CHAPTER 8
STRATIGRAPHY

1 INTRODUCTION

1.1 Up to now, in this course, you have heard about sedimentary rocks only one the scale of hand specimens. Now it's time for you to deal with what sedimentary and volcanic rocks are like on a larger scale.

1.2 This chapter deals with sedimentary and volcanic rocks on *scales much larger than hand specimens*: outcrops, and large areas of the land surface that geologists tend to call "field areas" (because they "go out in the field" and "do field work" to study such rocks; you will be doing some of that yourself, on the field trip.).

1.3 The study of stratified rocks is called ***stratigraphy***. It's the branch of geology that deals with *the description, correlation, and interpretation of stratified sediments and stratified rocks on and in the Earth*. Inasmuch as by far the greatest part of the uppermost zone of the earth's bedrock is sedimentary rock, stratigraphy is an important branch of Earth science.

2. MORE ON STRATIFICATION

2.1 You will soon see many examples of stratification in hand specimens, but the best way to see stratification in all its beauty and complexity is to look at outcrops. We won't have a chance to do that until the field trip, later in the semester, but I will be showing you some color slides of stratified outcrops in class. Those pictures will be worth much more than the proverbial thousand words in giving you an idea of what stratification is like. You'll see that *strata range in thickness from submillimeter scale to many meters*—although you will see that there is an upper limit: by the time you get to whole rock units, you' are no longer dealing with stratification, even though in a sense they are "stratified".

2.2 *How is stratification produced?* That very fundamental question goes right to the heart of how and where sediments are deposited. There was some material on that earlier in the course, but here are some reminders.

2.3 In an approximate sort of way, processes of two different kinds produce stratification in sediments:

- variations in slow and continuous depositional processes with time, because of slow changes in environmental conditions, and
- brief and often catastrophic depositional events that punctuate slow "background" sedimentation. The latter tend to produce more striking, and usually thicker, stratification than the former.

2.4 Here's a very skeletal survey of modern environments of deposition. (There will be whole chapter on depositional environments later.)

marine (ranging from shallow to deep; a wide variety of environments)

fluvial (i.e., in rivers)

lacustrine (i.e., in lakes)

glacial (both directly beneath glaciers, and at and near the margins of glaciers)

eolian (i.e., by the wind)

2.5 It should be easy for you to understand how sediments can be buried and preserved "permanently" in the ocean, but probably less easy for you to understand how sediments deposited on the continents (all of the other kinds of environments listed above) can be preserved, inasmuch as the continents are, in the long run, being worn down by erosion. The answer lies in what's meant by "temporary" and "permanent". In the first place, by virtue of the workings of plate tectonics, the oceans don't actually afford a "permanent" resting places for sediments anyway. Moreover, *in a great many situations on the continents, thick successions of sediments can be deposited in areas that undergo substantial subsidence and might escape reerosion for geologically long times*.

2.6 A few words about event beds and the events that deposit them seem in order here. The main kinds of events responsible for sediment beds are *storms at sea, river floods, and sediment gravity flows in the ocean and in large lakes*. The first two are easier to understand than the last.

2.7 *Turbidity currents* are the most important kind of sediment gravity flow. Here's an instructive but messy home experiment on turbidity currents. You will need access to a bathtub. Obtain a mixture of sediment ranging in size from mud to sand (a volume of sediment no bigger than the size of a shoebox will do), and a big plastic rubbish barrel. Fill the barrel about half full of water, pour in the sediment, and stir it up well with a paddle to maintain a suspension. Now fill your bathtub, and pour the sediment–water mixture into the sloping "back" end of the tub (the end away from the faucets and drain). The suspension will flow down the slope of the bathtub and out onto the "basin plain" as a bottom-hugging density underflow, with a well-defined head and a following body and tail with a roily, turbulent interface with the overlying clear water (Figure 8-1). The result is a bed of sediment deposited from the turbidity current as it moves. Such a bed, called a ***turbidite***, tends to show normal grading: the particle size in the deposit is coarsest at the base and fines upward to the top of the layer. Turbidites of this kind are classic examples of event beds. The sedimentary record is replete with turbidites, each deposited in a matter of minutes to hundreds of minutes, interbedded with muds or shales that might have been deposited at rates as slow as a few centimeters per thousand years!

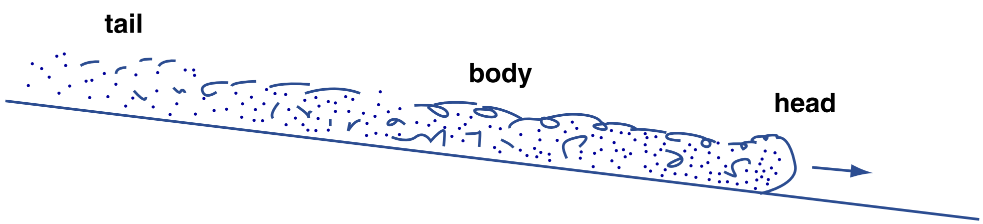

Figure by MIT OCW.

Figure 8-1: A turbidity current

2.8 Here are some other examples of events or processes that give rise to the strata we see in the modern and ancient record of stratified rocks:

- A sand bed deposited on the continental shelf by a gigantic storm
- A gravel bed spread over a small area of the bed of a braided stream by a flood
- A thin lamina of clay deposited in the deep ocean, with slightly different composition and/or texture, caused by slight change in depositional conditions, that serves to distinguish it from underlying and overlying strata
- A basalt flow spread over a land surface by a volcano
- An ash bed deposited over a wide area by an explosive volcanic eruption

2.9 Incidentally, *how do we know about such depositional processes in the first place?* That might seem like a trivial question, but in fact it's a serious one. Geologists make a distinction between *"the modern"* (what is happening, and what we can observe, at present) and *"the ancient"* (what's recorded in the rock record of the earth). It's ironic that we can actually see the deposit better in the ancient than in the modern, because of the great difficulty of sampling the sediment after the event in the modern, to say nothing of the difficulty of even watching the event happen (divers have a dangerous enough time without having to contend with powerful currents that would sweep them away). The deposits are easy to see in the ancient, but of course we have to deduce the depositional processes, and deduction can be very dangerous when one is dealing with phenomena as complex as turbulent two-phase flow (in the parlance of the fluid dynamicist).

2.10 Keep in mind that *a given stratum may not have a very great lateral extent*. If you were able to follow or trace your stratum laterally, what would happen to it? It would either *change gradually into another stratum* or it would *disappear by pinching our or wedging out*. Distances vary greatly, from just a few meters to hundreds of kilometers.

3. HISTORICAL BACKGROUND

3.1 Up until about 1800, thinking about the Earth's past was largely flood-dominated, except for a few who were ahead of their time, like Leonardo da Vinci, who perceived the true significance of fossils in rocks. Nicolaus Steno (born Niels Stensen; 1638–1686), who should be considered the father of stratigraphy, recognized not only the significance of fossils but also the true nature of strata. His thinking has been summarized in the form of *Steno's Laws* (although "principles" would be a better choice of word than "laws"):

- **superposition:** younger rocks are deposited on older rocks
- **original horizontality:** strata were close to being horizontal when they were originally deposited.
- **original lateral continuity:** strata were originally laterally extensive relative to their thickness when they were deposited.

I suppose that these things seem obvious to you now, but they were revolutionary in Steno's time, and they profoundly affected the practice of geology.

3.2 In the earliest 1800s, William Smith in England and Georges Cuvier in France used the successions of faunas in stratified rocks for mapping. This led to the development of the principle called the ***law of faunal succession***: *distinct faunas succeed one another regularly in the rocks*. Why fossil faunas work this way was not well understood, however, until the middle 1800s, as a result of the work of Darwin and Wallace.

3.3 The whole record of stratified rocks was well worked out by the middle of the 1800s, and almost all of the periods and subdivisions thereof we use today had been established. But the modern approach to the detailed stratigraphy of individual areas did not develop until the early 1900s. Later on, after some more preparation, we'll deal with another of what might be called the great principles of stratigraphy: *Walther's law of facies*.

4. SUCCESSIONS OF STRATA

4.1 Now think about *the sequence of strata you would see in one big outcrop*, or in a series of outcrops in a small area. This is called a ***local section***. Even though the physical dimensions of the outcrop might be fairly "equidimensional", you are seeing a stack of strata in essentially one dimension, because the changes from stratum to stratum in the sequence are almost always much more rapid and substantial, per unit distance, than lateral changes along the strata. Figure 8-2 is a cartoon of an outcrop that shows a local section, along with a schematic column that represents the section you might measure and describe.

