformation associated with regional rather than local deforming forces*, folding and faulting being perhaps the most obvious examples. This stuff is not the province of sedimentologists or stratigraphers, although they have to be prepared to deal with it. These could be prefaced with the adjective *tectonic*.

1.3 Study of sedimentary structures is important because they are far and away *the most valuable features for interpreting depositional environment*. We know a lot about how most structures are formed, so finding them in the rocks can tell you a lot about the conditions of deposition. They're much more useful than textural things like grain-size distribution and grain shape.

2. CLASSIFICATION

2.1 It's not easy to classify sedimentary structures, because both their origins and their geometries are so highly varied. Two reasonable ways of classifying them are on the basis of: *kind of mechanism that produces them* (***physical*** sedimentary structures, ***chemical*** sedimentary structures, and ***biogenic*** sedimentary structures) and *time of development relative to time of deposition* (***primary*** sedimentary structures and ***secondary*** sedimentary structures).

2.2 Figure 3-1 is a pigeonhole chart showing most of the important structures in terms of such a twofold classification.

	physical	chemical	biological
primary	stratification sole marks	stratification	biotubation (tracks, trails)
secondary	deformation intrusion desiccation	nodules concretions deformation stylolites	bioturbation (burrows)

Figure 3-1 Classification of sedimentary structures

2.3 *Physical primary structures are certainly the most common and widespread and striking*, and I think it's fair to say that in general they're the most useful in interpretation. Most are related to *transportation and deposition of sediment particles* at a fluid/sediment interface. Such structures can be classified further on the basis of their relationship to transportation (the movement of sediment past a point on a sediment bed by currents) and deposition (the increase in bed elevation at a point with time). Figure 3-2 is an unofficial classification of this kind. It doesn't serve very well as a catalogue, but it should help to get your thinking organized.

		TRANSPORTATION	
		no transportation	transportation
DEPOSITION	deposition	draped stratification	even stratification cross-stratification (most)
	no deposition, no erosion	(no structures)	cross-stratification (some) bed configurations (R, D, A, PB; tool marks)
	erosion	IMPOSSIBLE	bed configurations (R, D, A, PB; flute marks, tool marks)

Figure 3-2 Classification of primary sedimentary structures formed by transportation and deposition of sediments at a fluid/sediment interface

3. STRATIFICATION

3.1 General

3.1.1 *Stratification is by far the most important sedimentary structure*. Most, although not all, sedimentary rocks are stratified in one way or another. There are many scales and geometries of stratification. And *stratification is certainly the single most useful aspect of sedimentary rocks in terms of interpreting depositional conditions*.

3.1.2 ***Stratification*** can be defined simply as *layering brought about by deposition*, the term ***layering*** being more generally used for *any arrangement of rocks in bodies with approximately planar-tabular shape*. I suppose it's obvious, but I'll say it anyway: *stratification comes about by changes in depositional conditions with time*.

3.1.3 In dealing with stratification, there are two separate but related matters you have to worry about:

- θ What it was about depositional conditions that changed with time to give rise to stratification?
- θ What it is about the rock itself that makes the stratification manifest? (Changes in *composition*, *texture*, or even other *smaller-scale structures*?)

3.1.4 Stratification is *usually obvious*, especially on the scale of large outcrops, but *sometimes it's subtle and hard to find*, either because depositional conditions didn't vary much or because the rocks have been messed up since, or perhaps just because the outcrop is inadequate. Finding the stratification under such conditions is a skill that has to be sharpened by practice.

3.1.5 In looking for the stratification, always think in terms of *changes in composition, texture, and/or structure from bed to bed*. Failing that, look for *preferred orientation of clasts*, which although not stratification in itself, often reveals the stratification.

3.1.6 Here's a list of things that tend to make stratification apparent to the eye:

- θ obvious differences in *grain size*
- θ obvious differences in *composition*
- θ *color/shade differences* caused by slight differences in composition (subtle differences in underlying composition can cause even greater color/shade differences as large ones);
- θ *differential weathering* caused by differences in composition/texture; these range from gross to subtle;
- θ *zones of larger or smaller concentration of individual components*, like pebbles or fossils in otherwise homogeneous sediment;
- θ *preferred orientation of nonspherical components* (technically not stratification itself, but it can reveal the stratification; often useful in unstratified conglomerates)

3.2 Terminology

3.2.1 Stratification is officially subdivided into ***bedding*** and ***lamination***, depending upon the thickness of the strata, and bedding and lamination are in turn subdivided according to thickness. Figure 3-3 is a chart that gives you all the official terminology. Get used to using this terminology in your descriptions of strata.

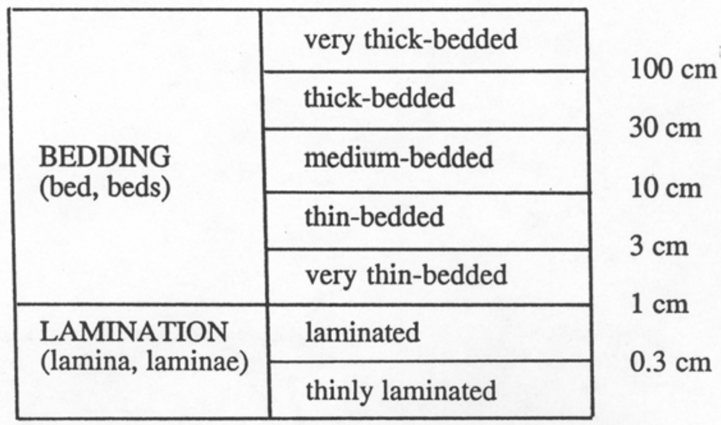

Figure 3-3 Terminology for thickness of strata

3.2.2 With that said, I suppose I should point out that in everyday sedimentological and stratigraphic usage, *people commonly use the term bedding as a synonym for stratification* rather than just in its technically restricted sense.

3.2.3 Also, stratification is often *hierarchical*, in that *beds commonly show internal lamination on a much finer scale*.

3.2.4 One of our little terminological peeves is that people sometimes use the term lamination not just for the *phenomenon* but for the *object*, instead of ***lamina***. That's not good practice, and I want you to avoid it. It makes you sound uncultured.

3.3 Parting

3.3.1 Keep clearly in mind the distinction between *stratification* and *parting*. ***Parting*** is *the tendency for stratified rocks to split evenly along certain stratification planes*. (The word is also used for *the plane itself* along which parting has developed.) The approximately planar-tabular units developed by parting are usually just called beds, but it might be better to think of them as *parting units*.

3.3.2 There's *official terminology for parting units*, corresponding to that for stratification, although it's not in as common use; see Figure 3-4.

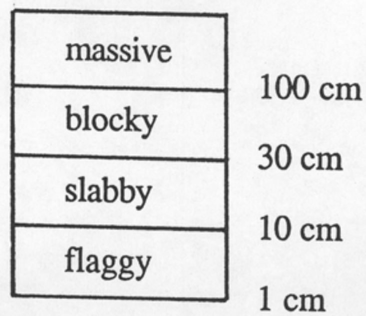

Figure 3-4 Terminology for parting units

3.3.3 The problem with making a big deal of parting is that it depends *not only upon the underlying existence of weaker bedding planes but also upon the extent and nature of weathering*: A freshly blasted outcrop usually won't show any parting at all, but if you go back to the outcrop years or decades later, it might show well developed parting.

3.4 Origin

3.4.1 Here are three major "scenarios" for the origin of stratification. These are the broad ways loose sediments get deposited.

3.4.2 Quiet-fluid deposition of particles by settling: ocean bottom (plus lakes) mainly; low-velocity currents carrying a supply of suspended sediment from upcurrent; usually fine-grained but not always; usually thin lamination, because deposition rate is slow relative to the slight changes in settling regime; usually nearly or perfectly even and planar, unless later deformed. Often such deposits are later bioturbated to the point that none of the original lamination remains.

3.4.3 Deposition of particles by tractional currents: deposition onto a well defined fluid-sediment interface during bed-load (or bed-load plus plus suspended-load) transport by moderate to strong currents; stratification thick to thin depending on nature of variations in sediment supply, currents, and deposition rate; even stratification and cross stratification can both be important; usually fairly coarse sediment, coarsest silt size into gravel range.

3.4.4 Mass deposition of coarse and fine sediment mixtures (or only fine sediment, or rarely only coarse sediment) by sediment gravity flows (high-concentration sediment-water mixtures flowing as a single fluid) coming to rest without differentiation or particle-by-particle deposition; usually thick-bedded, with little or no internal stratification.

4. CROSS STRATIFICATION

4.1 Introduction

4.1.1 ***Cross stratification*** is *stratification that is locally at some angle to the overall stratification* as a consequence of changes in the geometry of the depositional surface during deposition. (This definition leaves some uncertainty about what's meant by the scales of "local" and "overall". Usually "local" is on lateral scales ranging from centimeters to hundreds of meters.) Usually one or more beds in some part of a section show cross stratification, which you recognize as cross stratification because the attitude of the stratification varies from point to point within the beds, or, if it's the same everywhere within those beds, then you can see that the orientation is different from that of the bounding surfaces of the beds, or the orientation is different from what you know to be the overall stratification within the outcrop or within the local stratigraphic section.

4.1.2 The *vertical scale* of cross stratification varies from *millimeters to several meters*, and the geometry is infinitely varied. Cross stratification comes about by deposition upon a sediment surface that is locally at an angle to the overall plane of the depositional surface; this usually but not always involves erosion of the depositional surface as well, either prior to or concurrent with deposition. Some terminology: ***small-scale cross stratification*** is *on scales of up to several centimeters*, ***medium-scale cross stratification*** is *on scales from several centimeters to several decimeters*, and ***large-scale cross stratification*** is *on scales from several decimeters to several meters*. (But as far as I know, there's *nothing official or standardized* about these boundaries.)

