GEL 109: SEDIMENTS AND STRATA (SUMNER)



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Dawn Sumner

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UC Davis Geo 109
Earth History: Sediments and Strata
Spring 2017: Sumner

Lecture Notes • **Depositional Environments** • Virtual Field Trips

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CHAPTER OVERVIEW

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1.1: Course Information

The Course web site is the SmartSite for GEL109 and http://mygeologypage.ucdavis.edu/sumner/gel109 ~~which is linked on the SmartSite. GEL109L has its own SmartSite.~~

I am responsible for:

1. Coming to lecture prepared to provide you with the opportunity to learn about sedimentology.
2. Preparing instructive homework assignments and tests that will help you learn the most important material. My philosophy is to make it clear what I think is important and provide you with tools to learn the material. I provide old tests and detailed study guides so that you can thoroughly learn the material and demonstrate your knowledge of it on the various assignments.
3. Grading your homework and tests in a fair and timely manner.

You are responsible for:

1. **Coming prepared for lecture by reviewing your previous lecture notes and reading the text book.** Reading the book is very important because it includes some information that I will cover only briefly in class, but I'll expect you to know. For example, I will not discuss rock classification schemes in lecture because it is boring and the book explains the rock types well. However, I will use the terms sandstone, siltstone, shale, etc. because they are always used in geology, and you need to know them. In most cases, the material I cover in lecture and with the homework assignments are the concepts I think are most important, so the tests will focus on those.
2. **Asking questions when you have them in class, through e-mail, during office hours, when you see me in the hall, etc.** Asking questions is VERY important for two reasons. First, it will help you and your fellow students learn, which is the entire reason you are in this class. Second, it helps me gage how well I'm communicating information to you. The more I know about how much you are understanding and what you are thinking about, the better I can prepare explanations that are both clear and interesting.

Grades

Grades will be calculated using two formulas: 2 tests and 10 homework assignments with the midterm=40%, final=40%, and homework=30%; and 2 tests with the midterm=50% and final=50%. You will get the higher grade from the two formulas. I do not grade on a curve, so if you all thoroughly learn the material, you can all earn A's. I have taught this class enough times that I know you can do so if you work hard and ask lots of good questions.

Tests

My tests are hard, but fair. They are hard because they ask you to think about the material. I will give you detailed study guides which will contain all of the material that will be on the tests (plus some). The homework will include questions like those on the tests, and practice tests are available. The only people who have failed the tests are those that did not take advantage of the study tools.

Homework

The homework assignments will be posted on SmartSite as pdf files. For some assignments, there are supplemental web materials. These materials are very useful, and you should plan to use them. Homework is due by 5 pm of the date listed.

Study Resources

Over the years, I've accumulated numerous study resources including images and videos. I have posted summary videos on YouTube since 2007, and those videos are used by people all over the world to help learn sedimentology and stratigraphy concepts. Since some of them are quite old, I'll be remaking some this year. I made/make them for you, my students in GEL109, and they emphasize the key concepts from many of the lectures. My channel is sumnerd. Use the videos!

For people not taking the lab:

The students who are also taking the lab (GEL109L) are spending an additional 6 hours per week working on sedimentology, so they will be more familiar with the material than you are. You can still do well, and it is particularly important that you ask questions. Also, there are two field trips required for the lab. I strongly recommend coming on them. You can learn much more in the field than in lecture or even lab!

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1.2: 2. Fluid Flow 1

Key Concepts from Lecture 1

The *Principle of Uniformitarianism* – the processes that formed ancient deposits are the same as those that form modern deposits.

The *Principle of Original Horizontality* - strata (or sedimentary rock layers) are deposited in a nearly horizontal position. If they are no longer horizontal, later deformation much have changed their orientation.

The *Law of Superposition* - younger sediments overlie older sediments.

Walther's Law

Key Concept: (Walther's Law) Depositional environments vary in space and time such that "The facies [rock types] that occur conformably next to one another in a vertical section of rock will be the same as those found in laterally adjacent depositional environments" (Johannes Walther, 1894).

One of the most important implications of Walther's Law is that rocks of the same type are not necessarily deposited at the same time. There is a BIG difference between correlating rocks based on having the same lithology and rock being deposited at the same time. This is a critical conceptual idea that we will focus on throughout the class.

Case study of Walther's Law: Gale Crater

Summary of Walther's Law: http://www.youtube.com/watch?v=ZSsULiPouTo

Sediment Transport

Most sediment transport is due to gravity. Things fall down hill in slumps, debris flows, and mudflows, and are transported downhill by fluids, like water, ice, and air. In some cases, processes like waves, currents, and wind transport sediment up a slope such as on a beach or mountain slope. This transport goes against gravity and is driven by the processes of fluid dynamics. Fluid dynamics is the main topic of today's and the next lectures. We will come back to mass wasting processes when we talk about erosion. Mass wasting is important for transporting large volumes of sediment short distances, but fluid transport is required to move sediments long distances and is responsible for most sediment transport. To understand sediment transport, it is essential to understand the mechanics of fluid flow.

Fluid Flow

There are two end member ways fluids flow: 1) laminar flow and 2) turbulent flow. There is a wide gradation between these two end members, specifically "transitional" flows.

Laminar Flow- In laminar flow, water molecules move in straight, parallel lines down current. If you add a dye to water that is in the laminar flow regime, the dye would not mix into the water; it would streak out in an approximately straight line. Laminar flow is characteristic of very slow moving, shallow water, which is uncommon in nature. It is also characteristic of flows in "fluids" that are very viscous, like glacial ice or mud flows that have little water. (https://youtu.be/_dbnH-BBSNo)

Turbulent Flow- In contrast, turbulent flow is characterized by complex motion of water (or other) molecules. Molecules move in all directions in bursts of upward, downward, and forward motion, and even some backward movement. There is abundant mixing in the flow because neighboring molecules move in different directions, and an added dye mixes into the water very quickly. Most water and air flows are turbulent, at least to some degree. Turbulence is important for sediment transport in water and air because it makes grains easier to transport and tends to keep them moving longer. (https://youtu.be/LSi_2fw6ySY)

Transitional Flow– Transitional flows have some characteristics of laminar flow and some of turbulent flow. For example, dye may take some time to mix into the flow, but it does mix. (https://youtu.be/XOLl2KeDiOg)

Movies of Laminar and Turbulent Flow: YouTube Fluid Dynamics Playlist, YouTube Fluid Dynamics Playlist 2018 (for videos shown in class)

The image to the left is of two rivers in Costa Rica mixing turbulently. The suspended sediment in the brown river is mixed into the clear water of the other river downstream.



The image to the right is of a glacier in Pearse Valley, Antarctica. Is the flow in glaciers laminar or turbulent? How can you tell? What properties of ice make it behave differently than water in terms of the amount of turbulence?



Reynolds Number

The Reynolds number predicts the extent of turbulence in a fluid based on how fast the fluid is flowing, the geometry of the flow (how deep and wide it is, etc.), and the density and viscosity the of the fluid.

Viscosity is a measure of the resistance of a material to flow, i.e. how "thick" and easily deformed it is. Viscosity is sort-of like the amount of friction within a substance. Walking through air is easy, because there is not much friction between air molecules. Air has a low viscosity. Swimming is more difficult because the water drags on your body. This is due to the "friction" between adjacent water molecules, i.e. higher viscosity. Ice is more viscous and impossible to move through because of the crystal bonds between the water molecules. It flows, but it does so slowly. It has a high viscosity relative to water and air (but low compared to most rock).

Back to the Reynolds number. The variables for the Reynolds number (**Re**) are: flow velocity (**u**), characteristic length (**l**) which represents flow geometry, say river depth, fluid density (**ρ**), and fluid viscosity (**μ**). The book uses **μ/ρ = v** (kinematic viscosity). **Re** = (fluid inertial forces)/(fluid viscous forces) = **l*u*ρ/μ**. The units for this equation are typically (length)*(length/time)*(mass/length^3)/(mass/(length*time)). These all cancel out to form a unitless number, if you choose the same set of units for each variable, which you should always do.

Re can be viewed as inertial forces divided by viscous forces. Inertia is the resistance to change in motion, and inertial forces tend to make a bit of the fluid keep flowing in its own direction if it is misdirected from the main flow direction. Thus, high inertial forces tend to cause more turbulence. In contrast, viscous forces tend to suppress turbulence by damping out variations in motion through friction. Thus, a flow with a high viscosity (ice) tends to have less turbulence than a low viscosity flow (air).

The magnitude of **Re** gives an idea of whether the flow is turbulent or laminar. Turbulent flow has **Re greater than 2000** and laminar flow has **Re less than 500**.* Flow with **Re** between 500 and 2000 is transitional and has some characteristics of laminar flow, but some turbulence as well. In most cases, water and air flows have high Re because **l** is large, **u** is high and **μ** is low. Rivers and wind storms are good examples of turbulent flow. In contrast, ice has a high **μ** and flows slowly (**u** is low), so it is usually laminar. Also, very thin, slow flows of water, such as water flowing off a smooth cement parking lot, have low **Re** because **l** and **u** are small. Thus, it can be laminar. Laminar flow also occurs locally in turbulent flows right at the contact between the fluid and a smooth surface because **u** becomes very slow. This is really important for sediment transport, and we'll talk more about it in a few minutes.

* There are a number of different ways to define a Reynolds number. For example, a flow in a pipe has more surface interactions than a flow in a wide channel, and the radius of the pipe is used rather than the flow depth. When the Reynolds number is defined differently, the numbers where flow transitions from turbulent to transitional to laminar are different. For this class, we will always use these numbers as the boundaries, but they will be different for other applications, such as in hydrology and civil engineering.

It is useful to think about which variables are important for different comparisons. When comparing ice and water, the main difference is viscosity; the viscosity of ice ranges from about 10^3 kg/(m*s) up to more than 10^{20} kg/(m*s) depending on temperature. In contrast, the viscosity of water is about 10^{-3} kg/(m*s). The density of both is very close to 1000 kg/m^3. Thus, ice is almost always laminar but water is usually turbulent, although it can be laminar. When considering water flows, the flow speed and water depth are both very important. The viscosity and density change a little bit with temperature, but variations in flow speed and water depth are typically much larger effects.

For air, both the density and viscosity are low, so does **Re** tend to be high or low? The density of dry air at 1 atm at 15°C is 1.225 kg/m^3, and its viscosity is $1.8\text{x}10^{-5}$ kg/(m*s), giving an inverse "kinematic viscosity" of **ρ/μ**=$6.8\text{x}10^5$ s/m^2 for air versus $1.0\text{x}10^6$ s/m^2 for water. Thus, air would have a slightly lower value for Re than water for the same flow depth and speed. However, the

thickness of typical air flows (meters to 100's of meters) promotes turbulence. **p/μ** for ice is 1 to 10^{-17} s/m^2, which is why it is essentially always in a laminar flow regime.

Here is a video of a gust of wind that probably has a maximum **u** somewhere around 40 m/s: http://www.youtube.com/watch?v=iXlYEJaJ66A That's me putting rocks on the fly of the tent. Note the turbulence and the snow transport.

Boundary Layer

Video of a boundary layer in a flume: https://youtu.be/cUTkqZeiMow

There is boundary layer at the edge of every flow, and it is illustrated in the video above. Flows have an average speed in the middle, but friction with immobile surfaces slows down the speed of the flow right at the surface. This creates a boundary layer that has different flow characteristics than the rest of the flow. Right at the surface, the water does not move, but as you go higher into the flow it starts to move more like the average flow. The area of the flow that has a reduced speed is called the boundary layer. The thickness of the boundary layer depends on **Re** (i.e. the amount of turbulence) and the roughness of the surface the flow is moving past. If the main water flow is very turbulent, it changes the velocity distribution because more of the high speed water is mixed down into the lower speed areas. Thus, the boundary layer tends to be thin. In less turbulent flow, there is little mixing of water from the center of the flow toward the edge of the flow, so the boundary layer tends to be thicker.

Viscous/Laminar Sublayer - Within the boundary layer, right next to the surface, there is a laminar sublayer. **Re=u*l*ρ/μ** - remember this defines the difference between laminar and turbulent flow. Because **u** (water speed) is very low at the base of the boundary layer, the **Re** is low there and the flow is laminar. The laminar flow part of the boundary layer is called the viscous or laminar sublayer, "viscous" because the viscous properties of the fluid are more important than the inertial effects. The fluid is NOT more viscous here; rather, the inertia of the fluid is lower because **u** is lower, and the viscous properties dominate the behavior of the fluid. Farther up in the flow, **u** is higher, so the inertial properties of the flow dominate, and the flow is typically turbulent. If grains do not extend above the top of the laminar sublayer, they do not "see" much turbulence, and they are less likely to be transported. If they do stick up beyond the laminar sublayer because the laminar sublayer is thin or the grains are large, the grains feel the force of the turbulent flow.

Bed roughness or the characteristics of the surface also affect the boundary layer by affecting the amount of water that interacts with the surface. A very smooth bed, say one made of mud, does not deflect the water at all, so there is less mixing and less turbulence. There is a well developed laminar sublayer. In contrast, a bed with pebbles or boulders disrupts the direction of water flow in the boundary layer. The water gets deflected around the pebbles. Water from above tends to take its place. Since it is moving faster, the average water speed in the boundary layer increases. Thus, a rough bed reduces the thickness of the boundary layer much like a more turbulent flow does. A rough bed also disrupts the laminar sublayer by forcing the flow to move around objects. The laminar sublayer is developed locally, but in general, rough beds increase the amount of turbulence in a flow.

Sediments and Flow

Key Concept: The boundary layer strongly affects the amount of "Bed Shear Stress" which corresponds to the forces that tend to roll particles along the bed and the pressure differences above and below grains, which tend to lift them off the bed.

Bed Shear Stress - Sediments are affected by the difference in flow speeds from the bottom to the top of the boundary layer, gravity, and friction with the ground. Bed shear stress is a measure of these differences; it is the differential force that a grain feels from top to bottom. In a thick boundary layer, the speed of water flow at the top of the grains is not much different from the bottom, so bed shear stress is lower, and sediment is less likely to move. In a thin boundary layer, bed shear stress is much higher, and grains are likely to roll down flow. Thus, more turbulent flow (with a thinner boundary layer) results in more sediment transport. Bed shear stress increases with increasing fluid density, slope, and turbulence (water depth and flow speed). For example, water is better at moving sediment than air because it has a higher density and exerts a larger bed shear stress than air can. Deep, fast rivers move more sediment than shallow, slow rivers because of more turbulence and higher flow speeds in the boundary layer in fast rivers.

Next Time:

The Bernouli Effect, which causes grains move, the Hjulstrom Diagram, and sediment transport. Read Chapter 4 again.

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1.3: 3. Fluid Flow 2

Key Concepts from Lecture 2

Reynolds Number

Reynolds number predicts the extent of turbulence in a fluid based on how fast the fluid is flowing, the geometry of the flow (how deep and wide it is, etc.), and the density and viscosity the of the fluid.

$$Re = \frac{\text{fluid inertial forces}}{\text{fluid viscous forces}} = \frac{l \times u \times \rho}{\mu} \tag{3.1}$$

where the variables are

- flow velocity (u),
- characteristic length (\(**l**\)) which represents flow geometry, say river depth,
- fluid density (ρ), and
- fluid viscosity (\(**μ**\)).

For the version of the equation we are using, turbulent flow has **Re is greater than 2000** and laminar flow has **Re is less than 500**. Flow with **Re** between 500 and 2000 is transitional and has some characteristics of laminar flow, but some turbulence as well. (Note that different versions of the Reynolds equation are used for different flow geometries and different equations have different numerical boundaries between laminar, transitional, and turbulent flows.)

Boundary Layer and Laminar Sublayer

There is boundary layer at the edge of every flow where flow speed decreases due to friction. Within the boundary layer, right next to the surface, the flow speed is very low, creating a laminar sublayer.

Sediment Transport

Bed Shear Stress

The boundary layer determines the amount of “Bed Shear Stress” which corresponds to the forces that tend to roll particles along the bed and the pressure differences above and below the grain which tend to lift them off the bed. Bed shear stress is related to the thickness of the laminar sublayer. The narrower it is, the more bed shear stress. It also depends on the slope. If the slope is steep, gravity helps pull grains down the slope, increasing bed shear stress. Also, the roughness of the bed is a factor. A rough bed deflects flows and increases turbulence, which increases the bed shear stress, particularly in places where flow is directed into the sediment and the boundary layer is compressed. (See http://en.wikipedia.org/wiki/Sediment_transport#Bed_shear_stress for more detailed information.)

The Bernoulli Effect

A higher pressure above grains than below them can “pull” grains off the bed into the flow. The pressure difference comes from a difference in water (or air) speed above and below the grain. As water flows faster, there are fewer collisions between the water and the surface it flows over than there are between standing water and a similar surface. Pressure is due to collisions. Thus, fewer collisions means lower pressure. The upstream side of a grain experiences the most collisions because the water is flowing into it. The downstream side experiences the fewest collisions, and the sides of the grain experience fewer collisions where flow is faster and more where the flow is slower. The net result is a low pressure zone above and slightly downstream of a grain. If the force exerted by this pressure difference is larger than the force of gravity, the grain will lift off the bed. This lift due to the pressure difference is the Bernouli Effect.

Which Grains Move?

Which grains get entrained in the flow depends on their size and density (how much they weigh) because that determines the force of gravity holding them down. It also depends on the shape of the grain. A grain with a large area to experience the low pressure (like a plate) will be more susceptible to being picked up than a round grain of the same mass (although flat grains may see a

smaller flow difference from top to bottom if the boundary layer is thick, and thus flat grains may experience a lower Bernoulli Effect per unit area.) The other thing that really matters is the position of a grain relative to surrounding grains. If a grain is sandwiched between larger grains, i.e. in their flow shadows, it will not experience as big a pressure difference as if it is on a flat surface. Also, if a grain is upstream of a big grain, it has to be lifted over it, so it has to experience enough force to lift it high into the flow. Thus, things can be complicated if you are trying to predict the behavior of a specific grain. However, experiments and theory provide statistically meaningful predictions for how grains behave on average.

Bedload and Suspended Load Transport



Two things can happen once a grain is lifted into the flow: 1) it can fall back down or 2) it can stay there. It depends on how quickly the grain settles out versus how turbulent the water is (back to **Re**...). **Bedload** refers to the grains that are transported along the sedimentary bed, e.g. grains that are rolling and being lifted off the bed, but they fall back quickly. The name bedload comes from the fact that the grains moving by traction and saltation never get too far from the bed and "load" is an engineering term for the amount of sediment transported by a river. Rolling grains are in **traction**. Grains that are pulled off the bed with the Bernoulli effect but are large enough that gravity causes them to fall "quickly" back to the bed are said to be **saltating**. (The word saltating refers to the way salt from a salt shaker bounces when it is shaken onto a hard surface. The word is derived from a Latin word meaning dance.) Bedload grains are the ones that form sedimentary structures in flowing water.

Here is a playlist with movies related to sediment transport: Sumnerd's Sed Transport Playlist

Suspended sediment consists of grains that are light or small enough that they do not settle out of the water; the turbulent bursts of water keep them in the flow (see brown water in the photo). The more turbulence in the water, e.g. the higher the Reynolds number, the larger the grains in suspension will be. The upward motions of turbulent flow are faster than the rate these grains settle, so gravity is counteracted and they stay "floating" in the water even though they are denser than the water. Very small grains do not settle out of flows unless the Reynolds number is low, which means that the flows need to be either have a very low flow speed or be very shallow.

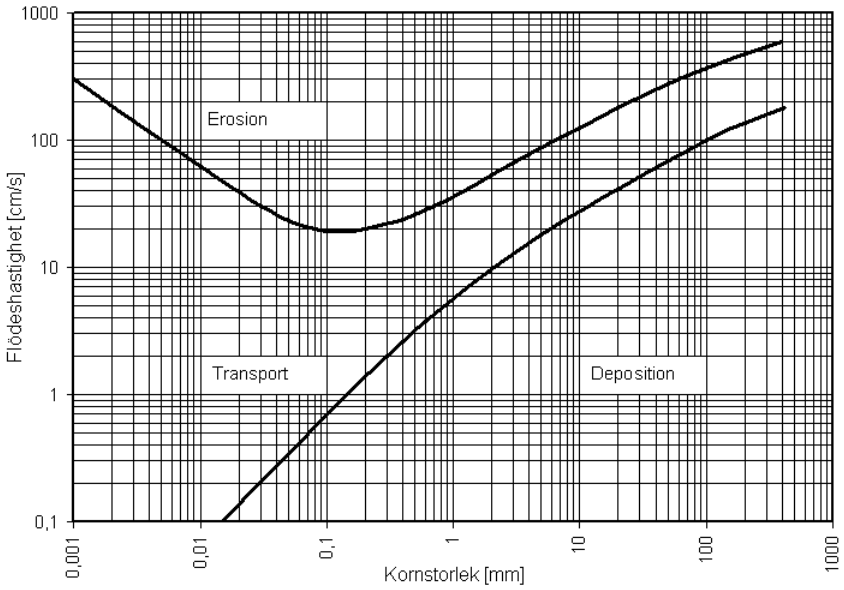
YouTube video of white clay in a turbulent flow in a flume: http://tinyurl.com/78kg3z The pulsing in the flow is (probably) due to the pump that is making the water flow.

Hjulstrom Diagram

The flows that are required to pick up grains of certain sizes have been extensively studied in experiments and the results are plotted in Hjulstrom (or Shields) diagrams. Hjulstrom diagrams show grain entrainment on a plot of log grain size versus log flow speed. This diagram shows the areas where grains of different sizes are left on the bed, where they get moved sometimes (this is the gray zone), and where they get lifted up often and eroded away. Note that larger grains require higher flows - in general. The water speed that is required to transport a grain is call the *critical velocity*. This is important. If there is gravel in a sedimentary deposit, you can say that the water flow had to be above the *critical threshold* for it to get there! That might require a fast flowing river or strong wave action, and thus, a large part of narrowing down the depositional environment has already been done!

Here is the Hjulstrom Diagram we will use (or the one in the Nichols text, which has additional information on it):

(https://commons.wikimedia.org/wiki/File:Hjulstr%C3%B6ms_diagram_sv.PNG)



The vertical axis is flow speed in cm/s (in Finnish!) and the horizontal axis is grain size in mm (in Finnish!); note that both axes are on a log scale. This diagram is for a flow depth of 1 m. If the flow speed and grain size are in the field labeled "Deposition", grains of this size will not be lifted into the flow, and if they are already moving, they will be deposited onto the sediment surface. If the flow speed and grain size are in the field labeled "Transport", grains in motion are likely to continue in motion. A few grains will be deposited and a few grains will be eroded, but there will not be a significant change in the number of grains that move. If the flow speed and grain size are in the field labeled "Erosion", more grains will be transported than deposited until the flow is transporting as many grains as it can, e.g. it is at its "carrying capacity" for sediment.

The boundaries for deposition, transport and erosion shift with changing flow depth. For example, deeper flows can move larger grains at the same flow velocity because they are more turbulent:

$$Re = \frac{l \times u \times \rho}{\mu} \tag{3.1}$$

and **l** is larger. This is because deeper flows can have larger variations in flow speed and the laminar flow layers are very thin. They can have bursts of very rapid flow relative to the average flow speed and these bursts can pick up larger grains.

Actual flow characteristics are much more complex in detail than just Hjulstrom diagrams, which summarize a lot of characteristics into two axes. However, like a lot of people, we will use the diagram anyway, because it is very useful as a rule of thumb. Just remember that it does not accurately represent what will happen in detail - it represents a reasonable guess.

Silt and Clay Transport

Notice that for the small end of grain size, the speed of flow required for erosion actually increases. One reason small grains are hard to erode is that they tend not to stick up through the laminar sublayer; they are just too small. Thus, thinner boundary layers are necessary to roll them or for the pressure differences to pick them up off the bed. Also, the surfaces of clay minerals tend to be charged and the grains stick together. This is most obvious when big clumps of mud stick to your shoes. That just does not happen with sand (unless there is something gross in it). The stickiness of the clay grains makes them difficult to erode, so faster water flows (a greater pressure difference or larger turbulent burst down to the sediment surface) are required to move them. The smaller the grains, the more surface charges stick the grains together, thus the stronger the flow needed to erode them. The stickiness of the clay grains also depends on the amount of water between them and the mineralogy, so there is a big gray zone where a clay may or may not erode.

In the Hjulstrom diagram, there is an interesting area where the flow is not strong enough to move any of the particles on the bed, but those that are in the suspended load do not settle out either. This zone includes many of the waters on the surface of the Earth.

In flows with any velocity or that are very deep, **Re** is high enough to keep some clay in suspension. Clay deposition usually occurs very slowly, e.g. when the rate of settling is just slightly faster than the average rate at which turbulence moves clay particles upward or when the clays clump together to form larger grains (which is common when fresh and salty waters mix).

Miscellaneous Notes

A few more words about saltation: Saltation is a very interesting and important process in sediment transport, because the force of the impact when the grains land tends to knock new grains up into the flow even if the flow is not fast enough to lift them with the Bernoulli Effect. These new grains can kick up more grains when they land, etc. This increases the rate of sediment transport above the amount the flow can lift grains off of the bed. This is one of the causes of the gray zone in the Hjulstrom diagram at larger grain sizes. Once saltation starts, it can trigger sediment transport that would not otherwise occur.

Deposition: Deposition is the accumulation of grains. If a flow starts slowly and gains speed, it will start to move larger and larger grains. As it slows down, it can only move the smaller ones. Deposition happens when a flow slows down and starts to leave grains on the bed. The combination of changing average flow speeds and local variations in flow speed caused by topography on the bed give rise to very informative sedimentary structures – including cross stratification - which are extremely useful for interpreting depositional environments.

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1.4: 4. Bedforms

A Few Definitions:

1) *"Stratification" - layers in rocks*; stratified rocks are those organized into beds

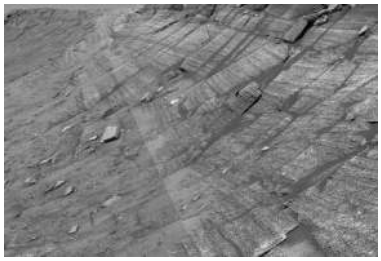

Grand Canyon Beds

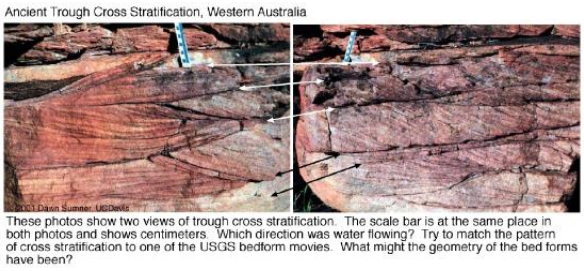
2) *"Beds" are separated by "bedding planes"* - cm to m thick units of sedimentary rock that were deposited approximately horizontally (beds) and are separated by approximately horizontal planes (bedding planes); the rocks typically weather more along these planes. Beds are usually fairly uniform or change gradationally in composition. Bedding planes usually represent breaks in sedimentation or changes in grain size. In other words, they usually represent changes in flow characteristics.


Cache Creek Turbidite Beds and Bedding Planes. They were originally deposited about horizontally and were tilted due to tectonic activity.

3) "*Laminae" are color, composition, or grain size variations defining surfaces within a bed*. They typically represent variations in flow velocity, sediment supply, sediment composition, etc. *Planar Laminae* are parallel to bedding, e.g. planar and deposited approximately horizontally.

4) *"Cross Lamination", "Cross Stratification" or "Cross Bedding" are laminations or layers that are oriented obliquely to bedding.* They truncate older laminae and are truncated by younger laminae. The erosional surfaces that separate "sets" of similarly oriented laminae are called "bounding surfaces". There are lots of subdivisions of cross stratification; different types represent different types of bedforms and different flow conditions.

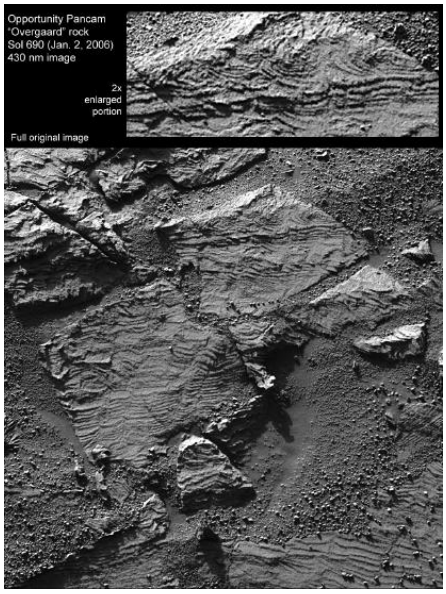

Burns Cliff on Mars photographed by the rover Opportunity: The upper part of the image has planar lamination, and the lower part to the far left has cross lamination or stratification. (The very straight line running diagonally from top to bottom is a seam where two images were merged together.)



Trough cross stratification

Other examples of dune cross stratification can be found here.

See ripple cross lamination on Mars



Bedforms

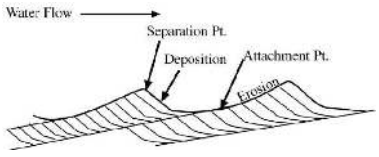
When sediments get deposited from turbulent flows, the sediment interacts with the geometry of the flow. Depending on the flow speed, turbulence, and sediment characteristics, different structures or bedforms develop.

Bed Geometry and Flow Separation

Until now, we have been implicitly assuming that the bases of beds are flat and smooth, but if sediment is present, they are not. If you start with a smooth bed of sand and increase water speed above it, irregularities form from irregularities in the flow. Irregularities in sand develop into ripples if the flow speed is appropriate. First, a few grains pile up. Once the height of the pile is several grains high, there is a flow shadow down stream of them, and the laminar sublayer detaches from the base of the flow. The water has enough momentum that it does not hug the bed surface and instead, goes shooting out over the top. This point is called the separation point. The water flows forward and downward and reconnects with the bed at the attachment point. At the attachment point, water is flowing directly towards the sediment with a lot of force. This force moves the grains and causes erosion. In contrast, the area between the separation point and the attachment point has a very low flow speed. In fact, there can be back eddies, where the flow is moving upstream. Thus, sediment transport is very irregular along the bedding surface at a local scale.

Sediment Transport Over a Ripple

Sediment grains are mobilized at the attachment point - more so than in normal flow because the water is shooting directly into the sediment - and the grains are moved downstream by saltation and traction. As the flow becomes parallel to the sediment surface again, its ability to transport sediment decreases. Thus, the grains tend to pile up and a new mound forms. This gives a periodic chain of mounds - the beginnings of ripples. As flow continues, grains roll and saltate up the stoss (upcurrent) side of the ripples. Once they pass the crest, they reach the low flow on the lee side of the ripple. The larger grains settle out and roll partway down the slope; this is the site of net deposition. As the process of deposition on the lee side and erosion on the stoss side continues, the ripples migrate downstream. If there is net deposition of sediment, the ripples leave behind distinctive dipping layers between two erosional surfaces that can be preserved in the rock record. These layers slope downstream and are one type of cross lamination.



A sketch of a ripple or dune like the one in lecture

Watch the USGS bedform movies described at: Sedimentary Structures Lab and Homework Resources

Bedforms and Flow Velocity

The size and shape of subaqueous bedforms depends on flow strength and grain size and can be used to interpret ancient flow characteristics in a depositional environment from looking at sedimentary rocks. See Nichols (2009, Sedimentology and Stratigraphy, section 4.3) for bedform, flow speed, and grain size relationships.

Ripples

(crest-to-crest distance - or wavelength - of less than 50 cm and heights of less than 4 cm)

The minimum flow for ripples is determined by the minimum velocity for sediment transport. Once this flow speed is reached, ripples form if the sediment is transported as bedload. The maximum flow speed for ripples depends on the location of the attachment point on the stoss side of the ripples. As flow gets faster, too much erosion occurs at the crests of the ripples - the point of attachment is too far up the stoss side of the ripple- and the ripples flatten out. Dunes develop.

Dunes

(60 cm-100's m wavelength and 10's of cm to meters in height)

Dunes develop as ripples flatten out because large scale irregularities start to develop. The basic ideas of dune and ripple formation are the same. The difference is that the area of flow separation is much larger (see Fig 4.17, Nichols 2009). Roller vortexes (e.g. upstream flows along the lee sides of dunes) are common, and the upstream flow can be strong enough to form ripples that migrate upstream. As flow speeds increase, the dunes start to flatten out.

Planar/Flat Lamination

Planar lamination forms when the flow is strong enough that the beds flatten out. The momentum of the transported grains and fluid are high enough that they tend to move horizontally, eroding any irregularities in the bed. This zone of planar lamination is called "upper flow regime". (Why "upper"? - there is a zone of planar lamination in coarse grained sediment at low flow velocities.)

Antidunes



Antidunes form at flow speeds greater than planar lamination when shallow water moves very quickly (Putah Creek in flood; tidal channels; creeks flowing across beaches). Irregularities form on the planar beds, but there is no flow separation. Instead, the water surface mimics the bedding surface. On the down flow side of the antidunes, there is a very strong erosional force (from the Bernoulli Effect) and sediment gets plastered onto the upstream side. Thus, antidunes produce laminae that dip upstream, and they migrate upstream (anti normal dune behavior). Sediment is still transported downstream; it is just the peak of the dune itself that moves upstream. At even higher flow, the waves on the surface of the water break, and the dunes become very irregular. Antidunes are rarely preserved in the rock record because they are reworked into other sedimentary structures as the flow speed decreases.

Other Types of Flows

Not all flows are uniform in one direction. For example, waves move water back and forth, transporting sand back and forth. Because the transport direction varies through time, the orientation of cross laminations vary through time. Compare the ripple types at http://mygeologypage.ucdavis.edu/sumner/gel109/sedstructures/ARipples.html. Note that wave ripple lamination dips in two directions and the ripple crests are symmetric rather than steeper on the lee slope than the stoss slope. Flows can also be irregular due to combinations of currents and waves, etc. Some of these flows are very characteristic of specific environments, for example, storm-influenced beaches. The structures they produce are very useful for interpreting ancient rocks, and we will highlight them as we discuss different sedimentary environments.

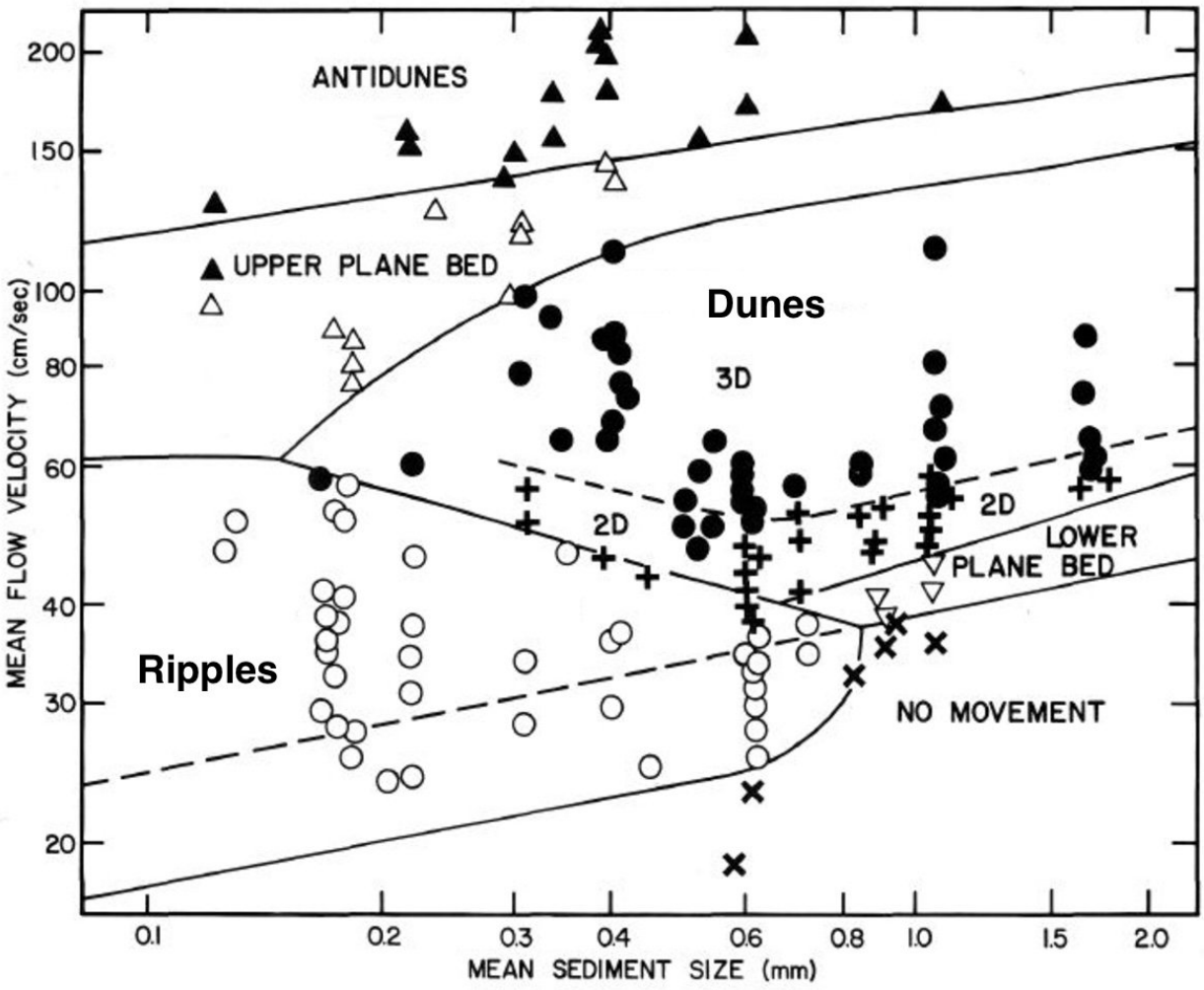
Bedforms and Grain Size

Bedforms also vary with grain size (see Figure 4.20, Nichols, 2009). Very fine sand and silt are very easy to transport and erode. They form nice ripples, but do not form dunes when transported by water. Instead, ripples transition into planar laminae. Coarse sand and larger sediment is too hard to transport and erode to get ripples. The erosional force at the reattachment point is not strong enough to erode the coarse grains and produce the erosional surfaces on the backs of ripples. Without this erosion, troughs do not form and without troughs, crests do not form. The sequence of structures in granules with increasing flow is:

1. no transport
2. faint planar lamination - the lamination is poorly developed because the sediment is often poorly sorted and not much transport is occurring
3. dunes - the flow is strong enough to erode at the attachment point
4. upper planar lamination
5. antidunes

In contrast, the sequence of structures in silt is:

1. no transport
2. ripples
3. upper planar lamination
4. antidunes



Harms et al., 1982

Extra: High Sediment Loads

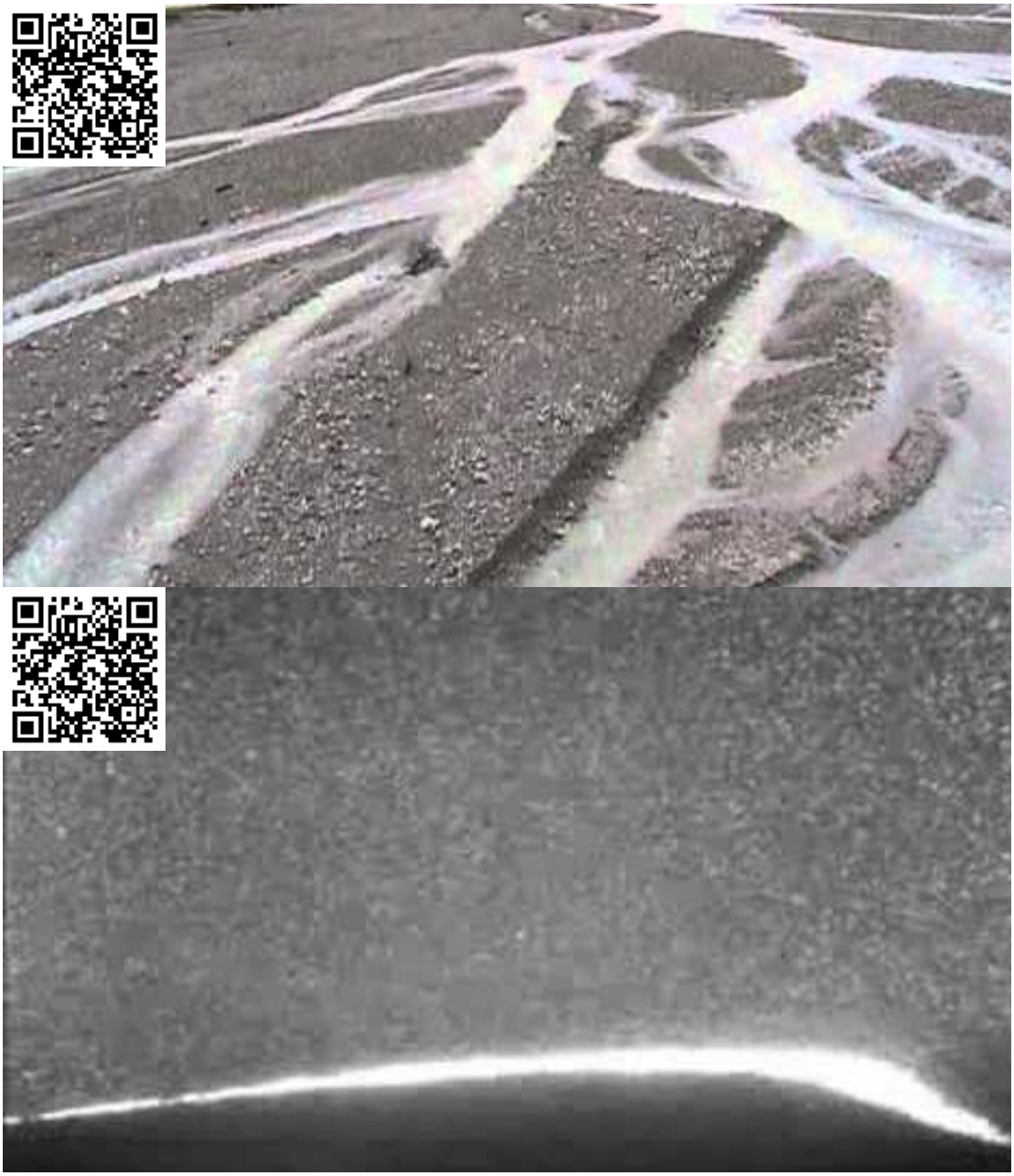
Sometimes with slope failures on land or under water, much more sediment can be put into motion than the flow would normally erode. Depending on the amount of water mixed with the sediment, the flow characteristics are different. When abundant water is present, the sediment can form a thick slurry with a higher density than sediment-free water, commonly leading to a higher **Re** and more turbulent flow (**Re=u*l*r/μ**). Also, collisions between grains become extremely important. Both of these tend to keep the sediment moving. Grain-to-grain collisions also have an important effect on grain sorting. The collisions tend to make sorting much less efficient and the sediment that gets deposited tends to consist of which ever grains make it to the base of the flow and are not kicked back up again. Usually, the largest grains are part of this first deposit because they weigh more, but small grains are also present. As the amount of sediment decreases, the flow becomes more like typical water flows. Turbidites are subaqueous flows that start out with a very high sediment load and decrease in time to more normal flows. They have characteristic sedimentary structures associated with them that reflect these changes.