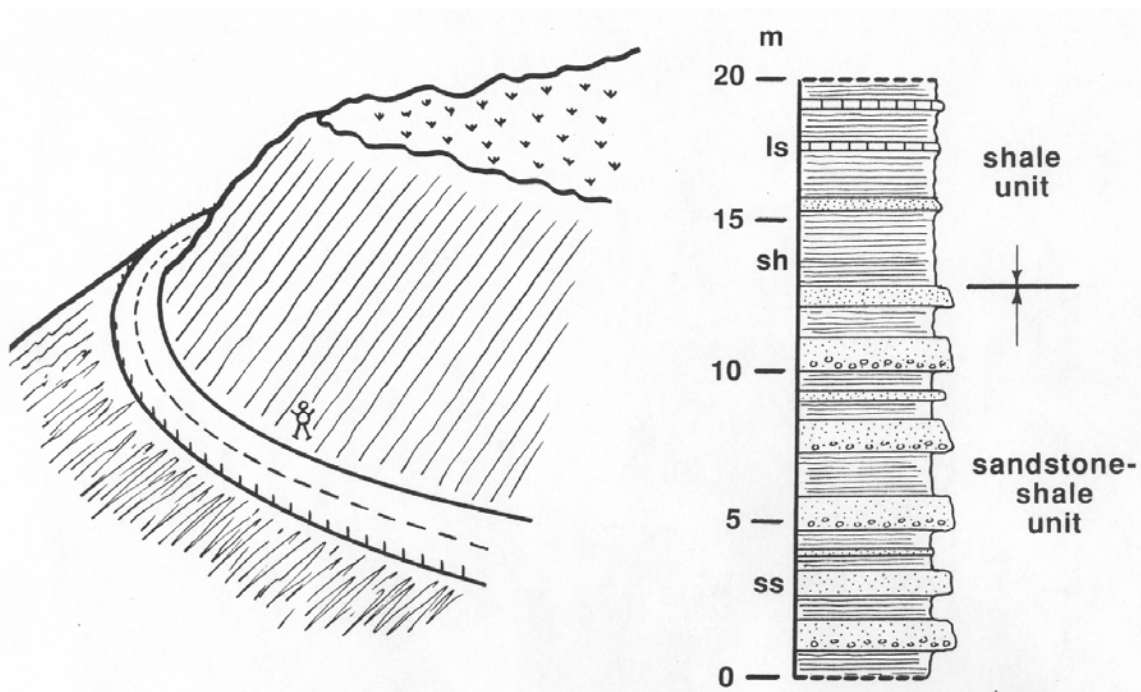

Figure 8-2. Cartoon of an outcrop showing a local section.

the "stratigraphic column" or the "local section"

4.2 It turns out that in any given area, *deposition is usually non-uniform in both space and time*; the nature of deposition changes laterally at a given time, and it changes with time at a given point.

4.3 It also usually turns out that *gradients of deposition in space and time are also non-uniform*: at certain times and places, changes are faster and more abrupt. This means that we have a good chance of recognizing what we could think of as *natural rock units*. When we examine a local vertical section we usually find that vertical variations are not entirely random or chaotic. Instead, there is usually some natural ordering or "signal" such that *the stack can be subdivided into rock units that show a high degree of internal sameness compared with rocks above and below*.

4.4 For example, if we could have seen more of the local section shown above, we might have seen the section shown in Figure 8-3 (here represented more generally and in less detail).

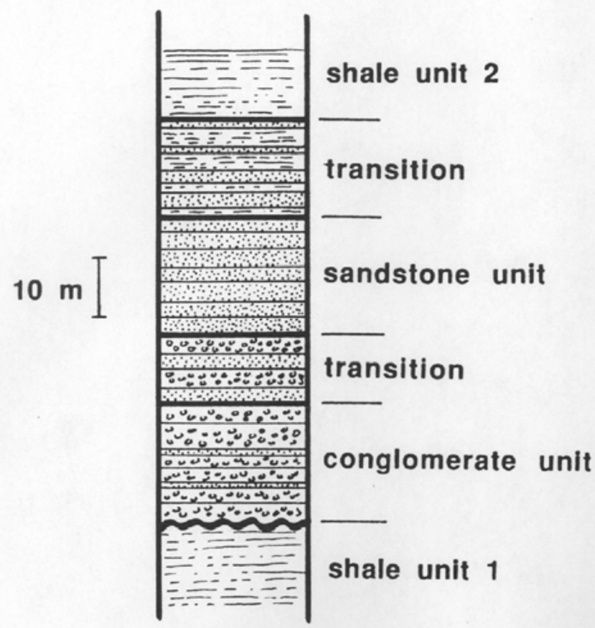

Figure 8-3. The stratigraphic section of which the section shown in Figure 7-2 is a part.

4.5 Contacts between sedimentary rock units can be

- gradational by continuous change
- gradational by interbedding
- abrupt by change in deposition
- abrupt by erosional break

4.6 Now think about what you would see if you *traced the beds and rock units laterally*—that is, if you hunted up neighboring local sections, maybe kilometers to tens of kilometers away from the highway cut shown above, but in the same part of the stratigraphic column.

4.7 Because except in unusual depositional settings the individual beds have lateral dimensions smaller than kilometers to tens of kilometers, *you should not expect to see exactly the same beds in the neighboring local sections*. (Keep in mind that you generally wouldn't really know that, because most beds aren't distinctive enough to be recognized among a whole lot of other similar beds.) But *the rock units you recognized at the highway cut probably would be recognizable in neighboring sections*.

4.8 Your natural inclination would probably to be a "layer-caker" and assume that the times represented by the contacts between rock units are the same from section to section. But you would generally be far wrong in such an assumption! One tip-off would be to find some unique bed in all the sections, like a distinctive bed of volcanic ash, and see where it lies in the section relative to the rock-unit contacts. (Such a bed is called a ***key bed.***) It would generally be in different positions from section to section. To investigate this effect we have to make a major excursion into the nature of deposition.

4.9 Imagine a coastal area where deposition is taking place and the sea is slowly advancing onto the land (either because sea level is rising around the world, or because the crust is locally subsiding relative to world sea level, or a combination of both; it doesn't make much difference for what we're doing here.) Look at a vertical cross section normal to the shoreline, shown in Figure 8-4. (Figure 8-4 is the most important figure in this chapter; be sure you understand the points I'm trying to get across with it.)

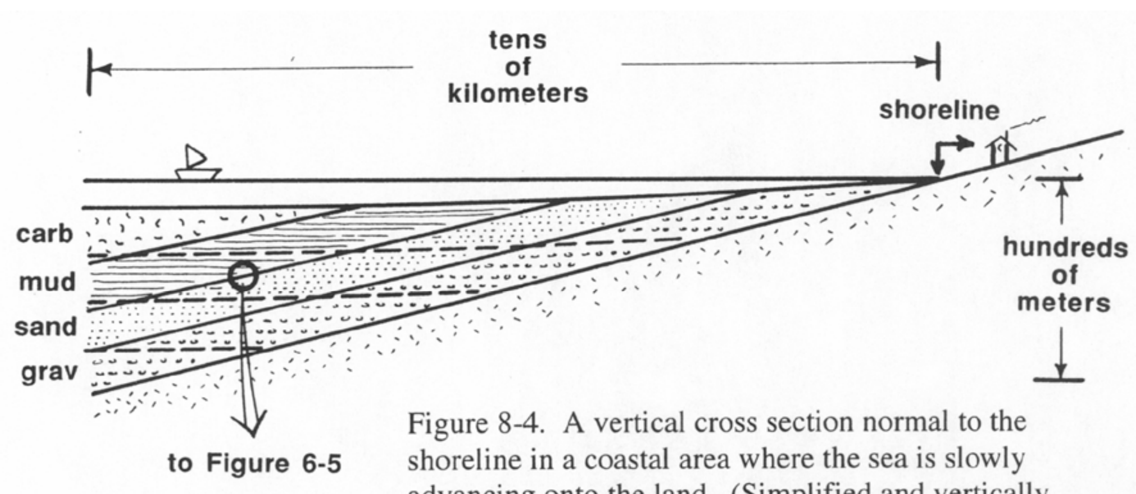

Figure 8-4. A vertical cross section normal to the shoreline in a coastal area where the sea is slowly advancing onto the land. (Simplified and vertically exaggerated.)

4.10 This cross section shows the basement upon which a sedimentary sequence is being deposited, and the sequence of sediments that has already been deposited on that basement. The dashed lines through the deposit represent imaginary surfaces of equal time; that is, they show where the sea floor was at a series of earlier times.

4.11 Look first at *the distribution of sediment types on the present sea floor*. I have drawn *belts of sediment parallel to the shoreline*, with finer and finer sediment farther and farther from shore. Often things work this way, although often they don't.

4.12 It's striking that *the deposit is arranged as units of differing sediment type that are parallel to the basement surface*. Just a little thought should convince you that this comes about because *the depositional belts on the sea floor are "tied" to the shoreline, and shift as the shoreline shifts*. The contacts between the sedimentary units therefore cut across the time surfaces. This nonparallelism of time surfaces and depositional-unit boundaries is termed ***diachrony*** (adjective: ***diachronous***).

4.13 (I should point out here that there's a lot of vertical exaggeration in my cartoon diagram; the angles between the time surfaces and the depositional-unit contacts are very small, because we're dealing with a thickness of tens to hundreds of meters over a shore-normal distance of some tens of kilometers.)

4.14 Note that the sequence of sediment belts on the present sea floor from the shoreline seaward is the same as the sequence of depositional units you would find vertically downward from some point on the sea floor. This is the manifestation of what's called ***Walther's Law of Facies***, the last great principle of stratigraphy I want to tell you about:

> **The lateral distribution of facies on a depositional surface is the same as the vertical distribution of these same facies in a vertical section through the deposits.**

(The term ***facies***, in very common use in sedimentology and stratigraphy, refers to *distinctive kinds of sedimentary deposits*.)