4.1.3 *Cross stratification varies enormously in geometry.* This is in part a reflection of the great diversity of bed configurations produced by fluid flows over loose beds of sediment. But there's an additional factor at work here too: some cross stratification comes about not from the movement of individual bed forms in a train, but from solitary or isolated flow-produced topographical elements, usually large, which usually come under the heading of bars or deltas.

4.1.4 Interpretation of cross stratification is well advanced, thanks to decades of careful field studies of cross-stratification geometry in ancient rocks, studies of modern depositional environments, and laboratory studies in tanks and channels. So *cross stratification is probably the single most useful tool in interpreting the physical aspects of loose-sediment depositional environments*. That's why I'm devoting what probably will seem to you to be inordinate space in these notes. (Another reason is that cross stratification is one of our own special fields!)

4.1.5 Because cross stratification is so environment-specific, it seems best to give you only a minimum of purely descriptive terminology and classification. I think it's better for you to get used to the various "styles" of cross stratification, which are closely bound up with mechanics of origin, and then deal with examples in the context of these styles. That's the way things tend to be done these days by the people who actually work on cross-stratified rocks.

4.1.6 Here's some geometrical terminology. More commonly than not, cross-stratified deposits are arranged as *packets or sets of conformable laminae separated from adjacent sets by* ***truncation surfaces***. A ***set*** (also called a ***laminaset***) is *a succession of two or more conformable laminae separated from other sets (or beds without sets) by surfaces of erosion, nondeposition, or abrupt* *change in lithology*. Figure 3-5 shows three common examples. In each example, the asterisk lies within a single set. The laminae within the sets may be planar or curving. Concave-up laminae are more common than convex-up laminae. The orientations of the truncation surfaces are usually different from the orientations of the laminae within the sets. Commonly the lateral scale of the sets may be not much greater than the vertical scale, or it may be much greater. In some cases, there are no truncation surfaces within the cross-stratified deposit; Figure 3-6 shows a common example.

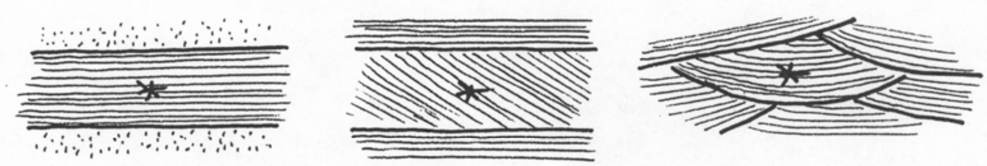

Figure 3-5 Three common examples of sets

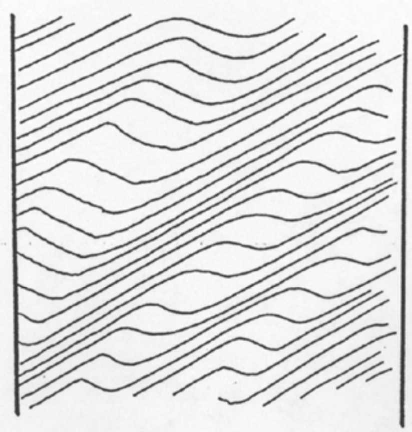

Figure 3-6 A common example of a cross-stratified deposit with no truncation surfaces

4.1.7 Another thing you should be thinking about is *one's view of cross stratification*. Usually it's seen on a fracture surface, weathered or unweathered, nearly normal to the overall stratification. Some cross stratification is approximately isotropic with respect to direction in the plane of overall stratification (the geometry of cross stratification looks about the same in differently oriented sections), but most is anisotropic (the geometry of cross stratification commonly looks different in differently oriented sections normal to the overall plane of stratification), so *try to see the cross stratification on as many differently oriented planes normal to bedding as you can*, because it might look quite different depending on the direction. Sometimes, but not often, you get to see what the cross stratification looks like on a plane within the cross-stratified bed parallel to overall stratification.

4.1.8 A final note on terminology: just as with stratification in general, you can think in terms of *cross stratification as the general term, and cross-bedding and cross-lamination according to the thickness of the strata within the sets*. People tend not to adhere rigorously to these distinctions, however.

4.1.9 Often a given cross-stratified bed may represent *not just one depositional event but two or more separate depositional events, each one superimposed on the the previous one*. Such beds are said to be ***amalgamated***. Sometimes it's easy to recognize the individual depositional events within the amalgamated bed; the stratification within each part of the bed can then be studied separately. But sometimes it's difficult to determine whether or not the bed is amalgamated.

4.2 How Bed Forms Make Cross stratification

4.2.1 In general terms, the fundamental idea about bed-form-generated cross stratification is easy to state (Figure 3-7): as bed forms of one kind or other pass a given point on the bed, both the bed elevation and the local bed slope change with time. Consider a short time interval during the history of decrease and increase in bed elevation. After a temporary minimum in bed elevation is reached, deposition of new laminae takes place for a period of time, until a temporary maximum in bed elevation is reached. Then, as the bed elevation decreases again, there's complete or partial erosion of the newly deposited laminae and formation of a new truncation surface. After the next minimum in bed elevation, another set of laminae is deposited.

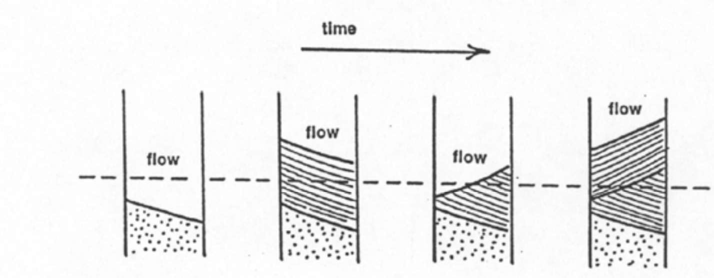

Figure 3-7 The fundamental idea about cross-stratification

4.2.2 The preceding paragraph is still too general to give you a concrete idea about how moving bed forms generate cross stratification. Now I'll be more specific. Take as an example a train of downstream-moving ripples in unidirectional flow. (The picture would be qualitatively very similar for dunes.) Each ripple moves slowly downstream, generally changing in size and shape as it moves.

Sediment is stripped from the upstream (stoss) surface of each ripple and deposited on the downstream (lee) surface.

4.2.3 In your imagination, cut the train of ripples by a large number of vertical sections parallel to the mean flow direction (Figure 3-8). The trough of a ripple is best defined by *the curve formed by connecting all of the low points on these vertical sections where they cut the given trough* (Figure 3-9). This curve, which I'll unofficially call the ***low-point curve***, is generally sinuous in three dimensions. The low-point curve moves downstream with the ripples, and it changes its shape as it moves, like a writhing dragon, because trough depths and ripple speeds change with time.

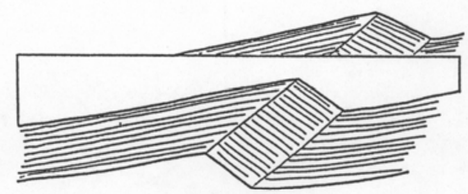

Figure 3-8 Cutting the train of ripples by a large number of vertical sections parallel to the mean flow direction

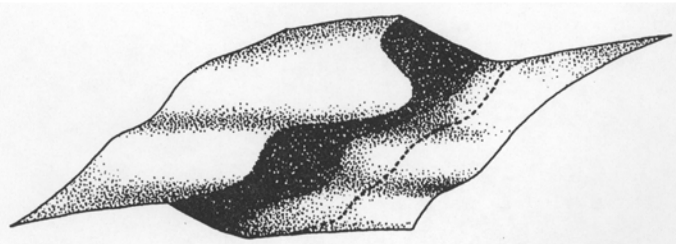

Figure 3-9 The trough of a ripple is best defined by the curve formed by connecting all of the low points on these vertical sections where they cut the given trough

4.2.4 As the low-point curve shifts downstream, it can be viewed as having the effect of a cheese-slicing wire: it seems to shave off the body of the ripple immediately downstream for removal by erosion, and in that way it prepares an undulating floor or surface for the deposition of advancing foresets by the ripple immediately upstream.

4.2.5 Depending on flow conditions and sediment size, *the foreset laminae laid down by an advancing ripple vary widely in shape*, from almost perfect planes sloping at the angle of repose to sigmoidal curves that meet the surface of the trough downstream at a small angle (Figure 3-10). But whatever their shape, these laminae are always deposited directly on the erosion surface that's formed (as just described above) by the downstream movement of the ripple trough into which the foresets prograde.

Figure 3-10 Geometries of foreset laminae

4.2.6 If no new sediment is added to the bed while the ripples move, the average bed elevation doesn't change with time, and the invisible plane that represents the average bed surface stays at the same elevation. On the average, the foresets deposited by a given ripple are entirely eroded away again as the next trough upstream passes by (Figure 3-11). But if new sediment is added everywhere to build the bed upward, the ripples no longer move parallel to the plane of the average bed surface but instead have *a component of upward movement* (Figure 3-12). *The resultant direction of ripple movement* is described by the ***angle of climb***, denoted by θ in Figure 3-12. The tangent of θ is equal to the average rate of bed aggradation divided by the ripple speed.