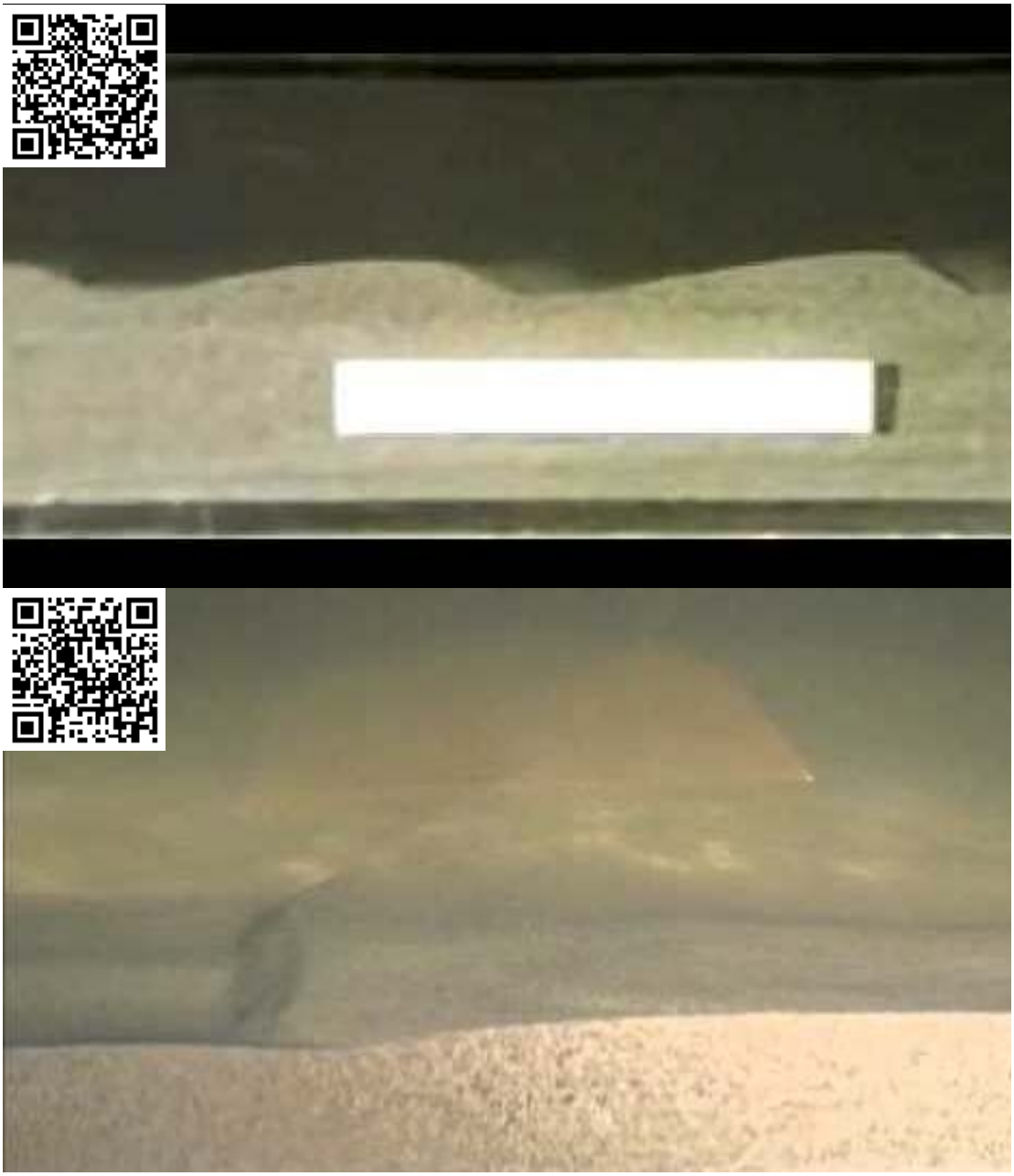
If there is very little water associated with a clay-rich sediment flow, the flow can be very viscous due to the charge attraction among clay particles. The high viscocity makes the flow laminar (**Re=u*l*r/μ**). Debris flows with lots of cohesive mud are like this. In laminar flows, there is no mixing of the water or grains (or ice) and there is no sorting of grain sizes. Thus, the sediment remains mixed up with large grains, sometimes boulders, “floating” in mud. They flow down hill pulled by gravity until the flow seizes up and stops. This can be due to too low a slope or loss of water. Underwater debris flows can also be diluted by water that gets incorporated at the edges of the flow and become less viscous and more turbulent.

There also are dry sediment flows in which air is present between grains. For example, rock avalanches and some pyroclastic flows from volcanoes lack water. For these to move significant distances, large amounts of energy from either gravity or explosions are necessary to keep the sediment in

motion.

Videos of Bedforms





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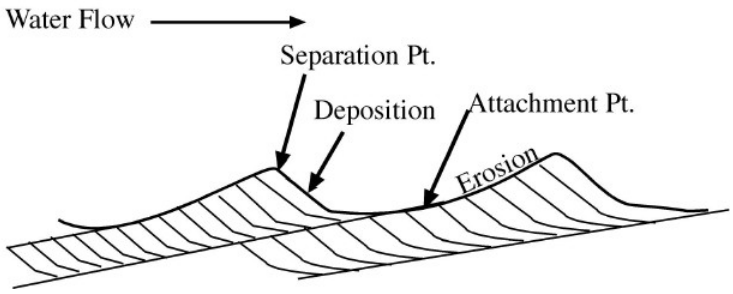
1.5: 5. Bedforms Continued and Facies Introduction

Sedimentary Structures Continued

Ripples and Dunes

(A review with a bit of additional information)

A sketch of a ripple or dune like the one in lecture:



Remember where the separation point and attachment point are located. The geometry of the flow tracks these points. Erosion can only occur where there the bed shear stress is high enough to move sediment. In other words, the the main flow must be near the sediment surface. Sediment accumulates into a deposit in the flow shadow downstream of the ripple or dune crest; sediment accumulates in the flow detachment zone. Laminae are visible where deposition occurs due to variations in flow speed which cause variations in grain sizes transported and deposited.

Sets of laminae are separated by erosion surfaces which form on the upstream side of the ripples or dunes. They represent deposition on the downstream side. The shape of the laminae reflects the shape of the depositional surface and the geometry of sediment accumulation. If the depositional surface is curved, the base of the laminae is curved. Laminae thicken into areas with higher deposition rates. Also, the maximum distance between erosion surfaces is less than the maximum height of the ripple or dune; since the erosion surfaces form on the upstream sides, they are closer to the underlying erosion surfaces than the ripple/dune crests. Thus, the maximum separation of erosion surfaces represents a minimum height for the ripple or dune.

Dunes and ripples behave similarly at the level of detail that I have been describing them. Their cross stratification geometries are similar. However, dunes are larger than ripples. If the distance between erosion surfaces defining cross sets is greater than a few centimeters, the cross stratification has to be from a dune. Ripples are only a few centimeters tall, and they cannot create laminae that are higher than the ripple crest-to-trough distance. Thus, if cross sets are greater than a few centimeters high, the cross stratification must be from dunes. However, if the cross sets are only one centimeter high, the cross stratification could be due to either ripples or dunes. It is possible for ALL sediment to be eroded as a dune migrates, leaving no cross stratification. If only a small amount of sediment accumulates, the cross sets might be only a centimeter high, much like ripples. In the field, grain size variations and changes in cross stratification along an outcrop can help you distinguish between ripples and dunes in a case like this. For example, you could look for an instance where the cross stratification is more than a few centimeters high. If you did not find one, that might suggest ripple cross lamination rather than dune cross stratification. Or maybe the grain size is wrong for one or the other.

Variations in Geometry and Bedform

Dunes and ripples are often irregular in plan view. This affects the geometry of the cross stratification/lamination. The laminae are always approximately parallel to the dip on the lee sides of the ripples or dunes. If the direction that these dip varies, the orientation of the laminae also varies. When looking at deposited cross stratification/lamination, these variations appear as variable dips in the laminae because you are viewing them at different angles.

Watch the USGS bedform movies described at: Sedimentary Structures Lab and Homework Resources

Remember that the structures also change with flow speed, both in terms of their geometry and which ones form. Grain size is also important. The sequence of structures in granules with increasing flow is:

1. no transport
2. faint planar lamination - the lamination is poorly developed because the sediment is often poorly sorted and not much transport is occurring
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Environments and Facies

Look at the photo of Scott Creek Beach above. Note that the antidunes are forming in one part of a creek. The middle of the creek has upper planar lamination flow speeds, and the closest part is very shallow and has some antidunes again. (I know some of this from being there more than from looking at the photo.) Note that there is a faint lamination present in the eroding bench on the far side of the creek. This lamination mimics the beach surface. It is lamination from the waves swashing and transporting sediment on the beach. If all sediment transport stopped immediately, one would see a suite of sedimentary structures: Antidunes and upper planar laminae next to each other in the creek, an erosional surface overlying planar stratification that undulates like a beach. The association of these features would tell you that the sediment was deposited in an environment with a variety of flow conditions.

The suite of structures forms a **facies**. A facies (Latin for aspect or appearance) is a body of rock (i.e. a sequence of beds) or sediment marked by a particular combination of compositional, physical and biological structures that distinguish it from bodies of

rock/sediment above, below and adjacent to it. A sedimentary facies has a characteristic set of properties that makes it distinctive, which the geologist defines. Usually facies are defined based on a suite of characteristics in rocks/sediment.

Facies vs Environments - By grouping characteristics of the rocks into facies, the depositional environments can be more easily compared and interpreted. It is important to remember that the sedimentary environment is the combination of physical, chemical and biological processes that influence sediment deposition, whereas sedimentary facies are the characteristics of the rocks/sediments after deposition. It is the difference between a water flow speed of 20 cm/sec and high angle cross stratification; the stratification is the result of high flow speed, but they are not the same.

Example Facies

Facies are groupings of rock types based on similar features. We use these groupings to generalize individual properties into useful, genetically related categories. Some examples include:

Facies based on grain size:

- Coarse-grained sandstone with 1-5% pebbles (suggests high flow speeds)
- Fine-grained, well-sorted sandstone (suggests low flow speeds with either only one size sediment source or a consistent flow speed)
- Mudstone (suggests standing water)

Facies based on sedimentary structures:

- Fine-grained sandstone with current ripple cross lamination
- Fine-grained sandstone with upper planar lamination
- Fine-grained sandstone lacking cross stratification, but with abundant burrows

Facies based on grain composition:

- Coarse-grained sandstone with 25% lithic fragments, 25% feldspar, and 50% quartz
- Coarse-grained sandstone with 80% quartz, 10% mica, and 10% feldspar
- Coarse-grained sandstone with 99% quartz and trace gold flakes

Beach Facies

What features do we see in the photo of the beach? How should we divide those into facies? We can compare them to what we would see in the rock record. Take a look at photos of Scott Creek Beach stratification again: http://mygeologypage.ucdavis.edu/sumner/gel109/sedstructures/Beach.html. Describe some of the facies.

From Sediment Transport to Rocks

We have been talking about sediment transport and structures. These are processes that influence sedimentary rocks. What we really need is to be able to use our understanding of the processes to interpret ancient rocks when we can no longer see the processes in action. As I mentioned in the first class, we can use the modern processes as a model for interpreting past processes, which is the Principle of Uniformitarianism (or actualism). However, it is often very different to see a process going on than it is to look at the ultimate deposited rock and interpret the process. For example, with bed forms, the entire shape of the structure you see as it migrates is rarely preserved. Instead, you only see a small part of it, if you get any sediment accumulation at all. Thus, we can also start the interpretation from the rock end by describing the general characteristics of the rocks and interpret flow from things like grain size, preserved cross stratification, and biogenic components. Then we can evaluate which environments are consistent with those characteristics.

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1.6: 6. Turbidites and Stratigraphy

Turbidites

Turbidites provide a good summary of the ideas we have been talking about, e.g. facies and sedimentary structures related to flows. Turbidites are deposited from slurries of sediment and water in any standing body of water (lakes, oceans). (photos of turbidites)

1. Turbidity flows start with slope failure in soft sediment. Slopes become oversteepened where sedimentation rates are very high, such at the mouths of rivers. Because flow speeds are very low in standing water, the sediment does not get washed downslope. Rather, it builds up until there is a subaqueous slope failure. Earthquakes can trigger these slides, too.
2. Sediment and water mix creating a “fluid” that is denser than the surrounding water because of the entrained sediment. Thus, it flows downhill even if the slope is very low (1°).
3. The base of the flow is commonly erosional on steep slopes, so more sediment is entrained in the flow.
4. Enough sediment is entrained that erosion stops. Deposition begins as the slope gets shallower or the flow starts to slow down. Initially, the coarsest grains are deposited (remember the Hjulstrom diagram) and then finer grains, so the sediment is “graded”. However, the sediment is usually poorly sorted because the flow is a slurry of water and sediment so hydraulic sorting is reduced. (Facies = Bouma a)
5. Sediment concentration decreases with deposition, so one gets more hydraulic sorting. The flow is very fast so the sediment has upper planar lamination. (Facies = Bouma b)
6. As the flow slows more, grain size decreases and ripples start to form. Dunes do not usually form for two reasons: a) often only fine sand and finer grains are left in the flow by this point; and b) dunes do not have time to develop. (Facies = Bouma c)
7. Eventually, the flow slows to the point that bedload transport stops and deposition is mostly settling of silt and then clay. The progressive settling of coarser and then finer grains produces a faint lamination, but it is not as strong as the planar laminations in Bouma b. (Facies = Bouma d)
8. Mud settles out producing shale. This can look identical to background settling of clays brought into the lake/ocean as suspended sediment. (Facies = Bouma e)

Bouma divisions a-d can take hours or a day or so to be deposited. However, division e, which is usually the thinnest, commonly accumulates over months or longer (e.g. hundreds of years) depending on how frequent turbidites are in the area.



The video above shows a turbidite fortuitously filmed by underwater equipment in Mendocino Canyon off the coast of California (see Sumner and Paull, 2014, for a full description).

Changes in Character Downslope

The parts of turbidites that are deposited change downslope and usually only a few of the subdivisions are preserved. In the most proximal (upslope) environments, divisions a and b are most common. In the more distal areas, all of the coarser sediment has already been deposited upstream, so divisions d and e are most common. Generally, there are also channels which fan out producing variations in rock types that change in space and through time.

Turbidite Facies Models

Over the decades, sedimentologists have described and interpreted sedimentary rocks and defined generalized facies and facies associations that are characteristic of different depositional environments. These generalized facies and associations are called Facies Models. Each depositional environment or system has its own facies model. This is a VERY powerful tool for interpreting ancient environments. See my video summary: http://www.youtube.com/watch?v=G05juwK2OTI



A nice, hour long lecture on turbidites in the Monterrey Bay Canyon, CA, is worth listening to for more information. The actual lecture starts about 5 minutes into the video.

Extra on Turbidites

Turbidite facies analysis and the resulting facies model led to the discovery of a new process. Sedimentologists had characterized turbidites all over the world. They all had the same flow characteristics consisting of a very strong erosive flow, deposition of a normally graded bed which was massive, followed by upper plane bedding, rippled finer sands, coarsely laminated silts, then shales. Comparisons with known flows showed that this sequence of deposits must come from a fast initial flow that slowed through time to still water. And this repeated again and again. The associated facies and the succession of different facies in these sequences suggested that the deposits had to be in deep water. For example, the fossils were all characteristic of deep water, shales were abundant and are characteristic of still water (shallow or deep), and they were sometimes associated with deep water storm deposits. Thus, the sedimentologists proposed slope failure and turbid currents flowing down slope and called them turbidity currents. A process like this had not been observed in modern depositional environments, so the idea was controversial. Many geologists did not believe that you could generate strong enough currents underwater to get those flow characteristics. Eventually in 1964, two geologists Heezen and Drake realized that an event in 1929 provided strong evidence for turbidity currents. In 1929, which is long before there were satellites, under water telegraph cables were strung from Newfoundland to Europe. In November, about 30 cables broke in order from farthest north and shallowest to farther south and deeper water. At the time, people did not know why they broke, but Heezen and Drake suggested that a turbidity current was triggered by an earthquake and the cables broke as the turbidity current passed over them (they are strong flows!). Because they were continuously used for communication, the time each cable broke was precisely known. Heezen and Drake calculated that the front of the flow traveled at 250 km/h (36,000 cm/s) when the turbidite first formed and then slowed to around 20 km/h (7000 cm/s) by the time the last cables broke 500 km from the source. This was a fast, strong flow and may be typical of turbidites. These flow speeds are very erosive. It is only after the turbidite slows down even more that you get deposition. The characteristics of the flow seen by the breaking cables fit the flow characteristics proposed by the sedimentologists, and now turbidity currents and the facies model developed for turbidites are widely accepted and often treated as a good example of rocks that closely reflect flow characteristics. Turbidites and their interpretation are almost an ideal example of a good Facies Model.

Extra on Dense Sediment Flows

Sometimes with slope failures on land or under water, much more sediment can be put into motion than the flow would normally erode. Depending on the amount of water mixed with the sediment, the flow characteristics are different. When abundant water is

present, the sediment can form a thick slurry with a higher density (ρ) than sediment-free water, commonly leading to a higher Re and more turbulent flow:

$$Re = \frac{u \times l \times \rho}{\mu} \tag{1.6.1}$$

Also, collisions between grains become extremely important. Both of these tend to keep the sediment moving. Grain-to-grain collisions also make sorting much less efficient, and the sediment that gets deposited tends to consist of whichever grains make it to the base of the flow and are not kicked back up again. Usually, the largest grains are part of this first deposit because they weigh more, but small grains are also present. As the amount of sediment decreases, the flow becomes more like typical water flows. Turbidites are subaqueous flows that start out with a very high sediment load and decrease in time to more normal flows. They have characteristic sedimentary structures associated with them that reflect these changes.

If there is very little water associated with a clay-rich sediment flow, the flow can be very viscous due to the charge attraction among clay particles. The high viscosity reduces Re (Equation 1.6.1). Debris flows with lots of cohesive mud can even be laminar. In laminar flows, there is no mixing of the water or grains (or ice) and there is no sorting of grain sizes. Thus, the sediment remains mixed up with large grains, sometimes boulders, “floating” in mud. They flow down slopes pulled by gravity until the flow seizes up and stops. This can be due to too low a slope or loss of water. Underwater debris flows can also be diluted by water that gets incorporated at the edges of the flow and become less viscous and more turbulent through time.

There also are dry sediment flows in which air is present between grains. For example, rock avalanches and some pyroclastic flows from volcanoes lack water. For these to move significant distances, large amounts of energy from either gravity or explosions are necessary to keep the sediment in motion.

Stratigraphy and Time

Stratigraphy is the study of sedimentary rocks in space and time. It is the basis of interpreting what happened in the past. We use facies to interpret depositional environments from the rocks. Changes in facies both vertically and horizontally allow us to interpret changes in ancient landscapes and processes.

Example: Beach Facies. Beach environments grade laterally into each other. The offshore areas grade into the swash zone of the foreshore. The foreshore grades into the berm (the highest point of the beach) and backshore (if present). Eolian (wind) dunes, marshes or erosional cliffs can be present landward of the beach. Rock facies similarly grade into each other because they were deposited in different depositional environments. If the depositional environments stay in exactly the same place through time, a stratigraphic column in each place would consist of a uniform facies, but each stratigraphic column would have a different style of rock (facies). However, depositional environments tend to migrate back and forth as sea level rises or falls, basins fill in with sediment, etc. Thus, facies in stratigraphic columns tend to change upward. They also vary laterally. See figure 19.8 on pg. 308 of Nichols.

Changes in sea level and depositional environment lead to variations in stratigraphic columns both laterally and vertically. If you compare different stratigraphic columns, there are several ways you might "correlate" them. If you correlate different rock types, e.g. **lithostratigraphy**, you are marking regions with similar characteristics, but the sediments in each unit were not necessarily deposited at the same time. In contrast, if you correlate rocks that were deposited at the same time, e.g. **chronostratigraphy**, each unit often consists of more than one facies. This is obvious when you look at the distribution of depositional environments now. Different areas are accumulating different types of sediment at the same time.

Lithostratigraphic correlations are relatively easy because you can directly observe rock type. These correlations are very useful for studies of reservoir properties, where one might want to identify a porous sand that acts as a water or hydrocarbon reservoir. However, these correlations do not help you interpret ancient depositional environments because they do not represent an ancient landscape. Chronostratigraphic correlations tell you the most about depositional environments and their distribution through time, but they can be VERY difficult because you have to have a time marker that tells you which deposits were synchronous. Sometimes volcanic ash beds or other depositional events allow you to directly observe which rocks were deposited at the same time, but these events are rare. Often, chronostratigraphic correlations require detailed facies analysis and an understanding of how depositional environments change through time.

Walther's Law

Walther's Law is key for understanding the differences between lithostratigraphy and chronostratigraphy. Walther's Law states that environments that are adjacent to each other are represented as vertical successions of facies in the rock record **if there is no break in sedimentation** (no unconformity). If sea level is rising relative to the shore line, the different depositional environments are migrating inland. This leads to different facies accumulating progressively inland as well. The most landward deposits are river deposits and alluvial plain deposits, followed by marsh and then marine deposits. Vertically, you see the facies representing those depositional environments in the same order. At any given time, rocks are being deposited in all of the different environments.

Chronostratigraphy

Chronostratigraphy enhances the interpretation of the stratigraphic record in terms of Earth history. Even when one has a detailed map of the distribution of depositional environments, it is difficult to say exactly how to correlate section in terms of time. In real rocks, there are a number of tools that you can use to get correlations of various accuracy. These include: fossils (biostratigraphy); magnetic properties (magnetostratigraphy); absolute ages of interbedded volcanic ash beds and basalt flows; some chemical properties such as elemental isotope ratios in carbonates; geological instantaneous depositional events such as huge storms, meteorite impacts, etc.; and unconformities due to sea level falls and the geometry of sedimentary deposits (sequence stratigraphy). We will get back to all of these in more detail throughout the quarter, particularly near the end.

Distribution of Rock and Time

One might think that sections can be correlated based on assuming that the same amount of sediment gets deposited in all places in the same amount of time. This is a BAD assumption, although many researchers are forced to use it. It is important to understand that the preserved rock does not represent all of time. In other words, time is not evenly represented by rock thickness. For example, with turbidites, the sandstones may have been deposited in a couple hours to a day at most, whereas the shales (Bouma E) represent 100's to 1000's of years of fine grains settling out. Thus, most of the "time" is represented in the much thinner shales. In addition, there is erosion at the base of some of the turbidites. Thus, there is a significant amount of time that is only represented by an erosional surface which produces a gap in the rock record. Generally, sedimentation is thought of as a continuous processes. This is NOT true. Sedimentation is episodic and there are unconformities in the stratigraphic record spanning all time ranges from minutes to millions of years. Gaps of minutes might occur in a river if there is a burst of strong flow that is erosive rather than depositional. Gaps of hours occur at low tides when the intertidal zone is exposed. Gaps of years to thousands of years can occur in land environments where there is no source of sediment or the topography is too high to collect sediment. Gaps of millions of years also occur in terrestrial environments, especially if there is erosion. The longer time gaps usually represent regional changes in deposition and can be very useful for correlating rocks chronostratigraphically. Also, different depositional environments accumulate sediment at different rates: thickness does not equal time!

References

Sumner, E.J. and C.K. Paull, 2014, Swept Away By a Turbidity Current in Mendocino Submarine Canyon, California. Geophysical Research Letters,, v. 41, p. 7611– 7618, doi:10.1002/2014GL061863

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1.7: 7. Weathering and Erosion

Weathering

Sediment comes from the break down of rocks into smaller, transportable components. This occurs via two processes: **physical weathering** and **chemical weathering**. Physical weathering consists of breaking apart rocks and crystals. The results of physical weathering are smaller components of the same material that is being weathered. There is no change in composition. In contrast, chemical weathering consists of changing the composition of at least some components of the rock that is weathering. The sediment does not have the same composition as the original rock.

Physical Weathering

Physical weathering occurs via:

1. **Freeze-thaw action**. Water in cracks expands when it freezes, putting force on the cracks. The cracks grow, and eventually crystals and pieces of rock break off into smaller components. Obviously, this process is most important in environments where temperatures cycle across the freezing point of water.
2. **Salt crystal growth**. When water evaporates, salts precipitate. If this happens in fractures in rock, the growth of the salt crystals can put pressure on the cracks, causing them to grow. This process is most important near oceans where rocks are exposed to lots of salt water spray and in arid environments where water evaporates rapidly.
3. **Temperature changes**. Minerals contract and expand as temperature decreases and increases, respectively, and different parts of the rock are heated different amounts. Those in direct sunlight expand as they heat, whereas the interiors and shaded areas do not. Differential expansion and contraction produces stresses which can result in cracks and physical weathering. This process is most important when temperatures change dramatically from day to night, a characteristic of many desert environments.

Physical weathering tends to produce mostly sand-sized sediment and larger grains because most of the fracturing occurs along mineral boundaries. Physical weathering of fine grained or finely crystalline rock can produce abundant very fine grains, but most of the sediment from these rock types consists of rock fragments (called lithic clasts).

Image of physically weathered rocks in New Zealand:



Chemical Weathering

Chemical weathering occurs via:

1. **Dissolution** of minerals. Some minerals like halite and other evaporites dissolve very easily in water. Other minerals, particularly silicates, do not dissolve easily. Carbonates are in between and dissolve in acidic waters. (Rain water has a pH of ~5.7 due to dissolved CO_2, even without “acid rain” pollution.) The results of dissolution are ions in water that are transported downstream. Ions are not deposited until the water evaporates, they react with other minerals, or organisms use them to make shells. Often, only part of a rock dissolves, leaving altered grains that can be transported by wind, water, etc.
2. **Alteration** of minerals. Silicate minerals do not dissolve very easily, but they do react with water to form new minerals. Feldspars react with water to form clay minerals and ions, olivine reacts with water and O_2 to form oxides, clay minerals and ions, pyrite reacts with water and O_2 to form oxides, acidity and sulfate ions. Iron oxides, such as hematite, are commonly red, giving weathered rocks a rusty hue. Alteration of minerals is one of the main sources of clay minerals and mud-sized grains.

Image of chemically weathered rocks in New Zealand. This outcrop originally had the same composition as the rock shown in the previous photograph, but has been exposed to much more water as well as plant-assisted soil processes.

Mineralogy of Weathered Rocks



Sediments that have been subjected primarily to physical weathering have a mineralogy that is similar to that of the parent rock. If the sediments have been subject to extensive chemical weathering, it is much harder to characterize the source rocks because the composition has changed extensively. Overall, the composition of sediment depends on the mineralogy of the original rock, how it is transported, and the weathering environment.

Some minerals alter more quickly than others. Quartz is difficult to dissolve and is hard, so it commonly lasts through both chemical and physical weathering and is the most common mineral in sand on Earth. In contrast, minerals like Ca-feldspar and olivine react to form new minerals quickly. They are substantially less common in sediments. Thus, mafic rocks (which contain Ca-feldspar, olivine and pyroxenes) tend to alter to clay minerals very easily and produce little sand and abundant mud. In contrast, granites (quartz, K-feldspar, Na-feldspar, mica) contain minerals that react more slowly and tend to produce sand-sized grains, especially quartz.

The following list includes minerals from most reactive (rarely found in sediments) to least reactive (common in sediments): Olivine, Ca-feldspar, Pyroxene, Amphibole, Na-feldspar, Biotite, K-feldspar, Muscovite, and Quartz

The other main control on sediment mineralogy is the hardness of the grains. During transport, grains hit each other. Softer grains tend to be damaged when they collide with harder grains, and this damage can cause them to break into smaller grains. Thus, soft grains become smaller very quickly when they are transported with hard grains. Quartz is the most common mineral in sandstones because it is hard and unreactive. Clay minerals are also very common because they are too small to damage much during collisions and they are the product of the alteration of other minerals.

Controls on Weathering

The extent and style of weathering is mainly controlled by climate. **Water** is extremely important, even for physical weathering. The more water present, the faster weathering occurs. **Temperature** is also important. Warmer temperatures promote faster reactions, so chemical weathering is more effective in warm climates. Thus, warm, humid climates tend to have the most rapid weathering (and poor outcrop). Finally, **vegetation** has a strong influence on weathering. Plants tend to increase the extent of chemical weathering by producing organic acids that help break down rocks into soil through both dissolution and alteration. They also help soil retain moisture, increasing the availability of water for weathering. Their roots can help widen cracks, increasing physical weathering.



Some of the big questions we have about Mars right now are about the extent and timing of chemical weathering. There is no vegetation. Right now, the climate is very cold and very dry, so the rate of chemical weathering now is extremely low. However, most of the rocks on the surface of Mars (that we have characterized) are basalts, which have glass and mafic minerals that should alter "quickly" if they come in contact with water. (The image to the right is wind-blow sand in Gale Crater, Mars.)

What do you expect a chemically weathered basalt to produce? What should we look for as evidence of past chemical weathering on Mars? How might products from basalt weathering look different if one looks at the weathered basalt itself or at sediment that was eroded from weathered basalt? (Basalt is mostly plagioclase (calcium feldspar) and pyroxene, with or without olivine, as well as glass. It has less than 20% quartz.)

Erosion

Once sediment is produced by weathering, it is available for transport. The two main forces in erosion are fluid flow and gravity. Fluid flow is what we talk about most, e.g. glacial erosion of sediment, wind blown sediment, and mostly water transport. Flowing water is the biggest influence in erosion on Earth because it is very common and effective at transporting sediment.

Transport Capacity

Erosion by water occurs when water is flowing across a surface, and the flow is capable of transporting more sediment than is currently moving as bedload. This is called the sediment transport "capacity". A certain number of grains of a certain size can be picked up by the Bernouli effect for a given flow. If there are too many grains, they start colliding and the characteristics of sediment transport change. Grains are directed back toward the bed and up into the flow. Eventually, more go back to the bed than are lifted into the flow, and sediment is deposited. Sediment can be deposited even at high flow speeds when there are more grains than the transport capacity of the flow.* In contrast, if there is a shortage of grains that are small enough to be transported by the flow, e.g. the flow is moving all of grains present, any new grains will be eroded off the bed as soon as they are available. The flow then has excess transport capacity.

* Think about dumping a truck load of fine sand into a fast moving river, it takes time to move all that sediment even if the flow speed is theoretically fast enough to erode fine sand.

One of the most common times for a flow to have excess transport capacity is when the flow is speeding up. We know from the Hjulstrom diagram that faster flows transport larger grains. They can also transport more grains. Thus, water flowing from a shallower slope to a steeper slope commonly speeds up, has excess capacity and erodes sediment. When it slows down, the transport capacity decreases, and sediment is deposited. In floods, the water gets deeper, speeds up, erodes sediment, and transports it. As the flood ends or flood waters extend over larger areas, the water slows down and deposits the excess sediment. In general, erosion occurs when flows are speeding up or when the water goes from an environment with low sediment (e.g. a dam spillway) to an environment with more sediment (e.g. a river bed).

Gravity Transport of Sediment

Gravity pulls sediment down steep slopes through creep, rock or debris falls, landslides and slumps. These processes are really important for the hills in coastal California where there is enough water for extensive weathering, but there is little runoff of water most of the time.

Here are some videos of gravity-transported sediment:



Usually, the concentration of sediment is very high in these flows, which means that the grains collide with each other frequently. Grain collisions can help keep the flow moving but the grains increase the viscosity of the flow (decreasing the Reynolds number). These collisions and higher viscosity keep the different grain sizes from being sorted out, and most gravity flow deposits are poorly sorted. If lots of mud-sized sediment is present, the viscosity of the flow is high, and the flows can be laminar (Reynolds number < 500), which produces very poorly sorted deposits. These are often called mud flows or debris flows. Watch the videos again, and predict the characteristics of the sediment that would be deposited by the different processes.

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1.8: 8. Rivers

Rivers are responsible for most sediment transport from mountains to lowlands and the oceans. They do the most to even out the topography that tectonic processes create. Rivers consist of channel, bank and overbank or floodplain deposits. Most of the sediment and many river characteristics are controlled by the highest common flow speeds.

River Types

1. Straight (rare, except for ones humans have modified)
2. Braided (many branches within a channel)
3. Meandering (high sinuosity)
4. Anastomosing (rivers with branching and merging channels)

The form of the river is controlled by the gradient of the river bed (steep = braided, gently dipping = meandering), local vegetation that stabilizes banks and limits the number of channels, sediment grain size, particularly the ratio of suspended versus bedload sediment, and sediment volume. A high bedload gives rise to abundant bars, which promotes formation of braided rivers.

Braided Rivers

Braided rivers develop when the proportion of bedload sediment is high, which produces abundant bedforms and promotes the development of bars, and thus, the braided character of the river. The sediment is commonly coarse, which requires fast flow and steep gradients for the sediment to be transported. Much of the geometry of braided rivers is shaped by the highest flows, e.g. spring floods, when the bars are covered in water. Many braided rivers have exposed bar tops for much of the year.

Flow speeds and transport capacity vary dramatically within a braided river. Friction with the riverbed tends to slow down the flow, particularly where the flow is shallow. Thus, the Reynolds number in shallow areas is relatively low (but still high enough that the flow is turbulent) and the transport capacity is low. In contrast, the transport capacity and Reynolds number are much higher in the deeper middles of channels in the river. Thus, the coarsest sediment is transported here, whereas finer sediment gets deposited in shallow areas. Also, bars block the flow on the upstream sides, and like dunes, the upstream sides tend to erode. Areas of low flow and eddies form on the downstream sides of bars, and they are usually sites of net deposition. Thus, bars migrate downstream through time. If we summarize the processes:

Sediment Transport

1. The coarsest sediment is only transported in the middle of the flow where the Reynolds number is highest. (All grain sizes that can be moved are transported where Re is high.)
2. Bars are eroded upstream where the bars deflect the flow. Sediment is deposited on downstream side of bars and some on the flanks of bars where flow is slower, particularly on the insides of bends.
3. Secondary bedforms, i.e. planar beds, dunes, and ripples, form as a result of sediment transport on the bars and in the channels.

Sedimentary Structures

1. Trough x-bedding in channels, due to the migration of irregular dunes
2. Coarsest sediment may be lower flat laminated if flow speeds are not fast enough to form coarse grained dunes
3. Sediment on the edges of bars fines upward because the flow is shallower and slower, e.g. has a lower Reynolds number. Sedimentary structures can include anything from upper planar to ripple laminations.

Braided River Facies

Channels migrate back and forth leaving a sheet of sand with abundant cross stratification. These sheets of sand tend to fine upward because the channels migrate due to bar migration, and sediment is finer grained higher up on the bars. General characteristics of braided river deposits include:

1. Scoured surface at the base of a channel
2. Gravel lag at base of channel
3. Trough x-bedded sands deposited just off the center of channels

4. Occasional tabular x-stratification from migrating bars
5. Sand deposited at slower speeds (ripple cross lamination possible)
6. Overbank deposits from floods mostly composed of sand and silt, with some mud

The large scale geometry of the deposits includes sheets of sand with various grain sizes representing bar migration, with sand sheets separated by floodplain deposits.

Example of a braided river in Alaska: http://g.co/maps/wrk9n It is cutting through glacial morraines deposited as a glacier retreated up the valley. Follow the river downstream (to the north and east) to http://g.co/maps/q5kq7. How does the channel geometry change?

Meandering Rivers

Meandering rivers have a low gradient and thus slower flow, and usually have a high proportion of suspended sediment relative to the amount of bedload. A meandering river channel has curves that meander back and forth on a gently sloping floodplain. The flow speed in the channel varies with the geometry of the meanders. Water has to travel farther on the outside of bends than on the insides of bends, so flow speeds are higher on the outsides of bends. We know from the relationships between Reynolds number and bed shear stress that higher flow speeds mean that more and coarser sediment can be transported at higher flow speeds. Thus, we can predict that:

1. There is more erosion on the outsides of bends.
2. The sediment moving near the outsides of bends and in the deepest parts of the channel should include the coarsest sediment available.
3. Sediment will accumulate on the insides of bends, and this sediment will be finer grained.

If we look at a channel in cross section, it is asymmetric, representing the sites of erosion and deposition. Variation in flow speed also produce different sedimentary structures. Upper planar lamination and dune cross stratification are common where the Reynolds number (Re) is highest, and ripple cross lamination is common where Re is lower.

The main parts of the channel include eroding bank, the thalweg (the deepest point of the flow) and the point bar (on the inside of the bend where most sediment is accumulating). As the channel migrates due to erosion and deposition, a distinctive suite of sedimentary structures accumulate. The deepest part is coarser and has upper planar lamination or dune cross stratification. This is overlain by finer sediment with current ripple lamination.

As meandering rivers migrate, the meanders tend to increase in size. Eventually, the channel forms almost a circle, and the meander gets cut off, often during a flood. This straightens the channel temporarily and produces an ox bow lake in the abandoned meander. The lake accumulates mud and organic matter since the flow speed is close to zero.

Levees and Floodplains

When a river floods, it goes from a confined flow in the channel, which is very fast, to a widespread flow across the floodplain. The flow slows down very quickly and the water becomes shallower, both of which cause a decrease in Reynolds number. Thus, the water can not transport as much sediment on the floodplain as it does in the channel. Thus, finer sands that may be in suspension during a flood are transported as bedload or rapidly deposited once the river overflows its banks. This sediment deposition produces levees. The finer silts and especially clays remain in suspension much longer and settle out on the floodplain as the flood waters dry up.

Over time, the levees build up and provide a higher bank for the channel than the level of the floodplain. Thus, the channel bottom can aggrade (fill in) until the bottom of the channel is as high or higher than the floodplain. When the next flood comes along, the river avulses and does not go back into its old channel which is higher than a new one on the floodplain. This results in the downstream part of the channel being completely abandoned.

Meandering River Facies

Meandering rivers produce suites of facies that vary depending on the subenvironment. Channel facies different from floodplain and ox bow lake facies because the flow characteristics and sediment supplies are different.

Channel Facies

1. Scoured base of flow
2. Lag deposit with mud rip-up clasts and the coarsest grains being transported by the flow
3. Fining upward sands with trough cross stratification
4. Rippled sands
5. Sigmoidal cross stratification from migrating point bars

Floodplain Facies

1. Fine sand with climbing ripples near channels
2. Mudstone/shale with mud cracks
3. Soils
4. Root casts

Ox Bow Lake Facies

1. Mudstone/shale without mud cracks (unless the lake dries out)
2. Organic-rich deposits, including coal
3. Anoxic water indicators (especially in fossils and absence of trace fossils)

Differences between braided and meandering river deposits

1. Braided river deposits are commonly coarser grained
2. Meandering rivers contain abundant suspended sediment, which is deposited in ox bow lakes and on floodplains.
3. Floodplain deposits are better developed and finer grained in meandering river systems.
4. Bar migration is much more regular in direction in meandering rivers because there is a well defined, single thalweg towards which the bars migrate. In contrast, braided river bar migration occurs in multiple directions at the same time. Thus, meandering rivers produce a more regular geometry of tabular cross bedding, when preserved.

General Characteristics of Fluvial Sediments

1. On a large scale, river deposits consist of sheets and lenses of sand deposited in channels associated with flat laminated shales and silts with rare rippled sand beds deposited on floodplains.
2. Fining upward sequences of beds in the sands with sedimentary structures that indicate decreasing flow speeds.
3. Abundant cross stratification in well sorted sands, particularly trough cross stratification.
4. Cut banks at the edges of channels - these are good indicators of a migrating river channel, but can be hard to see in outcrop since they are rarely preserved
5. Soil development in floodplain deposits, with root casts common if the rocks are Devonian or younger (and on Earth).

Look at pictures of fluvial rocks at http://mygeologypage.ucdavis.edu/sum...s/Fluvial.html

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1.9: 9. Deltas, Estuaries, Marine Processes Part 1

Marine Deposition

Most of Earth is covered with oceans, there is abundant life in the oceans, most sediments eventually get transported into the oceans, and shallow marine deposits are the most abundant in the in sedimentary record due to their large volume and the low erosion rates in shallow marine environments. You need tectonics to uplift them above sea level to get significant erosion. This happens commonly, so that we can also see them exposed.

Processes

Several processes are unique to shallow marine deposition (and some large lakes): Waves, storms, and tides

Waves

Waves have oscillating current directions every few seconds. The flow in both directions is equal in deep water, but not necessarily near shore. Draw a picture of wave water motion. (Water at the top of the wave moves in the direction the waves move.)

Wave Ripples - Wave ripples are different from current ripples because that they experience transport in both directions over the time scale of seconds. Draw a picture with the laminar boundary layer, etc. Wave ripples can be recognized in rocks by their symmetric shape (if flow in each direction is the same speed) and most importantly, the presence of cross-laminations dipping in two directions. This is the truly distinctive feature and can be present even if the ripples are not very symmetric. At low flow, the boundary layer doesn't have enough speed or momentum to remove the crest of the ripple and the grains that are moved are deposited right on the upper part of the lee slope. Thus, crests are sharp. At higher flow, the crests erode and deposition occurs farther down the lee slope. Thus, high flow ripples have rounded crests.

In shallow water, currents from the waves can be strong enough to flatten out the ripples, but they are not consistent enough in one direction to form dunes; the flow switches directions too frequently for dunes to build up. Thus, where flow speeds are too fast to form ripples, the sedimentary surface tends to be planar or broadly scalloped as the waves are focused into certain areas. This produces a flat lamination (not upper planar lamination) where waves are in very shallow water relative to their height, e.g. from the breaker zone towards the shore.

KEY POINT FOR WAVES: Bi-directional flow every few seconds

Storms

Storms produce both large waves and strong, irregular currents. Combined waves and currents produce unique deposits that can be used to recognize ancient storms in a marine sequence. Storms generally start far from shore and get stronger at the shoreline through time. Then they either die out or move on. Thus, near shorelines, storms tend to start out with low energy flows, increase in flow speed until they are erosional (if strong enough) and then decrease back to lower energy flows. For example, sharp crested wave ripples might mark the start of a storm, then transition into round crested wave ripples, followed by cross stratification due to large waves and strong currents, followed by erosion. As the storm wanes, the coarsest sediment would be deposited, then finer sand deposited by waves and currents, and then wave ripples, e.g. the reverse of the sedimentary structures seen as the storm approaches. There is usually little sediment being deposited at the beginning of a storm because not much sediment has been eroded yet and flow speeds are increasing through time. Thus, there is usually no record of the first half of a storm sequence in the rock record. It is only the second half that gets preserved. Storm deposits almost always consist of an erosion surface with sediment of decreasing grain sizes upward - like turbidites, but with different sedimentary structures.

HCS - The cross stratification that is deposited as a combination of strong currents and large waves is unique to storms (and is found only in medium to fine sands). It is called hummocky cross stratification (HCS) and swaley cross stratification. When currents are washing eroded sand into an area with strong oscillatory flow from waves, rounded mounds or hummocks of sand develop on the sea floor separated by lows (swales). These mounds are a few to 10 cm high and 10's of cm across. See Figures 14.3 and 4 in Nichols. Variations in current strength cause erosion locally, and the locations of the hummocks and swales change through time. This produces erosional surfaces which truncate the older laminae (note that Fig 14.2 has the wrong laminae truncated). HCS is characterized by low angle laminae truncated by low angle surfaces. There are abundant concave and convex up laminae and many fewer flat laminae.

Storm Sequence - A sample stratigraphic column consists of: Mud, scoured surface, sole marks, (gravel at base), normally graded, HCS, flat laminae or wave rippled top, return to suspension settling. Contrast this to a turbidite - I will ask you to do this!