4.15 The advance of the sea onto the land is called a ***transgression***, or ***marine transgression***, and the resulting sedimentary succession is called a ***transgressive succession***.

4.16 Now take a closer look at the depositional units in the picture above. Look at one small part of the contact zone between, say, the sand unit and the mud unit, and blow it up to a much larger scale (Figure 8-5).

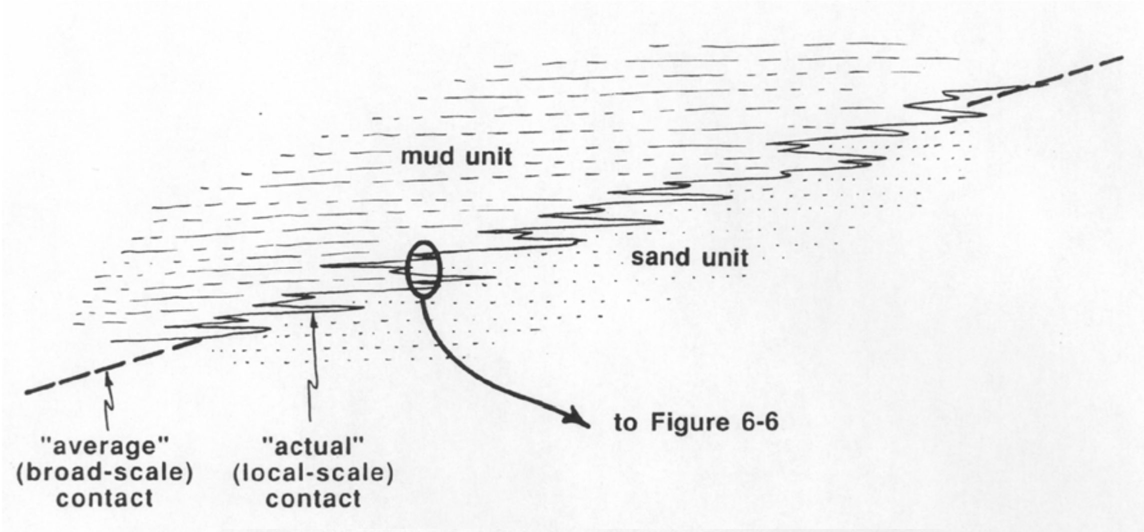

Figure 8-5. Blown-up view of one small part of the contact zone between the sand unit and the mud unit in Figure 8-4.

4.17 Because of the irregularly shifting nature of the depositional belts over geologically short times (caused by such things as minor fluctuations in sea level superimposed on the general rise, or minor fluctuations in climate, or inherent variability in depositional processes) the boundary would be very jiggly in cross section.

4.18 On an even smaller scale, that of individual beds, you would see more jiggliness, caused by such things as storm events (Figure 8-6).

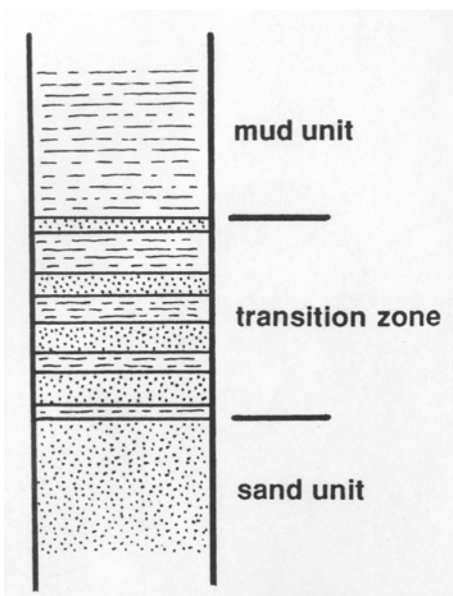

Figure 8-6. The nature of the contact between the sane unit and the mud unit on an even smaller scale, that of individual beds.

4.19 Once this sequence was buried, lithified, uplifted, and eroded for you to see as an outcrop of ancient rock, you would see a succession of interbedded sandstones and shales much like the cartoon outcrop along the highway earlier in this chapter.

4.20 The perceptive student might wonder how the picture in Figures 8-4 through 8-6 would differ if *sea level was falling and the shoreline was moving seaward*. Such a situation is called a ***marine regression*** (Figure 8-7).

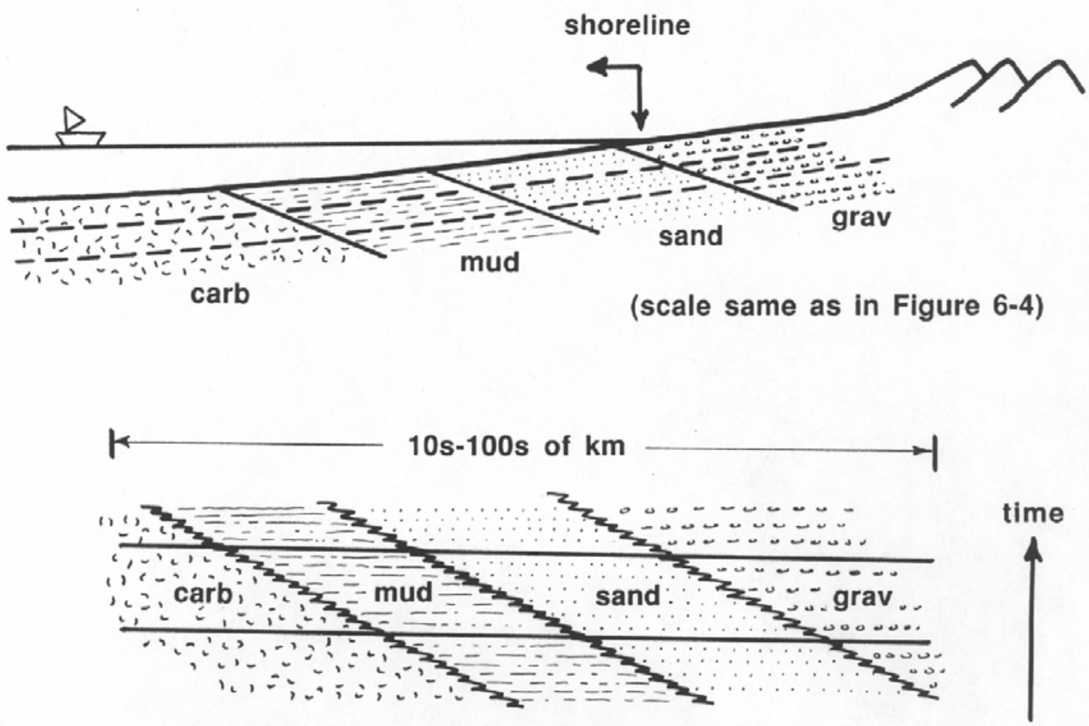

Figure 8-7. A) A vertical cross section normal to the shoreline in a coastal area where the sea is slowly retreating from the land. (Simplified and vertically exaggerated.) B) A different way of showing the relationships in Part A, by means of a diagram with equal times represented by horizontal lines.

4.21 Finally, Figure 8-8 shows another example of the nonparallelism of time surfaces and depositional-unit boundaries, this time extreme: filling of a fault trough with sediments shed from the rising block. Here, the contacts of the depositional units cut the time surfaces almost at right angles!

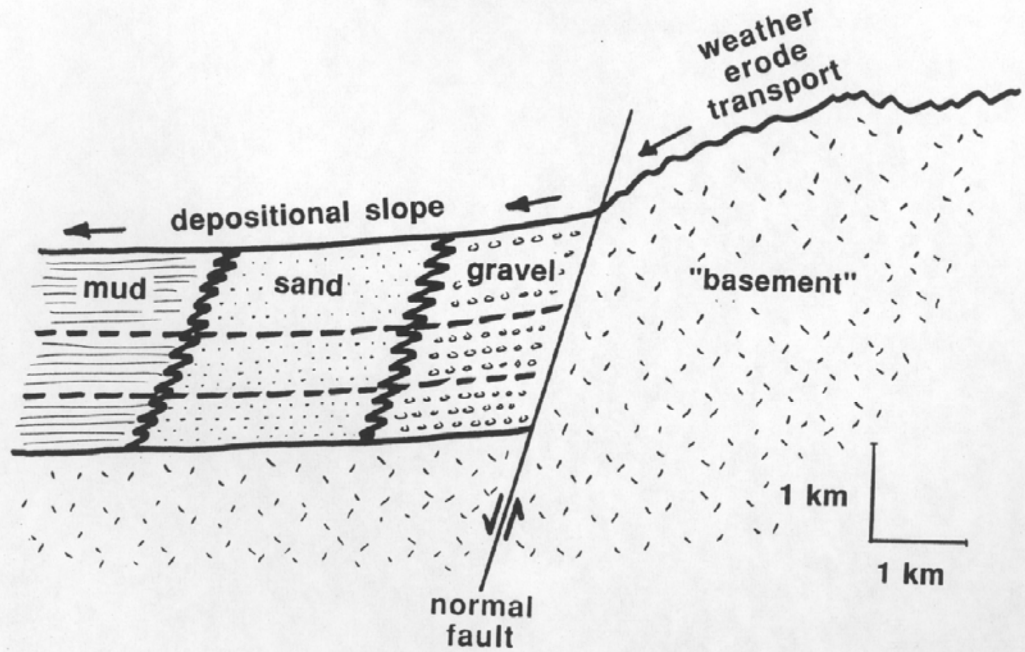

Figure 8-8. A vertical section through a sedimentary basin produced by movement on a normal fault.