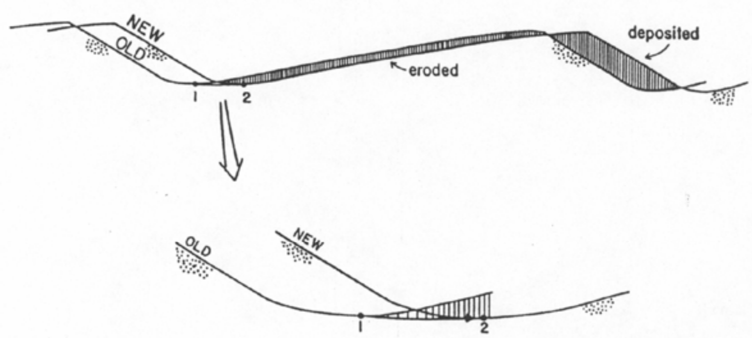

Figure 3-11 On the average, the foresets deposited by a given ripple are entirely eroded away again as the next trough upstream passes by

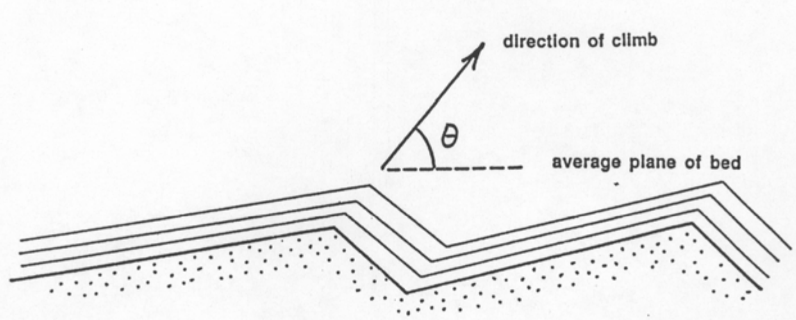

Figure 3-12 Climb of ripplelike bed forms

4.2.7 As the ripples climb in space, as described above, their troughs climb with them. So the erosion surface associated with the downstream movement of the low-point curve in a given trough passes above the erosion surface that was formed when the preceding trough passed by. *The lowest parts of the foresets deposited by the ripple that was located between those two troughs are then preserved rather than eroded entirely* (Figure 3-13). This remnant set is bounded both above and below by erosion surfaces.

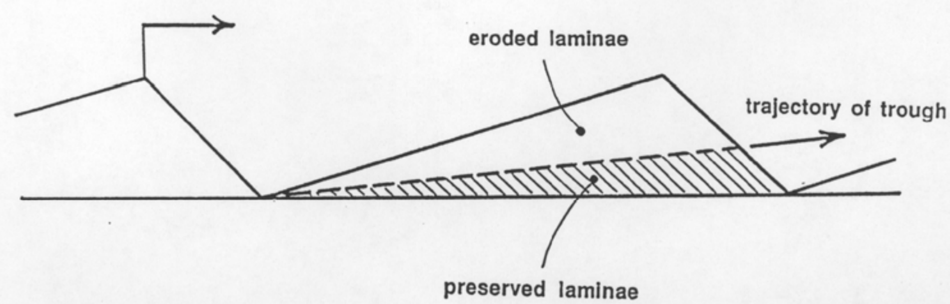

Figure 3-13 Partial preservation of ripple foresets as ripples climb at a small angle

4.2.8 Figure 3-14 shows cross stratification in an ideally regular deposit produced by low-angle climb of a train of ripples. The heavy lines are erosion surfaces, and the light lines are foreset laminae. The profile of the ripple train as it existed at a given time is shown also. The upper parts of each ripple in the train, underneath the dashed part of the profile, were eliminated by later erosion. In real cross-stratified deposits of this kind, the erosion surfaces are irregularly sinuous because trough geometry changes with time, and the sets tend to pinch out both upstream and downstream because the ripples exist for only a finite distance of movement.

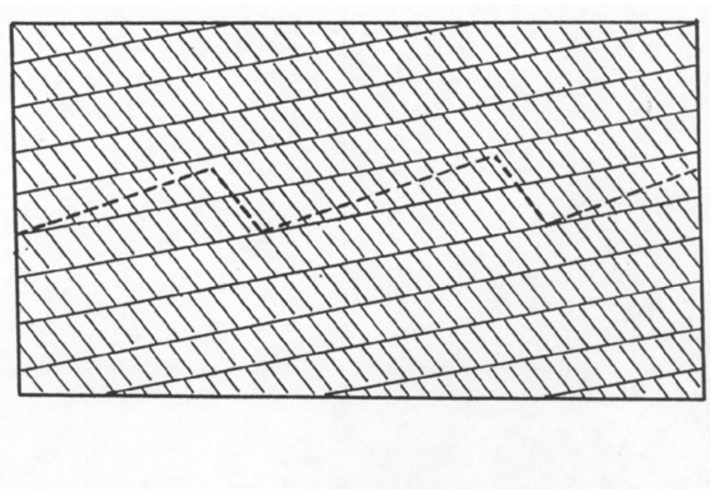

Figure 3-14 Erosional-stoss climbing-ripple cross-stratification

4.2.9 It's significant that *what's most important in determining the geometry of this kind of cross stratification is the geometry of the bed forms in the **troughs**, not near the **crests***. I should also point out that *the height of the sets is always less than the height of the bed forms that were responsible for the cross stratification*. If you compare the height of the cross-sets with the height of the ripples in the dashed profile in Figure 3-14, you can see that for low angles of climb, the set height is only a small fraction of the bed-form height.

4.2.10 The larger the angle of climb, the greater the fraction of foresets preserved. *If the angle of climb of the ripples is greater than the slope angle of the stoss side of the ripples, then laminae are preserved on the stoss sides as well as on the lee sides, and the full profile of the ripple is preserved* (Figure 3-15). This happens when the rate of addition of new sediment to the bed is greater than the rate at which sediment is transported from the stoss side to the lee side of the ripple. The differences in geometry between Figure 3-14 and Figure 3-15 seem great, but keep in mind that the differences in environmental conditions are not large. The only difference is in the value of the angle of climb.

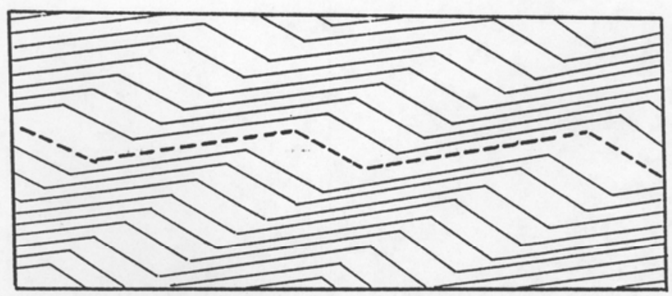

Figure 3-15 Depositional-stoss climbing-ripple cross-stratification

4.2.11 *The lamination produced when ripples move with a positive angle of climb* is called ***climbing-ripple cross stratification***. Examples with angle of climb so small that the contacts between sets are erosional (as in Figure 3-14) might be called ***erosional-stoss*** climbing-ripple cross stratification, and examples with angle of climb large enough for preservation of the full ripple profile (as in Figure 3-15) might be called ***depositional-stoss*** climbing-ripple cross stratification.

4.2.12 To recapitulate the important points in this section: cross stratification is formed by the erosion and deposition associated with a train of bed forms as the average bed elevation increases by net addition of sediment to some area of the bed. The angle of climb of the ripples depends on the ratio of rate of bed aggradation to speed of ripple movement. At high angles of climb, the entire ripple profile is preserved, and there are no erosion surfaces in the deposit. At low angles of climb, only the lower parts of foreset deposits are preserved, and the individual sets are bounded by erosion surfaces. The general nature of such stratification is common to moving bed forms of all sizes, from small current ripples to extremely large subaqueous or eolian dunes. Important differences in the details of stratification geometry arise from differences in bed-form geometry and how it changes with time.

4.3 Important Kinds of Cross stratification

4.3.1 Introduction

4.3.1.1 Here I'll present the substance of *what the major kinds of cross stratification in the sedimentary record look like*. They conveniently fall into (i) ***unidirectional-flow cross stratification***, on a small scale corresponding to ripples and on a larger scale corresponding to dunes, and (ii) ***oscillatory-flow cross stratification***. Unfortunately there's little I can say at present about ***combined-flow cross stratification***. I'll make a few comments about that in the section on oscillatory-flow cross stratification.

4.3.2 Small-Scale Cross stratification in Unidirectional Flow

4.3.2.1 Small-scale cross stratification formed under unidirectional flow is associated almost entirely with *the downstream movement of current ripples*. In accordance with the discussion of how moving bed forms produce cross-stratified deposits, discussed above, the general features of the cross-stratification geometry depend on (i) *the geometry of the ripples themselves*, as well as how that geometry changes with time as the ripples move, and (ii) *the angle of climb*.

4.3.2.2 For small angles of climb, the general geometry of the cross-stratified deposit is shown by the block diagram in Figure 3-16. In addition to the actual rippled surface, Figure 3-16 shows a flow-parallel section and a flow-transverse section perpendicular to the overall bedding. Figure 3-16 is the real-life counterpart of Figure 3-14.

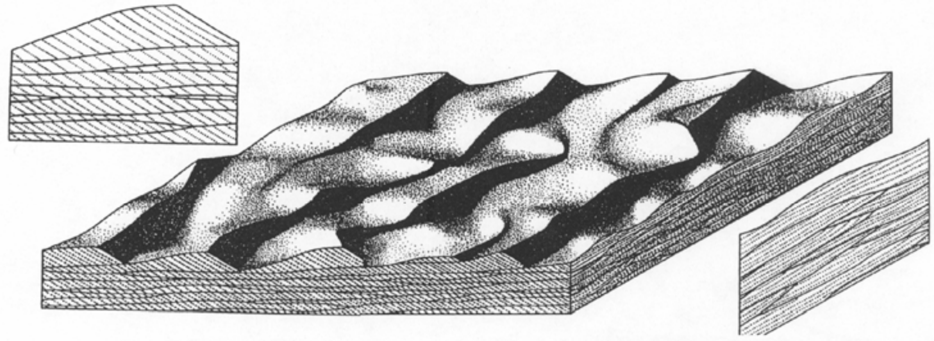

Figure 3-16 Block diagram showing geometry of climbing-ripple cross-stratification produced at small angles of climb

4.3.2.3 In sections parallel to flow (Figure 3-16) you see sets of laminae dipping mostly or entirely in the same direction (which is the flow direction), separated by truncation surfaces. The height of the sets is seldom greater than 2-3 cm, because it's always some fraction of the ripple height, which itself is seldom greater than 2-3 cm. The set boundaries are sinuous and irregular, because of the changes in the ripples as they move. Sets are commonly cut out at some point in the downstream direction by the overlying truncation surface. This is a reflection of either (i) locally stronger erosion by a passing ripple trough or (ii) disappearance of a given ripple as it moved downstream, by being overtaken or absorbed by another faster-moving ripple from upstream. New sets also appear in the downstream direction, reflecting the birth of a new ripple in the train of ripples.