KEY POINT FOR STORMS: Multi-directional flows over seconds, low to high to low energy in deep water

Tides

Two key characteristics that are unique to tides: 1) flow changes direction 1 or 2 times per day; and 2) The speed of flow is cyclical with flow going onshore, stopping at hight tide, then flowing offshore, and stopping at low tide. There is lots of variability in tides depending on geography. Flow speeds vary, producing different sedimentary structures. In the Bay of Fundy, which has the highest tides recorded in the world (up to 16 m - a 5 story building), the water moves up to 15 km/hr (417 cm/sec) which is fast enough to transport boulders. At the low end, tidal currents are essentially non-existent. Also, there are times of slack tides when the water is essentially still or wave-dominated. Thus, the range of sedimentary structures is wide, including dunes (often called tidal bars when very large) and ripples. The main characteristic to look for, though, is variations in flow speed and DIRECTION.

Tidal sedimentary structures - Due to changing flow directions, two sediment transport directions are common, one for onshore flow and one for offshore flow. Often the onshore and offshore flows are not in the same location, but they shift around. This gives rise to current ripples showing transport in two directions and dune migration in two directions producing herringbone cross stratification. See figures 11.6 and 11.7 in Nichols. If the dunes are small and sedimentation rates are very high, you can get ***herringbone cross stratification*** in one tidal cycle in a modern environment. It is usually not preserved in the geological record because it is eroded prior to lithification. It is almost always the longer term changes in current locations that gives rise to preserved herringbone cross stratification. Dunes migrate in one direction for a while, and then currents patterns change and they migrate in the other direction. Herringbone cross stratification is almost always due to tidal processes, although it is not all that common in the sedimentary record. Commonly, one tidal current is much stronger than the others or the flow locations aren't systematically shifting, so tabular cross stratification is more common. It is not unique to tidal environments, however.

Reactivation Surfaces - Reactivation surfaces form when flow in one direction is stronger than the other, but the other flow is strong enough to modify the bedform shape. See figures 11.6 and 11.9 in Nichols. Reactivation surfaces are erosion surfaces within the sets of cross stratification. They look like irregular surfaces that are similarly oriented to the foresets, but usually do not dip quite as steeply. Also, the foresets above and below the reactivation surface commonly have a slightly different orientation. Reactivation surfaces indicate varying flow directions, which is very common in tidal environments.

Mud Drapes - Flow speeds are also cyclical. During slack tides (low or especially high), fine grained sediment can fall out of suspension draping tidal bedforms with mud. Because mud is cohesive, it does not necessarily erode during the next tidal flow, particularly in the separation zone where flow is slow, e.g. at the bases of ripples and dunes. Thus, sand foresets coated with mud are very common in tidal environments as well. See figures 11.6 and 11.8 in Nichols.

KEY POINT FOR TIDAL PROCESSES: Bi-directional flow with varying speeds over hours

Deltas and Estuaries - Introduction

When rivers reach standing water such as a lake or the ocean, the flow speed slows down dramatically. And when flows slow down, sediment is deposited. Almost all of the sediment transported in a river is thus deposited close to the river mouth, with the exception of grains that are fine enough to remain in suspension. Lacustrine and marine processes can rework the deposited sediment to distribute it along shorelines.

Deltas form at the mouths of rivers that transport enough sediment to build outward. (*Building outward* is a key component of the definition of a delta. In contrast, ***estuaries*** are present where the ocean or lake waters flood up into the river valley.) Deltas require substantial accumulation of sediment, in contrast to estuaries which do not build outward. Sedimentary facies are similar to other depositional environments, but the association of subenvironments are recognizable as deltas. Some of the sub environments include: river facies with all the associated sub environments; shore line deposits including beaches, marshes/swamps, etc.; submarine shelf and slope facies, including storm deposits and turbidites; etc.

I will draw cross section and map views of a delta showing the delta plane, delta slopes, and prodelta. Rivers flow through delta planes and slow when reaching water, producing a mouth bar. Grain size decreases with distance away from the river mouth.

Progradation

Because deltas are sites of sediment building outward from the coast, they are progradational; the landward depositional environments move seaward over more marine/lacustrine deposits. Thus, delta sequences in the rock record start with deep water, marine (or lacustrine), fine grained sediments and grade upward into shallower water, possible more freshwater, coarser grained sediments. This is one of the distinguishing aspects of deltas that let you define them in the sedimentary record. These changes in grain size and environment typically occur over 1's to 100's of meters in the rock record and include many beds.

Sediment Transport Type

All deltas (by definition) have their sediment transported to the delta by rivers. Thus, fluvial deposits are always associated with them. In addition, depending on marine (or lacustrine) conditions, waves and tides can redistribute the fluvial sediment changing the morphology and facies of deltas. There are three main end member categories of deltas when characterized by processes: 1) River dominated; 2) Wave influenced; and 3) Tide influenced. We will come back to these delta types after discussing the marine processes.

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1.10: 10. Marine Processes 2

Shorelines are the interface between the land and the oceans. Their characteristics vary depending on the balance of sediment supply and transport processes. When the sediment supply from rivers is large compared to the rate at which transport processes redistribute the sediment, deltas form, building out into the ocean. If sediment supply is low compared to the rate of sediment transport seaward of the shoreline, the shoreline erodes back. When sea level rises, river valleys can become flooded with marine water, creating estuaries. When sea level falls, rivers tend to erode downward into the previously coastal sediments.

The balance between tides and waves also affects the geometry of shorelines. Wave-dominated shorelines tend to have beaches, whereas tide-dominated shorelines tend to have broad marshy flats. Either can be erosional if the offshore transport of sediment is higher than the sediment supply or constructional if offshore transport is lower. They can shift back and forth through time if sediment supply or transport processes change. Thus, most shorelines are dynamic environments that vary significantly on human time scales.

Wave Influenced Shorelines

Waves have very specific sediment transport characteristics, with the highest energy flows near the breaker zone and lower flows both onshore and offshore. The onshore flows transport sediments to form beaches. The swash zone is the area that forms the primary beach. During storms, the waves are commonly higher, and, if sufficient sediment is available, they carry sediment farther up the beach, creating a berm. This gives the beach a characteristic slope up away from the shore, a crest, and then a slope downward. In some cases, the beach can extend off the coastline, creating a barrier bar or barrier island. A lagoon then forms between the beach and the main coastline. When there is a large sand supply, these barrier bars and islands can grow to be quite large. However, waves also transport sand off shore, going from the high energy breaker zone to the lower energy deep water. If the sand supply is low, more sand can get transported offshore than is delivered to the beaches. This causes beaches, barrier bars, and barrier islands to erode.

Tide Influenced Shorelines

Tidal currents flow on and off shore every day or twice a day. When tidal ranges are high, tidal currents can be strong, redistributing sediment either onshore or offshore. These tidal currents often become channelized, and they begin to act like rivers, with meanders, etc.

Constructional Shorelines: Deltas

Deltas form at the mouths of rivers that transport enough sediment to build outward. (*Building outward* is a key component of the definition of a delta. Rivers where the ocean or lake floods the river valley flow into *estuaries*.) Deltas require substantial accumulation of sediment, in contrast to estuaries which do not build outward. Sedimentary facies are similar to other depositional environments, but the association of subenvironments are recognizable as deltas. Some of the sub environments include: river facies with all the associated sub environments; shore line deposits including beaches, marshes/swamps, etc.; submarine shelf and slope facies, including storm deposits and turbidites; etc.

Deltas consist of the delta plane, delta slopes, and prodelta. Rivers flow through delta planes and slow when reaching water, producing a mouth bar. Grain size decreases with distance away from the river mouth.

Progradation

Because deltas are sites of sediment building outward from the coast, they are progradational; the landward depositional environments move seaward over more marine/lacustrine deposits. Thus, delta sequences in the rock record start with deep water, marine, fine grained sediments and grade upward into shallower water, possible more freshwater, coarser grained sediments. This is one of the distinguishing aspects of deltas that let you define them in the sedimentary record. These changes in grain size and environment typically occur over 1’s to 100’s of meters in the rock record and include many beds.

Sediment Transport Type

All deltas (by definition) have their sediment transported to the delta by rivers. Thus, riverine deposits are always associated with them. In addition, depending on marine (or lacustrine) conditions, waves and tides can redistribute the riverine sediment changing the morphology and facies of deltas. There are three main end member categories of deltas when characterized by processes: 1) River dominated; 2) Wave influenced; and 3) Tide influenced.

River Dominated Deltas

River dominated deltas have very low wave energy and a very small tidal range. Delta top deposits are well developed and are very similar to meandering river deposits, including channel, levees and overbank deposits. Overbank areas are commonly heavily vegetated and result in peat and coal deposition. Channels build out into the ocean (or lake) on top of their mouth bars. This leads to a coarsening upwards of grain sizes within the mouth bars as well as a change from some marine processes to unidirectional river flow. Avulsion of the rivers is common due to low gradients on the delta plain. Lobes of the delta become abandoned creating a “bird’s foot delta”. Sheltered bays are common between the lobes, and are filled with overbank deposits from floods as well as marshy deposits. The Mississippi River Delta is a classic river dominated delta.

Facies:

- Prodelta -
  - mudstones
  - rare, very distal turbidites
  - bioturbation
- Delta slope -
  - mudstones
  - turbidites
- Delta top -
  - mouth bar with climbing ripples at channel mouths
  - floodplain deposits grading into slope deposits between channels at the shoreline
  - meandering river facies

Wave Influenced Deltas

Waves redistribute the sediment deposited by the rivers. Progradation of channels is limited because mouth bars are reworked by waves into shore parallel sand bars and beaches. Spits of sand are also common. The waves sort the sediment better than rivers and, if the grains are not already well rounded, the waves will round them. The big differences for wave influenced deltas are that beach facies are abundant and channel fill and overbank facies are less common. The Niger River Delta is a wave influenced delta.

Facies:

- Prodelta -
  - mudstones
  - rare, very distal storm deposits
  - bioturbation
- Delta slope -
  - mudstones
  - wave-rippled sandstones
  - hummocky cross stratification (HCS) in fine sand
  - erosion surfaces, particularly below HCS
- Delta top -
  - wave ripples
  - coarse-grained deposits with poor stratification representing breaker zones
  - planar stratification associated with beach swash zones
  - meandering river facies

Tide Influenced Deltas

Tides rework sands into elongate bars perpendicular to shore (vs. waves). These bars are analogous to mouth bars, but they contain tidal sedimentary characteristics including bi-directional flow indicators and slack tide mud drapes. Overbank areas can include tidal flats. The Ganges-Bramhaputra delta in Bangladesh is a tide dominated delta.

Facies

- Prodelta -
  - mudstones
  - rare, very distal sand units, sometimes turbidites
  - bioturbation
- Delta slope -
  - mudstones
  - sandstones showing reactivation surfaces and mud drapes
- Delta top -
  - mouth bar with bidirectional current indicators at channel mouths
    - herringbone cross stratification
    - reactivation surfaces
    - mud drapes
  - numerous channels showing bidirectional flow and mud drapes
  - evidence of exposure of intertidal zone (mud cracks)
  - meandering river facies

Constructional Shorelines: Coastal Planes

Coastal planes are broad areas where there is sufficient sediment for the land to build seaward, but it is not localized at a single delta mouth. Examples of coastal planes include the Everglades area of Florida and the coast of the Carolinas.

Each of these processes creates distinctive features in stratigraphic columns.

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1.11: 12. Interpreting Stratigraphic Columns

Step 1: Diagnostic Sedimentary Structures

Look for sedimentary structures that are characteristic of a specific environment or process

Examples:

- hummocky cross stratification - waves plus currents (storms)
- wave ripples (vs current ripples) - waves (standing water)
- herringbone cross stratification - bidirectional flow over hours or longer (tides)
- reactivation surfaces - reshaping of bedforms due to changes in flow (tides)
- mud drapes in sandstone - flow stops (tides)
- bouma sequence - rapid flow slowing down (turbidity current)
- mud cracks - mud contracts (exposed to air)
- root casts - from plants, usually land plants (land)
- faint ripple cross lamination with reverse grading - (eolian ripples)
- meter-high dunes in fine sand - (eolian dunes)
- diamictites - laminar flow - (debris flows, mud flows, melting ice)
- diamictites with facetted clasts and striations - (glacial)
- lone (or drop) stones in laminated shale - large grains rafted over quiet environment (icebergs; trees possible)

Step 2: Tentative Environmental Interpretation

Evaluate how these distinctive sedimentary structures relate to each other in the stratigraphic column.

- Are there several indicators of waves or storms?
- Are there several indicators of tides?
- Are there several indicators of wind-deposited sediment?
- Are there several indicators of glacial activity?

Evaluate the environment(s) in which these processes occur most commonly to develop a tentative environmental interpretation (or an environmental hypothesis).

Step 3: Consistency with Other Features

Compare your environmental hypothesis to the characteristics implied by other sedimentary structures in the column and evaluate whether they are consistent with your tentative environmental interpretation.

- Examples of other sedimentary structures:
  - Trough cross stratification
  - Planar cross stratification
  - Current ripple cross lamination
  - Planar lamination

Evaluate whether or not your tentative environmental interpretation is consistent with the presence of these other sedimentary structures. If it is not consistent, evaluate how you can revise your environmental hypothesis to take these other features into account.

Example: Turbidites vs River Channel Deposits

If you hypothesized that set of a fining upward sandstones were turbidites (which have planar lamination and current ripple cross lamination), but there is also trough cross stratification in a number of the beds, ask yourself if there is a way for trough cross stratification to form in turbidites. The answer is that trough cross stratification is VERY rare to absent, which is why trough cross stratification is not part of the Bouma sequence of facies defined for turbidites.) You would then look for another environment that includes sandstones with planar lamination and current ripples. Fluvial channels often have those features. Turbidites and fluvial

channels do not form in neighboring environments (see Step 5 below), so it is unlikely that both are present. You will thus want to go back to steps 1-3 to identify a more consistent tentative environmental interpretation.

Example: Turbidites vs Storm Deposits

If you hypothesized that set of a fining upward sandstones were turbidites (which have planar lamination and current ripple cross lamination), but there are also wave ripples in a number of beds, ask yourself if there is a way for wave ripples to form in turbidites. The answer is no because turbidites are unidirectional flows. However, waves and storms can influence the sediment in the same environments that produce turbidity currents. For example, lakes and the ocean can have both in environments above storm wave base. Thus, the presence of wave ripples in some beds that contain mostly turbidite features suggests that waves were ALSO present in that environment. Thus, your environmental interpretation does not need to be significantly revised. Rather, it can be expanded to include both turbidites and waves.

Step 4: Vertical Evaluation

Evaluate how the vertical sequence of sedimentary structures changes to refine or correct your environmental interpretations.

- Do structures occur in a distinctive pattern that suggests a depositional environment?
  - Is there an erosion surface followed by dune stratification followed by ripple lamination followed by a rooted horizon? (Then it might be migrating river channels or tidal channels if there are indicators of tidal currents.)
  - Do the structures suggest an environment that shallows from deep quiet water upward into a river system? (Then it might be a delta building out into standing water.)

Sometimes the main sedimentary transport characteristics change through time. For example, a storm influenced environment can become more dominated by tides through time as the geometry of the shoreline changes, as climate changes, or as relative sea level changes. All three of these can change at once, too, because climate and sea level are tightly linked to each other, and shorelines respond to the changing sediment transport processes.

Step 5: Walther's Law

Use Walther's Law to refine your environmental interpretations and to test whether or not they are reasonable. There are two ways to approach this: testing your hypothesis by starting with your predictions, or starting with the data from the stratigraphic column and seeing if you get reasonable environments next to each other.

Test your environmental hypothesis

If you have a good mental image of your hypothetical environments, this is a useful process:

1. Draw a cross section or map view (or both) that includes all of your hypothesized environments. Make sure that it is a reasonable landscape, e.g. something that would be reasonable to see in a satellite image. In other words, do not draw rivers flowing uphill or lakes on mountain peaks, etc.
2. Indicate things like the relative water depth and the characteristics of sediment transport in each area. Include the sedimentary structures that you predict will form.
3. Compare these environments to your stratigraphic column. Start with the interval of the column that you have the most confidence in for your environmental interpretation. Mark that environment on your cross section or map. Then go up (or down) in the column to the next facies (rock type) and mark the environment it represents on your cross section or map.
4. Evaluate whether the two points are consistent with Walther's law. Draw a line from the first environment to the second one. Does that line cross any depositional environment that is absent from your stratigraphic column? If the answer is yes:
   - How can you reconcile the missing environment?
   - Are there features that you missed in the stratigraphic column that could have been deposited in that environment?
   - Is there an erosion surface between the two facies in the stratigraphic column?
5. Revise your interpretation of either your depositional environment or the facies in your stratigraphic column until they are consistent with each other. Do not, however, ignore the sedimentary structures in the stratigraphic column because they are the data that will lead to an appropriate interpretation. Revise your cross section or map appropriately.

6. Repeat steps numbers 3-5 until you have marked every facies in your stratigraphic column on your cross section or map, and all inconsistencies are resolved. Sometimes there are remaining uncertainties because the rock record does not record everything and we miss features when we are collecting the data. If there are still inconsistencies, record them and why you could not resolve them. For example, if there is one set of trough cross stratification in a sequences that otherwise consists of turbidites and storm deposits, you could make a note of where it occurs and provide a tentative interpretation for why, e.g. maybe the flow speed was consistent enough for long enough to produce dunes even though that rarely happens in turbidity currents.

Recreate environments from your strat column

If you are having trouble creating a mental image of your hypothesized environments, this is a useful process:

1. Start with the interval of the strat column that you have the most confidence in for your environmental interpretation. Draw that environment on a map or in a cross section. For example, if there are interbedded sandstones and mudstones, and the sandstones have features consistent with the Bouma sequences, draw a standing body of water with a slope on one side.
2. Indicate things like the relative water depth and the characteristics of sediment transport in each area. Include the sedimentary structures that you predict will form.
3. Next, go up (or down) in the column to the next facies (rock type) and draw the environment that it represents on your cross section or map, again indicating the relative water depth, sediment transport processes, and sedimentary structures indicated by the stratigraphic column data.
4. Evaluate whether the two environments are consistent with Walther's law. Are they typically next to each other in a landscape? If the answer is yes, go the the next facies in the strat column (go back to 3). If the answer is no, evaluate whether any of these are possible:
    - Did you miss an environment represented in your stratigraphic column? Is that environment between the two you drew in your cross section or map?
    - Is there an unconformity in your stratigraphic column that would mean that Walther's Law does not apply? Could erosion have been caused by the flows in the "missing" environment?
    - Is one of your environmental interpretations wrong? What else could it be?
5. Revise your interpretation of either your depositional environment or the facies in your stratigraphic column until they are consistent with each other. Do not, however, ignore the sedimentary structures in the stratigraphic column because they are the data that will lead to an appropriate interpretation. Revise your cross section or map appropriately.
    - **Example**: Say you interpreted interbedded mudstones and sandstones with current ripples as turbidites. However, there are also sandstones with an erosional base, thick sections of trough cross stratification fining up into current ripples at the top that you interpret as river point bar deposits. If those two rock types are next to each other vertically, they would violate Walther's Law since turbidites form in lakes and oceans, whereas river channels form on land. You need a shoreline between the two. Possible resolutions to this "illegal" interpretations could include: a) there is an interval between the two with climbing ripples that you missed in the stratigraphic column that could represent a river mouth bar, providing a transition from the standing body of water into the river channel; b) there is an unconformity that is more significant than the erosion at the base of a fluvial channel in the stratigraphic column, and thus there are no rocks preserved that reflect the changes in environments between the standing water and the river channel; or c) the interbedded mudstones and sandstones actually represent floodplain deposits rather than turbidites. You would then go back to the stratigraphic column and evaluate which change in interpretation is best supported by the data in your column.
6. Repeat steps numbers 3-5 until you have marked every facies in your stratigraphic column on your cross section or map, and all inconsistencies are resolved. Sometimes there are remaining uncertainties because the rock record does not record everything and we miss features when we are collecting the data. If there are still inconsistencies, record them and why you could not resolve them. For example, if there is one set of trough cross stratification in a sequences that otherwise consists of turbidites and storm deposits, you could make a note of where it occurs and provide a tentative interpretation for why, e.g. maybe the flow speed was consistent enough for long enough to produce dunes even though that rarely happens in turbidity currents.

Summary

Often, there is some ambiguity about the depositional environment(s) represented in real rocks. By going through this process, you can reach a reasonable interpretation that is well supported by the data. You will also understand where the ambiguities are. This is

particularly helpful if it is your own data and you can make more observations by doing more field work. You will be able to focus your efforts on resolving the ambiguities, leading to a more accurate environmental interpretation.

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1.12: 13. Siliclastic Shorelines and Estuaries

Shoreline Geometry

The vast majority of ancient sedimentary rocks accumulated in near-coastal depositional environments. These environments have sediment supplied by rivers and the sediment gets deposited just below sea level due to the rapid decrease in flow speed as rivers enter the oceans. The overall geometry and characteristics of shore lines are generally determined by 5 factors:

1. Sediment supply (high=constructional, low=erosional);
2. Wave energy (high=erosional, low=constructional);
3. Tidal range (changes shape of the shoreline, but can be either erosional or constructional);
4. Climate (changes sediment composition due to weathering and carbonate/evaporite formation, can be either erosional or constructional).
5. Tectonics and geomorphology

Erosional Shorelines

Shorelines erode when the supply of sediment to the shoreline is less than the transport of sediment away from the shoreline. For example, coastlines with strong waves and storms but little sediment input from rivers tend to erode. Also, coastlines with steep topography and a narrow continental shelf tend to be erosional because much of the sediment gets transported offshore. These shorelines can develop wave-cut platforms.

Erosional shorelines are preserved as unconformities in the rock record.

Constructional Shorelines

Shorelines accumulate sediment when the supply of sediment is greater than the rate of transport of sediment away from the shoreline. Deltas are examples of prograding constructional shorelines because the sediment supply is so large that they build outward from the coast. Constructional shorelines also form with lower sedimentation rates. They just need enough sediment to accumulate material to go into the rock record. Estuaries are flooded river valleys that accumulate sediment and can be parts of constructional shorelines even though the rate of sediment accumulation in them might be low.

Shoreline Features

Beaches, Barrier Islands, and Lagoons

Well developed beaches tend to form in areas with high sediment supply and high wave energy. They are constructional features. Tidal range and climate can vary and will affect the geometry of a beach, but beaches can form in a full range of conditions.

Wave action is critical to beaches. Waves come in off the ocean, and start to feel the shore, especially on the upper shore face. Wave ripples form here, as well as other cross stratification from storms and tidal channels. In shallower water, the sand and rocks are washed back and forth almost continuously which produces well rounded and well sorted grains. The grain sizes present depend on the wave energy and can range from cobbles to fine sand. In the zone where waves break, the erosional force is particularly strong due to high flow speeds and abundant sediment suspended in the water. The eroded sediment is washed up onto the foreshore and deposited as the water drains back into the ocean. If the waves are breaking very close to the beach or the beach front is very steep, the sand gets washed back into the ocean and there is net erosion. The deposition of sand leaves stratification parallel to the slope on the beach. The angle of sand on a beach is always significantly less than the maximum angle of repose because of the constant wave action. As wave strength or sediment supply vary, you can get cross stratification. This is often disrupted by burrowing organisms such as clams and crabs, but can be preserved.

Over time, sand builds up at the far reach of the waves forming a high called a berm. Storm surges wash over the berm and deposit sediment on the landward dipping surface. They can also erode the berm. When a beach develops offshore of exposed land, it creates a barrier island. These islands are very dynamic, shifting in location, growing, and eroding as storms reshape them.

The area behind the berm can either be land or water. If the beach transitions directly into land, the overall depositional environment is called a strand plain (I don't know why). If the area behind the berm is a lagoon or estuary, the berm forms a barrier

island (or peninsula) that protects the area from the full force of marine processes, i.e. waves and storms.

Wind commonly reworks this sand to form coastal eolian dunes. These dunes are similar to those in arid environments, but due to the proximity of the ocean, they are commonly more moist, and vegetation is common. The vegetation stabilizes the dunes reducing their migration as well as disrupts stratification in them.

Tidal Environments

Tidal Channels: Areas of strong flow like river channels, scour, lag, dune migration (usually only one direction). migration avulsion, sand bars; mud drapes during slack flow, different fauna

Mud flats flooded at high tide and exposed at low tide, fine seds brought in w/ rising tide deposited as the tide turns. tidal channels develop w/ ebb flow, vegetation between them traps sed. High sed rates, very nutrient rich, lots of bioturbation.

Lagoons: Lagoons are areas of quiet water and generally sites of mud deposition (either carbonate or siliciclastic). Coarser sediments are washed in during storms and are commonly wave rippled. Tidal channels commonly cut into lagoonal deposits as the location of concentrated flow migrates back and forth. Lagoons have extremely variable water chemistry depending on climate. If the climate is humid, they commonly contain a mix of fresh and salt water (brackish). If the climate is dry and a river does not flow into it, they tend to be evaporitic and hypersaline. The types of organisms living in the lagoon is a good indicator of local climate.

Tidal range is very important for estuaries. If the tidal range is low, there is a stable shore line and little mixing of fresh and salt water. Most of the estuary is fresh water, like the Everglades. If the tidal range is high, the ebb and flood of the tide feeds way into the river mouths and tidal channels and mud flats develop.

Sea level change

Sea level can change due to subsidence of the shoreline, which can be tectonic or due to compaction. As sea level changes, the location of these different facies shift in space. As sea level rises relative to the land, they shift one way, and vice versa.

Estuaries: Estuaries are river mouths that have been drowned by relative sea level rise and contain a mix of fresh and salt water. Both marine and fluvial processes influence them. With long term global sea level rise, many river mouths were inundated with sea water and became estuaries which are very important ecological sites. We had more than geologically typical until we started filling them in.

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1.13: 14. Carbonates

Carbonate rocks form from ions in seawater. Thus, their deposition and accumulation is somewhat different than it is for siliciclastic sediments. They do not require that sediment is transported into the environment. Rather, they require specific chemical, temperature, and biological conditions in the environment where they form.

Most carbonates (during Phanerozoic time) are created by living organisms as shells and skeletons. (During Precambrian time, microbial communities strongly influenced carbonate mineral precipitation.) Corals, snails, clams, etc. are good examples. The reaction to form the carbonate minerals calcite or aragonite (which have the same mineral formula) is:

$$Ca^{2+} + CO_3^{2-} \rightleftharpoons CaCO_3 \tag{1.13.1}$$

Because HCO_3^- is more abundant in seawater than CO_3^{2-}, the actual reaction that takes place is:

$$Ca^{2+} + 2HCO_3^- \rightleftharpoons CaCO_3 + H_2O + CO_2 \tag{1.13.2}$$

The $\rightleftharpoons$ means the reaction can go either way. If it goes from left to right, calcium carbonate minerals - calcite or aragonite - form. If it goes to the left, calcium carbonate minerals dissolve.) The HCO_3^- comes from the weathering of siliciclastic minerals

The chemical reaction to form the minerals is most likely in warm water, particularly in warm agitated waters. Breaking waves help get rid of the CO_2 produced by the reaction, which makes the reaction proceed even faster. Also, some corals contain photosynthetic organisms within their tissues, and those organisms consume CO_2, which also helps with the mineralization process. Thus, carbonate minerals form in warm, shallow seawater. The accumulation of carbonates creates “carbonate platforms” around many tropical islands (e.g. Caribbean islands, Bahamas, Hawaii, etc.) and along tropical shorelines (Florida, Great Barrier Reef of Australia, etc.).

One major source of carbonate sediments in geologically recent time is from calcifying algae. These organisms are very abundant. They produce the minerals as sand or mud grains (depending on the species) within their tissues. When the algae die, the carbonate grains are released into the environment to be transported by waves and currents. At this point, the grains behave more or less the same as siliciclastic grains, with coarser sediment requiring high flow speeds to be transported, and mud-sized grains requiring very low flow speeds to settle from suspension. In shallow environments, muds accumulate in deeper areas of lagoons or get transported off shore into deeper waters. The grains get concentrated into shoals where water speeds slow down, for example, where water is channeled through a reef into a lagoon. These grains can also grow through carbonate mineral precipitation forming coated grains, or ooids. Thus, they get coarser with time.

A second distinctive feature of carbonates is the growth of reefs. Corals and other skeletal organisms grow well in high energy zones with breaking waves. Their skeletons make them resistant to erosion, and the breaking waves enhance carbonate mineral formation. Also, the precipitation of more carbonate as cements makes the structures hard and very resistant to erosion even though they are in high energy zones with breaking waves. These reef ecosystems can grow very quickly, creating a topographic high located off shore. This high induces more breaking waves, changing the energy distribution across the carbonate platform. The distribution of grain sizes around a reef depend on the flow speeds, similar to the dependence for siliciclastic grains, but the reef itself is cemented in place and provides a unique environment. Grains that are broken off tend to be transported to the inside or outside of the reef where water depths increase and flow speeds slow.

As reefs grow upward, they create very steep slopes, sometimes almost vertical slopes. These slopes can be unstable long-term, and they can fail, creating breccia in deep water and inducing turbidites as in siliciclastic sediments.

See figure 15.12 in Nichols, Edition 2 for the distribution of environments across a reef.

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1.14: 15. Chronostratigraphy - Event, Magneto, Bio

The idea behind chronostratigraphy is to correlate rocks that formed at the same time. This is useful for reconstructing events and depositional environments in earth history as well as finding resources like oil. There are several techniques that can be used for chronostratigraphy, including: event stratigraphy, magnetostratigraphy, chemostratigraphy, biostratigraphy, and sequence stratigraphy. Here, I will address event stratigraphy, magnetostratigraphy, and biostratigraphy. Sequence stratigraphy is very powerful, and lots of resources on it can be found at: http://sepmstrata.org/

Event Stratigraphy

Event stratigraphy involves identifying the sedimentary effects of an unusual event in multiple stratigraphic columns. If one can demonstrate the the effects were all produced by the same event, one can reasonably interpret the effects to have happened at the same time in the different columns. For example, if a volcano erupts and deposits ash over a broad region, that ash is preserved in the stratigraphy, and a geologist can demonstrate that the ash in multiple sections came from the same eruption, then the geologist can create a chronostratigraphic correlation among the sections. Other events that are useful for event stratigraphy can include impact debris layers (for example at the Cretaceous-Tertiary boundary), tsunami deposits, and sometimes large storms.

There are some shortcomings of event stratigraphy. First, there has to be an event that affects the stratigraphy. For it to be useful, it needs to be something that affects multiple depositional environments in a way that produces a distinctive set of features that can be distinguished from the normal depositional processes. Second, for a specific event to be useful for correlations, it has to have affected the stratigraphy at the sites of interest. For example, a tsunami that affected the west coast of North America might help one correlate Pleistocene coastal deposits in Oregon and Washington. However, it would not be helpful for correlating Pleistocene rocks in Florida because it did not influence them. Third, if there are multiple events, the geologist has to sort out which correlate with each other. For example, if there are multiple volcanic eruptions at different times, the geologist needs to evaluate which eruptions the ash beds might represent. It can become complicated to correlate many events. Sometimes correlations are more reliable if there are fewer events, but then there are not as many potential temporal ties between the stratigraphic columns. Even with these complications, event stratigraphy is a very valuable tool. When the events are volcanic, the ash beds can often be dated, providing a precise age for a segment of the stratigraphic column.

Magnetostratigraphy

Magnetostratigraphy uses preserved magnetization of rocks for correlation. The magnetization comes from the alignment of magnetic minerals in sedimentary rocks (and other types of rocks) with Earth's magnetic field. Small magnetic minerals, especially clay-sized minerals, align like little magnets, and when the sediment is lithified, that magnetization can be preserved. Under the right conditions, samples can be collected and the direction of magnetization measured. Data can be used to reconstruct the direction of Earth's magnetic field. This magnetic field can reverse directions due to the dynamics of circulation in the core. In other words, sometimes the magnetic field is aligned such that magnets point north (as they do now, and called "normal" in the scientific literature) and sometimes it is aligned such that magnets point south (called "reversed"). The earth's magnetic field changes at close to the same time globally, so the effects are seen everywhere. Paleomagnetists have studied well dated sedimentary and volcanic rocks and have mapped out the times in earth history where the magnetic field was normal and reversed (see: http://www.geosociety.org/science/timescale/). This provides a reference that can help correlate stratigraphic sections.

To correlate a suite of stratigraphic sections using magnetostratigraphy, one would collect samples, measure their magnetic properties using a variety of techniques, and evaluate whether or not they have been remagnetized. If they have not been remagnetized, changes in the direction of Earth's magnetic field can often be interpreted from the results. If a geologist has multiple sections that were deposited at the same time, they can interpret the changes in the direction of Earth's magnetic field to have happened at the same time. Unfortunately, however, one can not necessarily independently tell the many normal intervals apart from each other nor the many reversed intervals apart. Thus, the geologist needs additional information to make reliable chronostratigraphic correlations.

Biostratigraphy

Biostratigraphy is an extremely powerful tool for chronostratigraphic correlation. Life evolves through time, with new species emerging and other species going extinct. For time intervals and species that are well studied, the process of evolution provides a detailed temporal framework for correlating stratigraphic columns. The basic idea is for the geologist to identify fossils in the stratigraphic columns, compare them to the ranges of those organisms know from previous studies, and then interpret the age of the rocks from documented extinction and species origination events. This is an extremely powerful approach to correlating stratigraphic columns because each species is unique and changes through time. However, not all organisms are useful for biostratigraphy.

Good biostratigraphic species: 1) have short geological ranges, e.g. they did not live for millions of years, and evolved quickly; 2) were distributed over a large region of Earth; 3) were easily preserved; and 4) were abundant. They also need to be well studied.

Zones of well documented species with distinct origination and extinction times can be defined a number of ways. A zone could consist of the total time of existence of a fossil, it could consist of the time where two or more fossils coexist, it could be defined as the time between the origination of one fossil and the extinction of a different fossil, etc. An example of a biostratigraphic zone chart, combined with magnetostratigraphic reversals can be found at: http://www-odp.tamu.edu/publications/189_IR/chap_02/c2_f6.htm

Other

- I used a lot of diagrams in class, and we'll continue with biostratigraphy for the next lecture.
- The Oceanic Drilling Project Leg 207 has some wonderful stratigraphic data across the Cretaceous-Terteriary boundary: http://www-odp.tamu.edu/publications/207_SR/207TOC.HTM These images are particularly helpful:
- Map: http://www-odp.tamu.edu/publications/207_SR/102/c102_f1.htm
- Core Correlations: http://www-odp.tamu.edu/publications/207_SR/102/c102_f6.htm
- And these papers are good: (need full references and links)
  - Arz et al 2001
  - Smit 1999

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CHAPTER OVERVIEW

2: Depositional Environments

UC Davis Geo 109
Earth History: Sediments and Strata
Spring 2017: Sumner

Lecture Notes • **Depositional Environments** • Virtual Field Trips

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UC Davis Geo 109
Earth History: Sediments and Strata
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UC Davis Geo 109
Earth History: Sediments and Strata
Spring 2017: Sumner

Lecture Notes • **Depositional Environments** • Virtual Field Trips

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3.1.1: Gale Crater and Bagnold dunes

Gale Crater, Mars, is ~150 km in diameter and has a high central peak that formed during the impact that created the crater (Figure 3.1.1.1). The central peak (formally named Aeolis Mons and informally called Mount Sharp) is flanked by sedimentary rocks. These rocks have been partially eroded away. However, there is no fluvial outflow channel from the crater, so the debris from erosion must have been removed from Gale Crater by wind. Wind still actively moves sediment in the crater: the black areas in the crater consist of basaltic sand with active dunes.

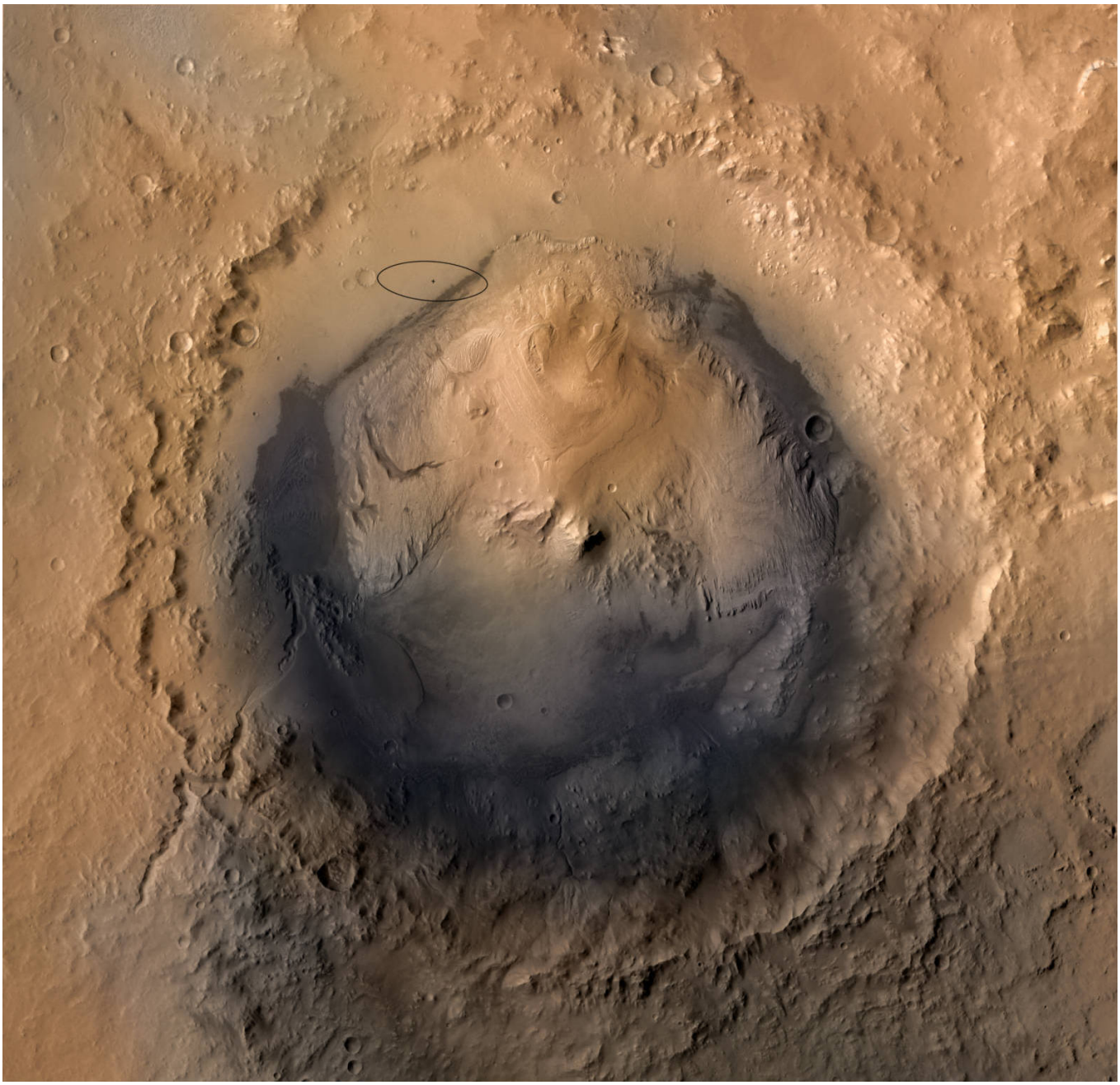


Figure 3.1.1.1: A satellite image of Gale Crater, Mars. The central peak, which we'll call Mount Sharp, is in the middle of the crater, and the ejecta from the impact surrounds the crater. The topography is lower in the northern half of the crater due to more extensive wind erosion north of Mount Sharp. The black areas consist of basaltic sand in modern eolian dunes. The ellipse represents the Curiosity rover landing target. Image credit: NASA/JPL-Caltech/ESA/DLR/FU Berlin/MSSS

The dunes surround Mount Sharp with the main transport of sand from north to south around the mountain. The dunes that cut across the landing ellipse (Figure 3.1.1.1) are informally named Bagnold dunes. They mostly consist of linear dunes, with some barchan dunes, particularly along the northern edge of the dune field (Figure 3.1.1.2).

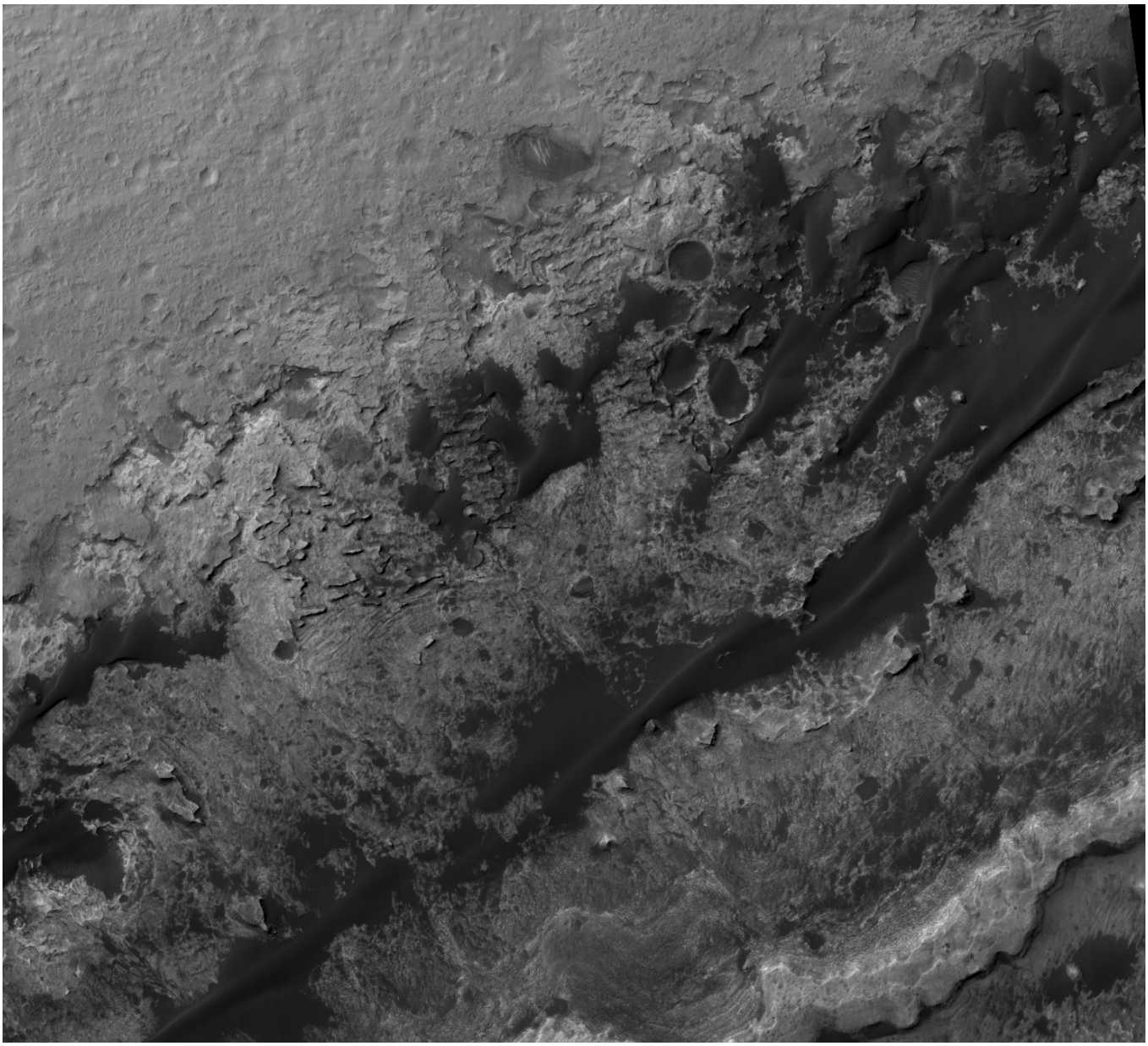


Figure 3.1.1.2: Image of part of Bagnold dunes. The actively transported sand is black and the bedrock is lighter colored. The northwest corner of the image consists of hummocky plains underlain by ancient fluvial deposits. The patches near the center of the image with parallel, linear ridges consists of cemented eolian sandstones of the Stimson formation. The rest of the bedrock consists of the mostly lacustrine Murray formation. The eolian Stimson formation unconformably overlies the Murray formation and has a similar distribution to the modern sand dunes. Image credit: NASA/JPL/University of Arizona

NASA's Curiosity rover landed just east of the center of the landing ellipse (Figure 3.1.1.1) on August 6, 2012. To better understand active sand transport on Mars, the Mars Science Laboratory (MSL) team chose to use Curiosity to investigate Bagnold dunes at two sites, one with barchan dunes (Phase 1) and one with linear dunes (Phase 2) (Figure 3.1.1.3).