5. MORE ON ROCK UNITS

5.1 Here's some material on the more formal aspects of physical (i.e., rock-unit) stratigraphy. There's a conventional system for recognizing and naming sedimentary rock units, which all stratigraphers have to follow. And there's rigorous priority in naming these units, just as there is in paleontology in the naming of species. Here we have to be more specific and use the term rock-stratigraphic unit for what I have casually been calling a depositional unit.

5.2 The basic rock-stratigraphic unit is the ***formation***. Here is the official definition of a formation:

> **A genetic unit of strata deposited under essentially uniform conditions or an alternation of conditions. Boundaries are to be drawn at points in the section where lithologic features change or where there are significant breaks in continuity of sedimentation.**

So the word *formation* in geology is very specific, and cannot easily be used as a general word outside its official stratigraphic meaning.

5.3 Points about formations:

relative uniformity: A formation exhibits a relatively high degree of uniformity compared to surrounding strata or rock units.

mappability: Formations should be mappable units on typical geologic map scales; they are not just beds but fairly thick successions of beds. Not many formations are thinner than several meters.

genetic significance: Lithologic differences can be anything, but they should be as genetically significant as possible.

time: There is no element of time in the definition; as you have seen from the example of a marine transgression above, a formation can (and in fact usually does) represent different spans of time in different places.

exhaustiveness: You are supposed to subdivide a local section exhaustively (and non-overlappingly) into formations. Of course, the number of places in the world where a stratigrapher gets a shot at a totally undescribed section is getting smaller and smaller. Nowadays you have to work with already-defined rock units. At most, you may have to deal with tracing already-defined rock units from adjacent areas into your own area, and perhaps erecting additional rock units specific to just your area.

connectedness: Formations start out as connected masses of strata, but subsequent history of uplift and erosion may eventually isolate certain parts of the formation from other parts. (This brings up the sometimes difficult problem of when to apply a different name. On the other hand, often the name changes at state boundaries!)

subdivision: Formations may be subdivided into ***members***, ***tongues***, and ***lenses***. And they can be grouped into ***groups***. But none of this is required. Practice is fairly flexible: (1) part of a formation can be subdivided and parts not; (2) the subdivisions can be formally named or just informal; and (3) some formations can be put into groups and others in the same section not.

preservation: Preservation of rock units varies enormously, from total (in the subsurface) to partial (subsurface plus eroded edges forming outcrop) to very cut up and scrappy (by later tectonism and erosion).

type section: The erector of the formation is supposed to choose a ***type section****—a local section that embodies his/her concept of the formation well*. This serves to tie down the concept so that it won't "drift" with later study by others.

convention for naming: Formations are named after geographic places; the second part of the name is either the dominant rock type or simply the word "Formation".

sacredness: You can't monkey with somebody's formation unless there is compelling evidence that the earlier guy was wrong.

6. UNCONFORMITIES

6.1 All stratified successions had to be deposited on some preexisting surface, and commonly that surface must have been subjected to substantial erosion before deposition commenced. *The contact between the stratified succession and the underlying rock* is called an ***unconformity***. (The term is also used in the abstract, without either definite or indefinite article, for *the relationship such a contact represents*.) The underlying rock itself may or may not be stratified. Geologic time is unrecorded at the unconformity surface; the time break may range from geologically short (perhaps only some hundreds of thousands of years) to a substantial fraction of all geologic time.

6.2 The unconformity surface can be cut into crystalline rock (Figure 8-9) or into deformed sedimentary strata (Figure 8-10). If the rock beneath the unconformity is stratified, it commonly shows evidence of deformation; unconformities showing *angular discordance between the strata above and below* are called ***angular unconformities***. In the figures, the strata above the unconformity are shown to be concordant with the unconformity surface itself. This is usually what you see, but it need not be true locally, because if sediment is deposited on an irregular surface the strata may abut against the surface at some angle, depending on the mode of deposition. This is called a ***buttress unconformity*** (Figure 8-11).

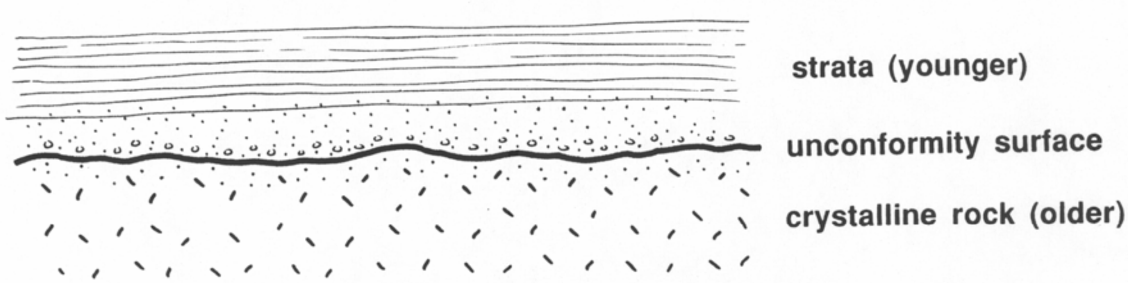

Figure 8-9. An unconformity on crystalline rock.

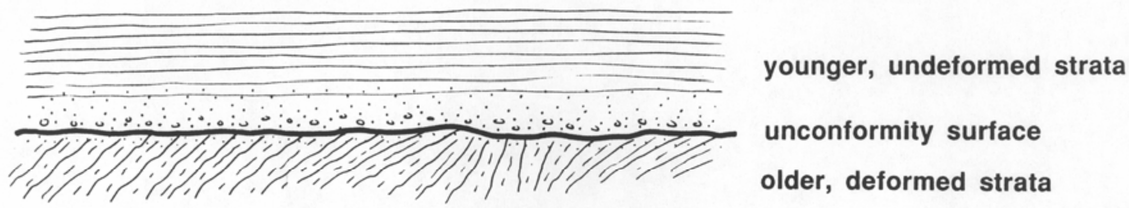

Figure 8-10. An unconformity on deformed sedimentary rock.

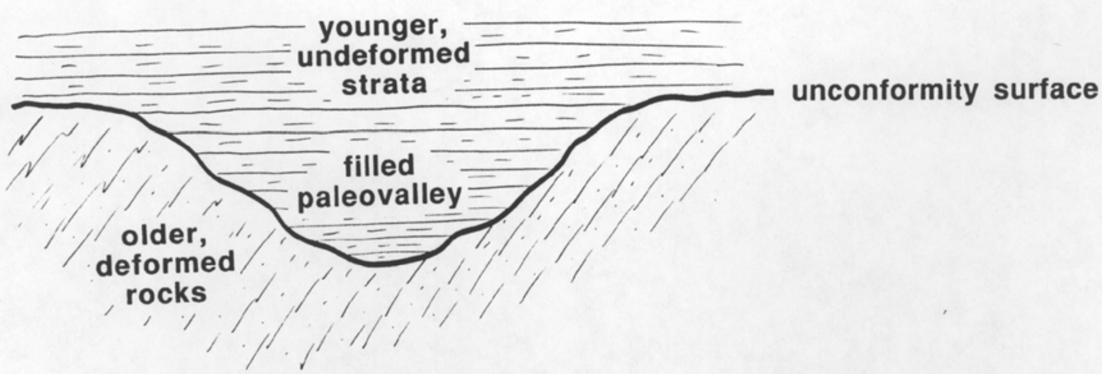

Figure 8-11. A buttress unconformity.

6.3 Common within conformable sedimentary sequences are **disconformities**—*surfaces representing breaks in time without any discordance of strata*. Disconformities represent temporary cessation of deposition, and these nondepositional episodes may or may not be accompanied by erosion of the preexisting sediment. Where there is erosion of the underlying sediment the disconformity is said to be an ***erosional disconformity***. If there is no erosion, the presence of the disconformity is difficult or impossible to detect. *The break or gap in time represented by a disconformity* is called a ***hiatus*** or a ***diastem***.

6.4 Although some sedimentary successions, especially those deposited in deeper marine environments, are truly continuous, most sedimentary successions preserved in the geologic record are discontinuous. In fact, in some sequences, especially very thin successions deposited over very long times, many or most beds must be separated from underlying and overlying beds by disconformities. Sometimes we actually observe this, but even when we don't, it seems a reasonable assumption, because rates of deposition of individual beds, interpreted from what we know from modern environments, would give far greater thicknesses over the long times known to be represented by such successions.

Without good evidence from fossils, it is impossible to evaluate the significance of these hiatuses.