4.3.2.4 In sections transverse to flow, the geometry of cross stratification is rather different (Figure 3-16): you see nested and interleaved sets whose lateral dimensions are usually less than something like five times the vertical dimension. Each set is truncated by one or more truncation surfaces. These truncation surfaces are mostly concave upward. The laminae within each set are also mostly concave upward, but the truncation surfaces generally cut the laminae discordantly.

4.3.2.5 The key to understanding this cross-stratification geometry lies in *the geometry of ripple troughs*. Remember that fully developed current ripples have strongly three-dimensional geometry, and an important element of that three-dimensional geometry is the existence of locally much deeper hollows or swales or depressions in ripple troughs, where the separated flow happens to become concentrated (because of the details of the ripple geometry upstream) and where scour or erosion is much stronger. As one of these swales moves downstream, driven by the advancing ripple upstream, it carves a rounded furrow or trench, oriented parallel to the flow, which is then filled with scoop-shaped or spoon-shaped laminae which are the foreset deposits of the upstream ripple. Eventually the resulting set of laminae is partly or mostly or even entirely eroded by the passage of a locally deeper swale in some later ripple trough. This accounts for both the geometry of the sets and their irregular interleaving.

4.3.2.6 On the rare occasions when you're able to see a planar section through the deposit parallel to the overall stratification, you see a geometry which looks like Figure 3-17, which shows the truncated edges of sets of laminae that are strongly concave downstream, separated laterally by truncation surfaces. This has been called *rib and furrow* (not a very descriptive term). It's an excellent paleocurrent indicator.

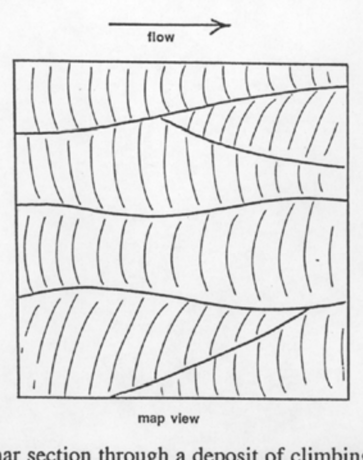

Figure 3-17 Planar section through a deposit of climbing-ripple cross-stratification, parallel to the overall stratification

4.3.2.7 For large angles of climb, the general geometry of the cross-stratified deposit is shown by the block diagram in Figure 3-18. In addition to the actual rippled surface, Figure 3-18 shows a flow-parallel section and a flow-transverse section perpendicular to the overall bedding. Compare Figure 3-18 with Figure 3-16.

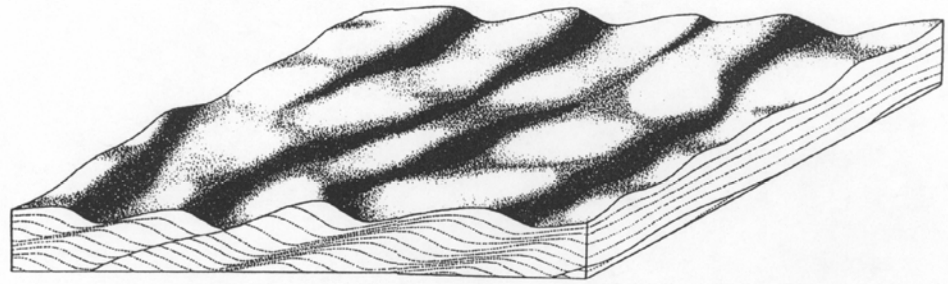

Figure 3-18 Block diagram showing geometry of climbing-ripple cross-stratification produced at large angles of climb

4.3.2.8 In sections parallel to flow, you see mostly continuous laminae whose shapes reflect the profiles of the ripples which were moving downstream while sediment was added to the bed. The local angles of climb vary from place to place in the deposit, because the speeds of the ripples are highly variable in time. So unless the overall angle of climb is very high, there are likely to be a few discontinuous truncation surfaces, where a particular ripple moved temporarily at a speed much greater than average.

4.3.2.9 In sections transverse to flow, you usually see just irregularly sinuous laminae which reflect the changing flow-transverse profiles of the ripples as they passed a given cross-section of the flow.

4.3.2.10 Remember that *for intermediate angles of climb, the stratification geometry is intermediate between the two end members presented above*. As the angle of climb increases, the density and extent of truncation surfaces bounding the sets decreases, and the average set thickness increases.

4.3.2.11 For a given sand size, current ripples in equilibrium with the flow don't vary greatly in either size or geometry with flow velocity, so unfortunately *there's little possibility of using the details of stratification geometry to say anything precise about the flow strength*.

4.3.3 Large-Scale Cross stratification in Unidirectional Flow

4.3.3.1 Large-scale cross stratification formed under unidirectional flow is mostly associated with *the downstream movement of dunes*. Again the general features of the cross-stratification geometry depend on the geometry of the dunes and the angle of climb.

4.3.3.2 Remember that dunes formed at relatively low flow velocities have a tendency to be two-dimensional: their crests and troughs are nearly continuous and fairly straight, and the elevations of the crests and troughs are nearly uniform in the direction transverse to flow. On the other hand, at relatively high flow velocities the dunes are moderately to strongly three-dimensional, in much the same way that ripples are three-dimensional. You should expect the geometry of cross stratification to vary greatly depending on whether the dunes were two-dimensional or three-dimensional.

4.3.3.3 *Three-dimensional dunes produce cross stratification that's qualitatively similar in geometry to the small-scale cross stratification produced by ripples*. You might reread the earlier section and apply it to the stratification produced by three-dimensional dunes.

4.3.3.4 Figure 3-19 is a block diagram of cross stratification produced by three-dimensional dunes in unidirectional flows. It shows the dune-covered bed surface and sections perpendicular to the overall plane of stratification and parallel and transverse to the flow direction. Most of what I said about the analogous section in Figure 3-16 for cross stratification produced by ripples at low angles of climb is applicable to Figure 3-19 as well. Set thickness ranges from less than 10 cm to as much as a few meters.

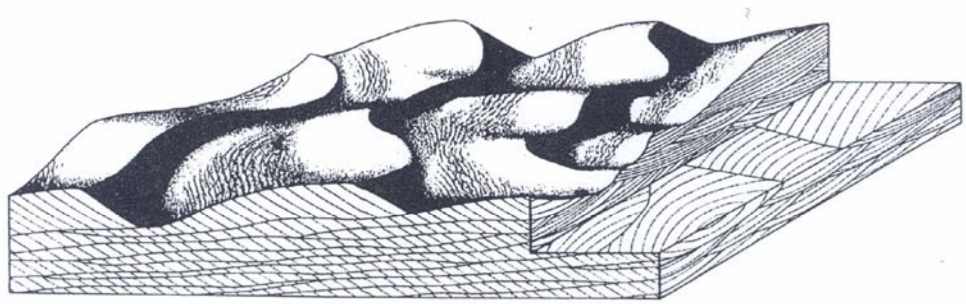

Figure 3-19 Block diagram of cross-stratification produced by three-dimensional dunes in unidirectional flows

4.3.3.5 Figure 3-20 is a corresponding block diagram of cross stratification produced by almost perfectly two-dimensional dunes in unidirectional flows. The stratification geometry is rather different from that in Figure 4-19: in flow-parallel sections the sets extend somewhat farther and the set boundaries are less sinuous, but *the biggest difference is in flow-transverse sections*, where both the sets and the truncational set boundaries are much more extensive and show much less upward concavity. This is because of the absence of locally strong scour swales in the troughs of the dunes.

4.3.3.6 There's *a whole spectrum of intermediate cases* for which the cross-stratification geometry is less regular than the extreme case shown in Figure 3-22 but not as irregular as in Figure 3-19.

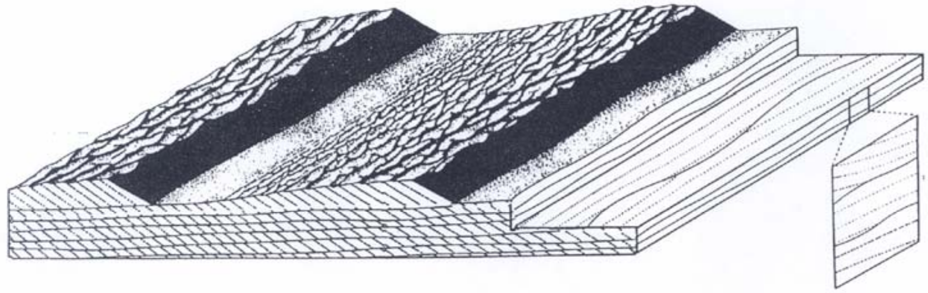

Figure 3-20 Block diagram of cross-stratification produced by almost perfectly two-dimensional dunes in unidirectional flows

4.3.3.7 In both Figure 3-19 and Figure 3-20, the angle of climb of the dunes is very small. *Dunes sometimes climb at higher angles, but that's not nearly as common as for ripples*, because it's uncommon for fairly coarse sediment to be settling abundantly out of suspension over large areas to build up the bed rapidly. In the very few cases I've seen, the geometry of cross stratification is very much like that shown in Figure 3-18.

4.3.4 Cross stratification in Oscillatory Flow

4.3.4.1 Remember that in truly symmetrical oscillatory flow at low to moderate oscillation periods and low to moderate oscillation speeds, the bed configuration is symmetrical two-dimensional oscillation ripples. Under these conditions, the sediment transport is also strictly symmetrical in the two flow directions. You might expect the ripples to remain in one place indefinitely. Then if sediment is supplied from suspension to build up the bed, *symmetrical oscillation-ripple cross stratification with vertical climb* would be produced (Figure 3-21). Although this kind of stratification is present in the sedimentary record, it's *not common*, presumably because even in purely oscillatory flow there's usually a minor degree of asymmetry of sediment transport which causes the ripples to move slowly in one direction or the other.