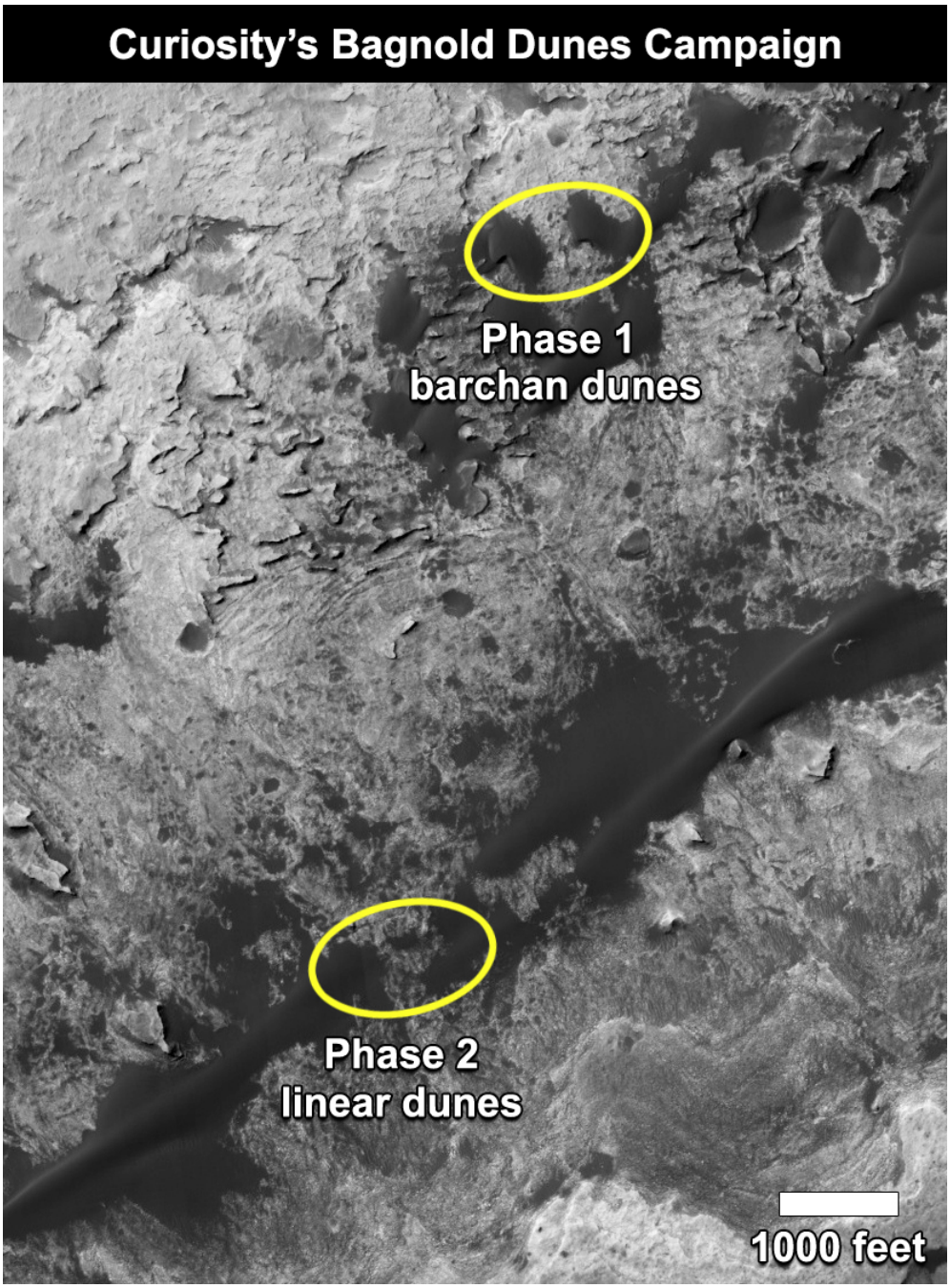


Figure 3.1.1.3: Areas where Curiosity investigated Bagnold dunes. Image credit: NASA/JPL-Caltech/University of Arizona

The main goals of the investigations were to (Lapotre et al., 2018): 1) develop an understanding of the mechanisms of eolian transport on Mars by directly observing eolian structures and their dynamics; and 2) characterize the physical properties and mineralogy of the sand in Bagnold dunes. To answer these questions, the MSL team planned observations for the Curiosity rover to image sedimentary structures and bedforms in enough detail to interpret bedform migration dynamics. They also performed experiments to look for movement of sand grains and associated bedforms, with synchronous wind measurements. The dune sand was sampled at two locations to determine its mineralogy to better constrain the origin(s) of the sand and weathering processes on modern Mars. Results were compared from the two phases of the campaign (Lapotre et al., 2018 and references therein).

Tags recommended by the template: article:topic

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3.1.2: Phase 1 - Barchan Dunes

Phase 1 focused on investigations of barchan dunes on the northwest border of Bagnold dunes (Figure 3.1.2.1). The team spent about 3 months during the low-wind season during Phase 1 investigating High and Namib dunes.

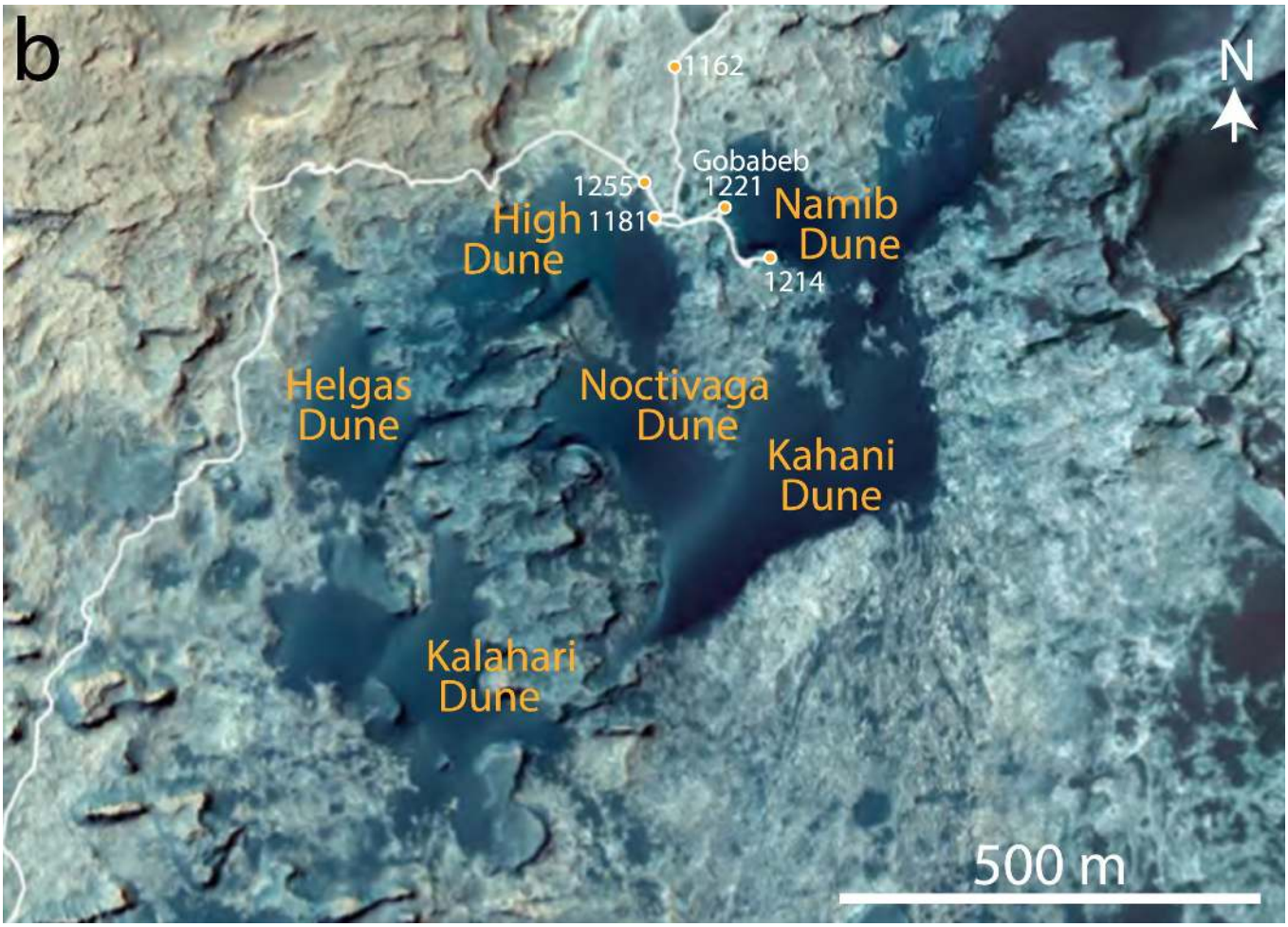


Figure 3.1.2.1: Satellite image of the Phase 1 investigation area showing the Curiosity rover path (white line) with the sols (martian days numbered from landing) where key data were collected as part of the dune campaign. Dune names are shown, with Namib and High dunes the focus of most of the observations. (Dunes were informally named after areas in Namibia, which has a large sand sea.) Image credit: Lapotre et al., 2018.

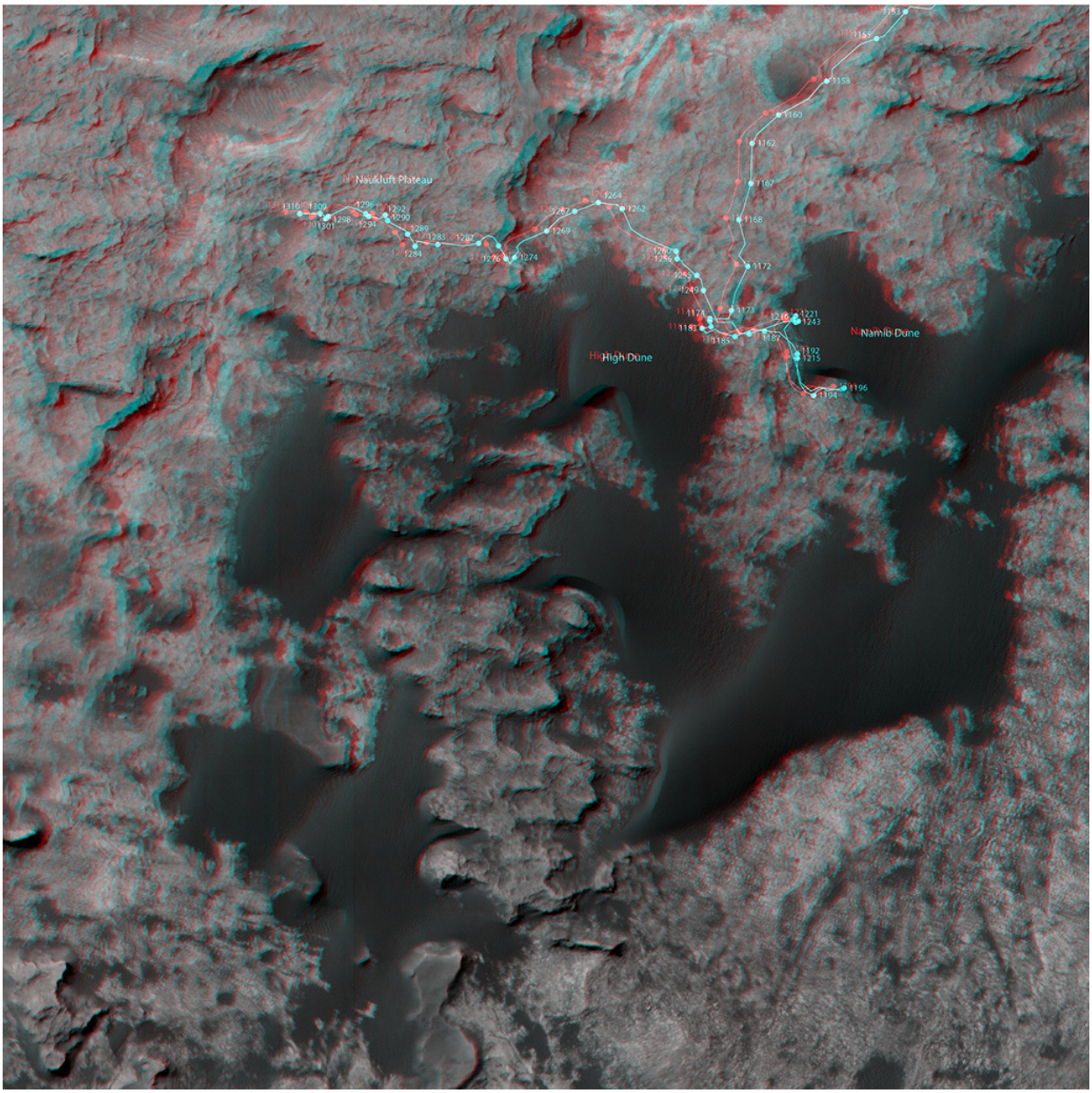


Figure 3.1.2.2: Satellite images combined to provide a 3d view of the Phase 1 field area. Use red-blue 3d glasses. North is about 7 degrees to the left of up. Image credit: NASA/JPL/University of Arizona/Phil Stooke/Emily Lakdawalla

Observations from orbit demonstrated that High dune has migrated to the south over six years of satellite observations (Figure 3.1.2.3). Thus, the team expected to evidence of active sand transport with bedforms that reflect the average modern wind conditions in this part of Gale Crater.

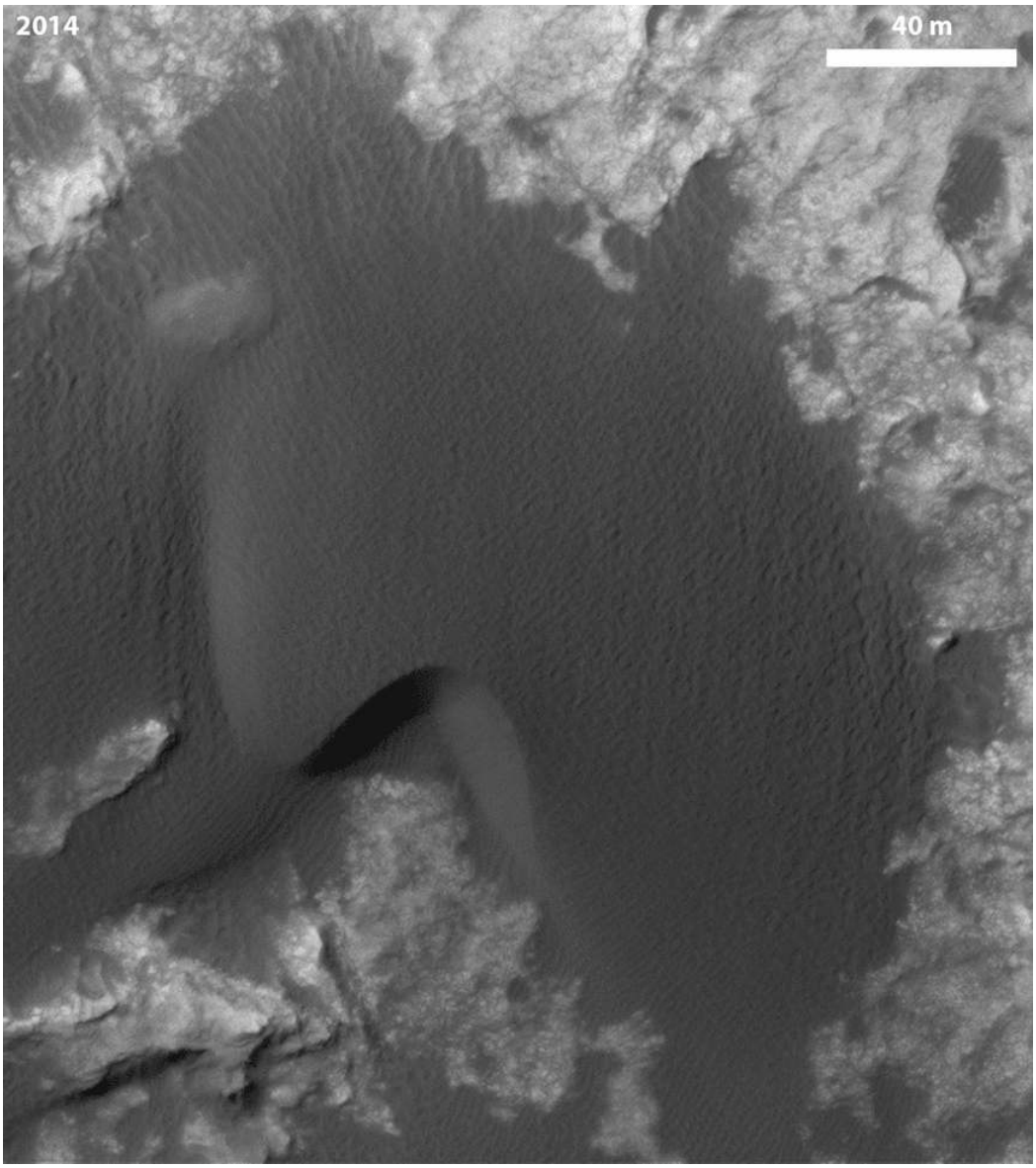


Figure 3.1.2.3: An animation of two HiRISE images of High dune. The first image was taken on August 22, 2008, the second on April 16, 2014. Comparisons of the images show that the dune migrated slightly to the south and ripples on the dune also moved southward. The two images were taken at slightly different angles, making parts of the bedrock appear to shift when it was actually static. Image credit: NASA/JPL/University of Arizona/Emily Lakdawalla

A summary of activities during Phase 1 is provided by Emily Lakdawalla in two blogs (sols 1166-1217 and sols 1218-1249) and in section 2.1 of Lapotre et al. (2018). Early on, the MSL team had Curiosity perform some drive tests on sand and characterize the elemental composition of the sand. Curiosity then imaged the back (stoss or upwind) side of High dune, documenting beautiful, and unusual, bedforms. The team wanted to monitor the slipface of a barchan dune, but it was not reasonable for Curiosity to observe the downwind side High dune due to the bedrock topography and the distribution of sand. Thus, the team had the rover drive to the slipface of Namib dune for several weeks over the US December holidays. After the holidays, Curiosity sampled the sand, characterizing its mineralogical composition. Some excellent images from Phase 1 are compiled here.

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3.1.3: Phase 2 - Linear Dunes

Phase 2 focused on linear dunes. Curiosity passed through a break in the sand between two linear dunes, investigating the bedforms and sand (Figure 3.1.3.1). These investigations occurred during the high-wind season. The focus of Phase 2 was thus to characterize sediment transport and to understand how changes in wind direction might cause the linear dune form.



Figure 3.1.3.1: Satellite image of the Phase 2 investigation area showing the Curiosity rover path (white line) with the sols (martian days numbered from landing) where key data were collected as part of the dune campaign. Dune names are shown, with Nathan

Bridges and Mount Desert Island dunes the focus of most of the observations. Image credit: Lapotre et al., 2018.

Summaries of the activities in Phase 2 are provided by Emily Lakdawalla in a blog and in section 2.2 of Lapotre et al. (2018). Briefly, Curiosity investigated two sides and the crest of Nathan Bridges dune and then moved to Mount Desert Island dune to sample the sand and observe sand grain transport.

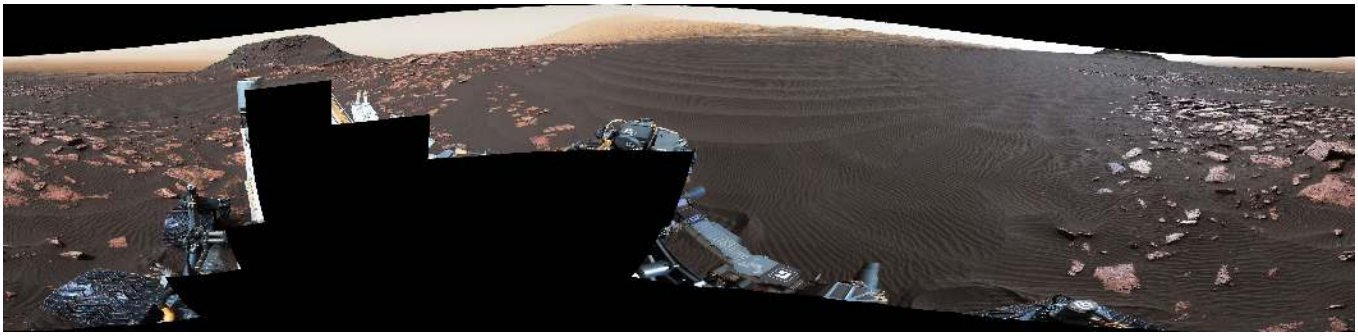


Figure 3.1.3.2: Nathan Bridges dune with the hardware of the Curiosity rover in the foreground and Mount Sharp in the background. This image is from the Mapleton location on Figure 3.1.3.1. Image credit: NASA/JPL-Caltech/MSSS

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3.1.4: Links to great images for Phase 1

These images (in approximate time order) provide many great observations for Phase 1 for you to explore:

- Wheel tracks on High dune
- Close up of sand disturbed by wheel tracks on High dune
- Undisturbed sand on High dune
- Slipface of Namib dune and an annotated version showing sediment transport types
- 3d image of the slipface of Namib dune
- Telephoto view of the slipface with interesting sedimentary features
- Full circle panorama of Namib dune
- Rover tracks on the side of Namib dune where sand was sampled to study its mineralogy
- Curiosity selfie at the sampling site on the side of Namib dune
- Close-up image of sieved sand dumped after sampling

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3.1.5: Bedforms in Eolian Dunes on Mars (vs Earth)

Eolian Landforms and Bedforms in Gale Crater

There are multiple scales of eolian landforms and bedforms in Gale Crater (Figure 1). The largest scale is the erg (a large area covered in eolian sand) that extends along the sides and south end of Mount Sharp in Gale Crater (link to figure of whole crater annotated with eolian bed/landforms). The next smaller scale of bedforms is draas (Figure 2), which are undulations in the erg that have a length scale of hundreds of meters to kilometers. Two can be seen in the large sandy area west of Mount Sharp. The draas are composed of dunes, which range from 3 m to 600 m in wavelength. The dunes have several different morphologies. On Mars, megaripples with 0.8 to 3 m wavelengths are common on many dunes. Impact ripples with wavelength of centimeters to about 20 cm (Lapotre et al., 2018) are very common. These impact ripples are similar to the ones that migrate on dune slopes on Earth.

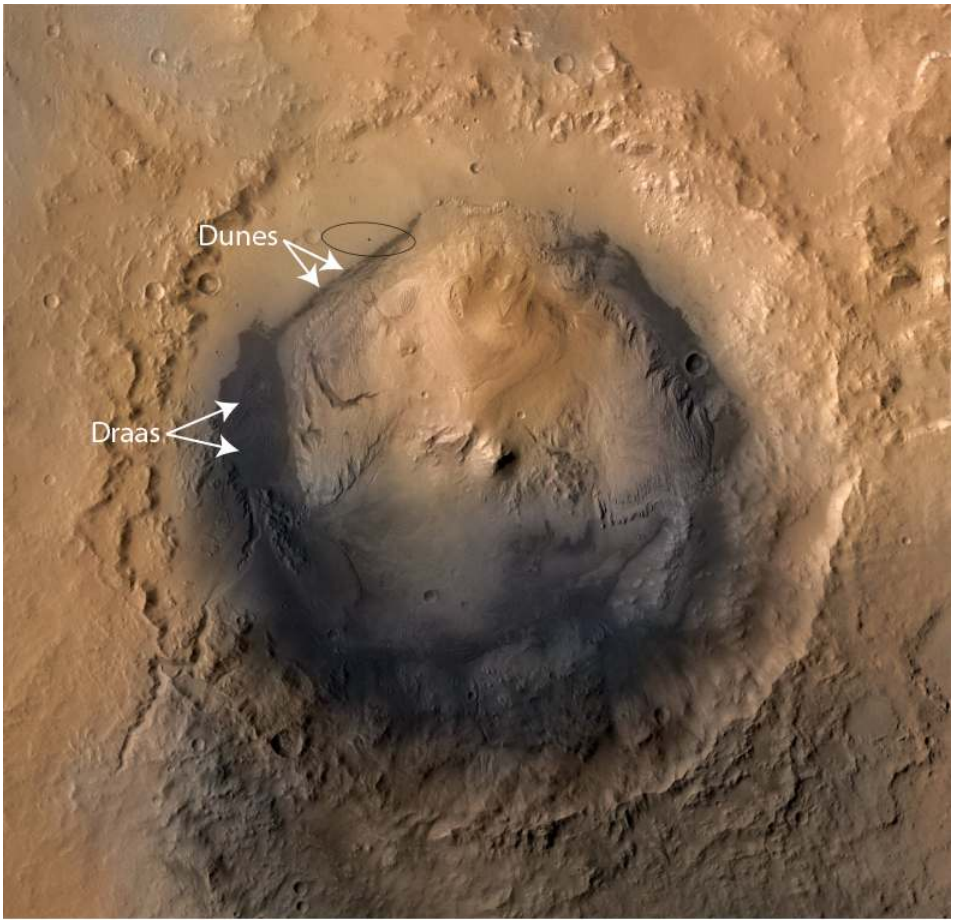


Figure 1: Satellite image of Gale Crater, which is ~150 km in diameter. The black areas consist of sand that has been actively transported by wind in modern times. The area covered by sand is large enough to be considered an erg. Bedforms visible at this scale include draas and individual dunes.

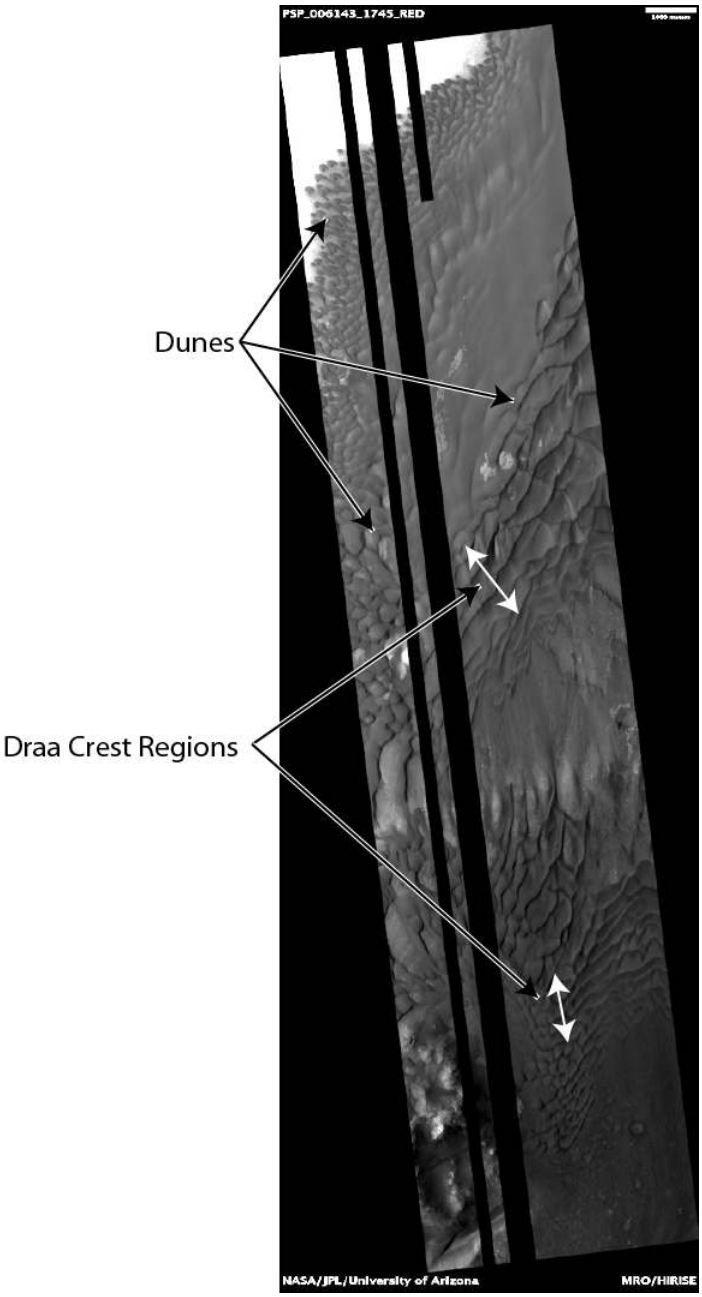


Figure 2: A higher resolution image of the area labeled "Draas" in Figure 1 with dunes and the draa crest regions labeled. Taken with the HiRISE camera. A full resolution version is available as are other forms of the image. Image credit: NASA/JPL/University of Arizona/Sumner

Martian Megaripples - A New Beform Type

Some martian sand dunes have bedforms that are not observed on Earth. Specifically, the megaripples, roughly 3 meters apart, are not seen on Earth nor have they been previously recognized as a distinct type of bedform on Mars. Wind grain transport on Earth produces decimeter-wavelength ripples and hundred-meter– to kilometer-wavelength dunes. Similar bedforms also form from wind on Mars. However, a third stable bedform with meter-scale wavelengths is stable on Mars. These bedforms typically have sinuous crestlines (unlike smaller ripples and larger dunes) as well as asymmetric profiles with lee slopes that are sometimes slip faces at the angle of repose. There is a gap in size between the small wind ripples, the new megaripples, and the dunes (Lapotre et al., 2018). These gaps in size suggest that the formation of the megaripples is controlled by different wind-grain interactions than either the small ripples or the dunes. The specific interactions that form them are controversial. To some, these new bedforms resemble

fluid-drag ripples, which form in water on Earth when the laminar sublayer at the base of the flow is very thick due to a low flow speed (Lapotre et al., 2018). Lapotre, et al. (2016) speculate that the low atmospheric pressure of Mars creates the equivalent of a very thick laminar sublayer. However, this model has not yet been generally accepted by the sedimentology community.

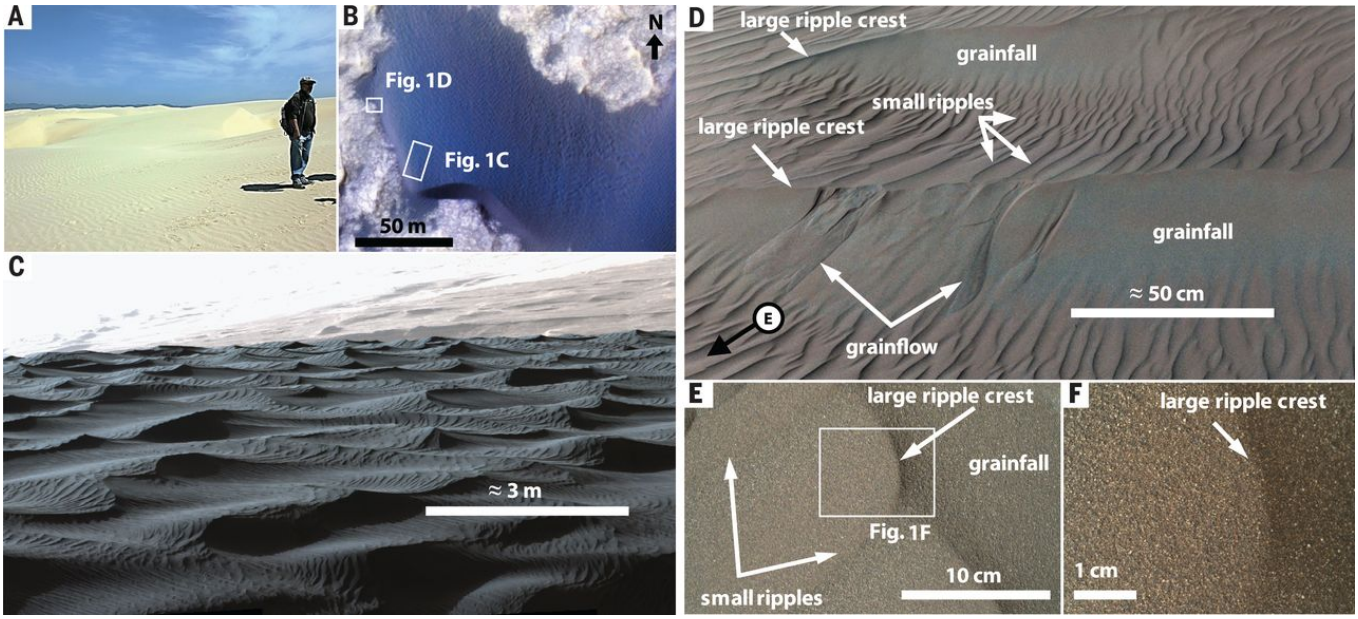


Figure 3: Figure 1 from Lapotre, et al. (2016). A) Dunes and ripples at Oceano Dunes, CA, lack the megaripples seen on some dunes on Mars. B) Satellite image of Namib dune showing the locations of figures. Taken by the HiRISE camera. C) Part of the image shown in Figure 1. D) Image showing the megaripples (called large ripples in the figure) and small ripples on the side of Namib dune. E) and F) The sand forming the megaripples.



Figure 4: Megaripples on the back of Namib dune taken during Phase 1 of the Bagnold dunes investigation with a scale bar. Image credit: NASA/JPL-Caltech/MSSS

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3.1.6: Slip Face on Namib Dune (a barchan dune)

Images

1. The different characters of the dune face labeled: https://mars.nasa.gov/multimedia/images/?ImageID=7624&s=2
2. In 2D: https://mars.nasa.gov/multimedia/images/?ImageID=7623&s=2
3. In 3D (get out your red-blue glasses!): https://mars.nasa.gov/multimedia/images/?ImageID=7625&s=2
4. Here's the face of the dune after the holiday: https://mars.nasa.gov/multimedia/images/?ImageID=7626&s=2

Questions to Ask Yourself:

1. Where are the rippled areas?
2. Where are the slope failures?
3. What characteristics do you expect to see the layers deposited by these two different transport processes? Think about the lateral continuity of layers, cross stratification, sorting (or not) of grains, etc.

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3.1.7: Active Sand Transport - Ogunquit Beach (Phase 2)

This page will include the MAHLI images that will allow you to evaluate which sand grains were transported by saltation and creep. For now, use the images from Lab 1 2020 social distancing version of GEL 109L. (Avery Peak)

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3.1.8: Wind by Season and Sand Transport

This page will discuss the seasons on Mars and variations in wind speed. We were in a low wind season for the stop at Namib dune. We were in the high wind season at the linear dunes near Ogunquit Beach.

To Add: graph of wind speeds, with the intervals of dune studies marked.

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SECTION OVERVIEW

3.2: Bodega Bay

3.2.1: Salmon Creek Beach

3.2.2: Bodega Head

3.2.3: Wave Energy and Sediments (Energía de las olas y los sedimentos)

3.2.4: Bayside Park

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3.2.1: Salmon Creek Beach

Welcome to Salmon Creek Beach located in beautiful Sonoma County, California!





This site was visited, along with several others in Bodega Bay, on January 31, 2015 in order to observe active sedimentary processes and to document spacial trends in sediments within an environmental context. Salmon Creek Beach consists of an estuary that is fed by Salmon creek that originates from the surrounding coastal hills and empties into the Pacific Ocean. Depending on the time of the year and the meteorological conditions, the estuary may or may not fully reach the ocean; however, on the day the site was visited, the Pacific Ocean and Salmon creek were connected. Looking at the left, southern side of the **above** image, the back of the estuary is lined with dunes and is a very low-energy environment where flow velocities are very low. In the images **below**, we see an increase in energy and flow velocity as water moves through a smaller, narrower area and bends around to where it meets with the Pacific Ocean. We can also see the cut bank of where the channel water level used to be at higher tides as it meanders on the beach toward the ocean. The most prominent sedimentary structures that were observed at Salmon Creek Beach were current ripples, antidunes, dunes, and wind ripples, along with the bioturbation (human and wildlife footprints).



1. Current Ripples

The first observed sedimentary structures were current ripples. These type of ripples indicate present unidirectional flow moment, which was initially determined to be north and then west closer to the bed of the ocean. The direction of the ripples changed where the flows of Salmon creek and the Pacific Ocean began to meet. The flow direction can be concluded by the direction of the Lee side, or grain attachment point. This side is where the grains being transported go from being suspended in the flow to depositing "down" to the bed again. The process of lamination is where such grains begin to repeat the process and produce wavy surface features known as ripples. The ripples seen at the beginning of Salmon creek, **bottom images**,were in between sinuous and linear and were measured to have a wavelength (from crest to crest) of 30mm with a flow direction going north. This small wavelength was suggestive of calm flow speeds, allowing fine sediment to be deposited.



(penny for scale) (footprint for scale)



Sample SC-01 was collected here and was later analyzed. The sample contains well-sorted very fine to fine sand consisting of quartz, lithics, and occasional pieces of glass and shells. The sediments here overall are well-rounded to rounded and spheroidal which suggests the grains are texturally and compositionally mature, meaning they are far away from the source of sediments.

(Sample SC-01)

Closer to the ocean as the channel meanders, ripples are still observed however they change in magnitude and direction. Given the flow is directed towards the ocean, the ripples change to that direction (west), **bottom left**. As the channel nears the ocean, ripple wavelengths were observed to get longer and sand grains became coarser. Wavelengths were now measured to be up to 90mm, consisting of the same sediments. These sediments were coarser and didn't share the uniform spherocity of the grains up the creek. The reason for this change in ripple characteristics was a result of flow differences. The flow had increased here and was able to carry more coarse sediments. The changes in flow allowed for the formation of reactivation surfaces, **bottom right**.



Reactivation surfaces occur from bidirectional flow where a one flow direction dominates and creates the ripple structure while an opposing weaker flow erodes the top of the ripple.

Aside from the current ripples observed, an area by the bend of the channel had interference ripples. Unlike the unidirectional ripples formed by current flow, these ripples indicate bidirectional flow. This means that at some point in tide fluctuations there were two different flow directions. These directions were from the creek to the ocean and from the ocean to the creek, or east to west. Indicative features of interference ripples are visible in the picture **below**, where sinuous ripples cross one another.



(penny for scale)

2. Antidunes

Along the stream connecting the lagoon and the ocean was observable a sedimentary bedform recognized as antidunes. These formations are possible when Froude's number of a flow is close to one so standing waves may form on the surface of the water before steepening and breaking in an upstream direction. As a result, the sand on the bed develops a bedform surface parallel to the standing wave; therefore, as the flow steepens, sediment accumulates on the upstream side of the bedform creating these unique structures. In the video recorded at Salmon Creek, we find that the fluvial environment present has the flow velocity needed to form the antidunes.



Video taken at Salmon Creek Beach showing the antidunes that formed in the shallow stream with a high flow rate.

Further down from where the antidunes were seen where the channel meets the swash zone, Sample SC-02 was taken. Sample SC-02 was analyzed to be coarser than SC-01 and consisted of well-sorted fine to medium sands primarily composed of quartz and lithics. Sediments in the swash zone are exposed to medium energy processes which gives us the medium sized grains as opposed to those finer grains found in the breaker and surf zone. The main sedimentary structures associated with Sample SC-02 would be bioturbation and faint lines of longshore drift.





Sample SC-03 was collected about halfway towards the dunes (going east) from the swash zone of the ocean past the antidunes. (See pictures at top of page for exact location). This sample contains moderately-sorted very fine sand to granule-sized grains that are composed of quartz, lithics, and shells. In this area, bioturbation as well as ripples were observed in the area. Coarser grains were concentrated on top of finer grains.

3. Aeolian Dunes and Ripples

Other sedimentary structures present were dunes and wind ripples. Dunes, also recognized as "megaripples," are bedforms distinctly larger than ripples. These bedforms are usually known as hills of sand that are produced by either water flow or wind. Dunes vary in size and are formed as sediments are pushed up the stoss side and are deposited on the lee side. At Salmon Creek Beach, we find that the dunes are primarily shaped by wind activity and are primarily comprised of the very fine-grained sediments transported and deposited by wind. These Aeolian dunesraneg from about 3 meters to 600 meters in wavelength and are between 10 cm and 100 meters high. Again, the migration of sediments, saltation, up the stoss side to the crest form structures like Aeolian ripples.

Aeolian Ripples are formed as grains migrate across a bed of sand creating patches of piled up grains. These "piles" of grains are due to irregularities on the surface of the sand that then pile in a perpendicular fashion equally spaced apart; therefore, the crests formed produce these aeolian ripples comprised of very fine to medium sized grains. The direction of these ripples are dependent on the direction of the wind which carries different sized grains depending on the strength of the blowing wind. The coarser grains in any given wind current are concentrated on the crests where the finer grains continue being transported by the wind. As the crests develop, the grains avalanche down the lee side into the rough forming cross-laminations.



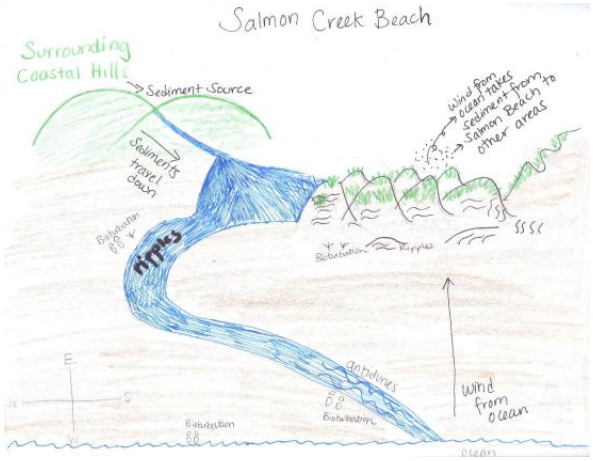
In the figure above, we can notice the aeolian ripples formed by the wind blowing in the southward direction. Each ripple is equally spaced out and is comprised, more or less, of the same fine sized grains.



Sample SC-04 was collected in this area and is consisted of well-sorted medium to very-fine quartz and lithic sands. The sedimentary structures associated with this sample are bioturbation (human and animal footprints), wind ripples, and dunes.

Interpretation

This coastal location has experienced an immense amount of sediment allocation from different sources. Methods including air and water have deposited the sediments seen today. The most dominant sediment redistributing source is water, carrying sediments during tidal fluctuations. At low tide, which was observed the day of the trip, all of the sedimentary structures described were able to be seen. At high tide, some structures would have been destroyed or altered due to water movement. With tides comes wind, which can also transport sediment. Both dunes and ripples at Salmon creek were created and sediment was transported out of the area to Bayside Park and further south as a result of these transport mechanisms.