6.5 Figure 8-12 is a sketch of a disconformity involving both erosion and change in sediment type; these are easy to spot. Figure 8-13 is a sketch of a disconformity without either erosion or change in sediment type; such unconformities are difficult or impossible to detect.

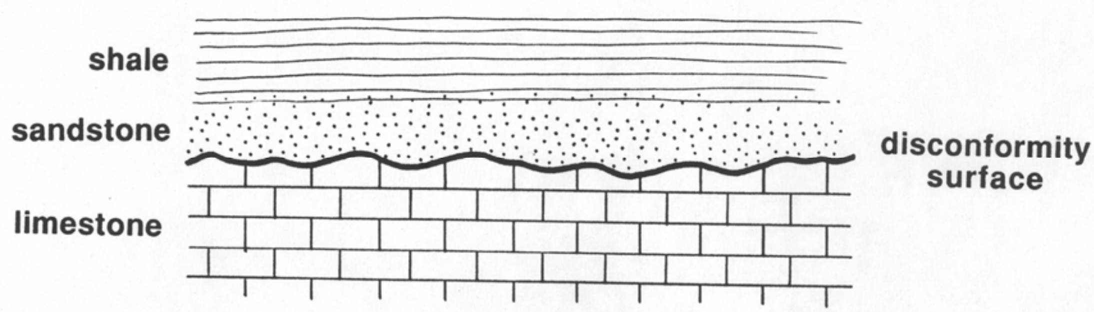

Figure 8-12. A disconformity involving both erosion and change in sediment type.

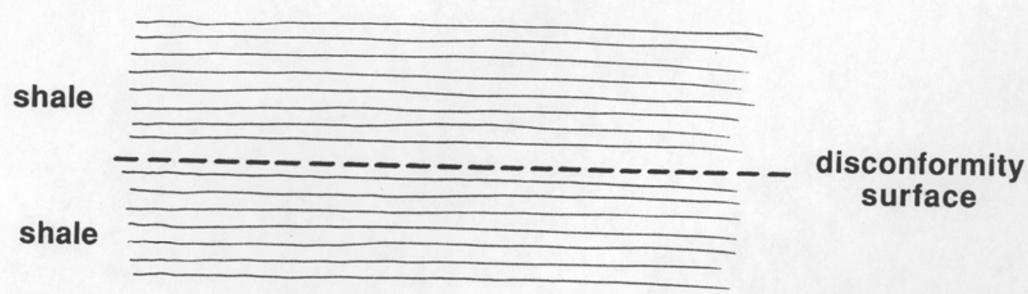

Figure 8-13. A disconformity without either erosion or change in sediment type.

7. TIME IN STRATIGRAPHY

7.1 I have not said much yet about *the time relations of strata*. First of all, let me remind you that in many sections, especially those deposited in nonmarine environments like rivers and in shallow-marine environments, much or even most of the time is unrepresented by rocks but is represented instead by hiatuses or diastems (breaks in the record).

7.2 You can still recognize natural rock units, because depositional conditions can be about the same for long periods of time, but deposition might represent only a very small fraction of the time. This is one of the major reasons why formations can look about the same from place to place but vary greatly in their thickness.

7.3 On the other hand, many sections represent slow and continuous deposition, so all of the time is recorded. It's a matter of the particular environment of deposition: nonmarine and shallow-marine sections are likely to be full of holes, whereas deeper marine sections are likely to be continuous.

7.4 Rock units are defined without regard to time. The critical operation in comparing local sections is ***correlation***: *establishing the time equivalence among strata in various areas*. This can range in scale from local areas to worldwide.

7.5 There are four ways of telling time, and therefore making time correlation, in geology:

radioisotopic dating: this has been of enormous importance in establishing absolute ages in geology (it's the only way of doing that), but in the context of stratigraphy it's generally too imprecise for anything but the broadest stratigraphic correlation.

magnetostratigraphy: This is good for rocks that are only a few million years old, but it's not of general applicability in stratigraphy.

fossils: This is the standard way of correlating strata. The succession of faunas (and to a lesser extent floras) is so well worked out for much of Phanerozoic time that correlation can be fairly precise. Obviously this provides only *relative time*, not *absolute time*. And there is the practical problem that not all sedimentary rocks are fossiliferous—in fact, the majority are unfossiliferous. More on paleontology and correlation by fossils later.

key beds: I mentioned above that if you know you have one or more unambiguously recognizable beds in your sections, like ash beds, you can tell relative time with satisfying precision. The trouble is that such key beds are not at all common.

chemostratigraphy: In recent years, the isotopic signature of sediments can be used to make correlations among widely separated sections, even worldwide. That is especially true of times in geologic history when there were glaciations and deglaciations. The isotopic ratio of the two naturally occurring stable isotopes of carbon, ^{12}C and ^{13}C, have been especially useful in that regard.

7.6 Two other kinds of stratigraphic units, in addition to lithologic units, are officially defined in stratigraphy. These have time as an essential part of their definition.

Time-stratigraphic units (also called time-rock units or chronostratigraphic units): units of rock that contain all the rock (in the world!) that were deposited between two different times.

Time units (or chronologic units): units, defined by time itself, that contain all the time between two different times.

These two kinds of units are not erected independently of one another; they come in pairs.

7.7 Table 8-1 gives the conventional hierarchy of time units and time-stratigraphic units. A few comments on this table:

Table 8-1. Hierarchy of time units and time-stratigraphic units.

time	*time-stratigraphic*
eon	-
era	erathem
period	system
epoch	series
age	stage
phase	zone

• Systems/periods are *always* worldwide

  • Epochs/series are *sometimes* worldwide

  • Ages/stages are *never* worldwide

7.8 There are zillions of names for these units, usually taken from place names. They always end in -ian or -an. Many are real tongue-twisters. I would be willing to bet that no one ever learns them all; you get familiar with just the ones relevant to the rocks you're working with.

8. SEA-LEVEL CHANGE

8.1 I am sure you know already that *sea level changes with time*. Much is made these days about sea-level changes on time scales of decades to a few centuries, owing to the likelihood of worldwide sea-level rise caused by (1) melting of continental glaciers and (2) expansion of the oceanic water column as a consequence of rising water temperature in the oceans. Sedimentary geologists are concerned with sea-level changes on time scales of centuries to tens of millions of years because of the influence of such changes on the sedimentary record.

8.2 Several processes can cause sea-level changes at a point in the world's oceans:

- vertical tectonic movements (uplift or subsidence) of the lithosphere
- compaction of the sedimentary column below the given locality
- worldwide changes in sea level caused by changes in the volume of water in the oceans or by rise or fall of the sea floor.

The third process above is known as ***eustasy*** (note the spelling: **not** *eustacy*). Eustasy is defined *as a change in the elevation of sea level worldwide relative to some stationary datum at depth*. There is a fundamental problem here, though: how does one define or specify that datum? The center of the Earth would be a good one, in theory, but it's unworkable in practice. Other datums you might consider suffer from the problem that they are susceptible to vertical movements themselves. For that reason, geoscientists deal with ***relative sea level***: sea level relative to the sea bottom in a given locality.

8.3 Eustatic sea level can change by virtue of changes in the volume of continental glaciers. The water contained in glacier ice is ultimately derived from the oceans, and when a glacier melts it delivers the meltwater back to the oceans. But there is another cause of eustatic sea-level change. You know that there is a worldwide system of mid-ocean ridges, where new oceanic lithosphere is continuously created. The mid-ocean ridges stand higher than the surrounding ocean floor not because of upward-directed forces underneath them but because they are hotter than the surrounding oceanic lithosphere and therefore more expanded. It has been generally accepted since early in the plate-tectonics era that the increase in ocean depths away from the mid-ocean ridges is well explained by progressive cooling of the lithospheric plates as they move away from the spreading axis. At times when plate tectonics is more active worldwide, the mid-ocean ridges, being hotter, stand higher than at times of relative plate-tectonic quiescence. This has the effect of raising sea level relative to the surfaces of the continents.

8.4 Although the effects of these two processes on sea level are the same, the time scales are widely different. Eustatic sea-level changes caused by growth of shrinkage of glaciers, called ***glacioeustatic*** (or glacio-eustatic) changes, occur on time scales of centuries to millions of years (and most of the changes are on time scales of tens of thousands to hundreds of thousands of years, the range of time scales referred to as the Milankovitch band, having to do with periodic changes in the Earth's orbital parameters). Eustatic sea-level changes caused by changes in the elevation of the ocean floor occur on much longer time scales of tens to hundreds of millions of years. Consequently, sedimentary geologists need to deal with the signature of eustatic sea-level changes in the sedimentary record on a very wide range of time scales.

8.5 Sedimentary geologists commonly classify the time scales of sea-level changes in terms of orders: first order (the longest), second, order, and so on to as high as fifth order (the shortest). Be warned, however, that different workers have different views of what constitutes these orders!

8.6 When relative sea level fluctuates in cycles, the time in the cycle when sea level is highest is called the ***highstand***, and the time in the cycle when sea level is lowest is called the ***lowstand***.