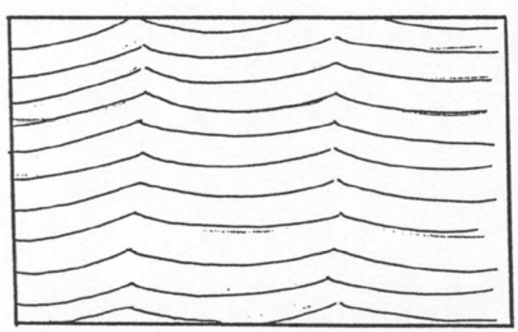

Figure 3-21 cross-stratification produced by vertical climb of symmetrical oscillation ripples

4.3.4.2 Figure 3-22 is an attempt to account for oscillatory-flow cross stratification types produced by the buildup of two-dimensional oscillation ripples as a function of (i) the slow net rate of ripple movement and (ii) the rate of aggradation of the bed. Along the vertical axis, for zero ripple movement, is symmetrical oscillation-ripple cross stratification, of the kind I mentioned above might be expected deductively. The chevron-like interleaving of laminae at the ripple crests, shown schematically, results from minor shifts in crest position back and forth during aggradation. This is shown by the first box from the top in Figure 3-22.

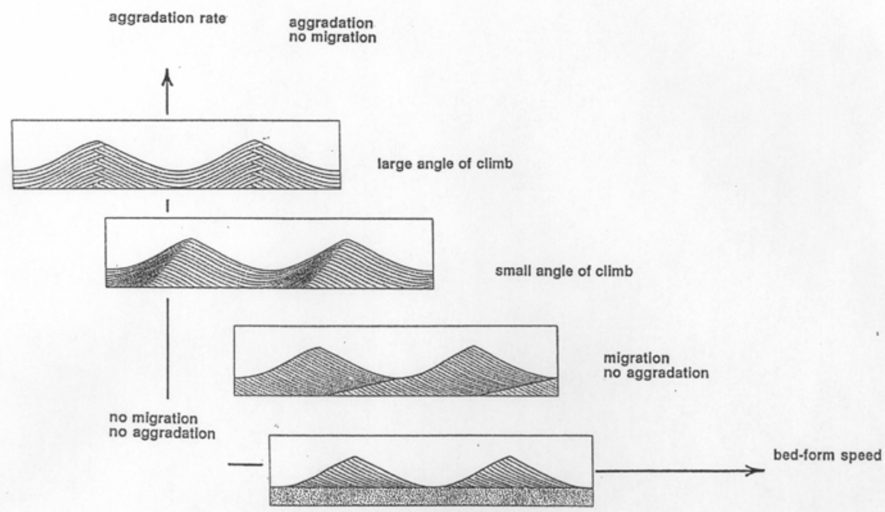

Figure 3-22 Kinds of oscillatory-flow cross-stratification produced by the buildup of two-dimensional oscillation ripples as a function of the slow net rate of ripple movement and the rate of aggradation of the bed

4.3.4.3 If the ripple speed is nonzero but slow relative to aggradation rate, the angle of climb is steep and *the entire ripple profile is preserved* (see second box from the top in Figure 3-22). If the ripple speed is large relative to the aggradation rate, ripple troughs erode into previously deposited laminae, and *the stratification shows laminae dipping in one direction only, in sets bounded by erosion surfaces* (see the third box from the top in Figure 3-22). This last type is the most common in the sedimentary record. Note that this stratification differs only in detail, and not in general features, from low-angle climbing-ripple cross stratification produced by ripples in unidirectional flows, discussed in the previous section. Finally, if a preexisting bed is molded into slowly shifting oscillation ripples without any net aggradation of the bed, *the thickness of the cross-stratified deposit is equal to only one ripple height* (see the bottom box in Figure 3-22).

4.3.4.4 *In the real world, oscillation-ripple stratification is likely to be more complicated*, because wave conditions seldom remain the same for long. Commonly there are a large number of sets of laminae dipping more or less randomly in both directions.

4.3.4.5 The origin and classification of stratification produced by oscillatory flows at *longer oscillation periods and higher oscillation velocities* is much less well understood, because there have been no studies in natural environments in which first the bed configuration was observed while the flow conditions were measured and then the bed was sampled to see the resulting deposit. And until only recently there had been no studies under laboratory conditions. Another element of complexity is that in the natural environment the oscillatory flows are likely to be more complicated than the regular and symmetrical bidirectional oscillatory flows that were assumed above, and essentially nothing is known in detail about the stratification types produced by these more complicated oscillatory flows.

4.3.4.6 In the face of this seemingly hopeless situation, I'll take the following approach. I'll describe in a general way a common style of medium-scale to large-scale cross stratification, called ***hummocky cross stratification***, which is generally believed to be produced by some kind of oscillatory flow, and I'll present what evidence I can for the kinds of flows that might produce hummocky cross stratification.

4.3.4.7 Figure 3-23 is a block diagram of one of the common styles of cross stratification that's been called hummocky cross stratification. It shows sets of laminae that are both concave upward and convex upward, bounded by broad truncation surfaces which themselves may be either concave or convex upward. Two characteristic small-scale features of the geometry of stratification are (i) *the fanning of truncation surfaces laterally into conformable sequences of laminae* (Figure 3-24) and, where the thickness of the bed is great enough to observe this, (ii) *a tendency for convex-up sets of laminae to be succeeded upward by concave-up sets, and vice-versa* (Figure 3-25).

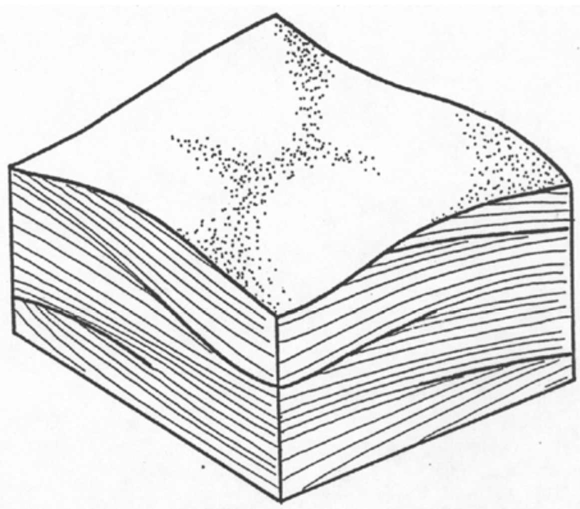

Figure 3-23 Block diagram of one of the common styles of cross-stratification that's been called hummocky cross-stratification

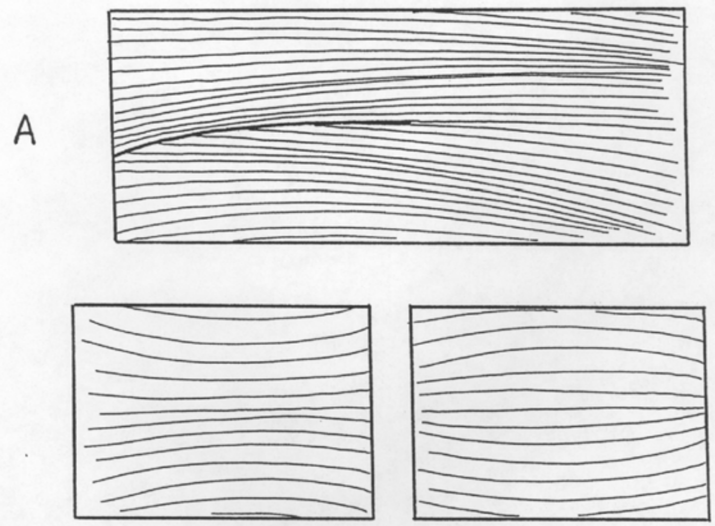

Figure 3-24 Characteristic small-scale features of the geometry of stratification in hummocky cross-stratification formed by bed aggradation during maintenance of oscillatory-flow bed forms. A: fanning of truncation surfaces laterally into conformable sequences of laminae. B: tendency for convex-up sets of laminae to be succeeded upward by concave-up sets, and vice-versa

4.3.4.8 Note that the two normal-to-bedding faces of the block are shown to have about the same style of stratification, and on each face there's no strongly preferred dip direction. In the rare cases where you can make serial sections of the deposit to ascertain the entire three-dimensional geometry of the deposit, it's clear that *there's no preferred dip direction in the entire deposit*. This is the kind of stratification I call *isotropic*.

4.3.4.9 The upper surface of the block diagram in Figure 3-23 is shown to be a bedding surface with a bed configuration that could be described as a collection of *hummocks* (locally positive convex-up areas) and *swales* (locally negative concave-up areas). Sometimes, but not often, the upper surface of a bed with hummocky cross stratification can be seen to have just this bed geometry. The general belief is that *isotropic hummocky cross stratification is produced by this kind of bed configuration*, although it's seldom possible to actually demonstrate this.

4.3.4.10 Very recent preliminary experiments have shown that *bed configurations which in their general features are like those just described are produced by symmetrical bidirectional oscillatory flows at long periods and high oscillation velocities*. This suggests that at least some isotropic hummocky cross stratification is produced by such flows. But it also seems likely that *more complex oscillations with more than one oscillatory component would also produce qualitatively similar bed configurations and therefore similar cross stratification*. Much more work needs to be done before the origin of hummocky cross stratification is well understood.

4.3.4.11 This brings us to the problem of *combined-flow cross stratification*. Unfortunately there's an almost complete lack of observational information on the origin of combined-flow cross stratification, so we have no actual models to guide interpretations. Up to now the recognition of combined-flow cross stratification has been a strictly *deductive* matter.

4.3.4.12 It seems convenient to think separately about the relatively small combined-flow ripples produced under combinations of relatively low oscillatory and unidirectional flow velocities, on the one hand, and the relatively large combined-flow ripples produced under combinations of relatively high oscillatory and unidirectional flow velocities, on the other hand.