Learning Modules

Ripples: https://www.youtube.com/watch?v=VAcr...ature=youtu.be

> **Preface-** Ripples were present at Salmon Creek and Bayside Park. Of course, they differ in some ways but are also similar. At both sites one is able to see grain size, composition, and angularity extremely up close. Both stops were at low tide which allowed for this. Given they have water flow fluctuations, one is able to see these ripples. Salmon Creek, however, had a slightly higher energy level than Bayside Park. At the creek ripples can be seen above and below a water surface. At Bayside Park, only ripples above a water surface are visible. This lead to the conclusion that although ripples are formed at both sides, different flow conditions influence their form and location on the bed.

Contributors

- Marcelle d'Almeida
- Rebeca Ontiveros
- Robert Torres

Works Cited

1. Sedimentology and Stratigraphy 2nd Edition, Gary Nichols, 2009. Print

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3.2.2: Bodega Head

Background

"One of our stops was Bodega Head. This beach is surrounded by large promontories, and is largely used recreationally by visitors. It lies just West of the San Andreas fault, and has coarse-sanded beaches with intrusive igneous parent material."

Walk down to the beach and observe the source material for the sands. The proximity to the San Andreas brought over the granitic rock of Bodega Bay, which differs from the Franciscan Complex on the mainland[1]. The fault actually shifted this area about 15 ft to the North as a result of the 1906 San Francisco earthquake. The Pacific Gas & Electric Company once tried to construct a nuclear power plant on Bodega Head in the 1950s[2], but this plan was ultimately stopped when realizing the hazards associated with seismic activity in the area. The abandoned site, which has since become a pond, is called "Hole in the Head".

1. U.S. Geological Survey Geographic Names Information System: Bodega Head
2. Paula Garb. Critical Masses: Opposition to Nuclear Power in California, 1958-1978 (book review) *Journal of Political Ecology*, Vol 6, 1999.
3.

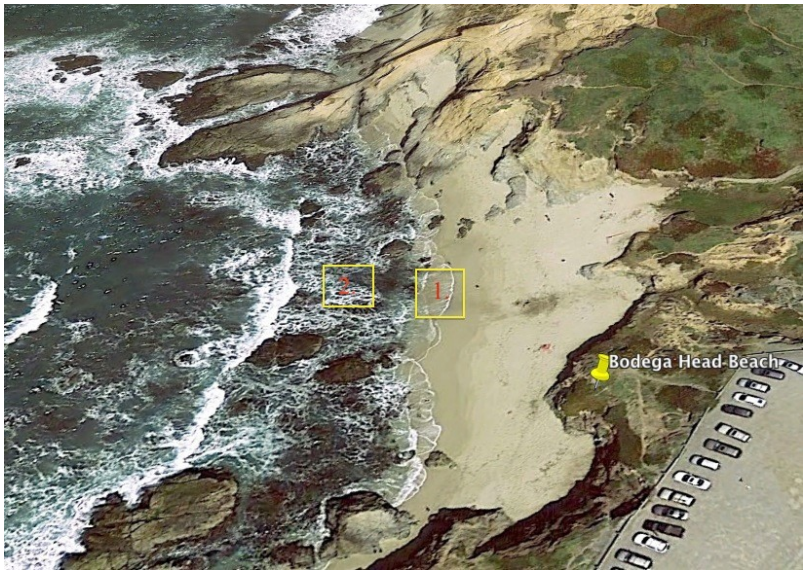


Photo taken from Google Earth and edited, there are cars for scale.

This is an area of Bay Head Beach. This photo shows the change in activity level throughout the beach. Medium energy waves can be observed in the swashzone at point 1. Higher energy waves can be observed at point 2.



This is side-view of Bodega Head Beach, those are people on the beach for scale. Our group collected two samples, one collected near point A and one from Point B. The samples show a difference in grain size, and sorting. Point A had well sorted grains while point B had very poorly sorted grains.



This image shows a rapid change of grain size and sorting observed in the transition from the swash zone to the breaker zone. Point B (Sample BH-1) grains are still course grained as high tide moves the breaker zone up to this point, though they are still more sorted and finer than sediment at point A (Sample BH-2).

Samples and Schematics



BH – 2:

Bodega Head

Sediment is local to igneous rock in the area.

- Collected: During high tides, it becomes the breaker zone. During low tides, it is the swash zone.

- Grain size: Coarse/Subangular – angular
- Sorting: Well sorted; however, the sorting declines if you go dig down a few decimeters.
- Interpreted energy: Medium – high energy
- Composition: 67% - Quartz, 30% - Lithics, 3% - Shells
- Facies - Fine

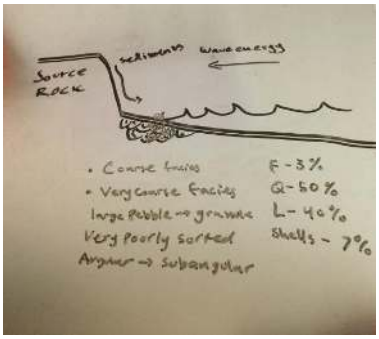


BH – 1

Bodega Head

Sediment is local to igneous rock in the area.

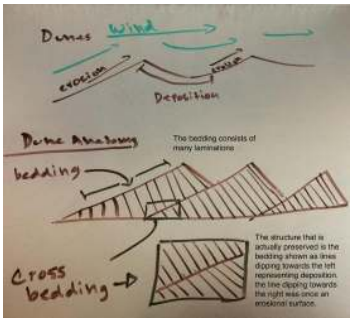
- Collected: Breaker zone
- Grain size: Very large pebble to granule
- Sorting: Very poorly sorted, subangular - subrounded
- Interpreted energy: Very high energy
- Composition: 40% - Lithics, 50% - Quartz, 7% - Shell Fragments, 3% - Feldspar
- Facies - Coarse

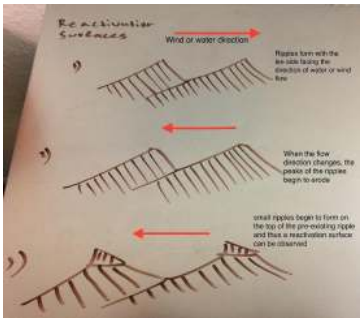


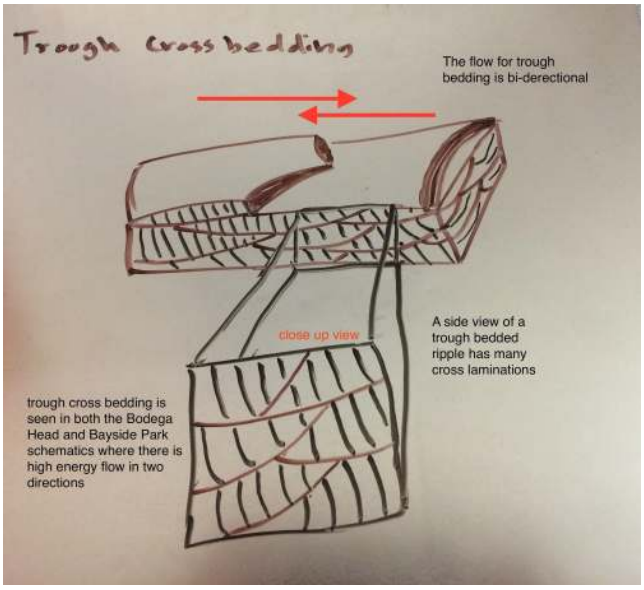
Bodega Head has a cliffside that is directly facing the ocean. The energy that brought by wave motion is thus high and is responsible for erosion of the source rock. Large grain sediments are found at the base of the cliff because they have been actively weathered out of the rock and have not traveled a long distance. In this environment, we observe the coarse facies from before and a new very coarse facies. In this new facies, we can expect to find large pebble to granule-sized sediments that are very poorly sorted and angular to subangular. The composition of the very coarse facies consists of mostly quartz then lithics followed by shells and feldspar.

Module D

Ripple Schematics from Bay Head and Salmon Creek/Bayside Park:







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3.2.3: Wave Energy and Sediments (Energía de las olas y los sedimentos)



On the day of our fieldtrip, we visited several locations that all had unique sedimentary features specific to the location. Each site had varying sediment grain sizes and different sedimentary structures. For the most part, I was able to obtain sediments that were fairly close to their sources. If one were to examine the samples collected, it would be noticed that those from Bodega Head consisted of coarse grains of granite diorite rock. At the beach, various large boulder sized granite diorite rocks were exposed showing just how close we actually were to the source; however, at our last stop, the mud and very fine sands collected were far from their source as we know that aeolian processes deposited them where we stood. Keeping all this in mind, we do see a notable change in grain size. Those sediments transported further distances were finer and had a defined rounded to sub rounded nature. Many of these grains were from other sources visited that same day which explains why we would notice granite diorite grains or plagioclase sediments from Horse Shoe Cove.

En el día de nuestra excursión, visitamos varios lugares que todos tenían características sedimentarias únicas específicas a la ubicación. Cada sitio tiene diferentes tamaños de granos de sedimento y diferentes estructuras sedimentarias. En su mayor parte, tuve la oportunidad de obtener los sedimentos que estaban bastante cerca de sus fuentes. Si uno fuera a examinar las muestras recogidas, se daría cuenta de que los de Jefe de Bodega consistía en cereales secundarios de diorita roca de granito. En la playa, varios grandes cantos rodados de tamaño granito diorita rocas fueron expuestos mostrando lo cerca que en realidad eran a la fuente; Sin embargo, en la última parada, el barro y arenas muy finas recogidos estaban lejos de su fuente ya que sabemos que procesos eólicos ellos depositan donde estábamos. Teniendo todo esto en cuenta, sí vemos un cambio notable en el tamaño de grano. Esos sedimentos transportados otras distancias eran más fino y tenía un definido redondeado a la naturaleza sub redondeado. Muchos de estos granos eran de otras fuentes visitaron ese mismo día, lo cual explica por qué notaríamos granos diorita granito o sedimentos de plagioclasa de Horse Shoe Cove.

With the Earth being covered by about 70 percent water, the Earths oceans play a vital role in shaping the terrain seen on any given beach. With that being said, each beach is shaped differently as they are ever-changing environments that are subject to spontaneous events.

Con la Tierra cubierta en 70 por ciento de agua, los océanos Tierras desempeñan un papel vital en la conformación del terreno visto en cualquier playa dado. Con eso se dice, cada playa tiene una forma diferente, ya que se los ambientes que son sujetos a eventos espontáneos en constante cambio.

At all the sites visited, one can notice that different wave energies affecting the sediments differently. Such forces shape the sediments that comprise each beach; therefore, each beach appears and feels different under our bare feet when on the sand.

En todos los sitios visitados, uno puede notar que las diferentes energías de onda que afecta a los sedimentos de manera diferente. Tales fuerzas dan forma a los sedimentos que componen cada playa; por lo tanto, cada playa parece y se siente diferente bajo nuestros pies descalzos cuando en la arena.

What is wave energy?/*¿Qué es la energía de las olas?*

Most waves acquire their energy and motion from the wind. When wind blows on the surface of an ocean or any body of water, friction created along the surface creates ripples that with added wind could increase in size; therefore, each wave is defined by the strength and length of time that the wave has been subjected to the wind. These two factors together can produce large waves that in turn carry vast amounts of energy that is directed at the coasts.

La mayoría de las olas adquieren su energía y movimiento del viento. Cuando el viento sopla sobre la superficie de un océano o cualquier cuerpo de agua, la fricción creada por la superficie crea ondas que con el viento agregado podría aumentar de tamaño; Por lo tanto, cada onda se define por la fuerza y la duración del tiempo que la onda ha sido sometido al viento. Estos dos factores juntos pueden producir grandes olas que a su vez llevan grandes cantidades de energía que se dirige a las costas.

Energy carried by the wave is transferred when the wave can no longer support its own height and breaks. When the waves break, the energy is then seen being transferred into the churning and turbulent water known as the surf. The surf is either directed at cliffs or beaches where the energy gradually shapes the terrain affected.

Energía transportada por la onda se transfiere cuando la onda ya no puede soportar su propia altura y se rompe. Cuando rompen las olas, la energía se ve entonces de ser trasladado en el agua agitada y turbulenta conocido como el surf. El surf es dirigido o bien en acantilados o playas donde la energía shapes gradualmente el terreno afectado.

How do certain parts of a beach experience different levels of wave energy*?/¿Cómo ciertas partes de una playa experimentan diferentes niveles de energía de las olas?*

On a beach, different grain sizes can be observed due to the different levels of energy directed at specific points on a shore. It is important to note how the topography of a coast is different depending on the wave energy present.

The three most important parts of a shore are:

- The foreshore (the area most affected by the breaking of the waves; high energy)
- The backshore (this region is only affected during high tides when the water levels are high and during storms; low energy

En una playa, diferentes tamaños de grano se pueden observar debido a los diferentes niveles de energía dirigida en puntos específicos en una orilla. Es importante observar cómo la topografía de una costa es diferente dependiendo de la energía de las olas presente.

Las tres partes más importantes de una orilla son:

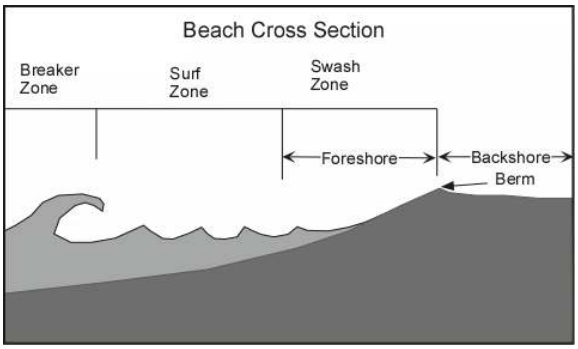
- *La playa (la zona más afectada por el rompimiento de las olas, de alta energía)*
- *El trasplaya (esta región sólo se ve afectado durante la marea alta cuando los niveles de agua son altas y durante las tormentas; baja energía*

At the foreshore, the high-energy waves scour the land and affect the sediments deposited. These sediments are subject to constant collision and abrasion that in turn produces fine-grained sands due to the high levels of energy available in the region.

En la playa, las ondas de alta energía recorren la tierra y afectan a los sedimentos depositados. Estos sedimentos están sujetos a la colisión constante y la abrasión que a su vez produce arenas de grano fino debido a los altos niveles de energía disponibles en la región.

On the backshore, the low energy environment doesn't have much room for shaping and reducing the grains sizes. Here, grains are less mature and vary in sizes. Fine-grained sediments can be seen but are mostly present due to transportation by wind; therefore, under the layer of wind-transported sediments, one can find coarser grains that have not faced much erosion.

Por trasplaya, el ambiente de baja energía no tiene mucho espacio para dar forma y reducir los tamaños de granos. Aquí, los granos son menos maduros y varían en tamaño. Sedimentos de grano fino se pueden ver, pero son en su mayoría presentes debido al transporte por el viento; por lo tanto, debajo de la capa de sedimentos transportados por el viento, uno puede encontrar granos más gruesos que no se han enfrentado mucho erosión.



Elements of beach topography/*Elementos de topografía playa*

How does wave energy shape the beach topography?/*¿Qué efecto tiene energía de las olas de la playa topografía?*

From the expeditions to various beaches, it was observed that different beaches contained different types of grains sizes.

A partir de las expediciones a diferentes playas, se observó que las diferentes playas contenían diferentes tipos de granos tamaños.

Salmon Creek Beach, CA:

At the Salmon Creek Beach, there was a noticeable difference in sand grains when it came to those that were near the swash zone and those at the backshore. Carried mostly by wind, we find that the backshore grains are fine to medium grain sized with some larger grains being found underneath.

Al Salmon Creek Beach, hubo una diferencia notable en los granos de arena cuando se trataba de los que estaban cerca de la zona de resaca y los que están en la trasplaya. Transportados en general por el viento, nos encontramos con que los granos trasplaya son de grano fino a medio tamaño con algunos granos más grandes se encuentran debajo.

On the other hand, the grains at the swash zone were well sorted and were, in general, very fine to fine-grained sands. The continuous motion of the waves sorted out the sediments leaving in the low tide zones pebbles and other larger rocks **(Picture to the right)**.

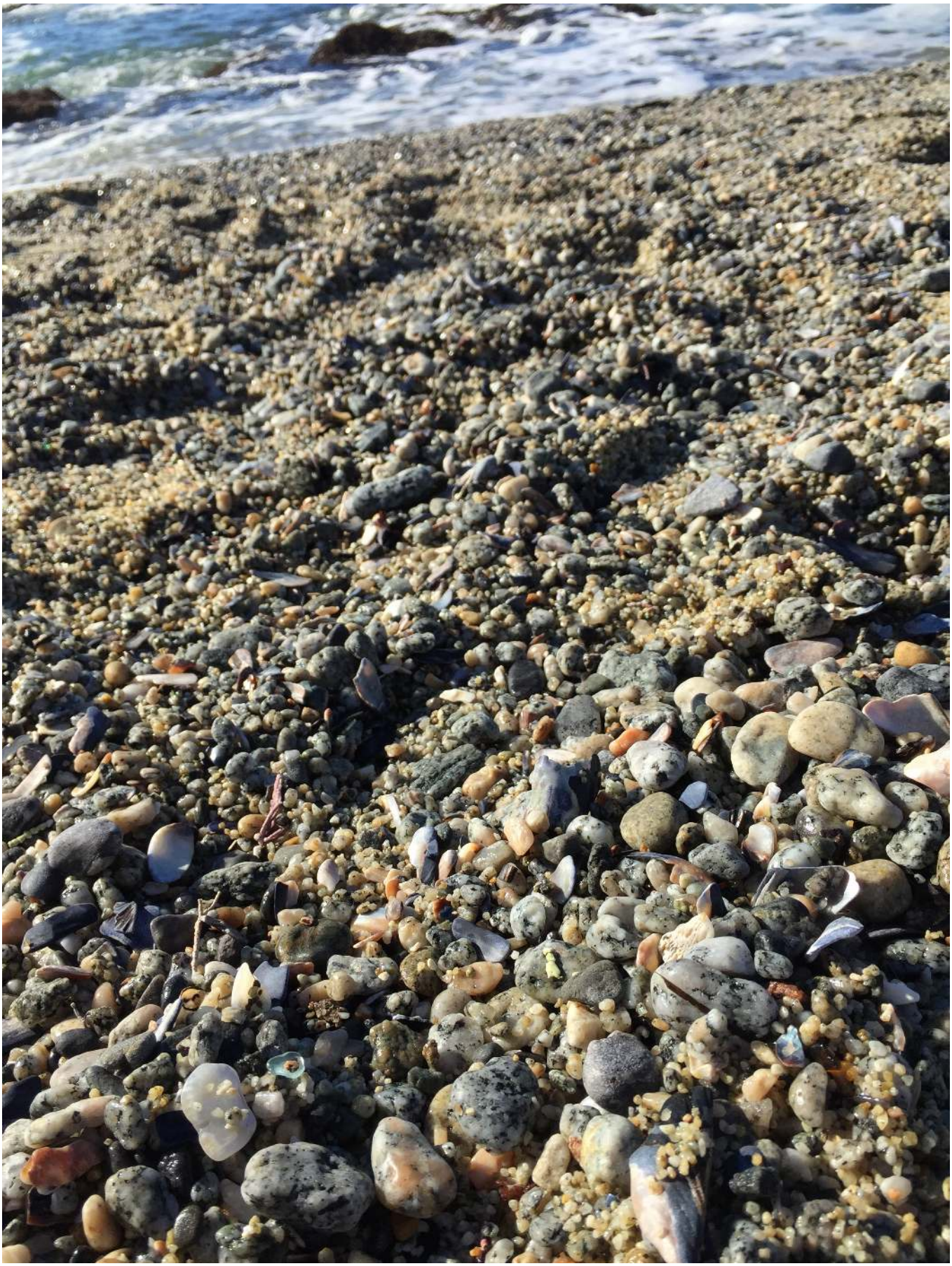
*Por otro lado, los granos en la zona de resaca estaban bien ordenados y eran, en general, muy bien para grano fino arenas. El movimiento continuo de las olas solucionaron los sedimentos que salen en las zonas bajas de la marea guijarros y otra roca más grande **(foto a la derecha)**.*

Bodega Head, CA:

Other beaches visited during the fieldtrip had similar grain sizes due to the wave energies present. At Bodega Head however, there were medium sized grained sediments ranging up to rocks along the backshore. Here, the sediments consisted of eroded clams and shells to decently sized granite diorite rocks that were washing up on shower. If one were to look at the sediments in the swash zone, they were finer in size and were well sorted **(Picture below)**.

*Otras playas visitadas durante el viaje de estudio tenían un tamaño similar de grano debido a las energías de ondas presentes. En Bodega Head sin embargo, hubo sedimentos de grano de tamaño medio que van hasta las rocas a lo largo del trasplaya. Aquí, los sedimentos consistieron en almejas y conchas a un buen tamaño rocas de granito de diorita que estaban lavando para arriba en la ducha **(imagen abajo)** erosionadas. Si uno fuera a mirar a los sedimentos en la zona de resaca, que eran más finas en tamaño y estaban bien ordenados.*





Contributors:

- Roberto Torres

Works Cited

Websites Visited:

http://www.scienceclarified.com/landforms/Basins-to-Dunes/Coast-and-Shore.html

http://www.mcz.harvard.edu/Departments/InvertPaleo/Trenton/Intro/GeologyPage/Sedimentary%20Geology/sedprocessesstructures.htm#waves

Additional Diagrams

http://www.tulane.edu/~sanelson/Natural_Disasters/coastalzones.htm

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3.2.4: Bayside Park



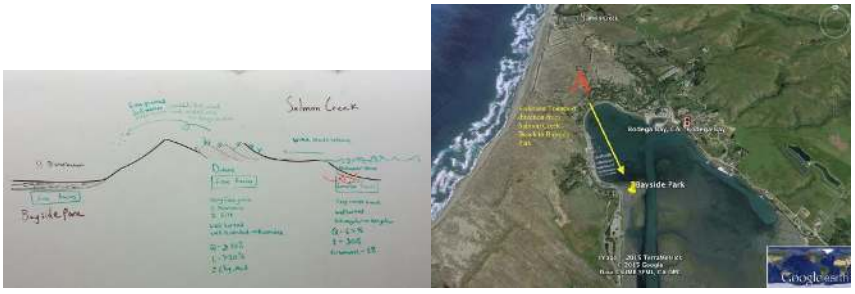
Background

"One of our stops is Bayside Park, an area within the inlet of Bodega Bay. The bay itself has a harbor and numerous residential and commercial areas, making it a popular destination for fishing, navigation, shellfish harvesting, and recreation. The spot can be observed as a wide, sandy-mud flat, rich with bioturbation."

The harbor is separated from the larger Bodega Bay with a jetty, allowing for calm tides. The area is known for its clams, oysters, and crabs, making the area's sediments rich with marine life[1]. On this stop, you will walk along the flats and observe a variety of ripple structures in a low energy setting. Observe how the motorboats might cause artificial currents to influence the general shape of the crests.

(Fun fact: Alfred Hitchcock's *The Birds* was filmed in Bodega Bay.)

1. "National Register Information System". *National Register of Historic Places*. National Park Service. 2010-07-09.



This is an aerial view(right) of Salmon Creek beach and Bayside Park. The yellow arrow represents 950 meters. It is important to note the relationship between the two areas. Sediments in bay side Park range from silt size to fine-grained sand sized grains. This indicates that one of the sources of the sediments must have been Salmon Creek Beach, in which sediments of similar size and composition were transferred by aeolian processes to Bayside Park.

Schematic picture (left) of relationship between Salmon Creek beach and Bayside park.

Different energy levels and erosional forces contribute to the different facies found at bodega bay. In Salmon Creek, we see that the coarsest grains are found in the breaker zone where there is a moderate amount of energy. the constant breaking of the waves provide enough energy to erode and further weather coarse grains. the sedimentary structure that appears when the grains are deposited are called ‘trough cross bedding.’ The facies we expect to see are very coarse grains that is well sorted subangular to angular and consist of mostly quartz.

As the wind moves inland, the low energy provided by gusts of air erode finer sediments. The fine sediments travel inland until the wind is broken up by local grass. This causes sand dunes to form (dune ripples). the facies we expect to see are well sorted, well rounded, very fine grained sands plus or minus bioclastic sediments and silt, consisting of mostly quartz and lithics plus or minus clay and mud.

As wind travels further inland, those grains that are eroded from the sand dunes or did not become deposited are then moved to bayside park. Bayside Park is a low energy lagoon and receives the bulk of its sediments from wind erosion although the occasional runoff and high tide may create altering layers of sand and muddy sand. the facies we expect to see here is the fine facies last observed in the dune area of Bodega Bay.



This is an image of current ripples found at Bay Side Park. The flow direction is indicated. Do you see any reactivation surfaces?

Module 2: Current ripples

Current ripples are the separation of sand within the viscous sublayer. The sand grains saltate to the crest, accumulating grains on the stoss side of the ripple. At the separation point, the grains flow down to the lee side of the ripple. As the grains deposit between the separation point and the attachment point, it creates a planar cross lamination (Bass 1994). This can be seen at Bayside Park. It shows the flow direction of wind and accumulation of grains.



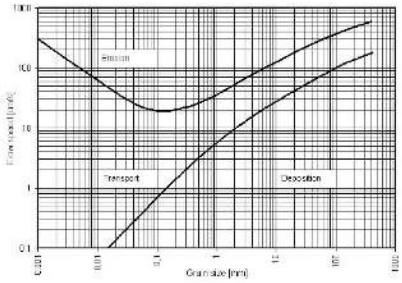
Baas, J.H. (1994) A flume study on the development and equilibrium morphology of small-scale bedforms in very fine sand. Sedimentology, 41, 185–209.

The flow is parallel to a flat bed, which there is a boundary layer separation between the separation point and attachment point. At the bottom of the boundary layer, there is a viscous sublayer. It has a laminar flow, which the grains barely move with the flow of wind or water. Above the laminar layer has a turbulent flow that allows the particles to become suspended. Some particles do not stay suspended due to the change in pressure around the grain (Bass 1999).

Baas, J.H. (1999) An empirical model for the development and equilibrium morphology of current ripples in fine sand. Sedimentology, 46, 123–138.

Fluid flow and Sediment transport

Below is a Hjulström diagram which demonstrates the interaction between grain sizes and flow speed and how this relates to deposition erosion and transport of sediments. These processes are predicted with help from the Reynolds number Re = (I*u*rho)/mu, where I is the flow depth, u is the flow velocity, rho is the density of the flowing material (100kg/m^3 for water), and mu is the viscosity of the material flowing. The Reynolds number is a balance of inertial forces over the viscous forces and is unitless. Laminar flow, Re<50, and turbulent flow, Re>2000, are the two main states . One phenomena that takes place is that, as you get closer to the floor of a flow, the interactions between that floor of the flow and the fluid is friction, which slows the fluid down until the velocity=0. As you move up in the fluid column, speed increases and the frictional forces decrease. The differences in flow causes a pressure difference that can transport, erode, or deposit grains, which is what the diagram below is describing.



For further explanation please check out the Aeolian Processes page.

Sample



BP – 1

Bayside Park

Wind transport sediments from Salmon Creek Beach

- Collected: Backshore of the bay

- Grain size: silt/clay – very fine sand

- Sorting: Well sorted

- Interpreted energy: Very low

- Composition: 60% - Quartz, 40% - Lithics

-Facies- Fine grain

Module 1: Urechis caupo (Echiura) worms found in Bayside Park.

Echiura worms are native to the mud flat areas of Bodega Bay found specifically at Bayside Park. These worms create U-shaped burrows that are used for respiration and food collection. A mucus net attached to one end of the burrow filters plankton and seston out of the water. I have attached a video showing the process by which a worm uses a burrow to collect nutrients from the water (Suer, 1984).



Suer, A. L. (1984). Growth and spawning of urechis caupo (echiura) in bodega harbor, california. *Marine Biology.Berlin, Heidelberg*, *78*(3), 275-284. Retrieved from http://search.proquest.com/docview/1...ccountid=14505



This is an image of an abandoned burrow. This one in particular stood about a centimeter and a half above the ground.



This image shows a mucus net used by the worms to filter plankton and seston. It is about 5 cm in length.

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SECTION OVERVIEW

3.3: Cache Creek

3.3.1: Cache Creek

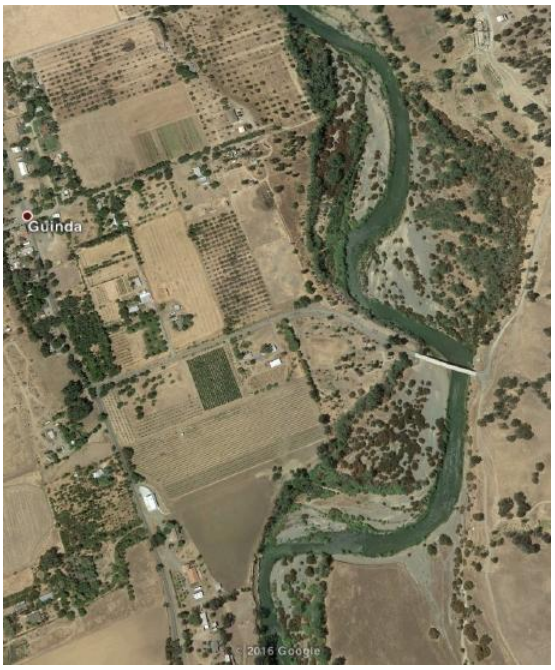
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Welcome to Cache Creek located in Guinda, California!





The photo below show the location of Cache Creek in relation to Guinda, California from Google Earth.



During this field trip, we observed modern sedimentary structures and environments along Cache Creek, and interpreted how they affected depositional and erosional processes. We used these observations to reconstruct channel flow variations from the past and how they are preserved in sedimentary structures. This was achieved by collecting sediment samples at five separate stations, representing the diversity of facies within the environment, how flow can vary, and how sediment size is affected by flow and vegetation.

Stops Along the Way:

o Stop 1 – On the bridge over Cache Creek east of the town of Guinda

The groves of trees and the roads that have not eroded away stayed relatively the same since the aerial photo was taken in 1993 (photo on the left below), but the bridge has been replaced in 2010. The channel geometry has changed a lot however. In the photo below on the right, south of the bridge, the river has migrated from the west side of the channel to the right side. North of the bridge, the modern channel immediately bends to the west and runs parallel to the bridge until it bends to the north in roughly eighty meters where a gravel bar formed creating two separate paths the flow can travel down the channel.



o Stop 2 – River deposits south of the bridge

Along Cache Creek south of the bridge, the first segment of the creek runs to the west and shows deposition from high flows from this past winter. We know the sediments are from this recent winter because foot traffic hasn't disturbed bedforms and other features as seen in the photo on the left below. We observed imbricate bedding fabric along the creek indicating that the flow was fast enough to flip over large cobble sized rocks so they run parallel to flow direction. Deposited gravel bars, grain size variations, cross stratification (photo on the right below, pencil for scale), and the patterns of deposition in relationship to bushes, bedforms, and bars was also observed.



o Stop 3 – Sample Collecting east of stop 2

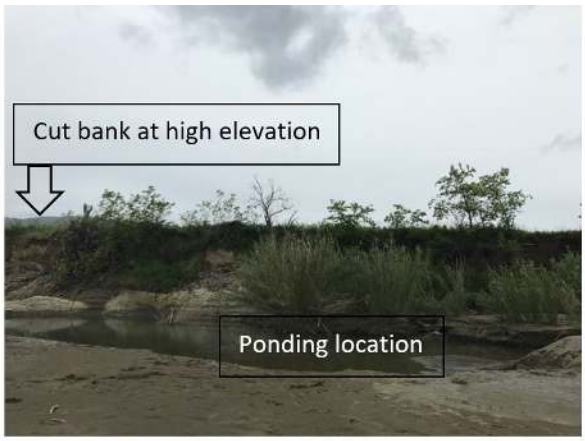
Further down the stream, we observed depositional environments of varying size and sorting of sediment is dependent on flow depth and velocity. We made observations at this location by analyzing five different stations and collected sediment samples. The stations were differentiated by grain size, where the largest grain sizes were at higher elevation while the smallest grains were found where ponding water was accumulating. Looking down stream, large cut banks on the right of the stream are observed were heavy erosion occurred when floodwaters cut into the bank is it accelerated around the sharp bend. Directly across the cut bank, a large gravel point bar formed from deposition is present.

Sedimentary Facies

There were three observed facies in the field area, distinguished by their varying grain size and sedimentary structures associated with each. Facies are distinguished by their grain sizes and represent a change in flow velocity.

Facies 1: Mud sized sediment

Station 1: Ponding water at lowest elevation with well sorted, saturated mud sized grains. There is minor rippling and deposition of planar bedding.





Station 4: Saturated terrace consisting of fine to medium grained sand, indicating a planar laminar flow occurred.



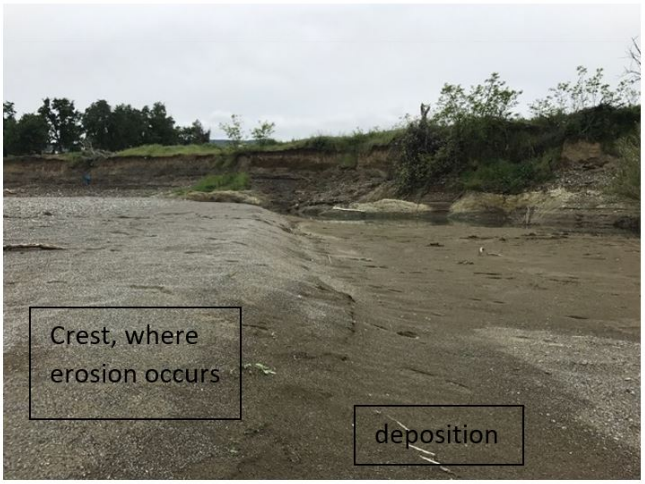


Facies 2: fine to coarse sand with lithic fragments

Station 2: above the ponding water, fine mud to medium grained sand with lithic fragments mixed in. Moderately well sorted, possess similar composition, and cohesive due to minor saturation. There was a visible decrease in grain size and increase in sorting as we transitioned from station 1 to station 2.



Station 3: Up slope from previous two stations and contains small dunes. Stepping and undulations is present along terrain, and the dunes are well sorted at crests and moderately sorted in between. The grains are very fine to cobble sized, with a decrease in grain size above the slope.





Below is the view seen while standing on top of the stepped terrain. There is a visible change in grain size as you walk up the slope.



Facies 3: coarse sand to cobble sized, with shell fragments

Station 5: Past creek channel, where imbrication of cobbles was observed. Poorly sorted medium to coarse grained sand, to granules, to cobble sized lithic fragments and contains shell fragments. As you go up slope, there is an increase in grain size,

indicating there was once a shallow channel with high velocity flows.



Interpretation

Water flow at higher elevations of creek deposited large gravel sized material. As water levels receded, smaller sediment was deposited forming steps in the terrain that ranged from cobble to fine sand sized as velocity decreased the carrying capacity of the flow. Sediments from upstream were eroded and deposited downstream eventually ending at the ponding location.

Facies one contains mud sized grains found at stations one and four, representing where the channel flow at the shallow ponding location has decreased to almost zero velocity, creating minor oscillations and rippling along the bedding surface. It is directly below the eroded cutbank, indicating that the flow depth used to be much greater with fast flows from floodwaters.

Facies two contains fine to coarse sand with lithic fragments found at stations two and three, representing a moderately fast flow. The Reynolds number during this type of flow is high enough for saltating coarse sand sized sediment, but not fast enough to transport anything larger.

Facies three contains coarse sand to cobble sized sediment with incorporated shell fragments collected from station five. This poorly sorted, angular sediment and broken shell fragments indicates when the flow was at its greatest depth and velocity. The flow velocity and Reynolds number was high enough that mud sized all the way to cobble sized sediment was carried as a suspended load, and was deposited along the center of the channel as flow velocity decreased.

These depositional environments and fluvial features directly relate to how the flow depth and velocity changes through time depending on the amount of discharge contained within the channel.

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CHAPTER OVERVIEW

4: Case Studies

UC Davis Geo 109
Earth History: Sediments and Strata
Spring 2017: Sumner

Lecture Notes • **Depositional Environments** • Virtual Field Trips

4.2: Oroville Dam 2017

4.2.1: Damages on Emergency Spillway

4.2.2: Erosion below the Auxiliary Spillway

4.2.3: Oroville Spillway Recovery, Plans and Design

4.2.4: The importance of bedrock characteristics

Contributors

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SECTION OVERVIEW

4.2: Oroville Dam 2017

Topic hierarchy

4.2.1: Damages on Emergency Spillway

4.2.2: Erosion below the Auxiliary Spillway

4.2.3: Oroville Spillway Recovery, Plans and Design

4.2.4: The importance of bedrock characteristics

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4.2.1: Damages on Emergency Spillway

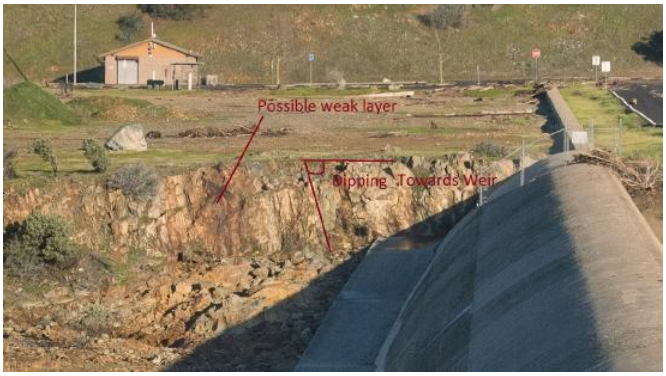
As the lake levels continued to rise and with the main spillway weakened, the only way to reduce the water levels was to utilize the emergency spillway. Lake Oroville can be seen towards the top of the photo, with the emergency spillway highlighted red.



February 11th

On February 11th, water from Lake Oroville began flowing over the emergency spillway as designed. Several hours later, near the top of the emergency spillway's concrete weir and along the ramp erosion was present. Below is an example of the erosional damages from the overflow. The second image displays how close the erosion was to the weir. Officials feared the erosion and down cutting into the weak layer of bedrock would continue upstream, further damaging the weir.





February 12th

On February 12th, officials were forced to reopen the main spillway to reduce strain on the weir, and with a flow less than 5% of the approved rate, the emergency spillway was determined to be unsafe and unpredictable. If the erosion occurring near the weir to fail, uncontrolled flow would cause the Feather River downstream to crest higher than levees were built to withstand, and towns from Oroville to Sacramento, along with Highway 70, would possibly flood.

February 15th

February 15th, with the expectation of more storms moving in, the Department of Water Resources, along with the help from construction crews, Caltrans, and other state agencies, worked quickly to reinforce the emergency spillway. More than 1200 tons of rock was being deposited in the damaged areas every hour as seen in the picture below, and there were over 125 construction crews on site. As this was happening, the Department of Water Resources was releasing water in an attempt to lower Lake Oroville below 840 feet.



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4.2.2: Erosion below the Auxiliary Spillway

Image captured from a video taken by drone on February 12, 2017 at 9:30 am: (Video from the CA Department of Water Resources)



The lake behind the dam is on the upper right, and the spillway extends from the right side of the image to the break in slope near the top. Beyond the break in slope, water is flowing over a parking lot and curb, which it was not designed to do. Note the road in the upper left of the image. Also note that there are no apparent gullies near the base of the spillway, but there is one starting to form near the break in slope.

This image was taken from a different angle at about 3 pm: (Video from CA DWR)



The lake behind the dam is at the top of the image, and the break in slope near the top. Beyond the break in slope is toward the left. The road is under water running across the bottom of the image. Note the prominent gully extending upward toward the spillway near the center of the image. This gully formed between 9:30 am and 3 pm!

Here's what it looked like by 3:30 pm:



The rapid erosion of the head of this gully triggered emergency management people to decide to evacuate the population. If erosion continued to the spillway and the spillway failed, a 10 m high wall of water might have rushed down the Feather River.

Here is an overhead view after they lowered the water in the dam to below the emergency spillway: (I labeled the "Danger Area".)



Here's an image of the area from February 16, 2017, showing the progress of engineering work:



The dark grey area is where the "Danger Area" gully was. Note that it is huge compared to the construction trucks nearby. It has been lined with boulders and concrete. You can see the cement truck and boulders beyond the dark grey area if you expand the image.

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4.2.3: Oroville Spillway Recovery, Plans and Design

While the integrity of Oroville Dam itself was never threatened, construction crews worked tirelessly making repairs once the emergency spillway flows stopped. “There have been multiple takeaways from the dam crisis,” says Bill Croyle, the Department of Water Resources Director, “the lessons learned is helping the damn safety industry get real with their infrastructure and ensure that inspections are carried out with the latest technology.” The main repair contractor, Kiewit Corp, won the $275.4 million dollar contract in April, beating two other competitors. The company has considerable experience with dam projects, including the upgrade of Folsom Dam in the Greater Sacramento Region and its auxiliary spillway.

I. Structural Objectives

Since the incident, the Department of Water Resources has two significant objectives they wish to meet within the next year, all posted on their Oroville Spillway Recovery page:

1. Ensuring public safety
2. Ensuring the integrity of the dam and its associated structures.

II. Future Repair Stages

By November 1st , the spillway can release flows of 100,000 ft^3 /sec if necessary during winter months. The Department of Water Resources plans on reinforcing the hillside with a cutoff wall into bedrock, keeping erosion that can occur in the future from cutting back into the emergency spillway weir. On March 6th , heavy equipment began removing debris from the diversion pool as employees from the Department of Water Resources and U.S. Army Corps of Engineers Geologists surveyed the spillway. Currently, the Department of Water Resources wished to return both the gated flood control and emergency spillways to their original design capacity, capable of passing maximum flood waters at Lake Oroville.

a. Gated Flood Control: Upper Chute

Replacement of the upper chute area shown in orange below is scheduled to be completed by November 1, 2017. Any chute slabs and walls not replaced will be anchored and finished during the next construction season. The the right, concrete is being poured onto the chute on June 7, 2017.





b. Gated Flood Control: Lower Chute

The damaged spillway structure downstream of the severely eroded area will be demolished and replaced, including reinforcement of adjacent slopes. On March 5th, specialized roller-compacted concrete was applied between the wall and the spillway weir, allowing construction to occur in heavily eroded areas. Below are progress photos along the Lower Chute taken on June 7th, 2017. The first round of concrete is being poured onto the Lower Chute.





d. Emergency Spillway

The Department of Water Resources expects the spillway to be capable of releasing flows of 100,000 ft3 /sec if necessary during winter months by November 1st , 2017. Other goals are:

- Reinforcing the hillside with a cutoff wall into bedrock, keeping erosion that can occur in the future from cutting back into the emergency spillway weir
- Place roller compacted concrete on the existing weir creating a buttress to adjust for future flood flows and possible seismic loading conditions
- Place roller compacted concrete downstream of the weir to direct flood floods and to create a slash pad to prevent erosion of the underlying bedrock

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4.2.4: The importance of bedrock characteristics

Erosion of bedrock depends on how competent it is, and zones of weakness can erode much faster than the bulk rock. Weathering and weaknesses in the bedrock below the main Oroville spillway shaped the pattern of erosion once the cement of the spillway failed. Erosion at the base of the auxiliary spillway accelerated once a zone of weakness eroded into a gully.

Here is a great article by UCD's Professor Emeritus Eldridge Moores discussing how weathering of the bedrock influenced erosion on the Oroville spillways: How 'Incompetent' Rock Led to the Oroville Dam Crisis

Here is professional publication about how variable bedrock erosion rates can be, depending on zones of weakness: Exceptional river gorge formation from unexceptional floods. This type of erosion occurred below the auxiliary spillway in the "danger area" marked in the image below.