8.7 Just to give you the flavor of how fluctuations in sea level affect the sedimentary record, look at Figure 8-14, which shows a cross section normal to a typical continental-shelf depositional setting. The little graph shows one segment of the curve of repetitive rises and falls in sea level, by perhaps several meters. (The curve isn't necessarily symmetrical like the sine wave I've shown for simplicity.) Because slopes on shelves are usually quite small, just a few degrees, even fairly small vertical changes in sea level cause the shoreline to move back and forth for long distances, tens to even hundreds of kilometers.

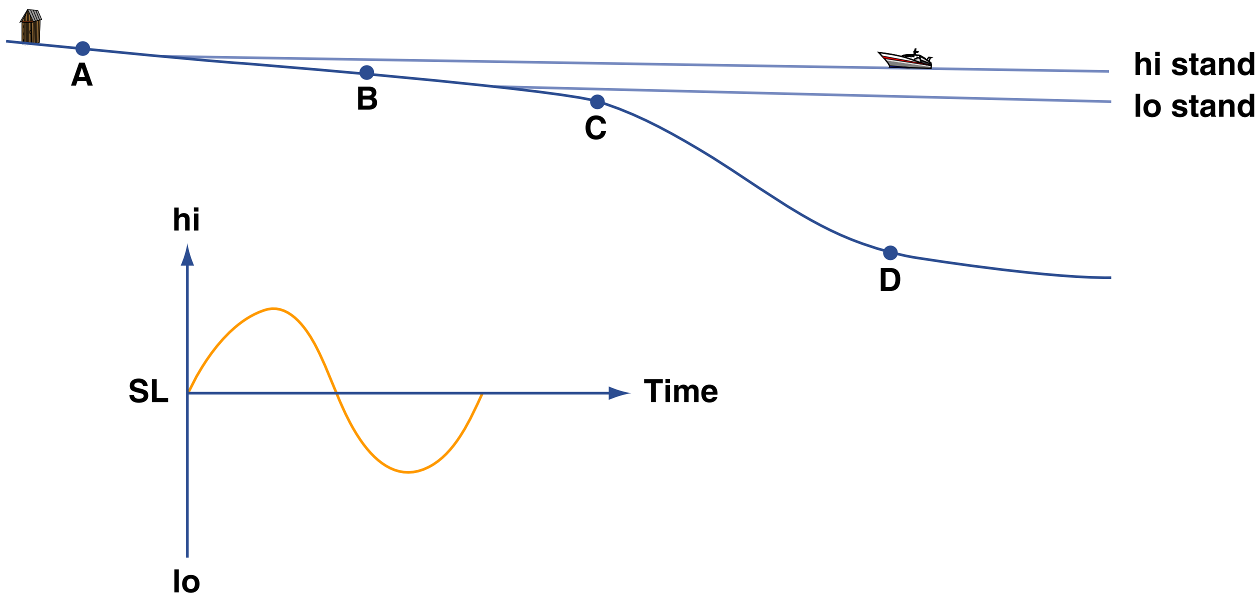

Figure by MIT OCW.

Figure 8-14: Cross section normal to a shoreline, to illustrate the effect of cyclic fluctuation. s in sea level on sediment deposition

8.8 Point A wouldn't be greatly affected, because it's always on land and therefore undergoing at least slow erosion. Likewise, Point D, in deep water and far from land, would always be undergoing slow deposition of fine sediment and would be little affected. But at Point C, always below sea level but subjected to great relative changes in water depth and distance from shore, the marine sedimentary section that gets deposited would show great differences in facies over a single sea-level cycle. The same is true for Point B, which is alternately submergent and emergent; there you should expect to see a disconformity in the sedimentary section in each sea-level cycle, representing the time during which the area is emergent and undergoing partial erosion of sediment deposited during the previous high stand of sea level.

8.9 As you can imagine, analysis of the kinds of local sedimentary sections that are deposited during such fluctuations in sea level get much more intricate than this: they depend upon such things as *the magnitude, shape, and periodicity of the sea-level curve, the shape of the bathymetric profile of the shelf, the climate in the region, and the sediment supply from land*, and other things as well. This is an area of stratigraphy that's just in recent years being applied to reexamination of ancient depositional settings around the world, and is leading to great advances in interpretation of ancient depositional processes.

9. SOME TERMINOLOGY FOR IMPORTANT CONCEPTS

9.1 In this course you have already learned some things about transgression and regression. The term *transgression* is used for the advance of the shoreline in the landward direction, owing either to crustal subsidence or to worldwide rise in sea level. Used without a preceding article (*transgression*), the term refers to the concept or the process; used with a preceding article (*a* transgression; *the* transgression), the term refers to a particular event. The opposite of transgression is *regression*: the retreat of the shoreline away from land.

9.2 I would like to show you, here, in the form of Figure 8-15: Prothero, D.R., and Schwab, F., 1996, Sedimentary Geology; An Introduction to Sedimentary Rocks and Stratigraphy: Freeman, 575 p. (Figure 15.16, p. 346) and Figure 8-16: Prothero, D.R., and Schwab, F., 1996, Sedimentary Geology; An Introduction to Sedimentary Rocks and Stratigraphy: Freeman, 575 p. (Figure 15.17, p. 347), two all-time classic examples of transgressive and regressive successions. In Figure 8-15 you can see how, at any given time, Devonian depositional facies across New York State ranged from nonmarine in the east to offshore marine in the west. As time went on, the shoreline shifted to the west, and with it, the depositional facies. In Figure 8-16 you can see how the Cambrian sea, advancing from west to east in the Grand Canyon area, left a transgressive succession that started with basal coarse siliciclastics, grading up into finer siliciclastics, and then into carbonates.

9.3 You should also know that the term ***progradation*** refers to the building or shifting of depositional units seaward, and the term ***retrogradation*** refers to the shifting of depositional units landward. The term ***aggradation*** refers to building of depositional units vertically upward, neither aggradational or retrogradational. The important term ***accommodation*** (sometimes termed *accommodation space*) is used for *the space made available for sediment deposition below sea level*. Accommodation is developed by crustal subsidence and/or sea-level rise.

10. SEQUENCE STRATIGRAPHY

10.1 Introduction

10.1.1 It has been recognized since the early days of modern geology that sea-level change, resulting in transgression and regression, gives rise to a vertical succession of sedimentary facies in a given area, by virtue of the control of water depth on the nature of the sedimentation. (The old saying was: "*The seas went in, the seas went out*".) The organized patterns of cyclic variation in stratigraphic sections occasioned by fluctuations in sea level come under the heading of ***sequence stratigraphy***—the hottest new area in the old field of stratigraphy.

10.1.2 Beginning in the middle of the Twentieth Century, this notion was put on a more systematic basis by the recognition of what were called *sequences*: packages of transgressive–regressive deposits bounded by major continent-wide unconformities. These sequences are believed to reflect eustatic sea-level changes on the longest time scales, tens of millions of years. Figure 8-17: Prothero, D.R., and Schwab, F., 1996, Sedimentary Geology; An Introduction to Sedimentary Rocks and Stratigraphy: Freeman, 575 p. (Figure 15.20, p. 349) shows the sequences in the North American continent, recognized and named by Sloss (1963).

10.1.3 Beginning in the late 1970s, and continuing to the present time, an increasingly detailed and sophisticated picture of marine stratigraphic successions deposited during times of fluctuating sea level have been developed. These concepts come under the term ***sequence stratigraphy***. It is difficult, nowadays, to read about marine sedimentary successions without reference to sequence stratigraphy.

10.1.4 Let's start with the basic definition of a sequence, in the modern sense of the term. A ***sequence*** is "a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities". (Incidentally, as with so many other terms in Earth science, a word that was originally in use in a general sense has thus been co-opted for a more specialized usage. There is a tendency these days to substitute *succession* for what used to be called a *sequence*, and reserve *sequence* for its specialized usage in the context of sequence stratigraphy!)

10.1.5 What are the fundamental controls on the nature of sequences? There are three of them:

- **rate of crustal subsidence**
- **eustatic sea-level change**: magnitude and period
- **rate of supply of siliciclastic sediment from land**, and/or rate of production of carbonate sediment in the depositional area

10.1.6 The first two of these together determine the rate of change of accommodation. So it comes down to this, in the broadest context: *the relative importance of rate of increase in accommodation, making way for more sediment deposition, versus the rate of supply of sediment to fill that accommodation*. Beyond that, however, a number of other factors are of non-negligible importance in determining what the stratigraphic succession comes out to be. I'll mention just two here: the physiography of topography of the region, which is determined by tectonism, and the climate of the region, which is important in determining the kind of sediment that is being deposited in the first place. Figure 8-18 shows an even more detailed view of the many factors associated with the stratigraphy of the resulting deposits.