4.3.4.13 When the combinations of oscillation period and oscillation velocity are such that in purely oscillatory flow the ripples would be at about the same scale as current ripples, there's a kind of *coherence* in the combined-flow ripples: they're on the same scale as unidirectional-flow ripples, but more nearly two-dimensional. Actual experiments indicate that only a very small unidirectional component is needed to make such ripples noticeably asymmetrical.

4.3.4.14 But for very short periods or very long periods, when the ripples that would be produced in purely oscillatory flow are much smaller or much larger than current ripples, the situation is more complicated, because in combined flows the bed configuration wants to be at two separate scales, and there's a complicated interaction between the two differing scales. There have been no detailed studies of the stratification produced under these combined-flow conditions.

4.3.4.15 The large oscillation ripples in fine sediments which are known to be produced at long periods and high velocities become asymmetrical in the presence of even fairly weak unidirectional components, and the stratification they produce during bed aggradation is probably what many workers recognize as anisotropic hummocky cross stratification. But detailed interpretations are a matter for the future.

4.3.4.16 Also still unstudied is the geometry of cross stratification produced when unidirectional-flow dunes are subjected to a nonnegligible oscillatory component. This situation must be important in natural environments, but systematic studies have yet to be made in either the field or the laboratory.

4.3.5 Eolian Cross stratification

4.3.5.1 So far our account of cross stratification has implicitly been directed toward subaqueous bed configurations. Everyone knows that *the shifting of eolian dunes produces large-scale cross stratification* too. To first order, *eolian dune cross stratification is similar in gross aspects to subaqueous dune cross stratification*. But behind the gross similarity are real differences. These differences are simply a consequence of the differing details of geometry of the dunes themselves, and of the sediment transport over them.

θ Eolian cross stratification tends to have *a "swoopy" look* (pardon the looseness of terminology here) that's difficult to pin down in detail. We think that that look reflects the tendency for the troughs of eolian dunes to be filled by plastering of new trough laminae not just on the mean-upcurrent side, as is usually the case in subaqueous cross stratification, but on the lateral and mean-downcurrent sides as well.

θ Eolian cross stratification is more likely to show *greater dispersion of dip directions of cross-sets*, because of the greater variability of wind directions than of subaqueous current directions. (But this is not as strong a tendency as you might think, because most of the major eolian sand bodies preserved in the sedimentary record were probably produced in sand seas swept by winds fairly constant in direction.)

θ The *nature of the lamination* in eolian cross-sets tends to be different from that in subaqueous cross-sets. The three basic kinds of laminae in cross-sets are:

— ***grain-flow laminae***, produced by the downslope movement of grain flows to iron out the oversteepening of the foreset slope caused by deposition at the brink

— ***grain-fall laminae***, produced by the rain of sand grains onto the foreset slope after they are carried across the brink in saltation

— ***translatent laminae***, produced by the movement and very-low-angle climb of ripples on sand surfaces that are undergoing net aggradation

The first two kinds of laminae are common to both subaerial and subaqueous cross-sets, but they are *much more distinctive and better differentiated in subaerial deposits*. *Translatent laminae are specific to subaerial deposits*, because in subaqueous environments the scale and movement of ripples in dune-lee environments is such as to produce recognizable small-scale cross-lamination rather than laminae so thin that the cross-stratified nature is undetectible, as in the eolian case.

4.3.6 Cross stratification Not Produced by Climbing Bed Forms

4.3.6.1 After all of the foregoing voluminous material on how to deal with cross stratification produced by trains of repetitive bed forms that climb at some angle owing to net aggradation of the bed, it's important to point out here that *not all cross stratification is produced by bed forms climbing at some angle*—although we think it's fair to say that most of the cross stratification you see is indeed formed in that way.

4.3.6.2 One case in point is pretty obvious, and has been touched upon in the earlier part of this chapter:

> a train of flow-transverse bed forms is produced by a neutral flow (by "neutral" we mean that there's neither net aggradation or net degradation) over a loose sediment bed, then the flow quits, and later the train of bed forms is mantled or draped by sediment deposited in such a way as not to disturb that underlying train of bed forms (by fallout without traction, for the most part).

This kind of cross stratification might be termed, unofficially, ***single-bed-form-train cross stratification***. It's common in both oscillatory flow and unidirectional flow. Depending on the thickness of movable sediment the flow has to operate on, and the size of the bed forms the flow wants to make, the train of bed forms may be starved (Figure 3-25A), full (Figure 3-25B), or starting to climb up one another (Figure 3-25C).

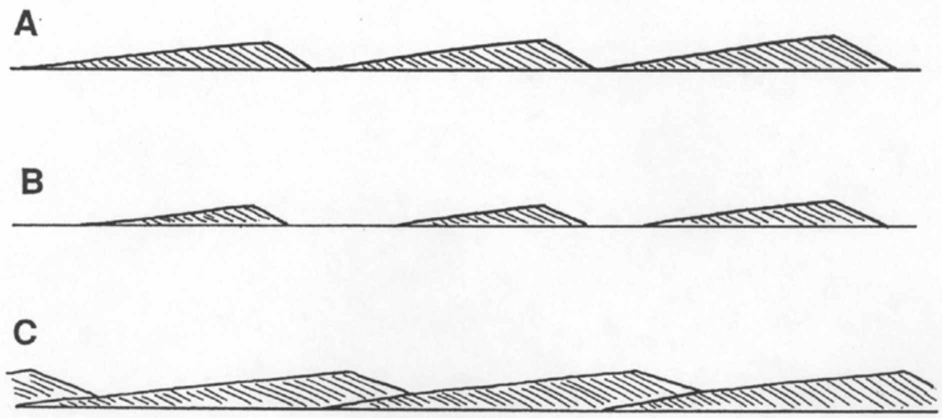

Figure 3-25 Single-ripple-train cross-stratification. A: full single train. B: starved train. C: ripples starting to overlap.

4.3.6.3 Usually the material presented so far in this section on cross stratification is relevant to small-scale bed configurations—ripples of various kinds—but sometimes *single trains of much larger dunes are formed and then interred within different, or at least differently structured, sediment*. When the dunes have large spacings and small height-to-spacing ratios, there's the added complication that you may on the outcrop *see a segment of a dune that's very short relative to the dune spacing*, and the cross stratification looks like a planar-tabular set with uniform thickness (Figure 3-26). We know of no way of knowing, just from looking at an outcrop like Figure 3-26, what the original spacing of the dunes was—or even if I'm really dealing with a train of dunes in the first place!

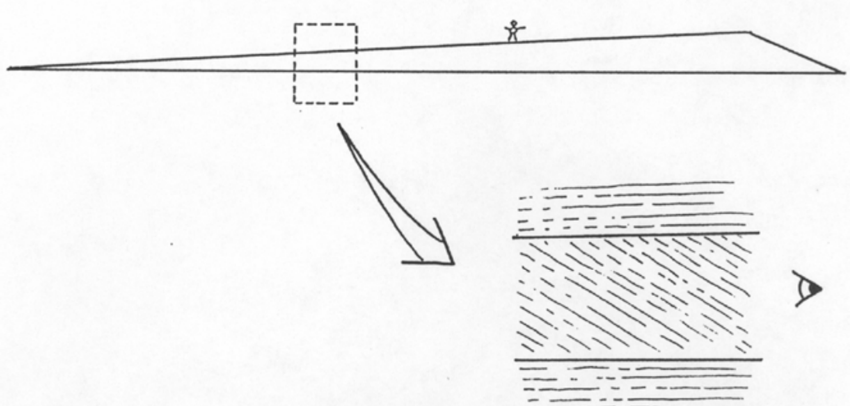

Figure 3-26 A planar-tabular cross-set that represents a small part of a single large dunelike bed form

4.3.6.4 In a situation like that shown in Figure 3-26, there's also the problem of *whether the full height of the dune is preserved*. You might find features at the upper surface of the cross-set that gives evidence of its having been the exposed upper surface of a dune, like superimposed smaller bed forms. Although that's not foolproof, it would suggest strongly that the dune was not eroded or shaved off by a later strong current after its own driving current ceased.

4.3.6.5 Finally, *cross stratification can be formed by the progradation of the sloping surface of an isolated element of positive relief*, like a sand bar or shoal or delta body. Scales of such features can range up to very large. Deciding between this situation and the one described above (a small part of a single train of dunes) would be impossible without a degree of lateral control not usually available in outcrop.

5. PLANAR STRATIFICATION

5.1 There is not as much to say about planar stratification as there is about cross stratification—because its geometry in inherently simpler! That's not to say that it is not important: there is at least as much planar stratification in particulate sediments and sedimentary rocks (conglomerates, sandstones, siltstones, shales, and limestones) as there is cross stratification, and even more in gravels and conglomerates, in particular. Planar stratification is also common in carbonate rocks, although less so than in siliciclastics. It is unfortunately true, however, that *the possibilities for interpretation of depositional conditions are less abundant for planar stratification than for cross stratification*.

5.2 We need to make a distinction here between *planar stratification in which an entire bed, which might be as much as some meters thick, has an overall planar geometry*, in the sense that the lower and upper surfaces of the bed are planar (the geometry of such a bed could also be described as *tabular*), on the one hand (this might best be called ***planar bedding***), and *planar stratification within such an overall planar–tabular bed*, on the other hand (Figure 3-27). The latter kind of planar stratification usually comprises strata that are sufficiently thin as to be called laminae, in which case we talk of ***planar lamination***, or a ***planar-laminated bed***. (Keep in mind the terminological distinction between beds and laminae.)