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CHAPTER OVERVIEW

5: Homework and Lab Resources

5.1: Sedimentary Particles Lab Resources
5.2: Sedimentary Structures Lab and Homework Resources

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5.1: Sedimentary Particles Lab Resources

See this page until content is transferred here: http://mygeologypage.ucdavis.edu/sumner/gel109/labs/grains.html

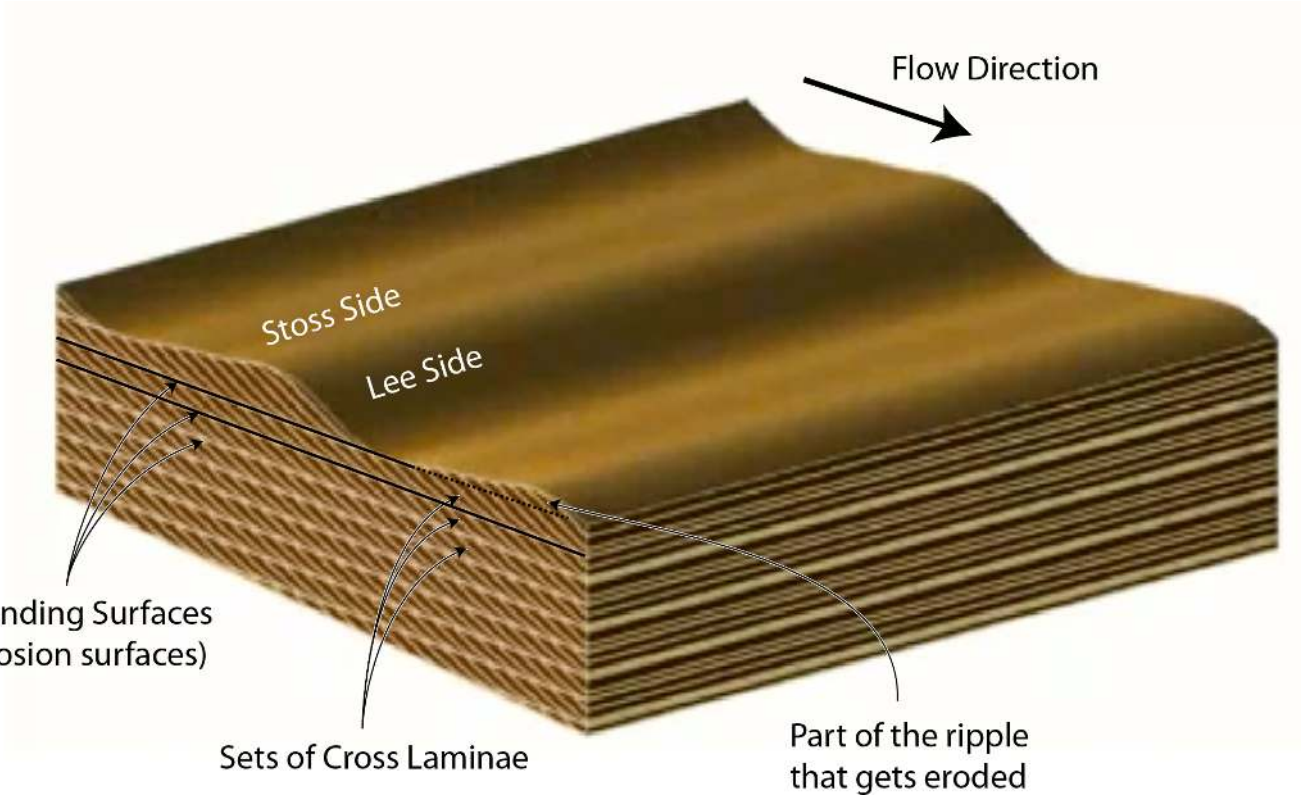
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5.2: Sedimentary Structures Lab and Homework Resources

USGS Bedform Movie Explanation

David M. Rubin, from the USGS Western Region Coastal and Marine Geology Program at Menlo Park, CA, published a book called Cross-Bedding, Bedforms, and Paleocurrents, which is available from SEPM and online at http://walrus.wr.usgs.gov/seds/bedforms/. He has posted some movies on the web site which demonstrate how various types of cross stratification are created. We will use these movies in lab to help interpret various styles of cross stratification.

First, here is an explanation of what you see in the movies:



The computer model that generated these movies starts with a bedform shape, which is constant throughout the movie. It is defined by the shaded surface. "Laminae" are deposited by moving the surface downstream and slightly up for each time step. Deposited laminae are represented by white lines. If the surface intersects the laminae, they are eroded, just like if laminae are exposed to an erosive current, they are eroded. Thus, the laminae change length and geometry as the "bedform" (surface) migrates.

All the movies associated with the publication are here. They are categorized by the shapes of the bedforms and photographs of real bedforms are also included. This is an EXCELLENT resource.

Flume Movie

Start with a movie of real current ripples in an experimental flume. This will give you a sense of how irregular ripples can be.



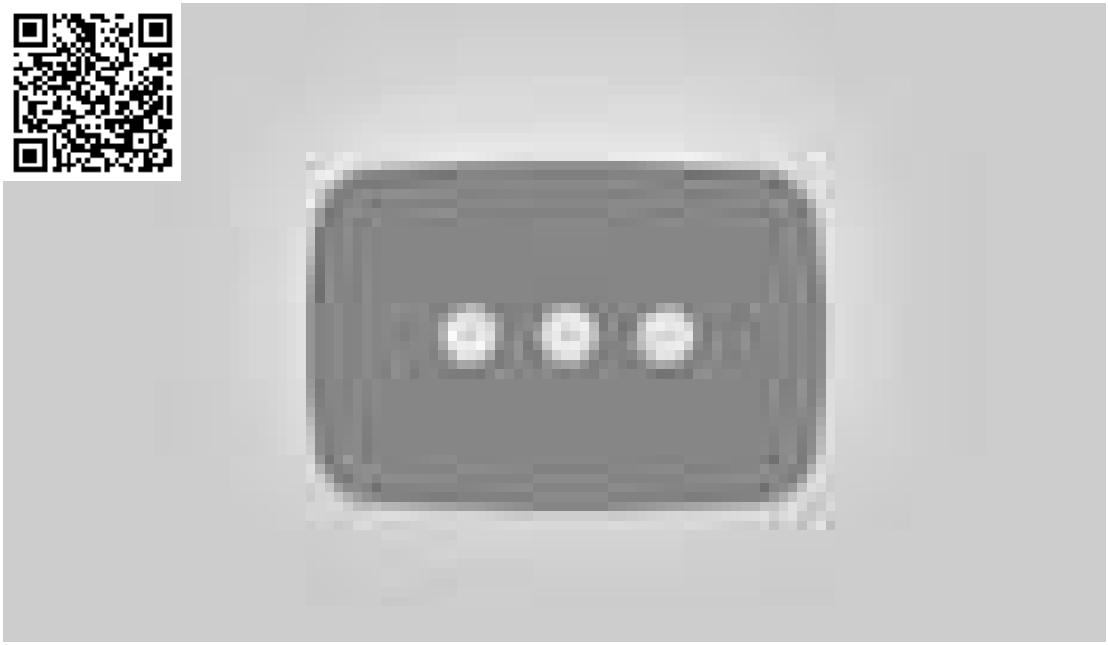
Linear Ripple or Dune

Here is a model-produced version of the migration of a linear ripple or dune:



Sinuous Ripple or Dune

Here is a model-produced version of the migration of a sinuous ripple or dune:



This movie ends with the top surface of the ripples/dunes getting eroded flat. The white lines represent the laminae that intersect the upper surface. Note how complexly shaped they are. Next the cross stratification is rotated to show how different surfaces show different cross stratification styles. Drag the marker at the bottom of the movie back and forth to explore these variations. Note how important it is to have a 3-D view of the cross stratification to interpret bedform geometry even when it is relatively simple!

Lots of other movies are available to explore as you wish. There are also LOTS of photos of different model-produced stratification styles and some outcrop photos associated with the online book.

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CHAPTER OVERVIEW

6: Photos of Sediments and Strata

This page has a growing set of photos of sedimentary structures, both modern and ancient. Many of the photos have explanations or questions associated with them. They are designed to supplement the text book, which I feel has too few photos. I recommend looking at these with the text in hand to compare the description of how stratification types form to actual structures. One of your first observations will probably be that the real world is much more complex than the text book descriptions!

The photos are arranged by sedimentary structure type and depositional environment. Each topic below connects to another page with thumbnail photos that are linked to larger photos. Many of the photos appear on more than one page because they show multiple features.

6.1: Sedimentary Environments

6.1.1: Aeolian Environments (Chapter 8)

6.1.2: Arid Environments (Chapter 8)

6.1.3: Carbonates

6.1.4: Fluvial Deposits (Chapter 9)

6.1.5: Fluvial Environments (Chapter 9)

6.1.6: Glacial Environments (Chapter 7)

6.1.7: Offshore Marine Environments (Chapters 14, 15)

6.1.8: Shoreline Environments (Chapter 13)

6.1.9: Slope Failure and Erosion (Chapter 6)

6.2: Sedimentary Structures

6.2.1: Beach Stratification

6.2.2: Current Ripple Cross Lamination

6.2.3: Diamictites

6.2.4: Mud Cracks

6.2.5: Soft Sediment Deformation

6.2.6: Sole Marks, Burrows, and Miscellaneous

6.2.7: Subaqueous Bedforms and Cross Stratification

6.2.8: Subaqueous Ripples and Cross Lamination

6.2.9: Turbidites

6.2.10: Wave Ripples in Sediment

6.2.11: Wave Ripple Cross Lamination

6.2.12: Wind Transported Bedforms and Cross Stratification

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SECTION OVERVIEW

6.1: Sedimentary Environments

Topic hierarchy

6.1.1: Aeolian Environments (Chapter 8)

6.1.2: Arid Environments (Chapter 8)

6.1.3: Carbonates

6.1.4: Fluvial Deposits (Chapter 9)

6.1.5: Fluvial Environments (Chapter 9)

6.1.6: Glacial Environments (Chapter 7)

6.1.7: Offshore Marine Environments (Chapters 14, 15)

6.1.8: Shoreline Environments (Chapter 13)

6.1.9: Slope Failure and Erosion (Chapter 6)

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6.1.1: Aeolian Environments (Chapter 8)

Saltating Dune Sand, Death Valley, CA



The saltating fine sand extends about 20 cm above the dune surface. Which direction is the wind blowing (based on ripple geometry)?

Figure 6.1.1.1***:*** *Saltating Sand*

Modern Coarse-grained Wind Ripples, Brazil



Strong winds produced these coarse wind ripples on a Brazilian beach. Which characteristic (besides location) allowed me to identify them as wind ripples? Which way was the wind blowing?

Figure 6.1.1.2***:*** *Coarse-grained Wind Ripples (Brazil)*

Modern Coarse-grained Wind Ripples, Brazil



In this close view, you can more clearly see the difference in grain size between the troughs and the crests.

Figure 6.1.1.3***:*** *Coarse-grained Wind Ripples (Brazil)*

Modern Coarse-grained Wind Ripples, Brazil



These wind ripples formed near the others, but are less regular.

Figure 6.1.1.4***:*** *Coarse-grained Wind Ripples (Brazil)*

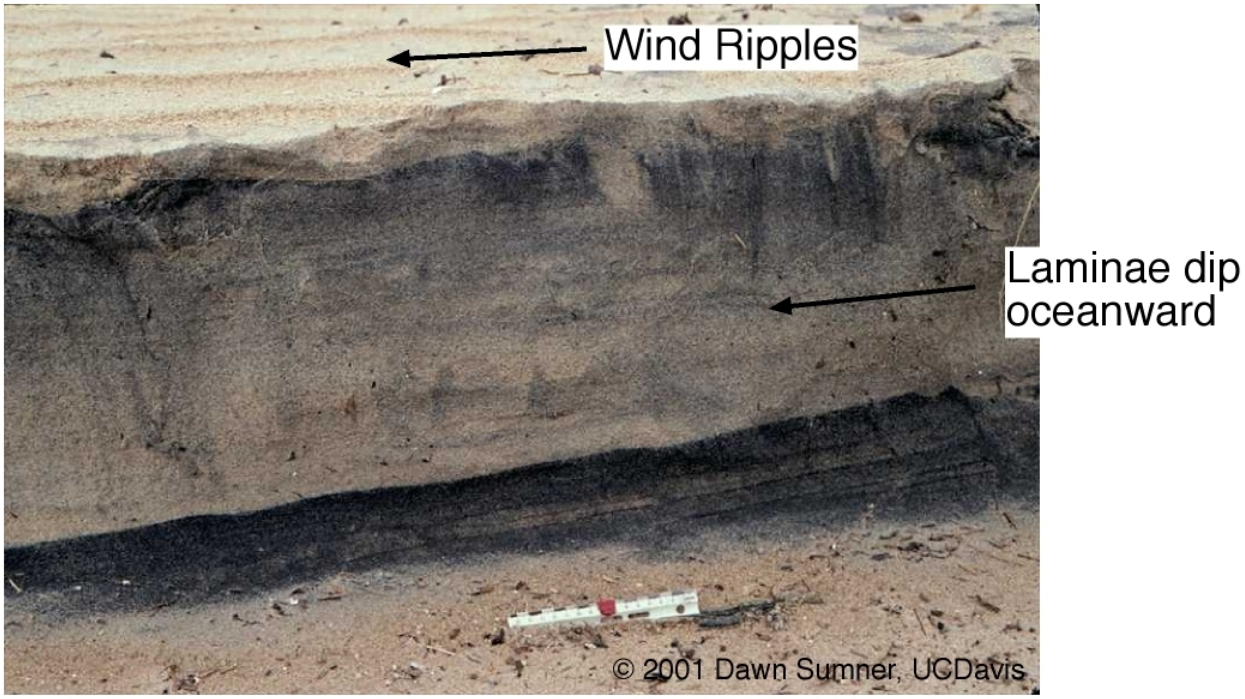


Figure 6.1.1.5***:*** *Coarse-grained Wind Ripples (Brazil)*

Return to Sedimentary Environments

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6.1.2: Arid Environments (Chapter 8)

Alluvial Fans and Debris Cones

North of Mormon Point, Death Valley National Park, CA

This photo shows an alluvial fan on the east side of Death Valley. Note the mouth area of the fan (arrow) and its smooth slope. Sediments in the foreground consist of alluvial fan sediment that was uplifted on the footwall of a normal fault (with a component of right lateral slip as well). Many of the fans along this side of Death Valley contain fault scarps. However, the one pictured here does not, at least through the center of the fan. The lack of a scarp suggests that sedimentation on the fan has covered the scarp since the last offset.



Figure 6.1.2.1***:*** *Alluvial Fan*

Death Valley, CA

This photo shows the view looking west across Death Valley from just north of Mormon Point. The large alluvial fan coming down from the Panamint Mountains merges into the flat playa in the lower part of the photo. Channels have been eroded into the fan surface. Their geometry suggests that the fan has been tectonically uplifted relative to the playa, with the result that water that flows down the channels erodes previously deposited alluvial sediment.



Figure 6.1.2.2***:*** *Alluvial Fan*

North of Mormon Point, Death Valley, CA

These alluvial fan sediments were uplifted along a fault and partially eroded. Much of the sediment is very coarse, like the sediment on the current canyon floor. However, lenses of finer sediment are present, such as the layer that Sara is looking at. (Sara has the orange and black back pack.)



Figure 6.1.2.3***:*** *Alluvial Sediments*

Death Valley, CA

Alluvial fan sediments exposed just north of Mormon Point. These sediments have layers of both coarse and finer sand to gravel, most of which is graded or cross stratified. The layer indicated by white arrows in both photographs is a diamictite that was probably deposited by a debris flow.



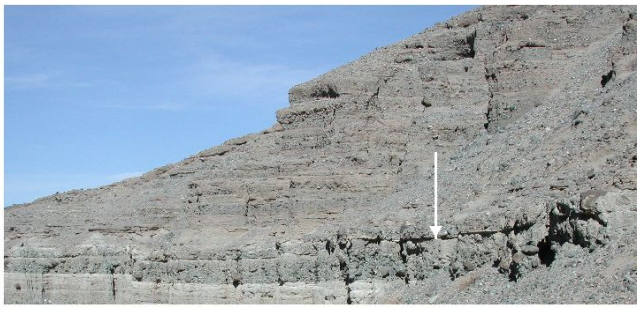


Figure 6.1.2.4***:*** *Alluvial Sediments*

North of Mormon Point, Death Valley, CA

These fining upward cycles were deposited on an alluvial fan. There are two possible causes for the grading of the sediments. An entire fining-upward cycle might have been deposited by a single flood, with the coarser sediment deposited during the flood peak, and finer sediment deposited as the flood waned. An alternative explaination is that a small channel deposited the sediment as it migrated. In this scenario, the coarsest sediments would have been deposited at the base of the channel, and finer sediment would have been deposited higher on a bar at the edge of the channel. What would you look for to tell the difference?



Figure 6.1.2.5***:*** *Alluvial Sediments*

South of Bad Water, Death Valley National Park, CA

Debris cones form where small, steep canyons end in a larger valley. The main sediment transport process is falling rocks with small amounts of water. Only a small channel is present at the mouth of the canyon, and mud is absent from the upper layers of the cones, suggesting that neither water nor viscous debris flows transported the cobbles to boulders. Gravity and momentum were the main processes. Variations in color on the cone reflect variable amounts of desert varnish. Darker, browner areas are older.



Figure 6.1.2.6***:*** *Debris Cone*

South of Bad Water, Death Valley National Park, CA

Debris cones form where small, steep canyons end in a larger valley. The main sediment transport process is falling rocks with small amounts of water. Only a small channel is present at the mouth of the canyon, and mud is absent from the upper layers of the cones, suggesting that neither water nor viscous debris flows transported the cobbles to boulders. Gravity and momentum were the main processes. Variations in color on the cone reflect variable amounts of desert varnish. Darker, browner areas are older.



Figure 6.1.2.7***:*** *Debris Cone*

Return to Sedimentary Environments

Race Track Playa, Death Valley National Park, CA

This playa predominantly contains clay to sand grain sizes, but some pebbles to boulders are present. The boulders have tracks behind them that demonstrate they were transported across the playa by sliding when the surface was wet. Although the mechanism of transport is controversial, it is likely that very strong winds pushed them across a very slick surface. Mud cracks are abundant, and the surface contains a large proportion of dried fillamentous microbes. These features (but not the large rocks) are characteristic of playas.



Figure 6.1.2.8***:*** *Race Track Playa*

Race Track Playa, Death Valley National Park, CA

In this close view of the surface of Race Track Playa, the large mud cracks are very clear. They are deep and evenly spaced. The upper surface of the mud, except in the travel path of the rock, is rough due to smaller mud cracks and rolled up mud. This layer contains abundant dried filamentous microbes (cyanobacteria?), which increase the cohesiveness of the mud. Note how the top layer appears to have been scraped off in the travel path of the rock. The rock probably was blown across the surface when this layer was very wet.



Figure 6.1.2.9***:*** *Race Track Playa*

Devil's Golf Course, Death Valley National Park, CA

Playas can show a large variety of sedimentary features. In the playa in Death Valley, the features vary with ground water inflow, surface water flow, and fine-grained sediment influx. Here, much of the water that is evaporating to form the irregular salt mounds flows in the subsurface. Capilary action draws the water upward, and when it evaporates, salts precipitate. The mounds form as the volume of salt increases. Dark areas contain wind-blown sediment, and rain disolves the tops of mounds making them very rough.



Figure 6.1.2.10***:*** *Salt Deposits at Devil's Golf Course*

Return to Sedimentary Environments

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6.1.3: Carbonates

Organisms produce a large volume of carbonate sediments, so it is important to know what is living in different carbonate environments. James Bishop has assembled these links to the organisms he observed in areas where he collected the Bahamian sediments you look at in this lab. Use these photos to help you interpret the sediments.

Organisms found in modern carbonate environments (e.g., the Bahamas)

- Mollusk (snail) (right photo)
- Mollusk (clam) **Scroll to the bottom of the page. The last four photos of shells are examples of this type of organism.
- This is a living (or recently living) coral with dark spots disease. This coral is colonial, with a coral animal living inside each little cup-like polyp on the surface. Coral sediment often appears porous due to these little calcareous cups or polyps.
- This site has some lovely photos of corals (the 3rd, 4th, and 5th photos).
- Diadema are black sea urchins which have calcareous spines that can be reworked into sand. Diadema themselves also excavate into hard surfaces, breaking down reefs and hardgrounds into sand.
- Homotrema rubrum is an encrusting foraminifera. It can be reworked into carbonate sand grains which are often colored pink. Scroll down to Figure 3. There is also other useful information on this page about reef-forming organisms.
- Branching coralline (or calcareous) red algae
- Halimeda is a calcareous green algae which is rooted into the sediment and disaggregates into carbonate sand
- The following 4 photos links are for calcareous green algae which are rooted into the sediment and disaggregate into carbonate mud.
  - 1. Penecillus looks a bit like a paintbrush.
  - 2. Rhipocephalus looks a bit like a pine cone.
  - 3. Udotea
  - 4. Acetabularia attaches itself to firm substrates, such as hardgrounds and reefs.
- Seagrass meadows (here comprised of Thalassia) can baffle wave energy, allowing for the deposition of muds and creating environments favored by foraminifera, snails, and clams.
- This sea fan is a soft coral or Gorgonid, which has neither a calcareous skeleton, nor photosymbionts. Gorgonids like to attach to firm substrates with high energy, such as reefs.

Return to Sedimentary Environments

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6.1.4: Fluvial Deposits (Chapter 9)

Fluvial Deposits at Vasquez Rocks County Park

Vasquez Formation, Transverse Ranges, CA

Note the sharp contact between the underlying shale and the overlying coarse, graded bed. Faint cross stratification is present in the coarser bed and overlying sand. This style of deposition is consistent with fluvial deposition, which is the broader interpretation of the Vasquez Formation.



Figure 6.1.4.1***:*** *Graded bedding with faint cross stratification deposited in a fluvial channel*

Vasquez Formation, Transverse Ranges, CA
(Look for these sediments in many western movies!)
A thick debris flow is interbedded with coarse fluvial sediments.



Figure 6.1.4.2***:*** *Debris Flow in a Fluvial Environment*

Vasquez Formation, Transverse Ranges, CA
Very large variations in grain size are present in these fluvial sediments. Here, a lens of granitic boulders was deposited on better sorted medium sand. Such changes suggest dramatic variations in flow speed. The large boulders (and the debris flow interbeds) suggest the presence of substantial topography nearby.



Figure 6.1.4.3***:*** *Gravel deposited in a channel*

Vasquez Formation, Transverse Ranges, CA

These mud cracks were deposited within an overall fluvial environment. A bedding surface view is present at the bottom of the photo, and they project through a shale layer at the black arrow. Sand from the overlying bed fills the cracks.



Figure 6.1.4.4***:*** *Mud cracks that formed in an overbank deposit*

Return to Sedimentary Environments

Fluvial Deposits Near Oberlin, OH

Quarry Near Oberlin, OH

This quarry wall contains fluvial sandstones. The vegitated bounding surfaces (black arrows) were the bases of channels that were filled by migration of river bars. The green arrow points to some bar stratification.



Figure 6.1.4.5***:*** *Quarry wall showing fluvial cross stratification, probably due to channel migration and bar accretion.*

Quarry Near Oberlin, OH

This quarry wall contains fluvial sandstones. The vegitated bounding surfaces (black arrows) were the bases of channels that were filled by migration of river bars. The green arrow points to some bar stratification.



Figure 6.1.4.6***:*** *Extension of the same quarry wall as above*

Park near Oberlin, OH

This large-scale cross stratification was deposited by migration of a river bar. It had ripples migrating across its surface as demonstrated by the small-scall cross lamination, visable here as undulating laminae (arrows).



Figure 6.1.4.7***:*** *Large Cross Stratification*

Park near Oberlin, OH

This large-scale cross stratification was deposited either by migration of a large subaqueous dune or migration of a river bar. If it was deposited on a bar, no smaller dunes were present as demonstrated by the lack of smaller-scale cross stratification. Arrow points to a bounding surface.



Figure 6.1.4.8***:*** *Large Cross Stratification*

Quarry near Oberlin, OH
These fluvial sandstones were deposited by a migrating river bar. Note that the layers in the bar (black arrow) continue to the channel floor (red arrow). Dune cross stratification is also present at the base of the photo (green arrow). (One of two photos of this bar.)

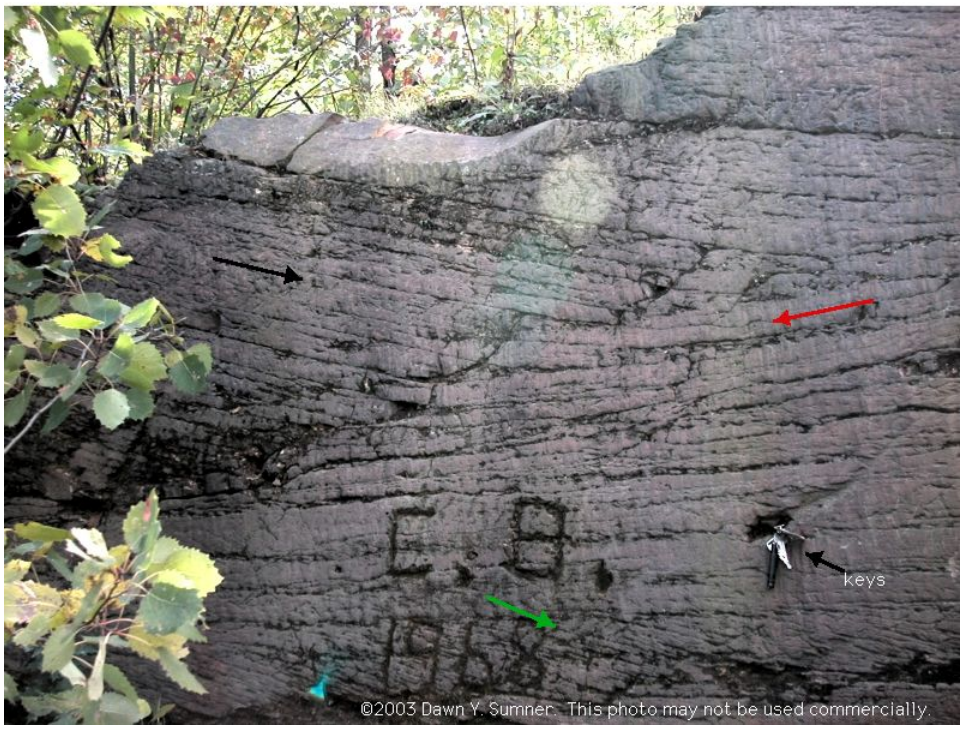


Figure 6.1.4.9***:*** *Cross stratified sediment deposited by a migrating bar based on the abundance of more planar laminae that would be characteristic of a channel bottom.*

Quarry near Oberlin, OH
These fluvial sandstones were deposited by a migrating river bar. Note that the layers in the bar (black arrow) continue to the channel floor (red arrow). (One of two photos of this bar.)



Figure 6.1.4.10***:*** *Different view of the bedform in the previous photo*

Quarry Near Oberlin, OH

These sandstones were deposited by a river. This photo shows a climbing dune that migrated to the right. It was part of a river bar that infilled a river channel. Black arrow points to the dune; green arrow to base of channel.



Figure 6.1.4.11***:*** *Climbing dunes*

Return to Sedimentary Environments

Ancient Fluvial Deposits near Lake Louise, Southern Canadian Rockies

Fluvial cross stratification due to bar migration and channel fill, southern Canadian Rockies. Marmot is about 30 cm tall at the shoulder.



Figure 6.1.4.12***:*** *Stratification from a migrating bar and subsequent channel fill*

Fluvial cross stratification due to channel bar migration. The marmot is about 25 cm in diameter. Southern Canadian Rockies.



Figure 6.1.4.13***:*** *Stratification from a migrating bar*

The following photographs were taken by Jeff Mount during the Integrated Watershed Science class trip down the Kaskawulsh River, Yukon (funded by his Roy Schelman chair). This river was dammed by ice from the toe of a glacier, which created a very large lake. The ice dam broke catastrophically, producing a huge flood. The flood waters transported very large volumes of sediment in huge dunes. After normal river processes resumed, the river eroded into the flood deposits, exposing the cross stratification in these impressive dunes.

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
The Kaskawulsh River was temporarily dammed during rapid advance of a glacier. The glacial ice created the dam and a large lake formed. This photograph shows beach terraces from the ancient lake (black arrows).



Figure 6.1.4.14***:*** *Lake shoreline terraces from the lake*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
The Kaskawulsh River was dammed by ice from a glacier, which created a large lake. Beach ridges are visible in the middle of this photo (green arrows). When the ice dam broke, sediment was transported downstream very rapidly in large dunes. The cross stratification (black arrows) in the river bank may have been deposited by migration of these dunes. The high on the bank may be a remnant of a dune crest (red arrow).

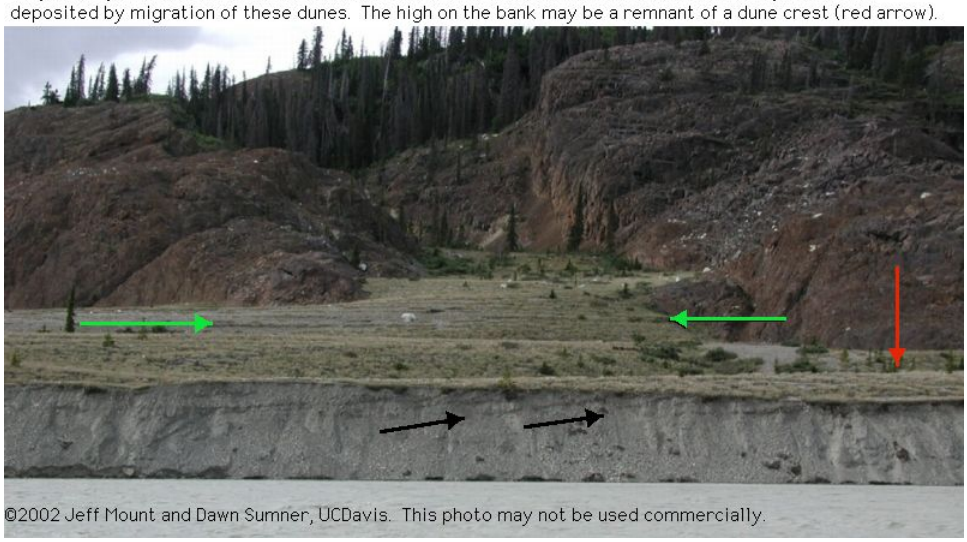


Figure 6.1.4.15***:*** *Lake shoreline terraces from the lake and cross stratification in the river bank. This cross stratification may have been deposited by the flood waters.*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
When an ice dam on the river broke, the lake water flowed extremely rapidly downstream, eroding and then depositing large volumes of sediment. The remnants of very large dunes are preserved both as large cross stratification and as bedforms, which are visible on this island in the river. Green arrows point to troughs.

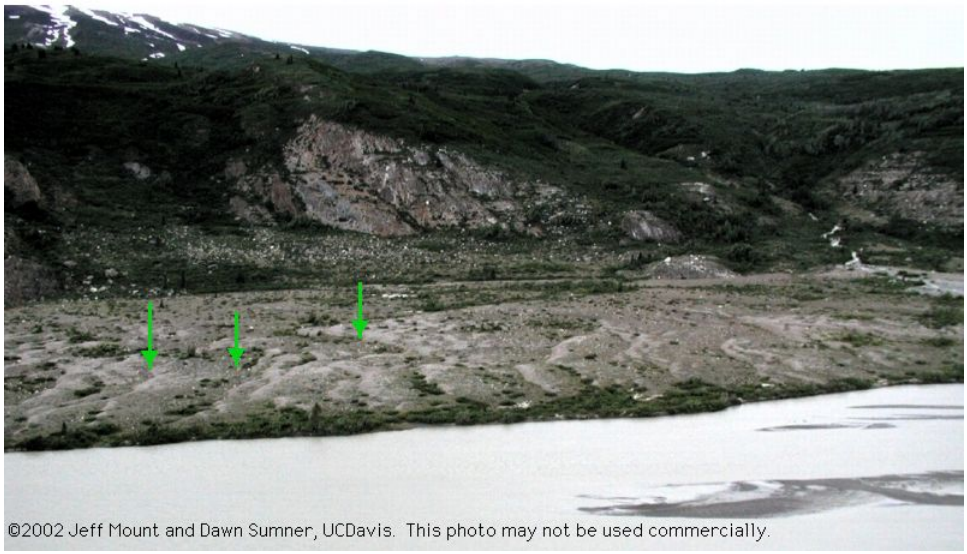


Figure 6.1.4.16***:*** *Remnants of giant dunes that migrated during the flood*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
During a flood due to the breaking of an ice dam, very large dunes deposited the sediments in this river bank. Cross strata extend almost the full height of the bank (black arrow). The remnants of large bedforms are present (green arrows indicate troughs), but they are much shorter than the maximum height of the dunes.



Figure 6.1.4.17***:*** *Large dune cross stratification and remnants of giant dunes*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)

When an ice dam on the river broke, large dunes deposited the sediment in the river terrace. The remnants of the bedforms can be seen at the top of the bank (green arrows indicate troughs).

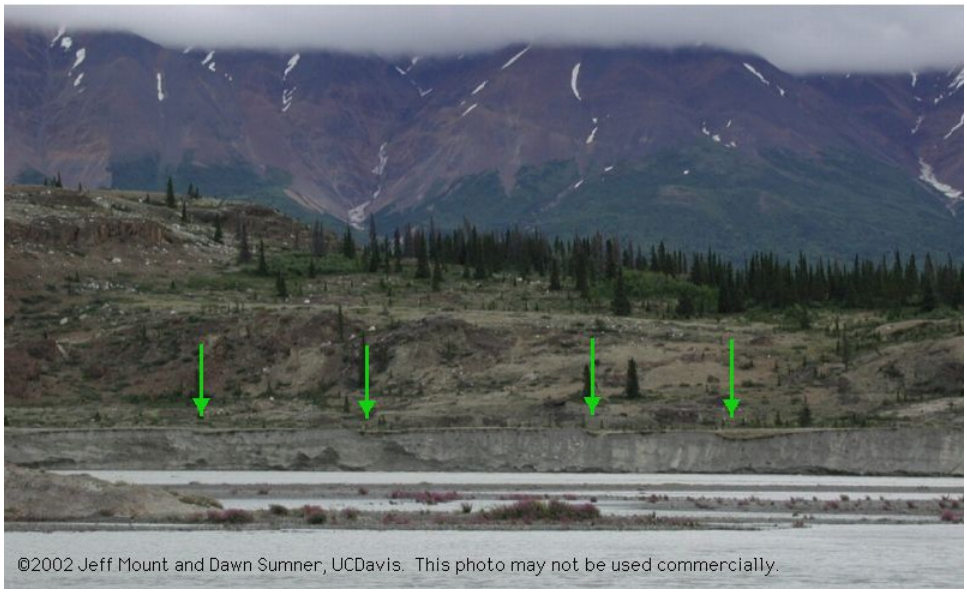


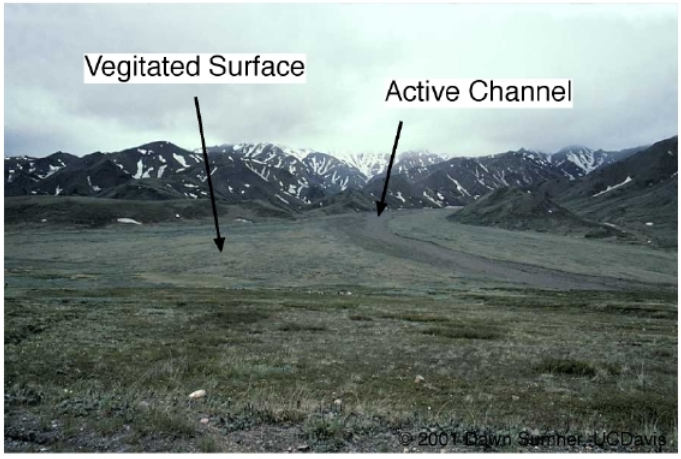
Figure 6.1.4.18***:*** *Large dune cross stratification and remnants of giant dunes*

Return to Sedimentary Environments

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6.1.5: Fluvial Environments (Chapter 9)

Modern Fluvial Fan, Denali National Park, AK



Sediment on the fan is derived from a glacier out of sight in the valley. Sedimentary structures will be similar to those formed in an arid alluvial fan (i.e. trough cross stratification, bar migration stratification, fining upward fluvial cycles, etc.)

Figure 6.1.5.1***:*** *Fluvial Fan (Alaska)*

Braided River, Denali National Park, Alaska



The sediment deposited by this braided river is derived from glaciers up the valley and out of view. Direct glacial deposits commonly are associated with sediment eroded by glaciers but reworked by glacial melt water to produce fluvial deposits. This river is braided, i.e. it has multiple channls in a larger and broader channel.

Figure 6.1.5.2***:*** *Braided River (Alaska)*

Alsek River, Alaska (photo taken by Jeff Mount)

The Alsek River is a braided river in this area. Note the multiple channels separated by longitudinal bars within a broader channel. The banks are heavily vegitated, whereas floods limit the establishment of plants on within the active river bed.



Figure 6.1.5.3***: Braided River (Alaska)***

Pescadero Beach, CA

Dunes are migrating in Pescadero Creek (arrows). Flow is toward the upper right side of the photograph. The tide is going out, so the level of the creek, which gets flooded at high tide, is going down. A small terrace formed when flow was higher (green arrow).



Figure 6.1.5.4***:*** *Dunes migrating in a creek*

Pescadero Beach, CA

Subaqueous dunes form in Pescadero Creek. Flow is towards the top of the photo, which was taken from the highway bridge. The water is cloudy from suspended sediment. Footprints are faintly visible in the current ripples in the lower right of the photograph.



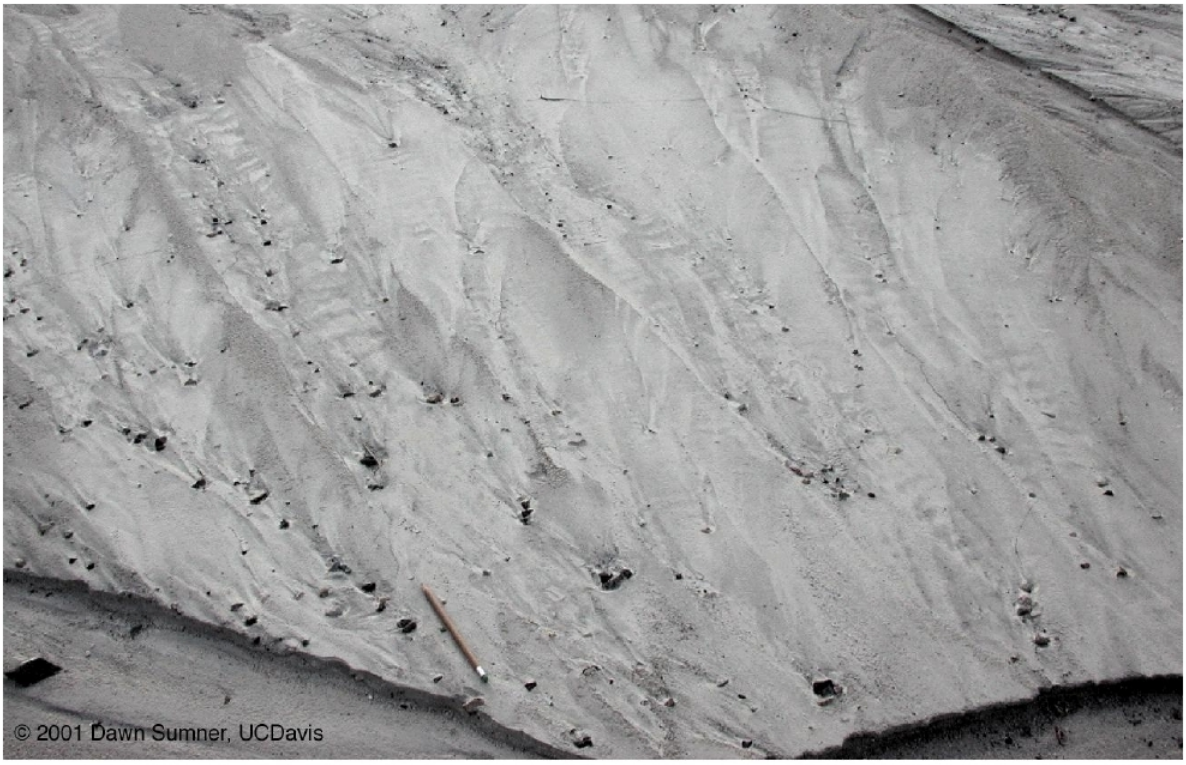
Figure 6.1.5.5***:*** *Dunes migrating in a creek*

Scott Creek Beach, CA

Antidunes are common in creeks flowing across beaches. Here, 7 can be identified by the waves on the surface of the water. They were migrating upstream. When the eroding sand bank collapsed, the antidunes were disrupted and took 10's of seconds to reform. Faint beach stratification can be seen in the bank.