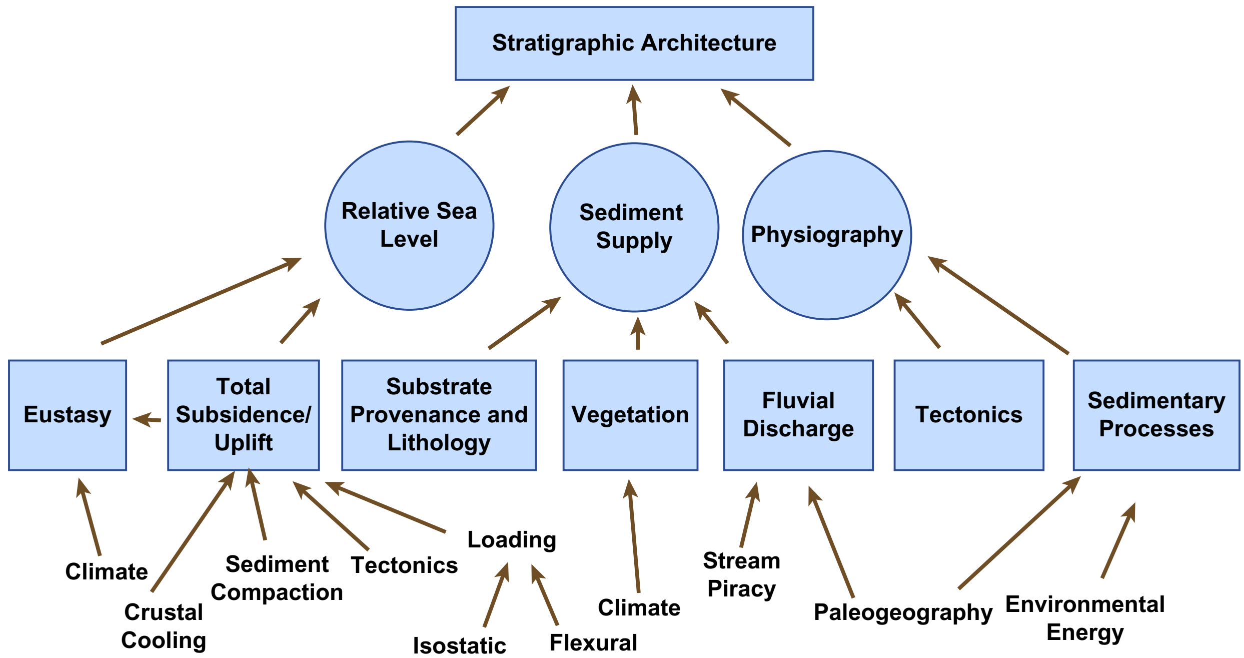

Figure by MIT OCW.

Figure 8-18: Interrelationships of the various factors, processes, or parameters that can influence the nature of a marine sedimentary succession

10.1.7 This is probably a good place to introduce the distinction between cyclic processes that are imposed upon the depositional system from outside (sea-level fluctuations, creation of accommodation) and processes that are inherent to the depositional system itself: things like shifting of tidal channels or delta distributary channels, which lead to vertical changes in the succession which have nothing directly to do with the cyclicity that is imposed by the external ("sequence stratigraphic") factors mentioned above. These processes superimpose an element of randomness on what is viewed as a largely deterministic process. There is considerable controversy among the experts about the relative importance of these two factors. A middle view is that the external signal is strong but is modified in substantial ways by internal processes.

10.1.8 Finally, here is a very important point: *there is no such thing as a single sequence-stratigraphic model*. If the rate of subsidence, the magnitude and period of sea-level change, and the rate and nature of sediment supply were always the same, there could be a useful such model In reality, however, *each of these fundamental governing parameters can take on a wide range of values*. For that reason, the nature of the resulting overall stratigraphic architecture—that is, the whole three-dimensional nature of the resulting deposit—varies extremely widely. (A cynic might claim that that's a good thing for sedimentary geology, because it will keep sedimentary geologists busy for a long time!)

10.2 Stratigraphy in the Subsurface: Interpreting Seismic Profiles

10.2.1 Many stratigraphers work mostly with subsurface data rather than outcrop data. The principal source of subsurface data is seismic reflection, whereby energy of vibration is created along a line on the land surface and the two-way travel time of seismic waves that reach certain reflecting layers and return to the surface. (An assumption needs to be made about the speed of the seismic waves through the medium, to convert to depths.) The data are processed in increasingly sophisticated ways by computers and are displayed, traditionally, as vertical sections or, nowadays, as gorgeous rotatable see-through cubes. Resolution has gotten down to as little as a few meters vertically—not quite bed by bed, but good enough to see much stratigraphic detail. To the novice, a seismic section looks like a tangle of wiggly lines, but the practiced eye can perceive much orders stratigraphic information. Once guiding lines are drawn along various surfaces, the relationships become apparent even to a casual observer.

10.2.2 What makes for a reflector? Any boundary between two layers with different densities and seismic wave speeds. The relevant quantity is called the ***acoustic impedance***, which is the product of the density of the medium and the wave speed of the medium.

10.2.3 Several kinds of relationships of sedimentary layers are characteristic of seismic reflection profiles (Figure 8-19). A ***clinoform*** is *an inclined surface, reflecting the sloping seafloor (or lake floor!) on which a body of strata is deposited*. The usual interpretation of clinoform is that they represent the progradation geometry of sediment packages that build out into deeper water. Also commonly seen on seismic sections are ***unconformities***, about which you learned earlier in this chapter. Unconformities usually involve actual erosional truncation.

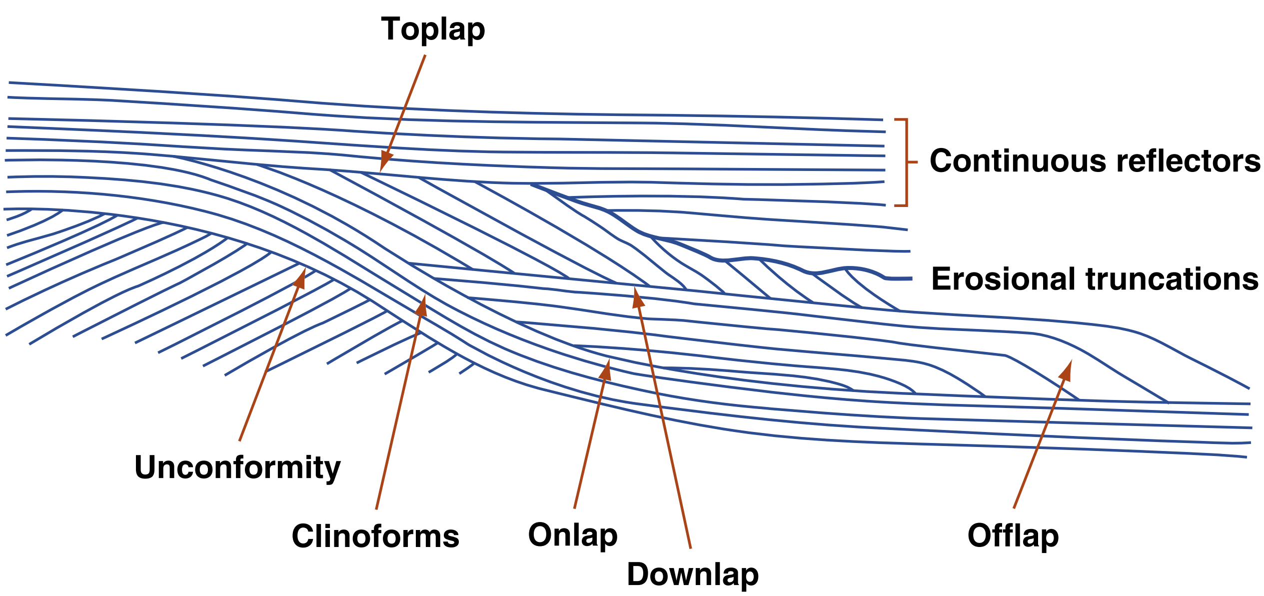

Figure by MIT OCW.

Figure 8-19: Kinds of relationships of sedimentary strata that are characteristic of seismic reflection profiles

10.2.4 There are also various kinds of "laps":\

onlap, by which packages of strata with relatively gentle dip are banked up against an older package of strata with greater dip.

downlap, by which inclined a package of inclined strata terminates downward against a less steeply dipping package of strata.

offlap, a pattern in which packages of strata build upward and outward into deeper water of a basin.

toplap, by which inclined strata, commonly clinoforms, terminate upward against a less steeply dipping, often almost horizontal, surface. There need not be erosional truncation.

10.3 The Nature of Sequences

10.3.1 A whole course could be given on sequence stratigraphy. Here I'll just give you a general idea of how sequences are built and what they look like.

10.3.2 Think about what happens in the course of a single cycle of sea-level change. Suppose that there is a broad, shallow shelf area, bounded on one side by land and on the other side by a slope that leads to a relatively deep marine basin. As sea level falls, the siliciclastic sediment supplied from land, or the carbonate sediment produced locally, is deposited in progressively shallower water. That results in a shallowing-upward succession. If the fall in sea level is sufficiently great, much of the depositional area becomes emergent, and is subjected to erosion. Sediment mobilized in this way is deposited on the slope or carried into the deep basin, commonly in the form of sediment gravity flows in canyons incised into the seaward margin of the shelf. A lowstand wedge of relatively deep-water sediment is thus deposited, and an unconformity is generated in the shallower areas. By convention, the ***sequence boundary*** is placed at this unconformity. As sea level rises again, the depositional area is progressively flooded. Any sediment deposited during this stage of rising sea level ends up as a *deepening-upward succession*. Such sediment is commonly either thin or missing entirely, however, for an understandable reason: siliciclastic sediment derived from land is stored far landward as river valleys incised during lowstand are flooded to become estuaries. This effectively shuts off the supply of sediment from land. This part of the succession is often described as a ***condensed section***, because sedimentation rates of the fine siliciclastics are often extremely low. Somewhere in the condensed section lies what is called the ***maximum flooding surface***, representing the time of sea-level highstand. (In reality, it's usually more like a maximum-flooding *zone* than a well-defined surface.) Eventually, as highstand conditions are approached and then reached, rates of sedimentation on the shelf increase again, and tend to coarsen (and shallow) upward. The cycle then repeats itself.