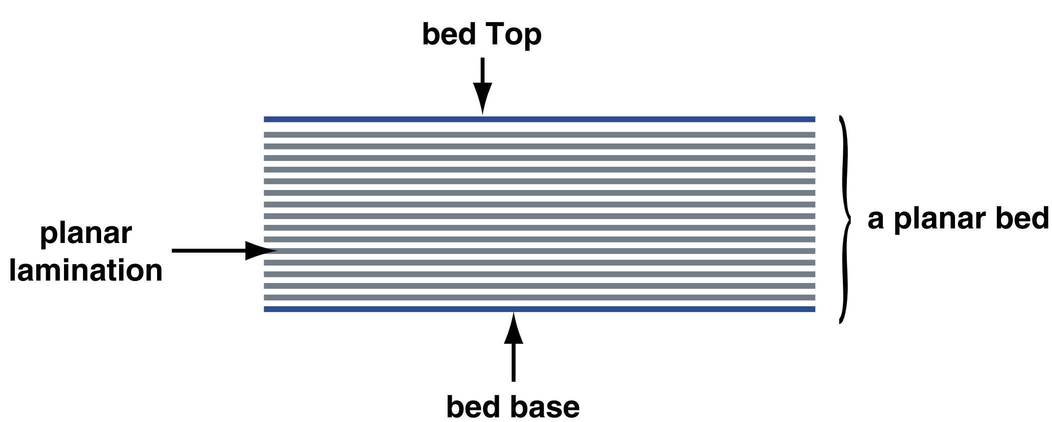

Figure 3-27: A planar bed, with planar internal lamination

5.3 *What is the origin of planar lamination?*

• In many cases, especially in fine siliciclastic sediments and sedimentary rocks, it must certainly be the outcome of deposition by *fallout without traction* in which the nature of the settling material varies, for some reason, with time. The differences might be in particle size or in composition. Such lamination is commonly way down in the submillimeter thickness range. Many mudrocks and shales show such planar lamination.

• Planar stratification is also common in successions of interbedded thin (on a centimeter or even a millimeter scale) event siltstones or very fine sandstones and "background" (that is, fallout-without-traction) mudrocks or shales. You will learn more about such event beds later. In brief, an event stratum (usually referred to as an event bed) is *any stratum that was deposited by a brief event, on a geologically instantaneous time scale*, by such things as turbidity currents, debris flows, river floods, or shallow-marine storms.

• In many well-sorted coarse siltstones and sandstones, the planar lamination is the outcome of *fallout with traction* or of *differential transport* (See the discussion of modes of deposition at the end of the preceding chapter.) How might we know that? Because of its commonly close association with ripple and dune stratification In what seems to be a flow environment in which the flow strength is decreasing with time (from plane-bed transport to ripples or dunes).

5.4 In interpreting planar lamination, there is a kind of "awkward range" in particle size in which *the size is not fine enough for a confident interpretation of fallout without traction but not coarse enough for a clear interpretation of a strong flow*. To put that another way, with increasing particle size it becomes less and less likely that the flow could be carrying enough sediment in suspension to form a planar-laminated deposit just by fallout without traction—because the settling velocity increases rapidly with particle size, thereby cutting down the possible distance over which suspension fallout can occur.

5.5 In planar lamination in sands and sandstones, the differences in particle characteristics from lamina to lamina are usually subtle, even to the point at which it takes special observational techniques (like x-radiography of thin slabs cut normal to stratification) even to detect its presence. In some cases, slightly varying concentrations of dark particles (heavy minerals; scraps of organic matter) highlight the lamination; usually, however, there are only slight differences in mean size and/or sorting. Such differences are often detectable on a fresh sediment surface but become accentuated by weathering of a rock surface or by etching of an unconsolidated sediment surface by drying by the wind.

5.6 For a long time the origin of the slight differences in texture in planar-laminated sandstones was poorly understood. Laboratory experiments in recent years, however, have revealed that much if not most such planar lamination is generated by the downstream movement of very low-amplitude bed waves (akin to very low, shingle-like dunes) on an almost planar transport surface.

6. SOLE MARKS

6.1 Sole marks are another important kind of sedimentary structure, less common than cross stratification. ***Sole marks*** are *geometrical features produced on a sediment bed by erosion by a strong current* (***flute marks***), *or by mechanical disruption of the bed by large objects carried by a strong current* (***tool marks***).

6.2 The line between bed configurations and sole marks is not entirely sharp, but with sole marks we're dealing with *a short-lived current acting upon a semicohesive bed*, usually of mud. This is usually *a sediment gravity flow in a moderately deep marine environment* (if you mention sole marks to most soft-rock geologists they'll think of turbidites), but *strong currents in other situations can make sole marks as well*.

6.3 *Strong currents are known to produce erosional flutes with characteristic geometries on semicohesive mud beds*. The flutes range in scale from just a few centimeters across to giants a few meters across. They are narrow, steep-sided, and often curled at the upcurrent end, and wider and shallower downstream. They thus make excellent paleocurrent indicators. Their origin was first deduced from the ancient record, but they have since been reproduced beautifully in the laboratory.

6.4 Important: *you almost always see sole marks in negative relief*, because usually the strong current that makes the marks later deposits a bed of sand (or even gravel). After burial, lithification, uplift, and erosion, what remains for you to see, usually in outcrops with steep dips, is the underside of the sandstone bed, the shale having been weathered away. For this reason you often see the term ***flute cast*** (although curiously, one never sees the term "tool cast"!).

6.5 I won't illustrate sole marks here, because I'll have slides for you later. See also Potter and Pettijohn, Atlas and Glossary of Primary Sedimentary Structures.

7. SOFT-SEDIMENT DEFORMATION

7.1 Introduction

7.1.1 The only other kind of sedimentary structure I'll talk about here is ***soft-sediment deformation***, also called (less felicitously) ***penecontemporaneous deformation***: *deformation, usually of the continuous sort involving folding and contortions, that developed long before the sediment was lithified*. One often sees mildly to grossly deformed strata, on scales of centimeters to a few meters, that by various kinds of evidence must have happened only shortly after burial, when the sediment was still effectively noncohesive and buried less than a few meters. Some deformation can be shown to have happened even earlier—during, not after, deposition.

7.1.2 There are several common styles of soft-sediment deformation, and a thorough analysis of the mechanics involved would take a lot of time and space. All I'll do here is point out what must be the principal underlying reasons for the occurrence of soft-sediment deformation, and some brief description and illustration of the most common kinds.

7.1.3 Sediments ranging from coarse silt size up into the gravel range can be viewed as a packed framework of grains in mutual contact. Usually, however, grain-by-grain depositional mechanisms are such that the resulting deposit is not packed as closely as possible: the porosity is greater, and the number of grains contacts smaller, than the ultimate values attainable by rearrangement of the grains. So any kind of disturbance to the sediment bed, like an earthquake, can cause a *sudden repacking of the grains*: the grains fall into a new, closer packing in a kind of wave that sweeps through a more or less large volume of the sediment. As this happens, *the repacking sediment finds itself suffused with excess pore water*, which can do nothing but drain more or less slowly outward by flowing through the surrounding porous sediment. *While there is excess pore water, the sediment is in a liquefied state*, in that it is not locked into packing by being in contact with surrounding grains. This process is called ***liquefaction***. Especially in finer sediments, like silts and very fine sands, the permeability is so small, owing to the smallness of the pore passageways, that the sediment remains in a liquefied state for some time—long enough to deform under the influence of whatever small anisotropic stress field happens to be present within the sediment.

7.2 Styles of Soft-Sediment Deformation

Loading. Sometimes the stratification in a sedimentary sequence is gravitationally unstable, in that a given bed has a greater bulk density than the bed underlying it. Then, if the sediment becomes mobilized as discussed above, there is a tendency for the material of the overlying bed to sink down into the underlying bed and (usually more diffusely) for the material of the underlying bed to rise up into the overlying material. This phenomenon is called ***loading*** (Figure 3-28).

In mild cases, there is just some local and partial downward motion of the overlying bed into the underlying bed, especially in places where the contact between the two beds is convex downward owing to deposition. Loading of this kind is usually seen where a water-rich sand bed was deposited over a semicohesive mud bed. Sole markings, for example, are often accentuated, sometimes grossly so, by later loading.

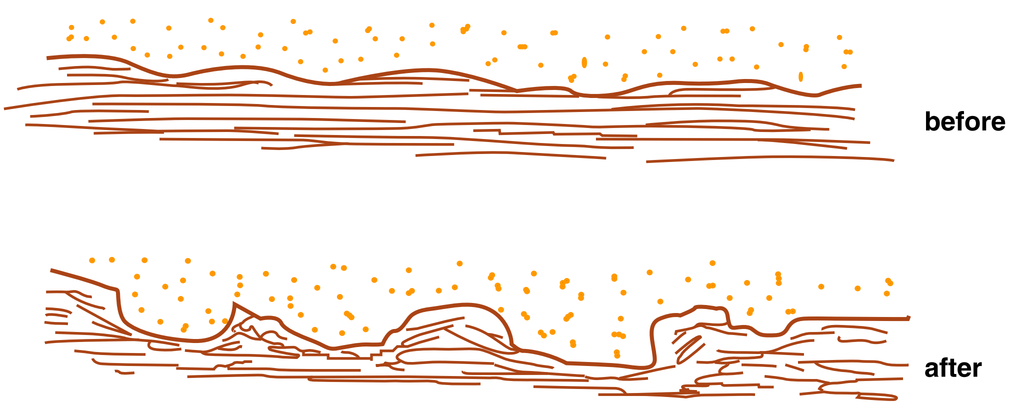

Figure by MIT OCW.

Figure 3-28: Loading

Ball-and-pillow structure. In more extreme examples of loading, whole masses of the overlying bed sink down into the underlying material. Usually these masses end up with concave-up stratification that is terminated abruptly around the margins of the sunken mass. This called ball-and-pillow structure (Figure 3-29).