Figure 6.1.5.6***:*** *Antidunes in a creek*



Modern Scours Around Pebbles, Redrock Canyon State Park

Figure 6.1.5.7***:*** *Pebble scours*

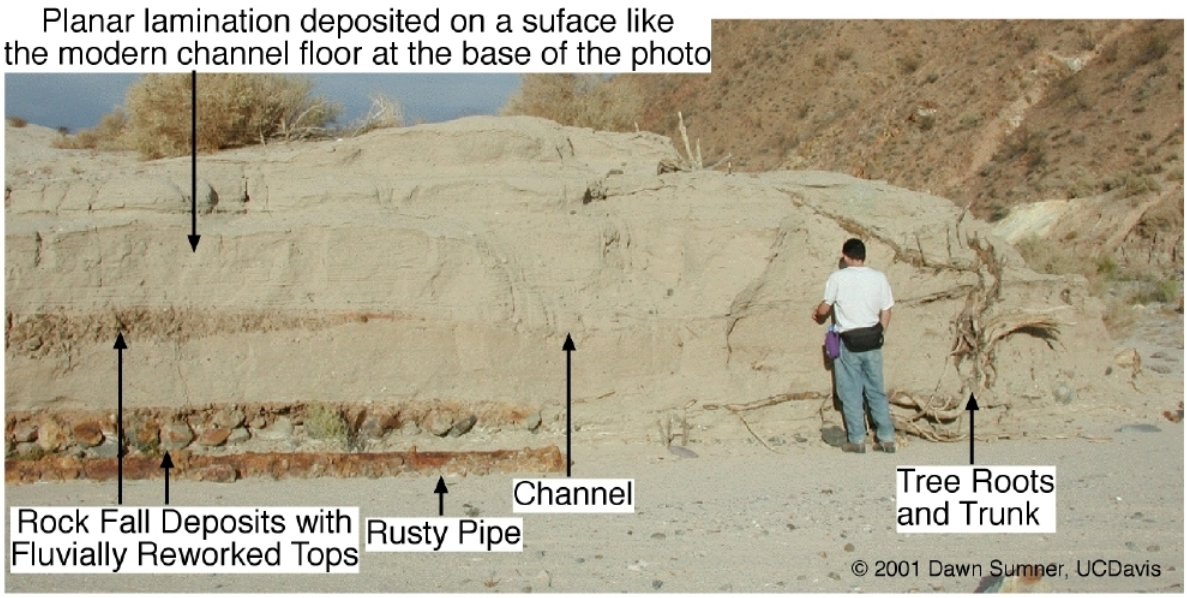


Figure 6.1.5.8***:*** *Recent Alluvial Deposits (Terrace at Redrock State Park, CA)*

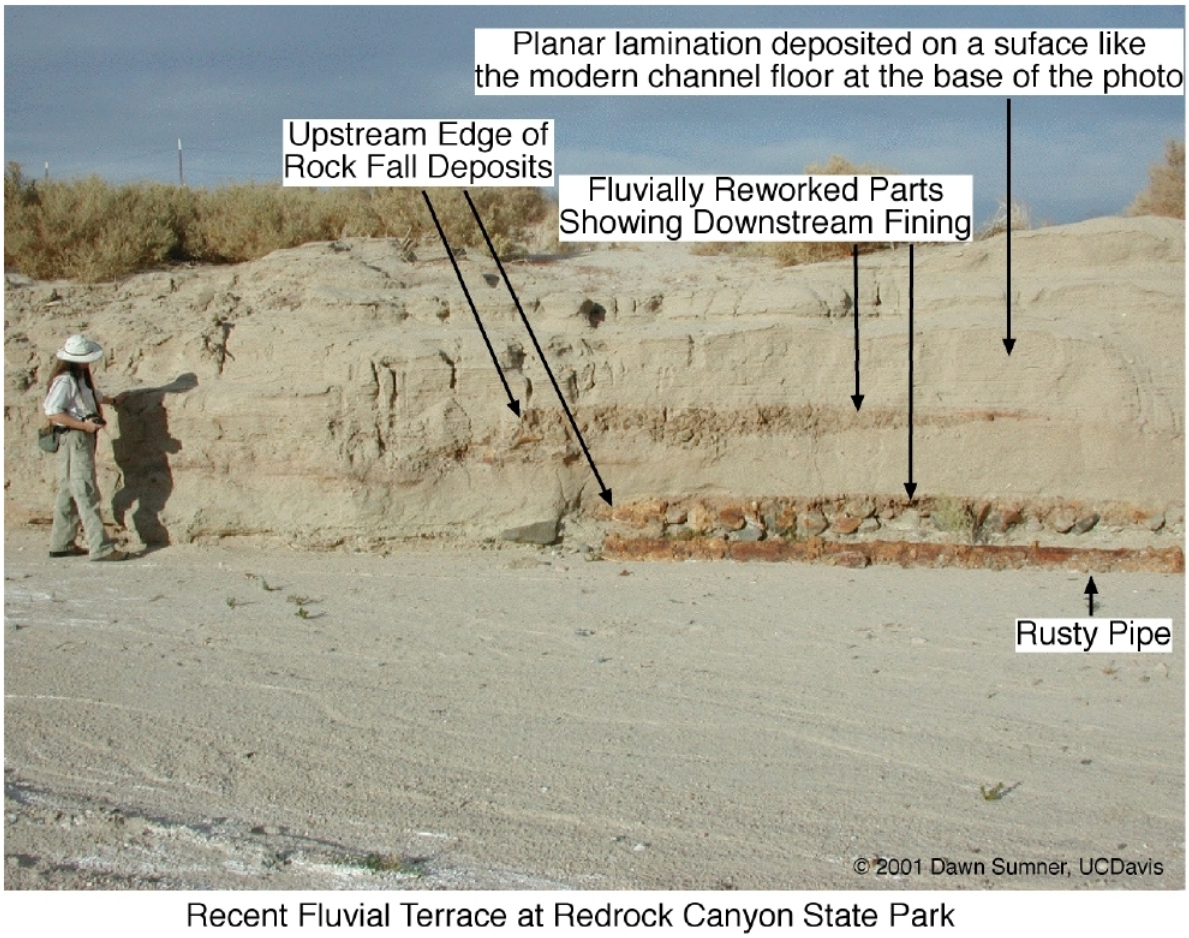


Figure 6.1.5.9***:*** *Recent Alluvial Deposits (Terrace at Redrock State Park, CA)*

North of Mormon Point, Death Valley, CA

These alluvial fan sediments were uplifted along a fault and partially eroded. Much of the sediment is very coarse, like the sediment on the current canyon floor. However, lenses of finer sediment are present, such as the layer that Sara is looking at. (Sara has the orange and black back pack.)



Figure 6.1.5.10***:*** *Recent Alluvial Deposits (Death Valley, CA)*

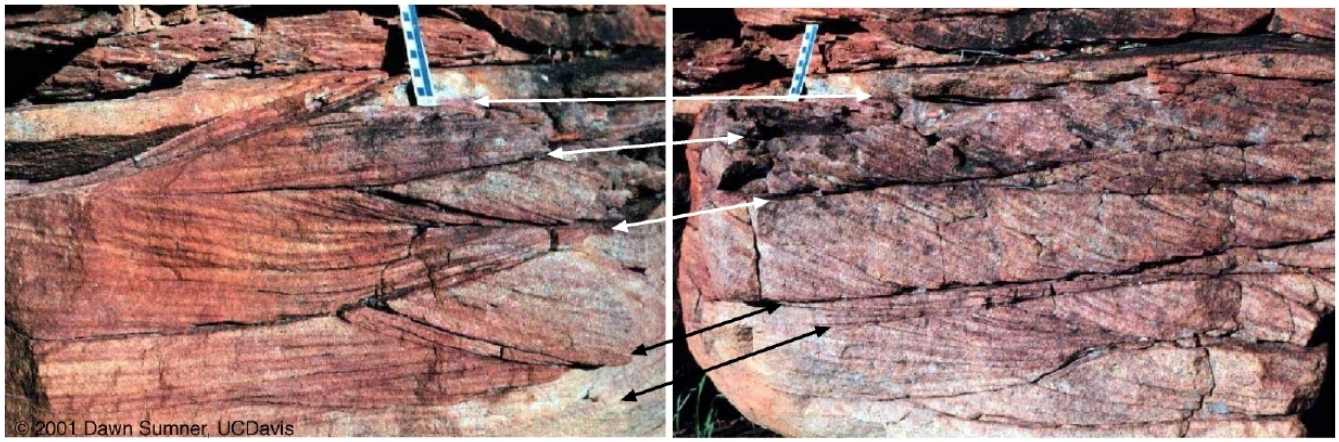
Zabriski Point, Death Valley National Park, CA

When the slope of a creek changes, sites of net deposition can become sites of net erosion and vice versa due to changes in flow speed. To the right, just out of the photo, Furnace Creek was diverted into a steeper canyon. This diversion resulted in higher flows in this region (when there is water). Higher flow speeds have resulted in erosion of the previously deposited alluvial gravels which now compose the terraces. This excess sediment is deposited at the mouth of the canyon where it opens into Death Valley.



Figure 6.1.5.11***:*** *Channel Erosion Due to Changing Base Level/Flow Speeds (Death Valley, CA)*

Ancient Trough Cross Stratification, Western Australia



These photos show two views of trough cross stratification. The scale bar is at the same place in both photos and shows centimeters. Which direction was water flowing? Try to match the pattern of cross stratification to one of the USGS bedform movies. What might the geometry of the bed forms have been?

Figure 6.1.5.12***:*** *Ancient Trough Cross Stratification (two faces of the same rock)*

Plan View of Fluvial Trough Cross Stratification, Western Australia



The paleoflow direction was from the bottom left of the photo to the top right.

Figure 6.1.5.13***:*** *Plan or Map View of Ancient Trough Cross Stratification*

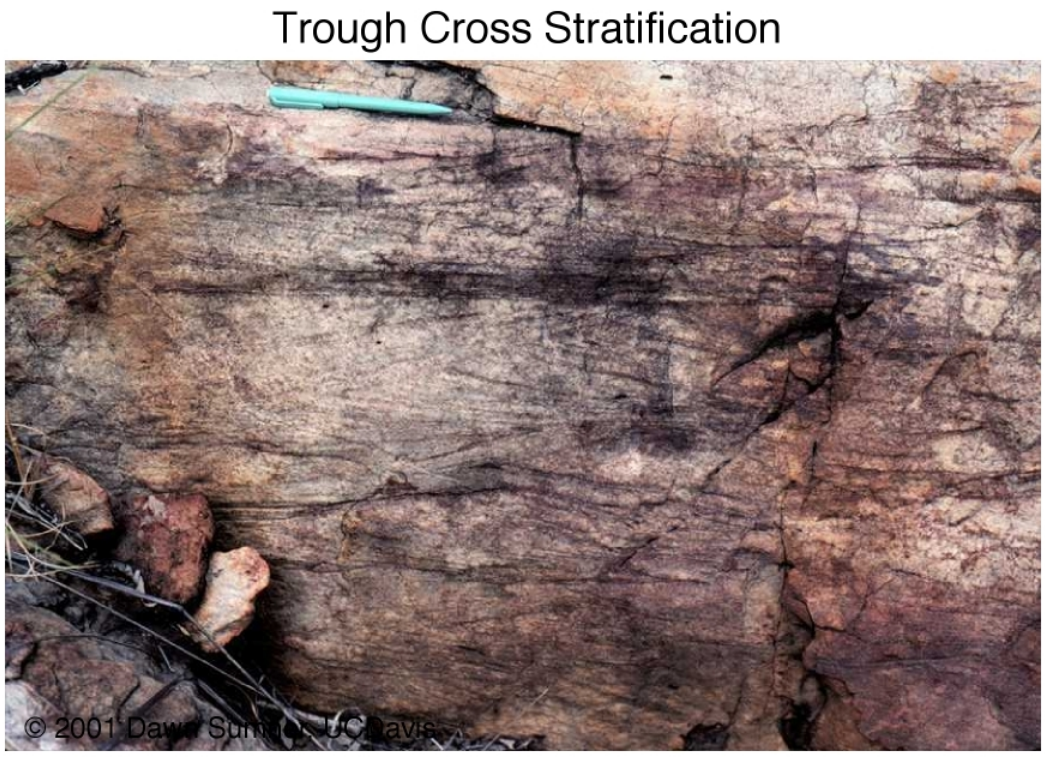


Figure 6.1.5.14***:*** *Ancient Trough Cross Stratification*



Trough Cross Stratification, Ricardo Group, Redrock Canyon State Park

Figure 6.1.5.15***:*** *Ancient Trough Cross Stratification*



Figure 6.1.5.16***:*** *Fining Upward Fluvial Cycles*

North of Mormon Point, Death Valley, CA

These fining upward cycles were deposited on an alluvial fan. There are two possible causes for the grading of the sediments. An entire fining-upward cycle might have been deposited by a single flood, with the coarser sediment deposited during the flood peak, and finer sediment deposited as the flood waned. An alternative explaination is that a small channel deposited the sediment as it migrated. In this scenario, the coarsest sediments would have been deposited at the base of the channel, and finer sediment would have been deposited higher on a bar at the edge of the channel. What would you look for to tell the difference?



Figure 6.1.5.17***:*** *Small Fining Upward Fluvial Cycle*

Red Rock State Park, CA
Stratification deposited as a bar migrated in a river channel. The larger geometry of the sandstone bed (not visible here) demonstrates that the stratification is due to bar migration rather than dune migration. Note the clay layer below the base of the channel (black arrow). It was probably deposited on the flood plane.



Figure 6.1.5.18***:*** *Single set of cross strata in a planar bed*

Alsek River, Alaska (photo taken by Jeff Mount)
The sediment in this river bank was deposited by either migrating river bars or subaqueous dunes. Note the variations between higher-angle cross strata (black arrows) and the overlying lower-angle strata (above the erosional surface marked by the green arrow). A bounding surface between two sets of cross stratification is marked by a red arrow.

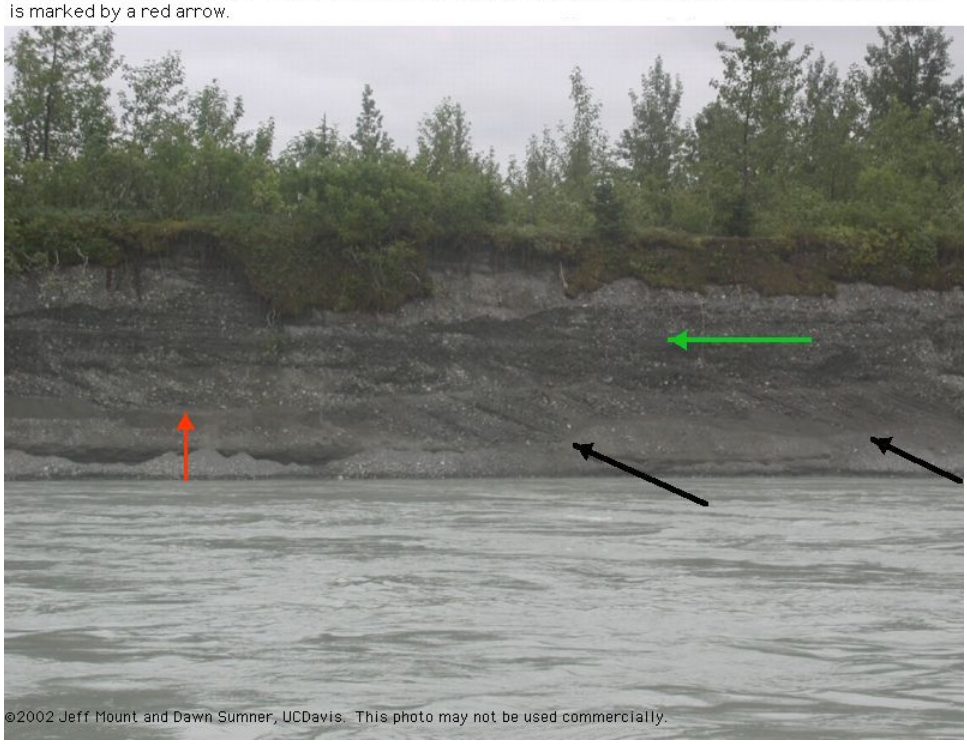


Figure 6.1.5.19***:*** *Recent Fluvial Deposits (Alsek River, Alaska)*

Return to Sedimentary Environments

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6.1.6: Glacial Environments (Chapter 7)

Modern Alaskan Glaciers

Glaciers Between Anchorage and Juneau, Alaska



This photo shows the high altitude zone of snow accumulation. With time, the snow recrystallizes to ice and flows down the slope as glaciers.

Figure 6.1.6.1***:*** *Zone of Snow Accumulation*

Glacier Between Anchorage and Juneau, Alaska



Note the dark lines on the surface of this glacier. They are rocks that were eroded at the edges of the glaciers. When two glaciers merge, these rocks get incorporated between the ice masses. The continuity of the trails demonstrates hat glacial flow is laminar, i.e. there is no turbulent mixing of the rocks into the ice or mixing of the two ice masses.

Figure 6.1.6.2***:*** *Merging Glaciers*

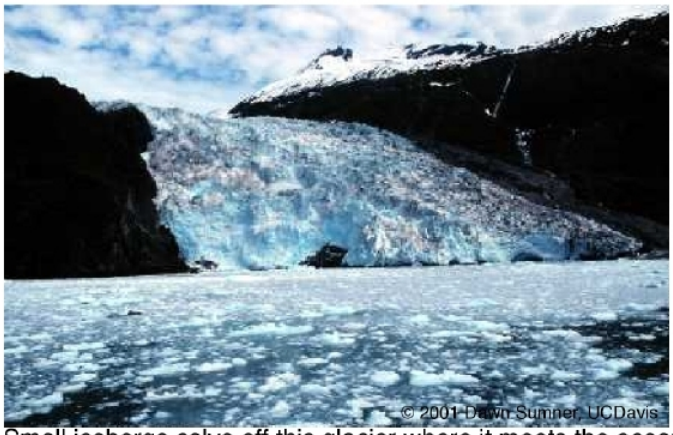
Glacier Between Anchorage and Juneau, Alaska



The glacier on the left is flowing into an ocean-filled valley that was carved by the glacier when sea level was lower. Sedimentary processes in the flooded valley include settling of rock flour from suspension, submarine reworking of glacially derived sediment by turbidites and submarine debris flows, and sediment dropped from melting ice.

Figure 6.1.6.3***:*** *Glacier Extending to Sea Level*

Glacier Near Anchorage, Alaska



Small icebergs calve off this glacier where it meets the ocean. Note the dark surface of the glacier due to a large number of rocks and abundant dirt in the ice. This sediment is deposited as the ice melts. The icebergs carry sediment far from the glacial front and can deposit coarse-grained sediment in quiet water environments.

Figure 6.1.6.4***:*** *Glacier Front at Sea Level (and ice bergs)*

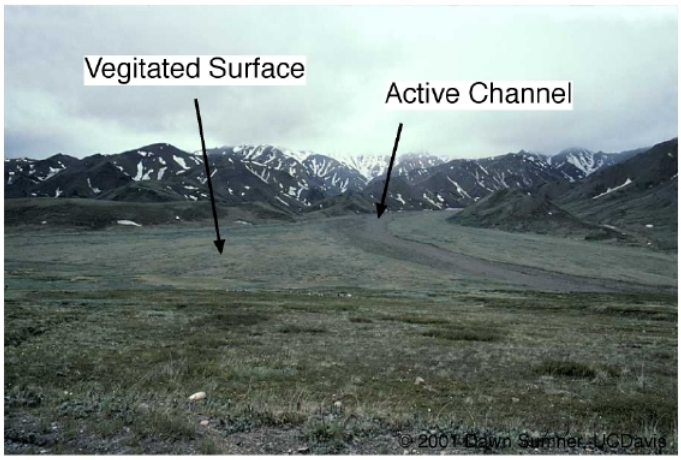
Glacial Till near Anchorage, Alaska



This terminal moraine consists of a jumbled mess of unsorted grains ranging in size from large clasts to clay-sized rock flour. The surface of the till is very irregular. Some of the hills contain blocks of ice under the debris. When they melt, they can produce holes that fill with water for form ponds. If this sediment was consolidated, it would be classified as a diamictite.

Figure 6.1.6.5***:*** *Modern Terminal Moraine*

Modern Fluvial Fan, Denali National Park, AK



Sediment on the fan is derived from a glacier out of sight in the valley. Sedimentary structures will be similar to those formed in an arid alluvial fan (i.e. trough cross stratification, bar migration stratification, fining upward fluvial cycles, etc.)

Figure 6.1.6.6***:*** *Fluvial Fan*

Braided River, Denali National Park, Alaska



The sediment deposited by this braided river is derived from glaciers up the valley and out of view. Direct glacial deposits commonly are associated with sediment eroded by glaciers but reworked by glacial melt water to produce fluvial deposits. This river is braided, i.e. it has multiple channls in a larger and broader channel.

Figure 6.1.6.7***:*** *Braided River*

Return to Sedimentary Environments

Ancient Glacial Sediments

Pleistocene Glacial Moraine, eastern Sierra Nevada, CA



These moraines were deposited by a series of glacial advances and retreats during the last glacial maximum. The glacier that deposited them carved the valley seen in the center of the photo.

Figure 6.1.6.7***:*** *Ancient Lateral and Terminal Moraine*

Neoproterozoic Glacial Diamictite, Namibia



This diamictite consists of fine-grained carbonate matrix with very large clasts. The clasts are unsorted. The lack of sorting, combined with the laminated fine-grained sediment, suggests that this diamictite was deposited in a quiet water environment with clasts derived from melting ice bergs. (Note the six-foot tall person for scale in the upper right of the photograph.)

Figure 6.1.6.8***:*** *Ancient Glacial Diamictite*

Neoproterozoic Glacial Diamictite, Namibia



This closer view of the diamictite demonstrates the poorly sorted nature of the clasts. Dark clasts are limestone and tan clasts are dolomite. The softer limestone clasts sheared after burial, whereas the stronger dolomite clasts did not.

Figure 6.1.6.9***:*** *Ancient Glacial Diamictite*

Permian Glacial Pavement on Archean Ventersdorp Lava, South Africa



This glacial pavement was eroded on the surface of 2.8 Ga lavas during Permian time. The glaciers polished this surface and left striae marking the direction of ice flow. They are visible here running from the bottom to the top of the photo.

Figure 6.1.6.10***:*** *Ancient Glacial Pavement*

Return to Sedimentary Environments

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6.1.7: Offshore Marine Environments (Chapters 14, 15)



Figure 6.1.7.1 - *Hummocky Cross Stratification*



Figure 6.1.7.2 - *Hummocky Cross Stratification (HCS)*



Figure 6.1.7.3 - *Storm Cross Stratification (HCS and wave ripples)*

Interbedded shaley sandstones, wave rippled sandstones, and shale, Belt Supergroup, southern Canadian Rockies.



Figure 6.1.7.4 - *Shallow subtidal sandstones and shales*

Wave rippled sandstone interbedded with shale and sandstones with mud chips; Belt Supergroup, southern Canadian Rockies.



Figure 6.1.7.5 - *Closer view of wave ripple in previous photo*



Figure 6.1.7.6 - *Shallow subtidal sandstone with mud chips from the same succession*

Return to Sedimentary Environments

The Devonian-Mississippian Boundary, Southern Canadian Rockies

Research Question: Did the depositional environment remain deep during this disconformity?



Figure 6.1.7.7 - *Overview photo of the outcrop*



Figure 6.1.7.8 - *Closer view of the disconformity*



Figure 6.1.7.9 - *Phosphatized bone on the disconformity*

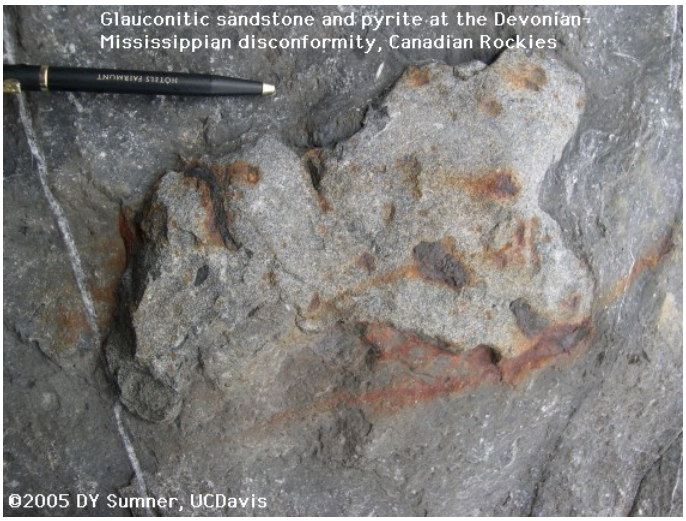


Figure 6.1.7.10 - *Glauconitic sandstone with pyrite on the disconformity*

See the turbidites page as well.

Return to Sedimentary Environments

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6.1.8: Shoreline Environments (Chapter 13)

Alhambra Creek Flowing into Carquinez Straits, Martinez, CA

Mouth bars commonly form where creeks meet larger bodies of water. The rapid flow of the creek slows dramatically as the water spreads out. A mouth bar (black arrow) formed at the mouth of the creek (path traced by dashed line). Here it is modified by wind waves from the delta breezes.

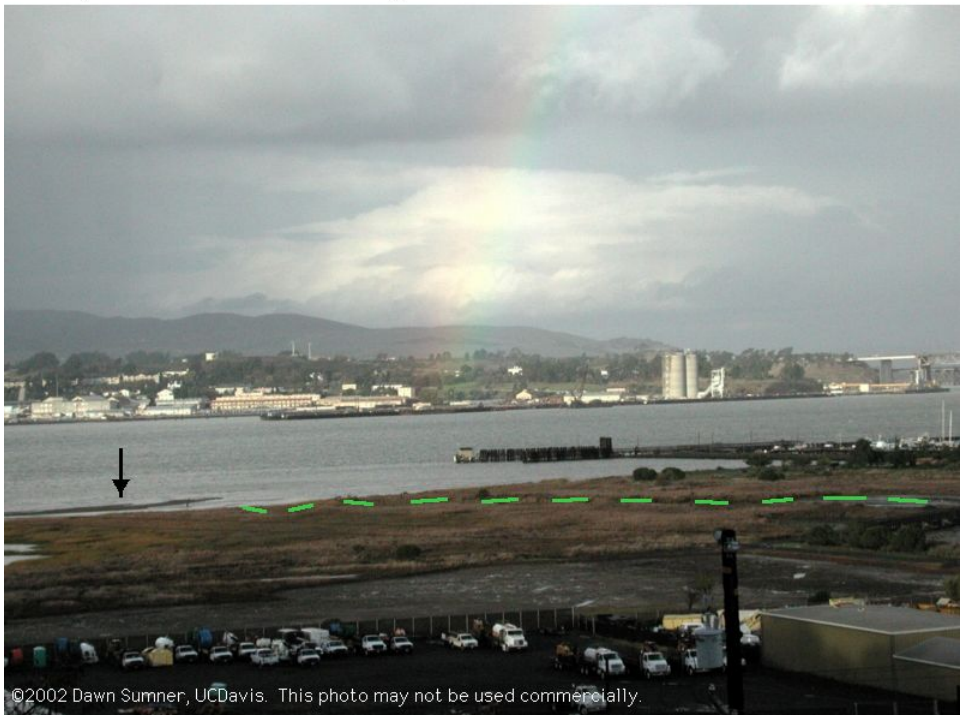


Figure 6.1.8.1***:*** *Mouth bar from a creek flowing into brackish water straits (California)*

Alhambra Creek Flowing into Carquinez Straits, Martinez, CA

Mouth bars commonly form where creeks meet larger bodies of water. The rapid flow of the creek slows dramatically as the water spreads out. A mouth bar (black arrow) formed at the mouth of the creek



Figure 6.1.8.2***:*** *Mouth bar from a creek flowing into brackish water straits (California)*

Large sections of the central California coast are mostly erosional with substantial cliffs.

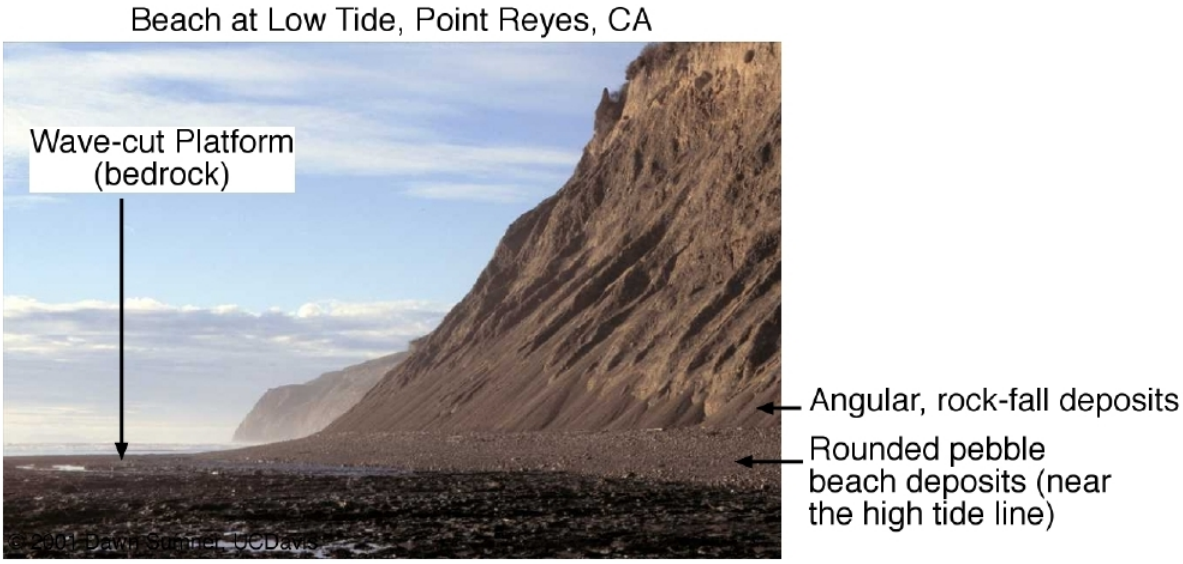


Figure 6.1.8.3***:*** *Modern Wave Cut Platform*

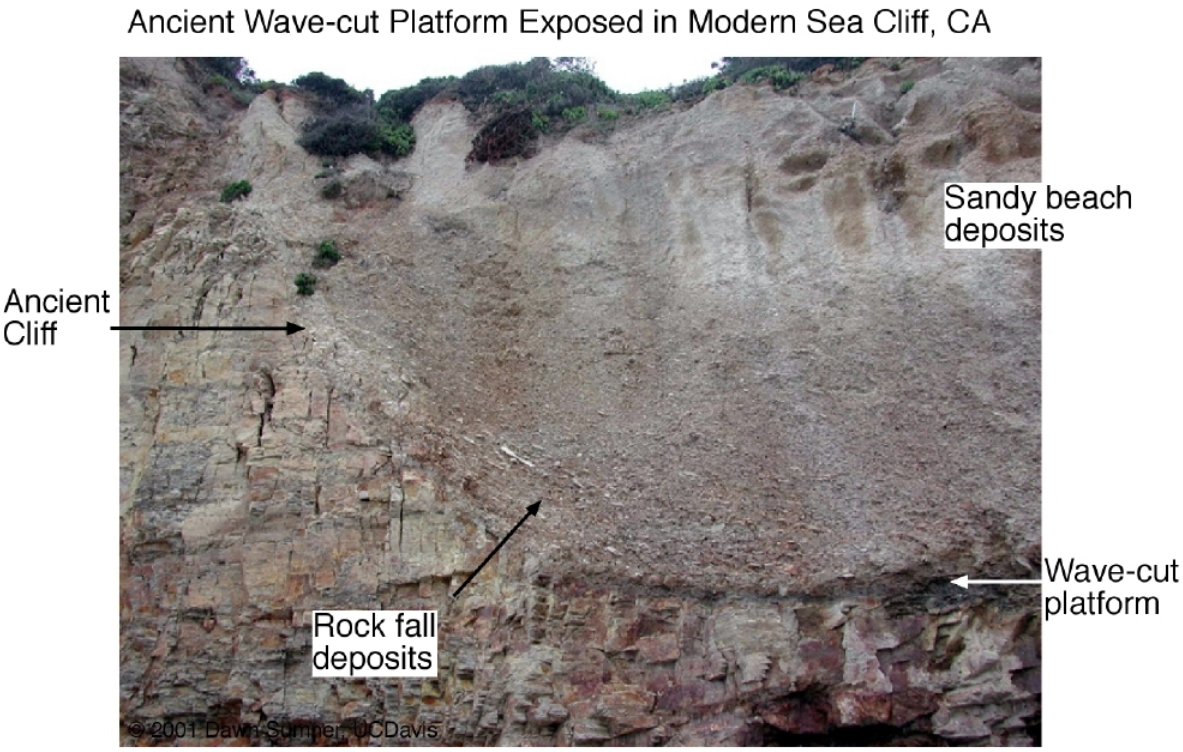


Figure 6.1.8.4***:*** *Ancient Wave Cut Platform*

Return to Sedimentary Environments

Scott Creek Beach

Scott Creek Beach, CA, is a wave and storm dominated beach. The following photos were taken near low tide. We go to this beach on the second field trip.

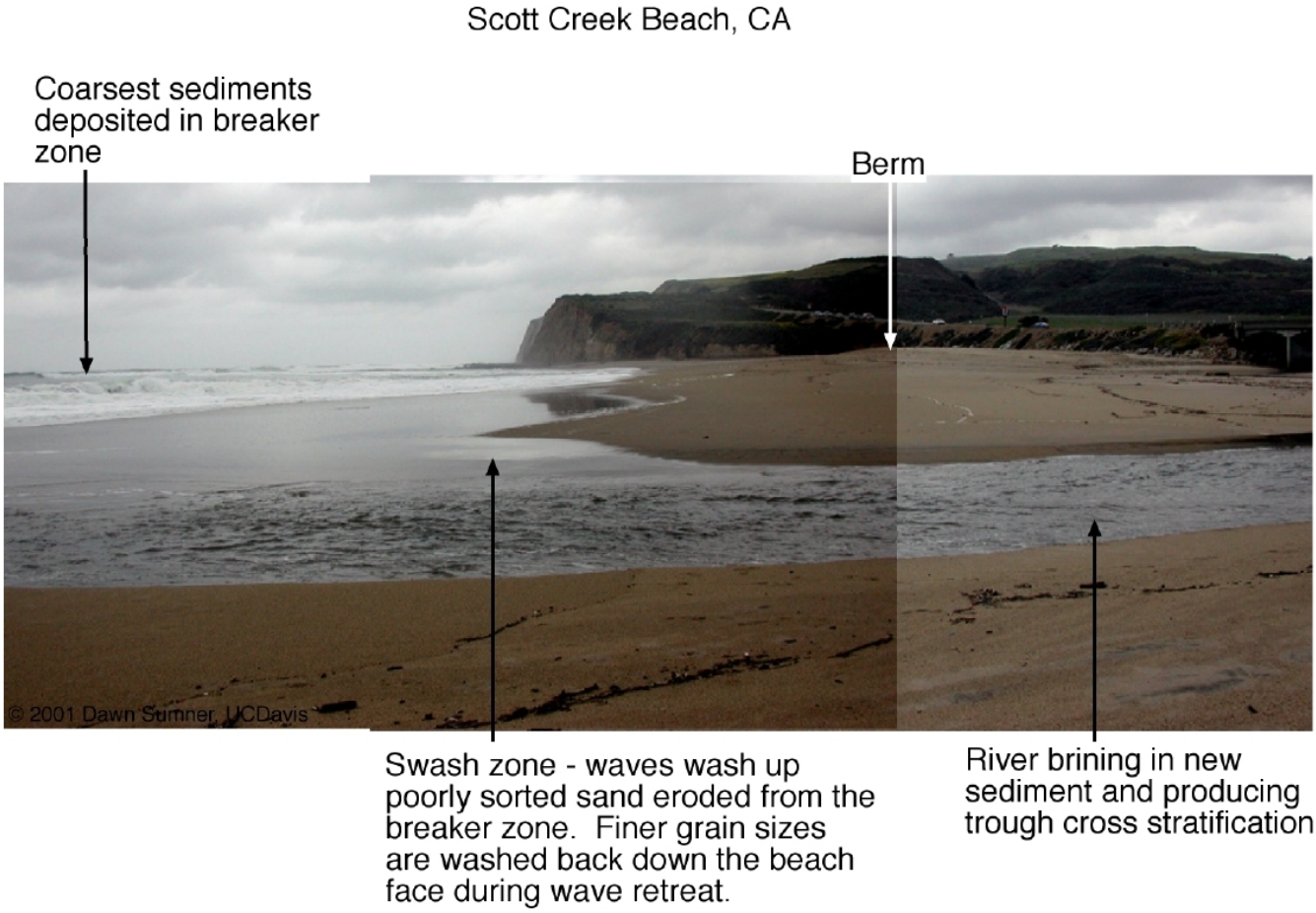


Figure 6.1.8.5***:*** *Scott Creek Beach*



Figure 6.1.8.6***:*** *Terrace at Scott Creek Beach*



Figure 6.1.8.7***:*** *Beach Stratification*

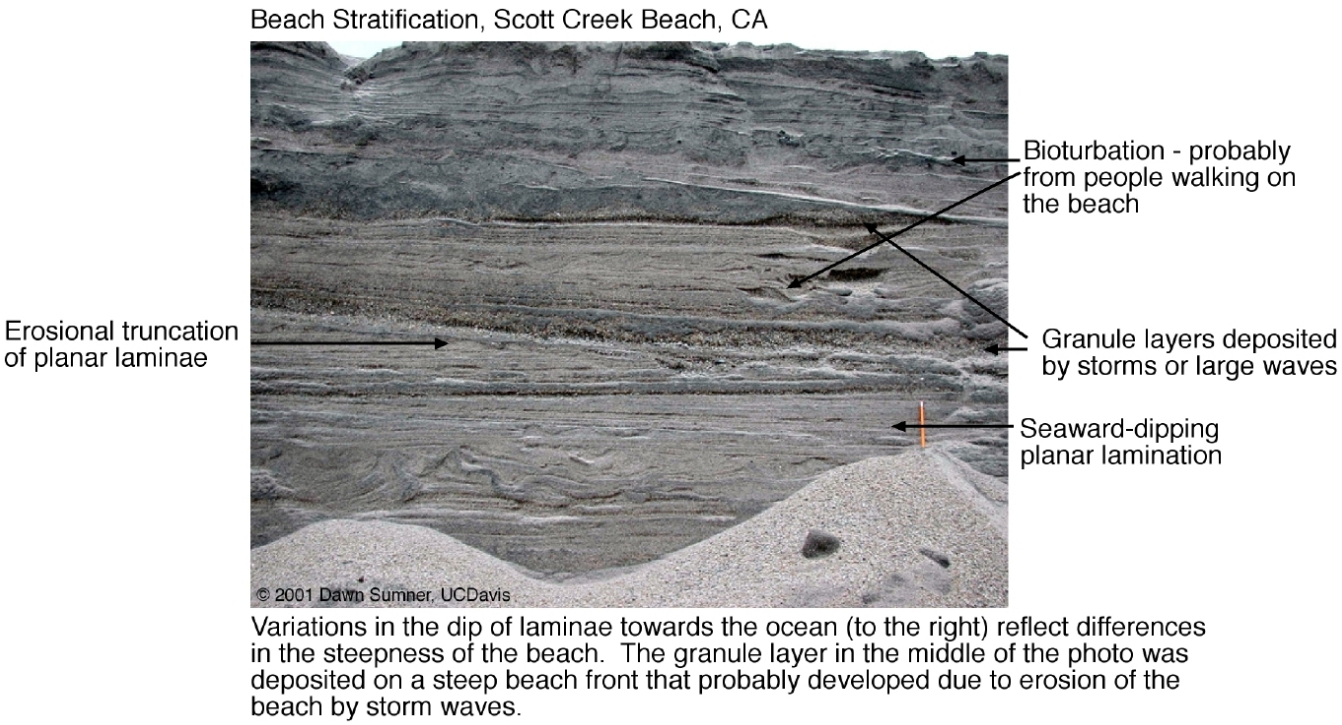


Figure 6.1.8.8***:*** *Beach Stratification*



Figure 6.1.8.9***:*** *Beach Stratification*

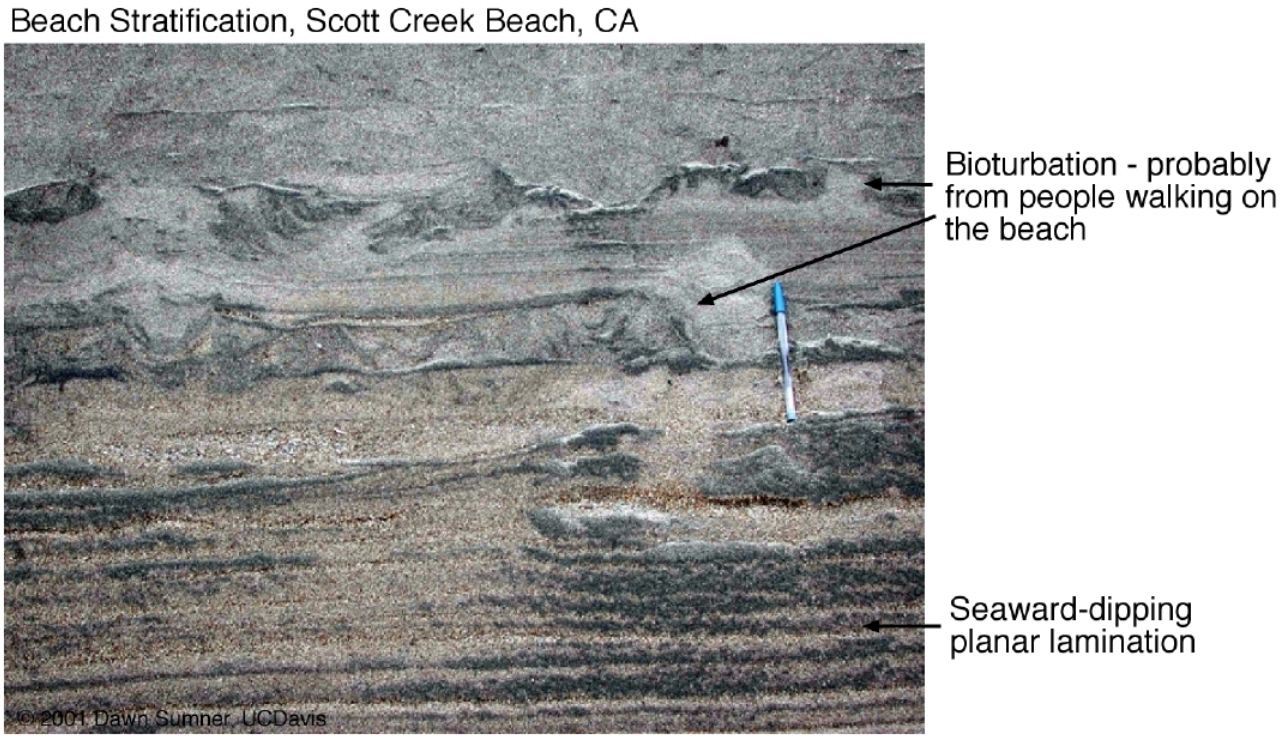


Figure 6.1.8.10***:*** *Beach Stratification*

The first photo shows beach stratification along the beach, whereas the next photo shows strata deposited at about the same time, but in a terrace perpendicular to the beach. Note how the laminae appear much more parallel in the first photo. This is because the main slope of the beach is towards the ocean. When looking in the rock record, it is important to understand the 3-D geometry of deposits for the best interpretations.

Scott Creek Beach, CA

This photo shows beach stratification parallel to the orientation of the beach. The stratification appears much more planar because changes in beach slope are mostly perpendicular to this outcrop. Small swells and dips (arrow) reflect topography on a beach surface.



Figure 6.1.8.11***:*** *Beach Stratification*

Scott Creek Beach, CA

This view of beach stratification is approximately perpendicular to the beach trend. Note that most of the layers are close to parallel, but there are numberous changes in the slopes of the layers (arrows). These layers were deposited at approximately the same time as those in the photograph showing stratification parallel to beach orientation.



Figure 6.1.8.12***:*** *Beach Stratification*

Scott Creek Beach, CA

Antidunes are common in creeks flowing across beaches. Here, 7 can be identified by the waves on the surface of the water. They were migrating upstream. When the eroding sand bank collapsed, the antidunes were disrupted and took 10's of seconds to reform. Faint beach stratification can be seen in the bank.