10.3.3 If you think carefully about the scenario described above, the resulting deposit, bounded by unconformities that developed because of subaerial exposure and erosion as lowstand is approached, has *a strong asymmetry*: the rising-sea-level (transgressive) deposits are relatively thin and fine grained, and the falling-sea-level (regressive) deposits are relatively thick and coarse-grained. Correspondingly, *most of the thickness of the sequence consists of shallowing-upward deposits*. That's one of the significant aspects of sequences.

10.3.4 Sequence-stratigraphic terminology gets much more intricate (and potentially confusing) than this. I will mention here only one set of terms. The term ***systems tract*** (I have always thought the term to be not very felicitous) refers to *distinct packages of sediment that are deposited during specific phases of the se-level cycle*: highstand system tract, lowstand systems tract, transgressive systems tract, falling-stage systems tract.

10.3.5 Recall that I mentioned earlier that there can be several distinct orders of sea-level cyclicity, from as short as centuries or millennia to as long as tens of millions of years. For that reason, one often has to deal with *sedimentary successions deposited during more than one order of sea-level cycle*. the result is: thinner and shorter-term sequences superimposed on thicker and longer-term sequences! In particular, the term ***parasequence*** is used for the shortest-period and thinnest such cycles, typically with thicknesses on the scale of one to a few meters, which are superposed on thicker sequences that may be tens to a hundred meters thick.

10.3.6 It's not easy to draw a diagram (a vertical cross section normal to the shoreline) that shows the essence of sequence stratigraphy without the diagram being overly complicated and confusing. Figures 8-20 and 8-21 show two examples, taken from the literature on sequence stratigraphy, that might help you.

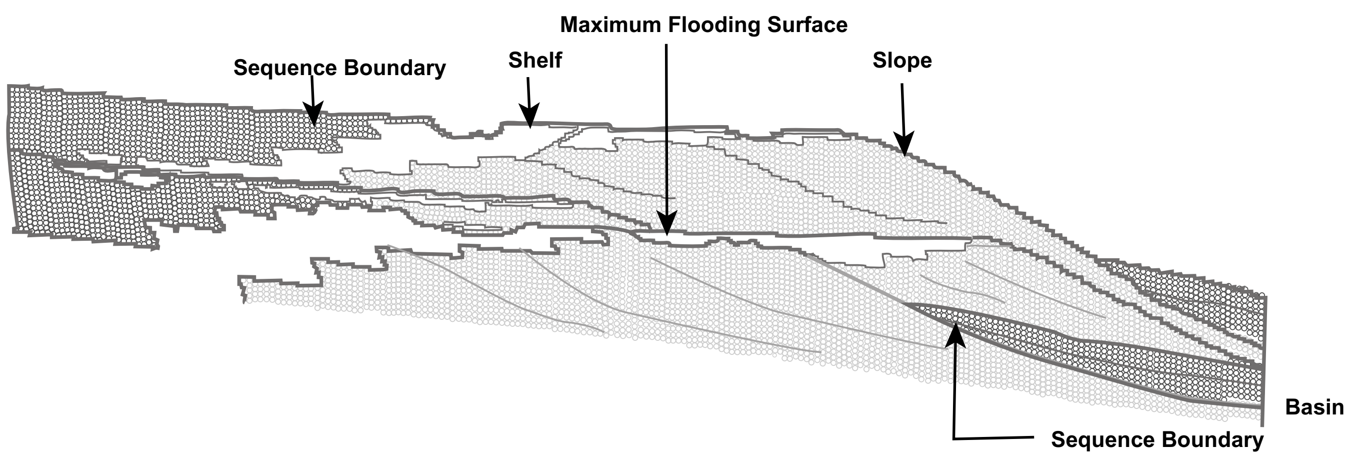

Figure by MIT OCW.

Figure 8-20: Schematic dip profile showing the key sequence-stratigraphic surfaces. Dark gray on left, nonmarine deposits; white, shallow-water shelf deposits; light gray, slope deposits; dark gray on right, deep-basin deposits

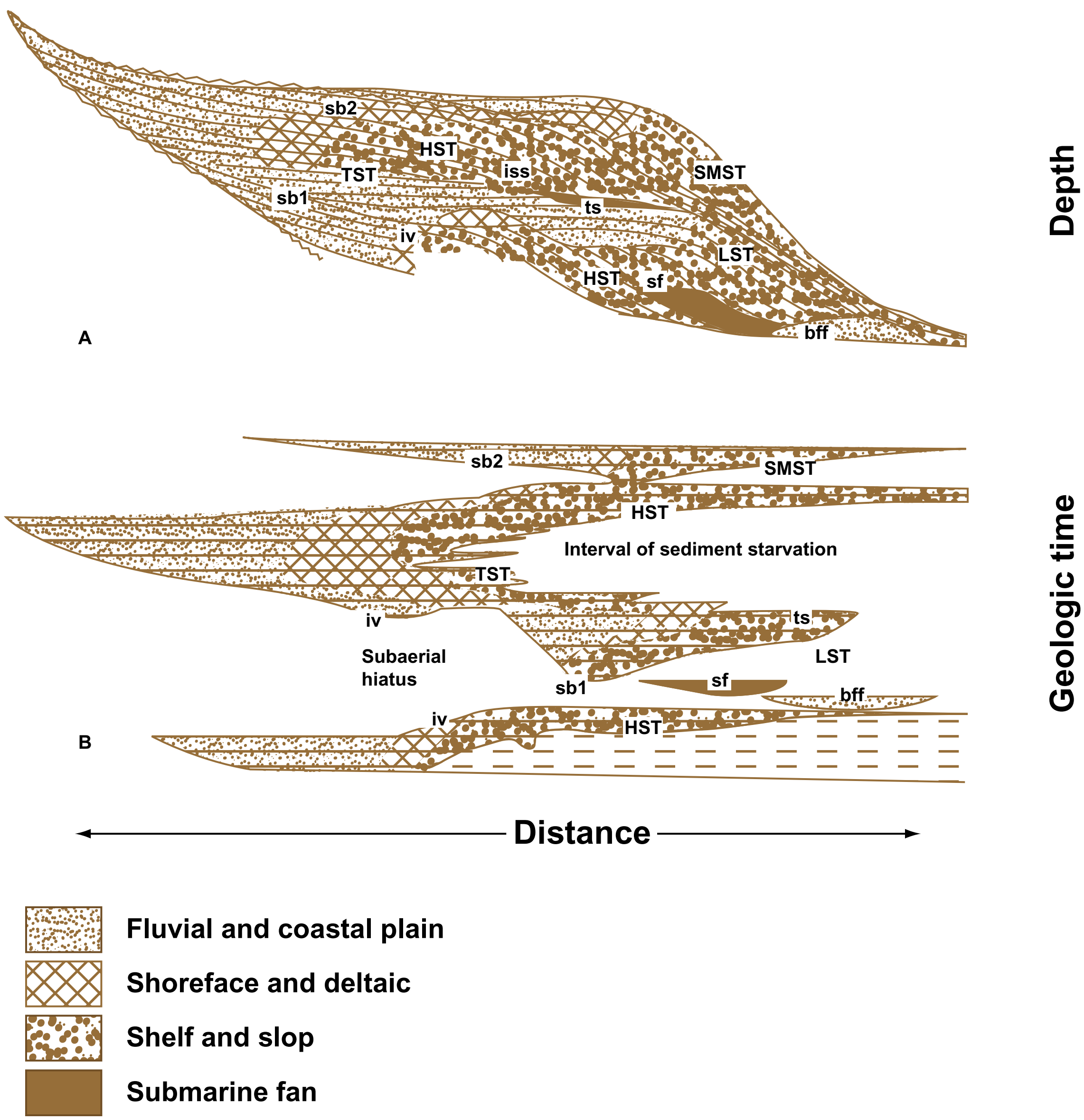

Figure by MIT OCW.

Figure 8-21: Conceptual cross section in relation to depth (A) and geologic time (B) showing stratal geometry, systems tracts, and the distribution of siliciclastic facies within unconformity-bounded sequences deposited in a basin with a shelf break. Systems tracts; SMST = shelf margin; HST = highstand; TST = transgressive; LST = lowstand. Sequence boundaries: sbl = type 1; sb2 = type 2. Other abbreviations: iss = interval of sediment starvation; ts = transgressive surface (corresponding to the time of maximum regression); iv = incised valley; sf = slope fan; bff = basin floor fan