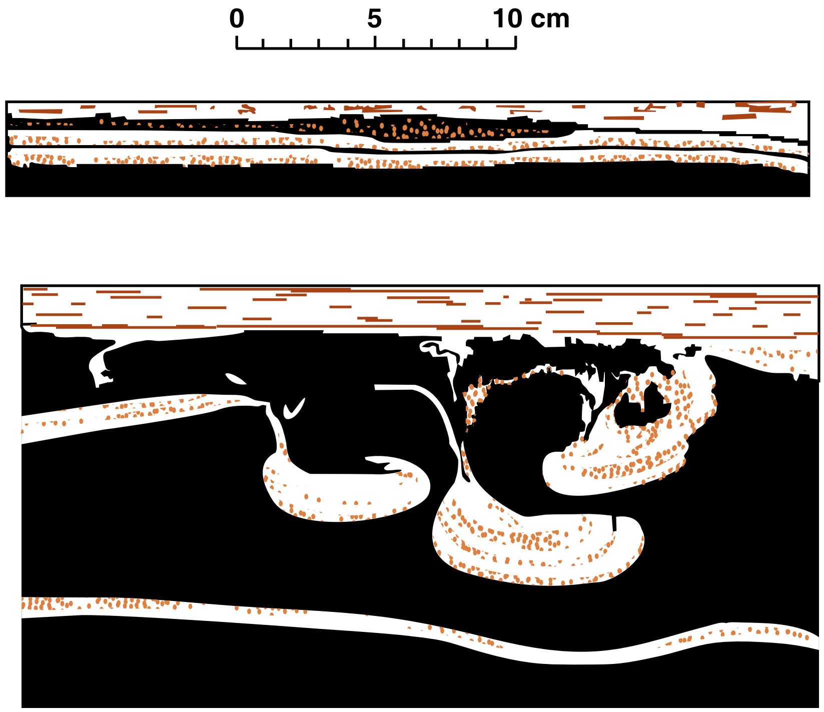

Figure by MIT OCW.

Figure 3-29: Ball-and-pillow structure

Slump folding. Another kind of soft-sediment deformation is slump folding (Figure 3-30). When sediment on a slope is liquefied, it tends to flow or slide down the slope, even if the slope angle is only a few degrees. Various patterns of folding develop, with downslope vergence of the folds. The folds are characteristically tight, often even isoclinal and recumbent. Scales range up to some meters. Sometimes these folds are truncated by erosion and overlain by very similar sedimentary material, emphasizing the slight depth of burial of material when it is deformed. Such erosion is presumptive evidence of penecontemporaneity (but you have to make sure that what you're thinking is an erosion surface isn't instead a gently dipping local fault associated with the deformation!).

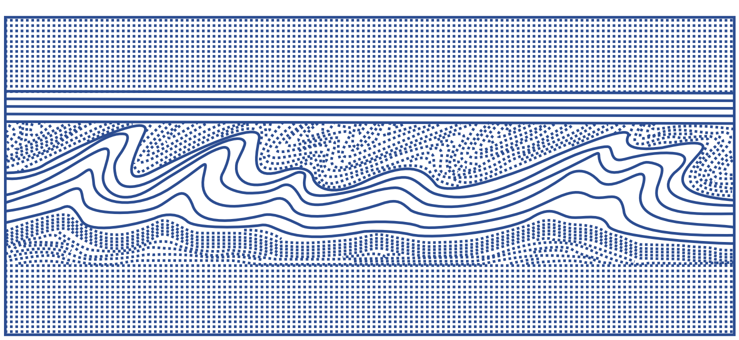

Figure by MIT OCW.

Figure 3-30: Slump folding

Convolute lamination. Finally, another style of soft-sediment folding, called convolute lamination, is characteristic of beds of fine sand, up to a meter thick, deposited rapidly by such events as turbidity currents (Figure 3-31). The beds have planar lower and also upper contacts, but the bed is internally folded into broad synclines and sharp to dome-shaped or even mushroom-shaped anticlines, which usually die out upward to planarity at the upper contact. Sometimes it can even be demonstrated that the folding developed concurrently with the development and downcurrent movement of ripples on the rapidly aggrading transport surface.

8. OTHER SEDIMENTARY STRUCTURES

Aside from stratification, sole marks, and soft-sediment deformation, there are many other kinds of sedimentary structures. In this final "wastebasket" section, I'll mention a few other primary sedimentary structures. Beyond that, there are biogenic sedimentary structures (trace fossils), which I will describe in more detail in a later chapter.

• **desiccation cracks:** Also called, less precisely *mud cracks*, these are tension cracks or fractures that extend downward from a bed top into the sediment below. They are arranged in a network, which in some cases comprises nearly regular hexagons or rectangles but more commonly are of irregular geometry. Their characteristic spacing ranges from a few centimeters to many decimeters in extreme cases. They commonly taper downward to a sharp lower end, at depths of centimeters to as much as a few decimeters in extreme cases. It is clear that the form during shrinkage consequent upon drying of the a surficial layer of unconsolidated sediment. The sediment can shrink vertically with no cracking, but lateral shrinkage causes tensile stresses that result in the cracking.

The significance of desiccation cracks is the evidence they give of *subaerial exposure of the sediment surface—that is, emergence of a previously submerged depositional surface*. They can also be a *top-and-bottom indicator*, inasmuch as they commonly taper downward, are capped above by a later-deposited bed, and are filled with that same later-deposited sediment (Figure 3-31). In some cases, when a thin bed is undergoes desiccation cracking, the individual segments of the cracked bed curl upward, and the later-deposited sediment insinuates itself beneath the up-curled edges (Figure 3-32).

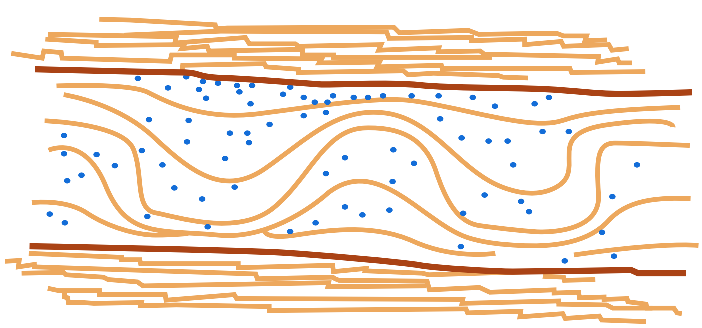

Figure by MIT OCW.

Figure 3-31: Convolute lamination

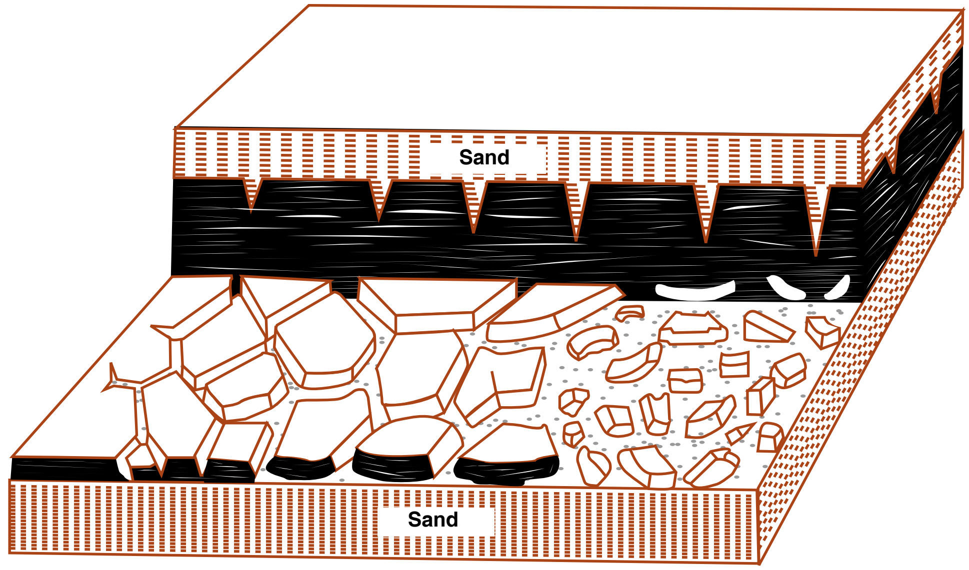

Figure by MIT OCW.

Figure 3-32: Desiccation cracks

• **Raindrop impressions:** When a soft, moist surface of freshly deposited sediment is exposed to a brief, light shower of large raindrops, tiny craters, circular in outline and with a slightly raised rim, are imprinted upon the sediment surface. If they survive long enough to be buried by later deposition, they can be preserved intact in the sedimentary record Figure 3-33: Shrock, R.R., 1948, Sequence in Layered Rocks: McGraw-Hill, 507 p. (p. 142, Figure 141). As with desiccation cracks (although they are much less common), they give excellent evidence of subaerial emergence and also of tops and bottoms.

• **Graded bedding:** If the particle size in a siliciclastic bed varies systematically upward through the bed, the bed is said to be *graded*. (In a sense, graded bedding lies somewhere between being a texture and a structure, but because I did not mention it in Chapter 1, I'm mentioning it here.) If the particle size *decreases* upward, the bed is said to be ***normally graded***; if the particle size *increases* upward, the bed is said to be ***reversely graded*** or ***inversely graded*** (both terms are in use).

The term "normal" probably arose because of the belief, commonly but not always justified, that in the normal course of a depositional event the strength of the depositing flow, and thereby the particle size of the sediment being deposited, decreases. Accounting for reverse grading is not as simple: one might appeal to a strengthening flow, or, alternatively, to collapse and immobilization of a highly concentrated flow in which, for dynamical reasons that remain unclear, the particle size in the moving sediment–water mixture increases upward.

Some workers have appealed to a simple kinematic effect that might account for reverse grading: the ***kinetic sieve effect***, whereby finer particles can find their way relatively easily downward among coarser particles but coarser particles cannot find their way easily down among finer particles.

A distinction can be made between two kinds of grading: ***distribution grading***, whereby the entire frequency distribution of the sediment shifts toward a finer or a coarser mean size, and ***coarse-tail grading***, whereby the frequency distribution of the main mass of the sediment stays about the same but the percentage of sediment in the coarse tail of the distribution changes significantly.