Figure 6.1.8.13***:*** *Antidunes in a creek*

Return to Sedimentary Environments

This Brazilian beach is also wave dominated

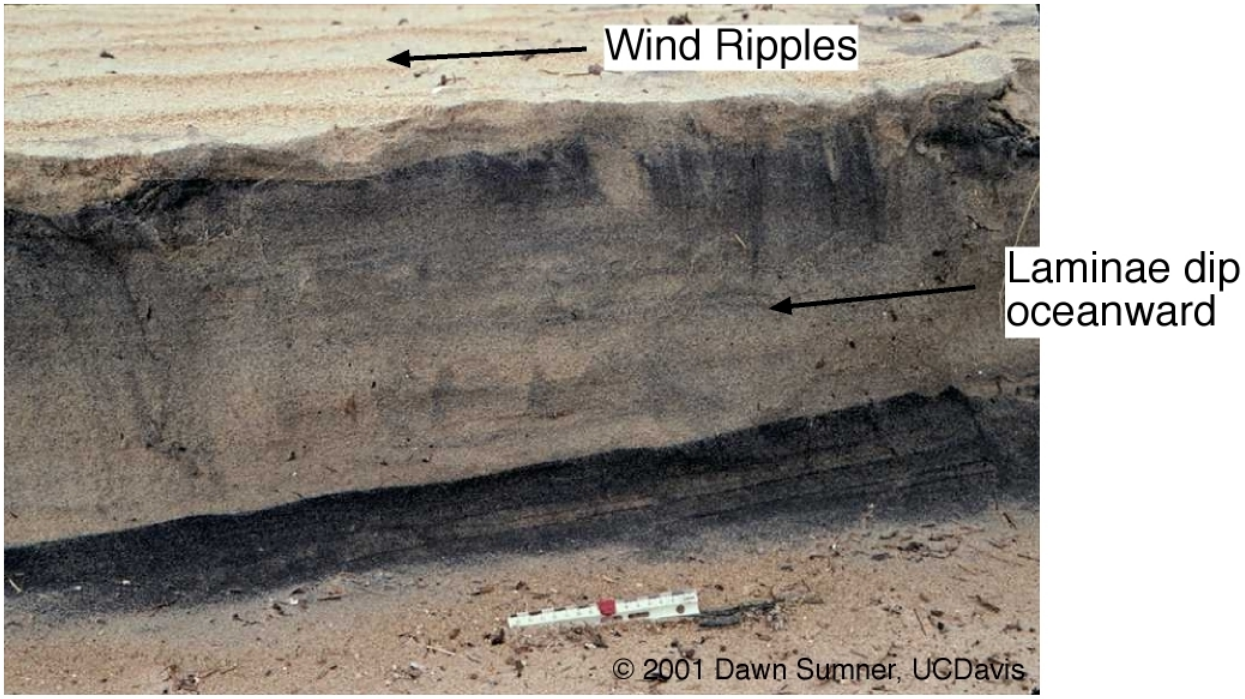


Figure 6.1.8.14***:*** *Modern Beach Stratification*

Pescadero Beach

Pescadero Beach and estuary have complex facies changes over short distances. We visit this site on the second field trip.

Pescadero Beach, CA

Pescadero Beach is a typical northern California beach. This photo was taken in the late winter. Strong waves produce a steep swash zone, and storms deposited abundant wood along the berm.



Figure 6.1.8.15***:*** *Pescadero Beach*

Pescadero Beach, CA

This photo shows the creek flowing into the breaker zone. The white areas where water is breaking within the creek are sites where antidunes are present. The line of wood and other debris is the level of the recent high tide, which floods into the creek.



Figure 6.1.8.16***:*** *The creek flows into the breaker zone*

Pescadero Beach, CA
This photo shows the Pescadero estuary. The creek eroded the hills to create the valley, which is now flooded by tides near the beach. Some of the tide water comes up the creek, and some seeps through the sediment below the sand dunes and into the area. The water is saltier closer to the beach. Most of the sediment deposition in this area consists of clays and organic matter accumulation.



Figure 6.1.8.17***:*** *Looking across the estuary*

Pescadero Beach, CA
Pescadero estuary is separated from the beach by the sand dunes (black arrow). The channel in the foreground is man-made and carries tidal water to the tidal flats, which are partially flooded in this photograph (white arrow).



Figure 6.1.8.18***:*** *Looking towards the shoreline from the estuary*

Pescadero Beach, CA

Dunes are migrating in Pescadero Creek (arrows). Flow is toward the upper right side of the photograph. The tide is going out, so the level of the creek, which gets flooded at high tide, is going down. A small terrace formed when flow was higher (green arrow).



Figure 6.1.8.19***:*** *Dunes migrating in the creek*

Pescadero Beach, CA

Subaqueous dunes form in Pescadero Creek. Flow is towards the top of the photo, which was taken from the highway bridge. The water is cloudy from suspended sediment. Footprints are faintly visible in the current ripples in the lower right of the photograph.



Figure 6.1.8.20***: Dunes migrating in the creek***

Pescadero Beach, CA

An estuary lies landward of Pescadero Beach. This photo shows the creek that is flooded by the tides. The vegitated rocks in the background are part of the Monterrey Formation. The smooth to rippled sandy area in the middle ground is in the tidal zone, whereas the area with abundant footprints is less frequently flooded.



Figure 6.1.8.21*: Tidal flats next to the creek channel*

Pescadero Beach, CA

Near shorelines, both wave and current ripples are common. Here, current ripples are visible in the foreground. They transition into more symmetrical wave ripples along this bar. In intertidal environments such as this one, water flow varies dramatically from place to place and with time as the tides change.



Figure 6.1.8.22*: Ripples beside the creek*

Pescadero Beach, CA

Current ripples formed when creek flow was amplified by tidal run-off from the Pescadero estuary. Which direction was the current flowing? How irregular was the flow?



Figure 6.1.8.23***:*** *Current ripples beside the creek*

Pescadero Beach, CA
These wind-deposited sand dunes are shoreward of Pescadero Beach. This face was eroded by the creek, and vegitation has stablized most of the dune surfaces. Bioturbation, mostly by plant roots, results in little preservation of cross stratification. The wood on the flats was deposited by storms and/or floods.



Figure 6.1.8.24***:*** *Eroded sand dunes*

Return to Sedimentary Environments

Broome Town Beach

Broome Town Beach, Western Australia, is tide dominated, although small waves are present. In the summer, typhoons are common. The following photos were taken at low tide on the tidal flat in the winter.

Modern Wave Ripples, Broome Town Beach, Western Australia



Ripple crests were flattened as the water drained off the tidal flat.

Figure 6.1.8.25***:*** *Modern Wave Ripples*

Modern Wave Ripples, Broome Town Beach, Western Australia



Figure 6.1.8.26***:*** *Modern Wave Ripples*

Modern Wave Ripples, Broome Town Beach, Western Australia



Ripples are disrupted by crab bioturbation (mounds of sand).

Figure 6.1.8.27***:*** *Modern Wave Ripples*

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Derby

The coastline near Derby, Western Australia, is dominated by extremely high tides (almost 12 m tidal range), and waves are essentially absent in the protected Prince William Sound. Mangroves line the shore. The following photos were taken at an exceptionally low tide when the tidal bars were exposed.

Modern Tidal Bar, Derby, Western Australia



This photo was taken at an exceptionally low tide. In Prince William Sound (which is the body of water in the photo), the tidal range is almost 12 m, which is the second highest in the world. Very few waves make it this far into the sound, so the coast line is dominated by tidal currents. The tide moves in calmly but very quickly producing strong currents that shape the bars.

Figure 6.1.8.28***:*** *Tidal bar*

Modern Tidal Bar, Derby, Western Australia



The tidal bars are elongate bars with secondary dunes developed on them, which are visible here. The dunes are flattened as the last of the water drains off of them at extreme low tide. They rebuild as the tide moves in and then out again. Some of dark sediment is granule to pebble sized demonstrating very rapid water flow.

Figure 6.1.8.29***:*** *Tidal bar dunes*

Return to Sedimentary Environments

Lake Louise

The sediment-rich creek that flows into Lake Louise, southern Canadian Rockies, creates a lacustrine delta, as seen in the following photographs.



Figure 6.1.8.30***:*** *Lacustrine Delta*

Fluvial delta entering Lake Louise, southern Canadian Rockies. Note the abandonded stream channels. The small lake waves help shape the front of the delta.



Figure 6.1.8.31***:*** *Lacustrine Delta*

Return to Sedimentary Environments

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6.1.9: Slope Failure and Erosion (Chapter 6)

Slope Failure



Figure 6.1.9.1***:*** *Recent Land Slide*

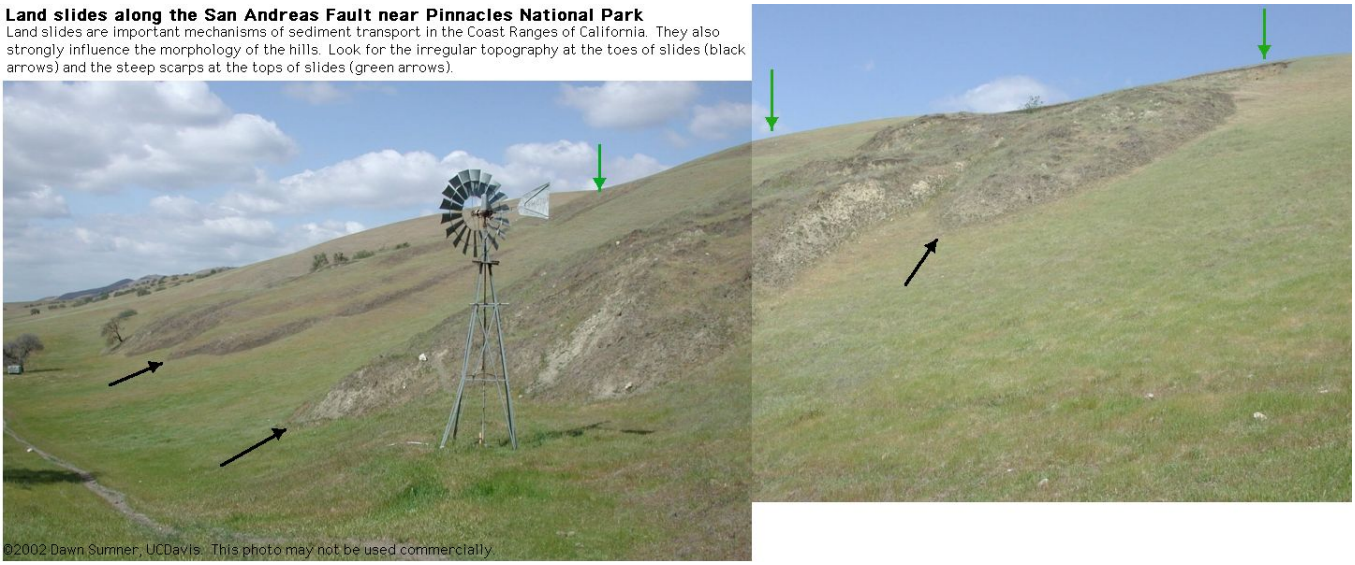


Figure 6.1.9.2***:*** *Recent Land Slide*

Land Slide, California Coast Ranges near Pinnacles National Park

The large land slide scarp and the relatively flat topography of the slide suggest that this land slide was fluid when it flowed. It probably had most of the characteristics of a debris flow, although closer examination of its sedimentary characteristics would be necessary to test this guess.



Figure 6.1.9.3***:*** *Recent Land Slide*

Return to Sedimentary Environments

Erosion

Differential weathering between sandstones and shales, southern Canadian Rockies



Figure 6.1.9.4***:*** *Differential Weathering of Shales and Sandstones*

Return to Sedimentary Environments

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SECTION OVERVIEW

6.2: Sedimentary Structures

Topic hierarchy

6.2.1: Beach Stratification

6.2.2: Current Ripple Cross Lamination

6.2.3: Diamictites

6.2.4: Mud Cracks

6.2.5: Soft Sediment Deformation

6.2.6: Sole Marks, Burrows, and Miscellaneous

6.2.7: Subaqueous Bedforms and Cross Stratification

6.2.8: Subaqueous Ripples and Cross Lamination

6.2.9: Turbidites

6.2.10: Wave Ripples in Sediment

6.2.11: Wave Ripple Cross Lamination

6.2.12: Wind Transported Bedforms and Cross Stratification

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6.2.1: Beach Stratification



Figure 6.2.1.1: *Beach Stratification (Scott Creek Beach, CA)*

Scott Creek Beach, CA

This photo shows beach stratification parallel to the orientation of the beach. The stratification appears much more planar because changes in beach slope are mostly perpendicular to this outcrop. Small swells and dips (arrow) reflect topography on a beach surface.



Figure 6.2.1.2: *Beach Stratification (Scott Creek Beach, CA)*

Scott Creek Beach, CA

This view of beach stratification is approximately perpendicular to the beach trend. Note that most of the layers are close to parallel, but there are numberous changes in the slopes of the layers (arrows). These layers were deposited at approximately the same time as those in the photograph showing stratification parallel to beach orientation.



Figure 6.2.1.3: *Beach Stratification (Scott Creek Beach, CA)*

Beach Stratification, Scott Creek Beach, CA



Variations in the dip of laminae towards the ocean (to the right) reflect differences in the steepness of the beach. The granule layer in the middle of the photo was deposited on a steep beach front that probably developed due to erosion of the beach by storm waves.

Figure 6.2.1.4: *Beach Stratification (Scott Creek Beach, CA)*



Figure 6.2.1.5: *Beach Stratification (Scott Creek Beach, CA)*

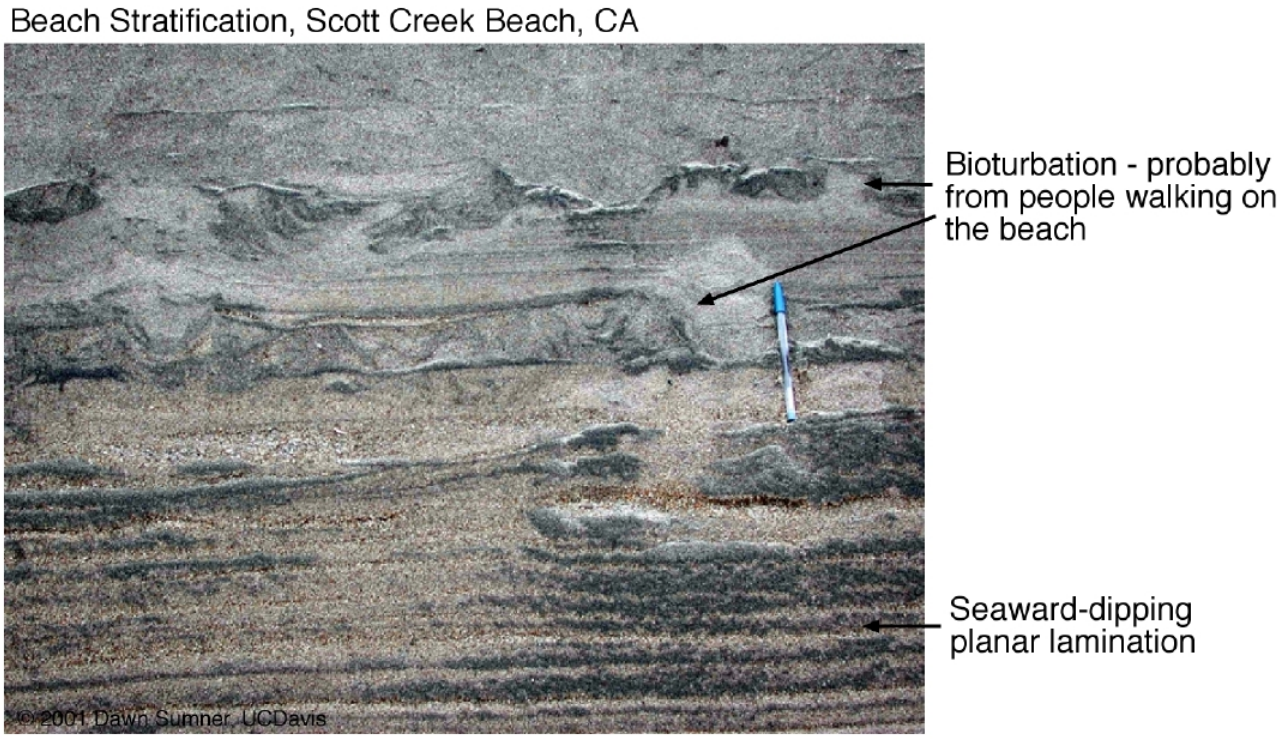


Figure 6.2.1.6: *Beach Stratification (Scott Creek Beach, CA)*

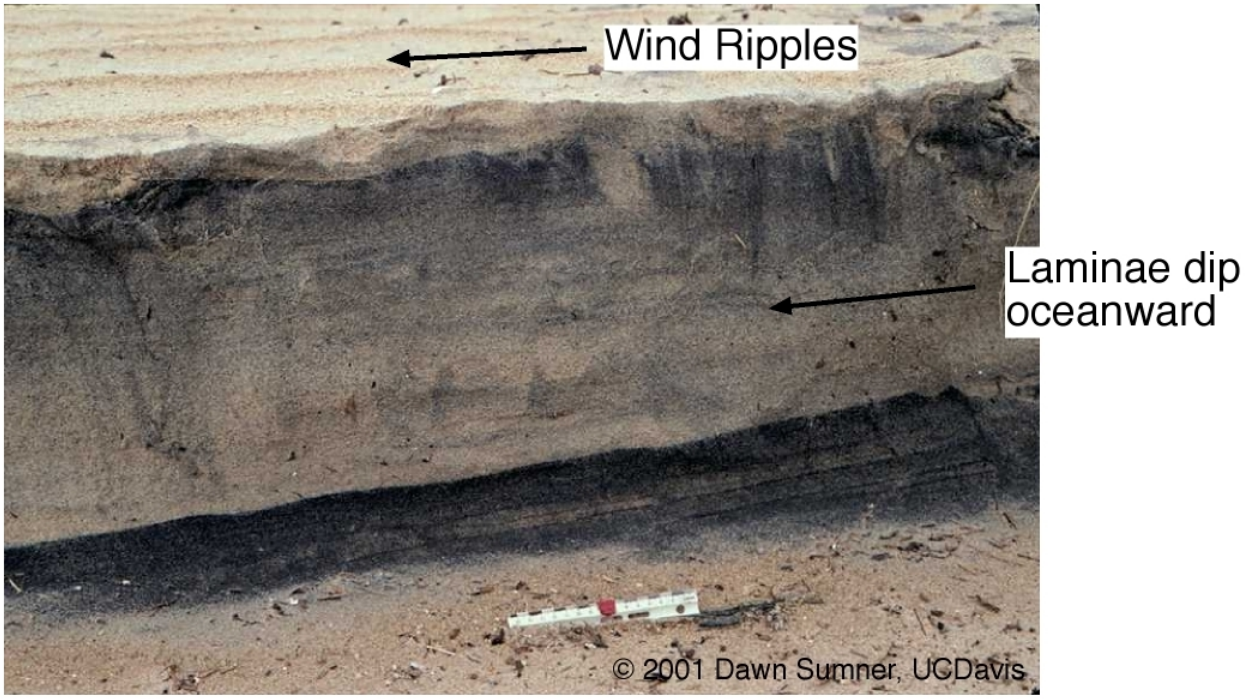


Figure 6.2.1.7: *Beach Stratification (Brazil)*

Return to Sedimentary Structures

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6.2.2: Current Ripple Cross Lamination



Figure 6.2.2.1: Current ripple cross lamination. Flow is mostly to the left near the bottom of the image and mostly out of the rock in the upper part of the image. The numerous scoop-shaped laminae demonstrate that the ripple crests were sinuous.



Figure 6.2.2.2: Planar lamination (near finger tip) overlain by current ripple cross lamination. The flow direction was to the left.

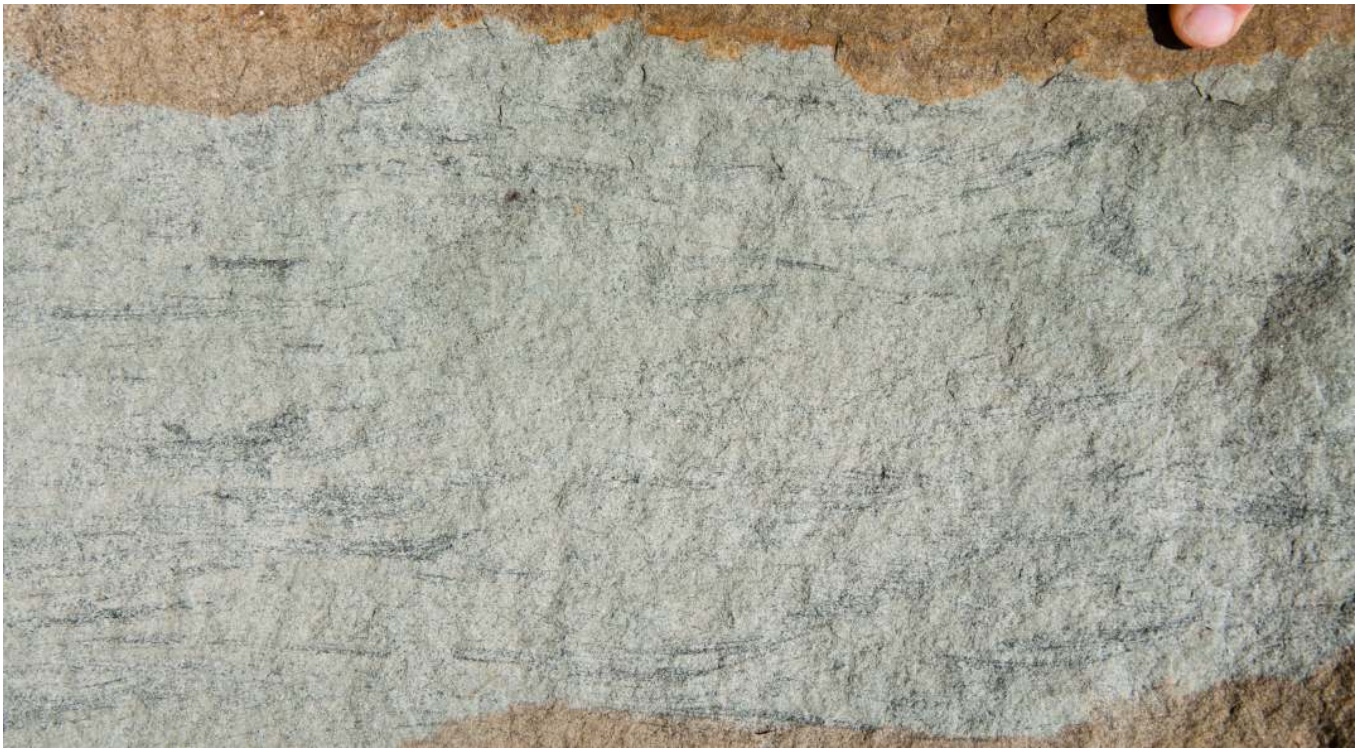


Figure 6.2.2.3: Current ripple cross lamination. The flow was mostly either into or out of the rock. The scoop shapes demonstrate that the ripple crests were sinuous.

Return to Sedimentary Structures

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6.2.3: Diamictites

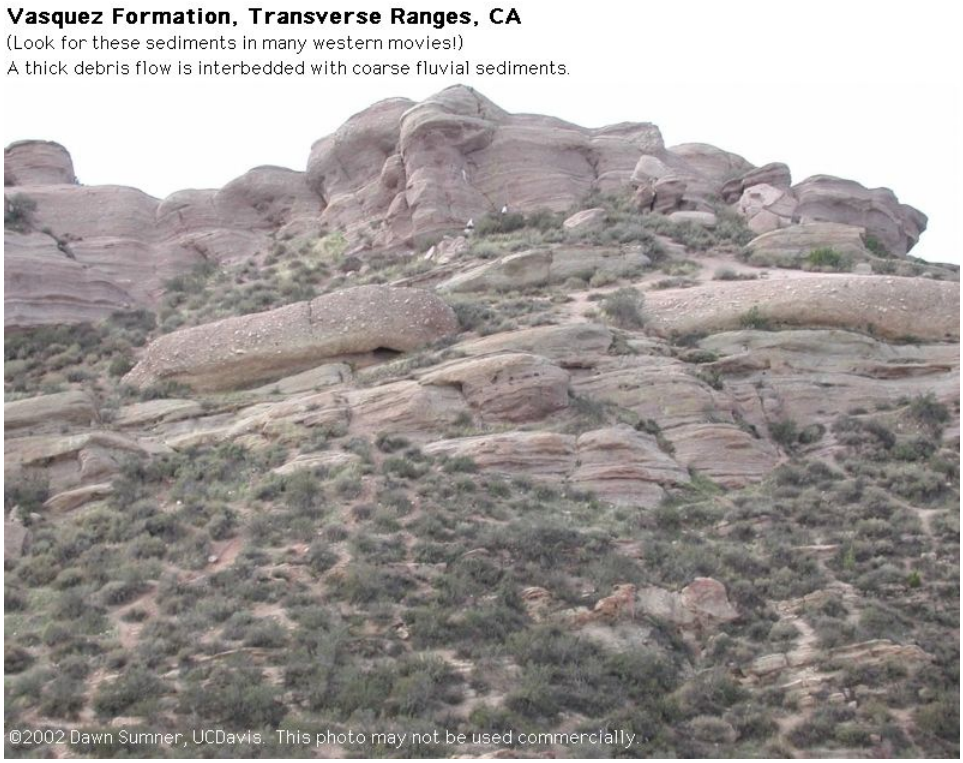


Figure 6.2.3.1: *Debris Flow Deposit in a Fluvial Environment*



Figure 6.2.3.2: *Debris Flow Deposit on an Alluvial Fan*

Glacial Till near Anchorage, Alaska



This terminal moraine consists of a jumbled mess of unsorted grains ranging in size from large clasts to clay-sized rock flour. The surface of the till is very irregular. Some of the hills contain blocks of ice under the debris. When they melt, they can produce holes that fill with water for form ponds. If this sediment was consolidated, it would be classified as a diamictite.

Figure 6.2.3.3: *Modern Glacial Till/Diamictite*

Neoproterozoic Glacial Diamictite, Namibia



This diamictite consists of fine-grained carbonate matrix with very large clasts. The clasts are unsorted. The lack of sorting, combined with the laminated fine-grained sediment, suggests that this diamictite was deposited in a quiet water environment with clasts derived from melting ice bergs. (Note the six-foot tall person for scale in the upper right of the photograph.)

Figure 6.2.3.4: *Ancient Glacial Diamictite*

Neoproterozoic Glacial Diamictite, Namibia



This closer view of the diamictite demonstrates the poorly sorted nature of the clasts. Dark clasts are limestone and tan clasts are dolomite. The softer limestone clasts sheared after burial, whereas the stronger dolomite clasts did not.

Figure 6.2.3.5: *Ancient Glacial Diamictite*

Diamictite, Neoproterozoic Johnnie Formation, CA



Is this diamictite a glacial till sheet or deposited by a debris flow? We don't know the answer to this question, but it is very important for interpreting the sedimentary and tectonic environment for deposition of the formation. Clast compositions are diverse due to either glacial erosion of an area with diverse rock types or fault uplift of diverse rock types and failure of tectonically uplifted slopes.

Figure 6.2.3.6: *Ancient Diamictite of uncertain origin*



Figure 6.2.3.7: *Ancient Diamictite of uncertain origin*

Return to Sedimentary Structures

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6.2.4: Mud Cracks

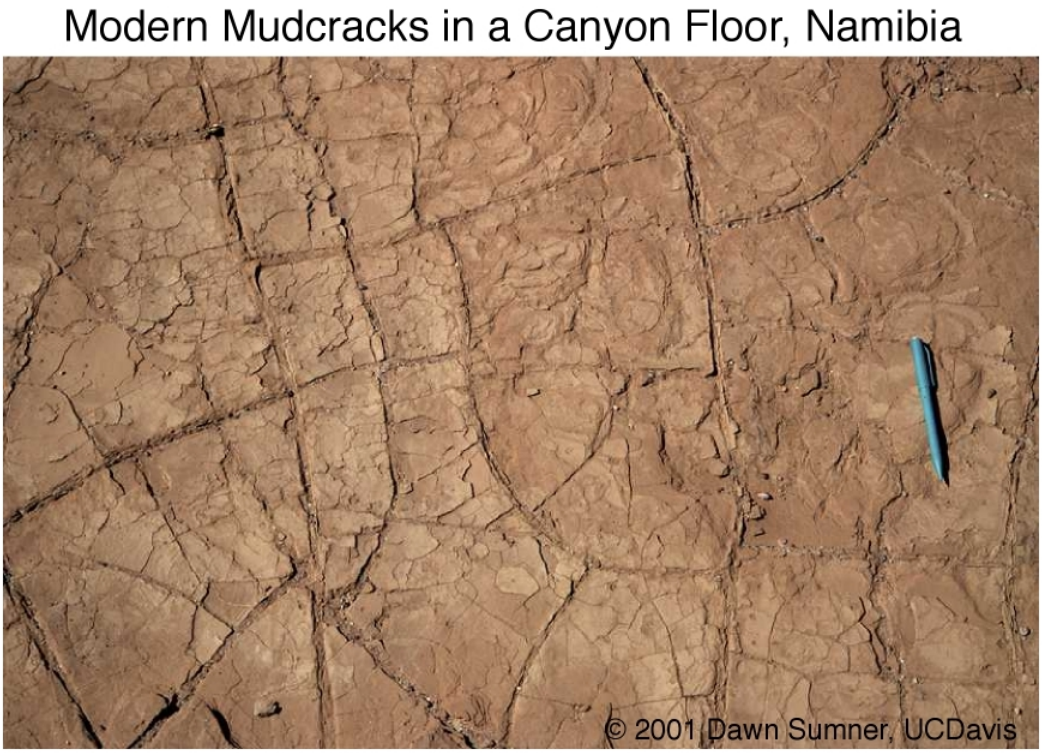


Figure 6.2.4.1: *Modern Mud Cracks*

Race Track Playa, Death Valley National Park, CA

This playa predominantly contains clay to sand grain sizes, but some pebbles to boulders are present. The boulders have tracks behind them that demonstrate they were transported across the playa by sliding when the surface was wet. Although the mechanism of transport is controversial, it is likely that very strong winds pushed them across a very slick surface. Mud cracks are abundant, and the surface contains a large proportion of dried fillamentous microbes. These features (but not the large rocks) are characteristic of playas.



Figure 6.2.4.2: *Modern Mud Cracks in a Playa*

Race Track Playa, Death Valley National Park, CA

In this close view of the surface of Race Track Playa, the large mud cracks are very clear. They are deep and evenly spaced. The upper surface of the mud, except in the travel path of the rock, is rough due to smaller mud cracks and rolled up mud. This layer contains abundant dried filamentous microbes (cyanobacteria?), which increase the cohesiveness of the mud. Note how the top layer appears to have been scraped off in the travel path of the rock. The rock probably was blown across the surface when this layer was very wet.



Figure 6.2.4.3: *A Closer View of Modern Mud Cracks in a Playa*



Mudcracked surface of a Neoproterozoic mudstone

Figure 6.2.4.4: *Ancient Mud Cracks*

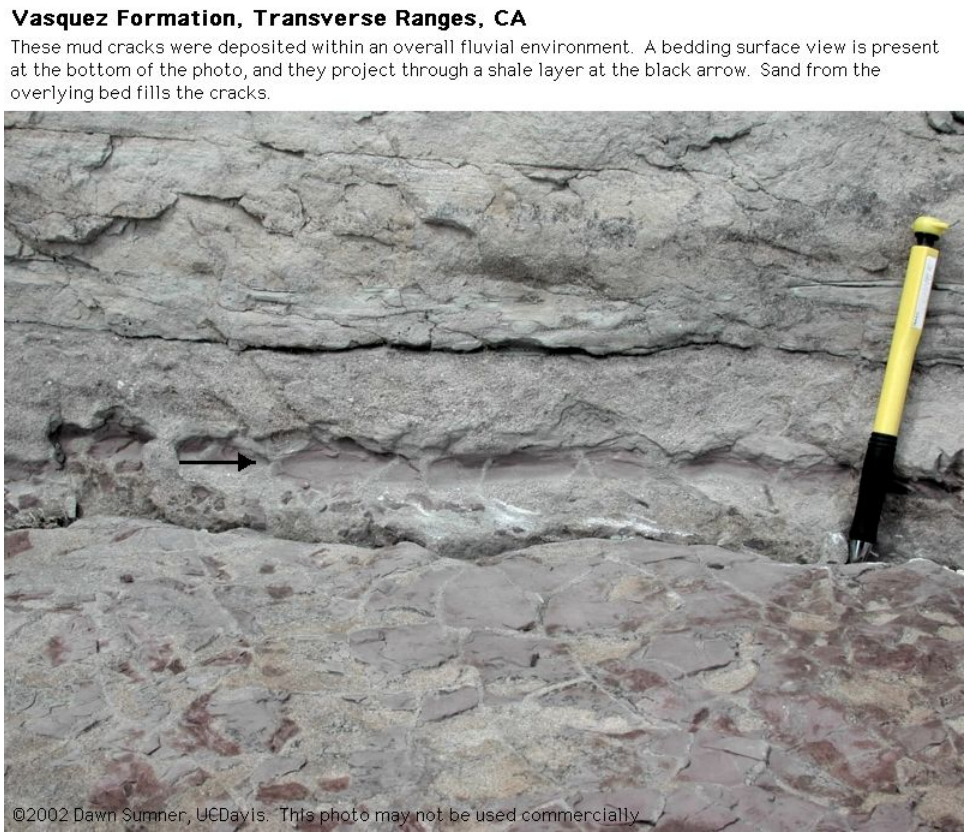


Figure 6.2.4.5: *Ancient Mud Cracks in Both Vertical and Plan Views*

Mudcrack Marks on an Ancient Rippled Sandstone



The ripples formed, and their crests were slightly flattened. Then a layer of mud draped them. The mud dried out, and cracked through the entire layer. The cracks filled with sand from the top. In this view, the mud has eroded away leaving the sand that filled the cracks and the underlying rippled sandstone.

Figure 6.2.4.6: *Ancient Mud Cracks and Wave Ripple Crests*

Ancient mud chips in a sandstone matrix; bedding plane view, Canadian Rockies



Figure 6.2.4.7: *Ancient Mud Chips in Sandstone*

Red mud chips in grey sandstone, Belt Supergroup, southern Canadian Rockies



Figure 6.2.4.8:*Ancient Mud Chips in Sandstone*

Syneresis cracks in shale, filled with sandstone; they form from dewatering of clays underwater. Belt Supergroup, southern Canadian Rockies



Figure 6.2.4.9:*Syneresis cracks due to dewatering of mud under water*

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6.2.5: Soft Sediment Deformation



Figure 6.2.5.1*: Flame Structures*

Pebble Beach near Pescadero, CA

These turbidites, in the Cretaceous Pigeon Point Formation, show faint current ripple cross laminations (black arrow), flame structures (green arrow), planar lamination (red arrow), and contorted ripple(?) laminae (white arrow).

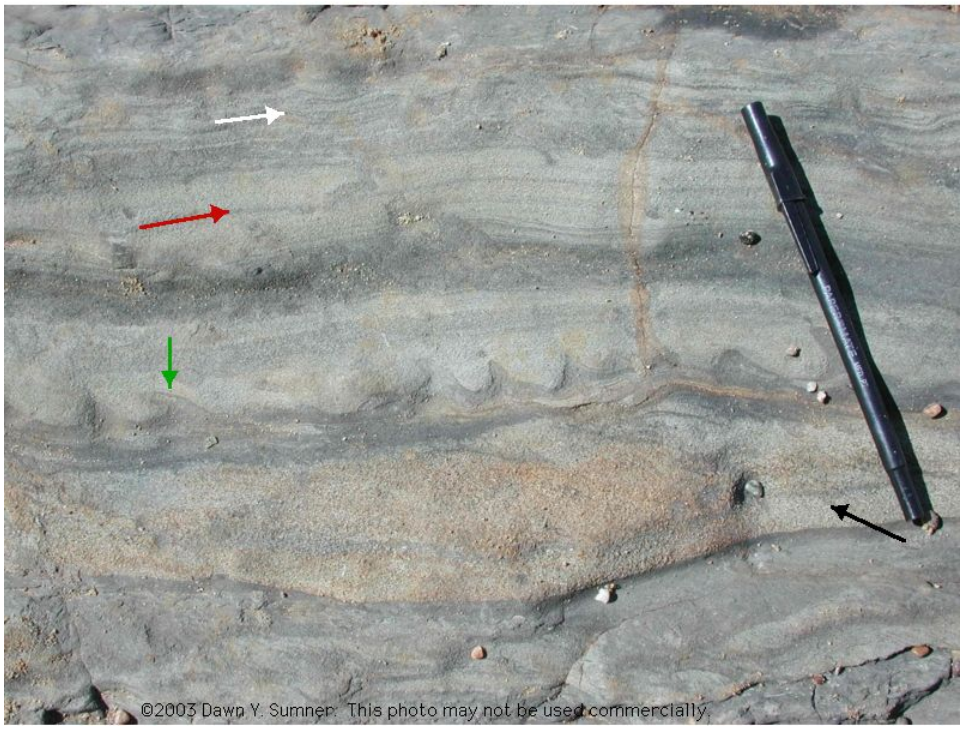


Figure 6.2.5.2*: Flame Structures*

Pebble Beach near Pescadero, CA

These flame structures formed where turbidites were deposited over shaley layers in the Cretaceous Pigeon Point Formation.



Figure 6.2.5.3*: Flame Structures*

Pebble Beach near Pescadero, CA

These sands to shales are part of a turbidite fan in the Cretaceous Pigeon Point Formation. In this photo, sand-filled burrows (black arrows) are abundant, and flame-structures formed at the base of the upper sand layer (green arrow).

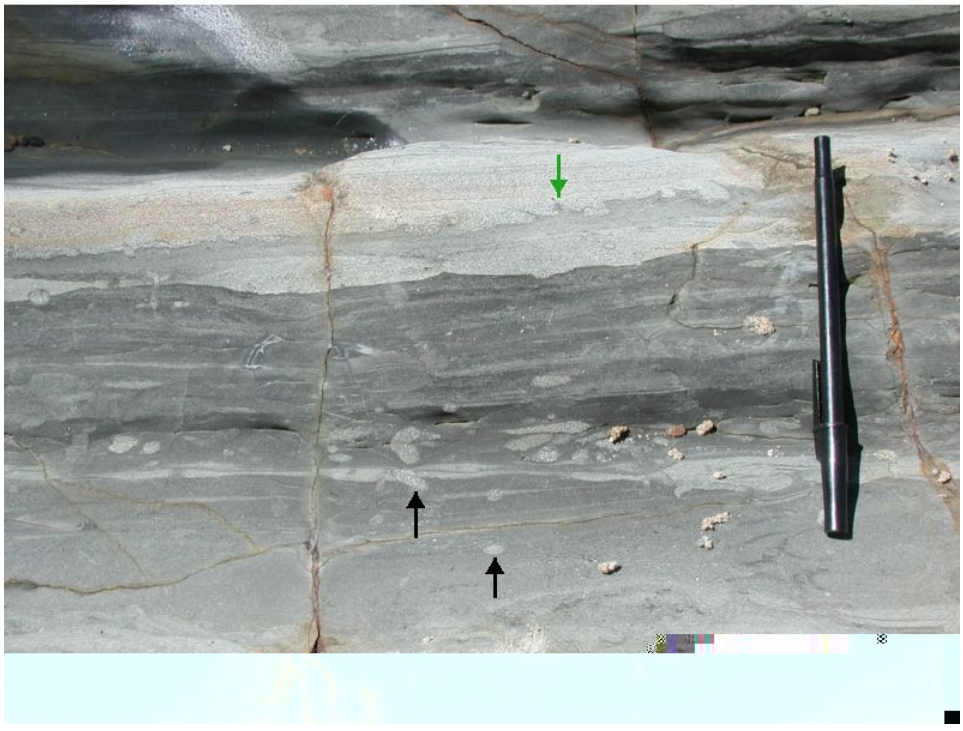


Figure 6.2.5.4*: Flame Structures and Burrows*

Pebble Beach near Pescadero, CA

In this photo of turbidites in the Cretaceous Pigeon Point Formation, flame structures are abundant where sandstones were deposited over shale (black arrow). Larger load structures formed where very coarse to granular sand was deposited over medium sand (white arrow). A closer photo of the flame structures is also available on this web site.



Figure 6.2.5.5*: Load Structures*

Shallow Marine Sediments near Oberlin, OH

The tan rock is sandstone (black arrows), and the darker rock is shale. The sandstone was originally deposited in a layer. Either compaction or seismic activity caused deformation of the sandstone layer. The interpretation is controversial with proponents for both causes. The hand lens case is ~2.5 cm across.



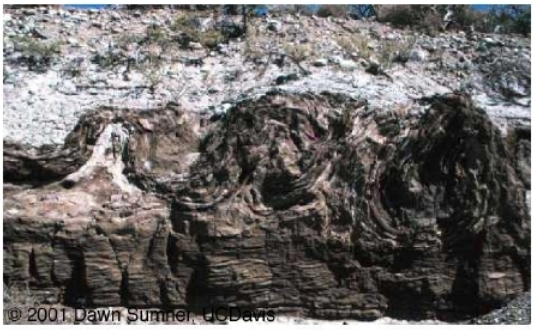
Figure 6.2.5.6*: Contorted Sandstone Beds*

Permian Soft Sediment Deformation, Guadalupe Mtns, NM



Figure 6.2.5.7*: Soft Sediment Folding*

Soft Sediment Deformation Below the Bishop Tuff, CA



Soft sediment deformation occurred in these sandstones when the hot, thick Bishop Tuff was deposited on top of them. The structures are due to water and possibly steam escape from the sediments.

Figure 6.2.5.8*: Soft Sediment Folding*

Return to Sedimentary Structures

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6.2.6: Sole Marks, Burrows, and Miscellaneous

Sole Marks

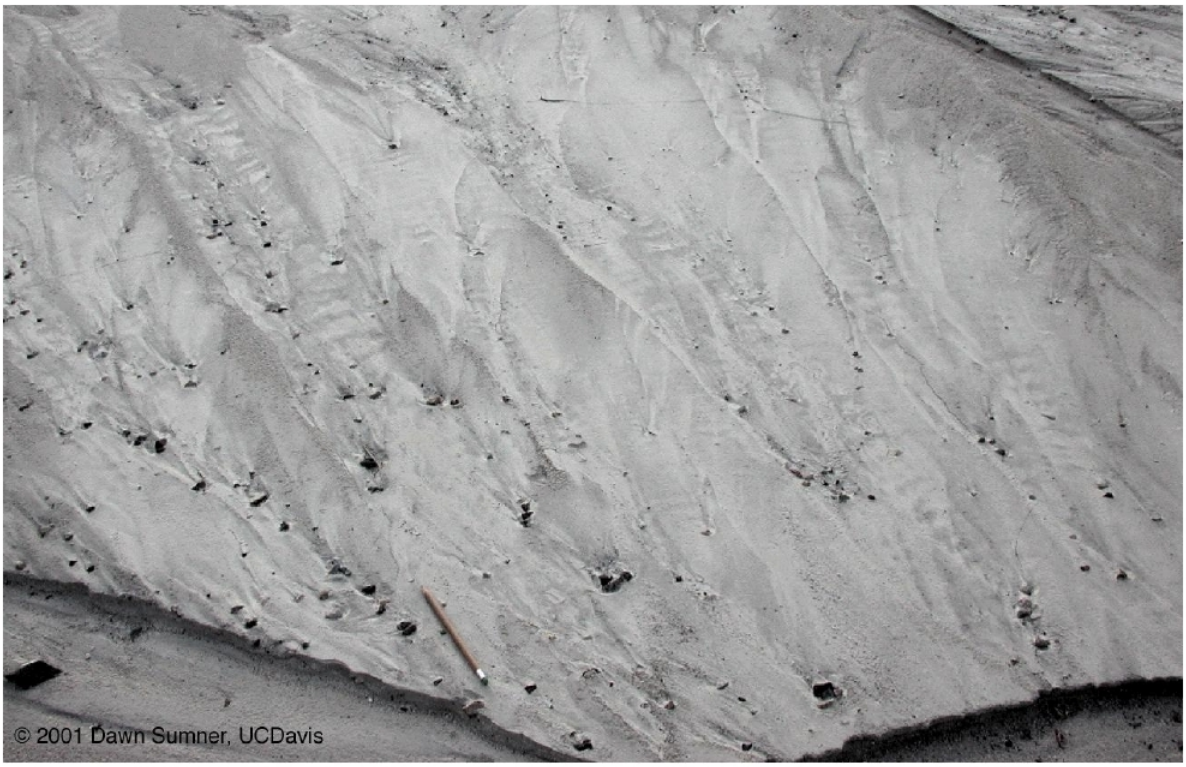


Figure 6.2.6.1***:*** *Modern Scour Marks Downstream of Pebbles*

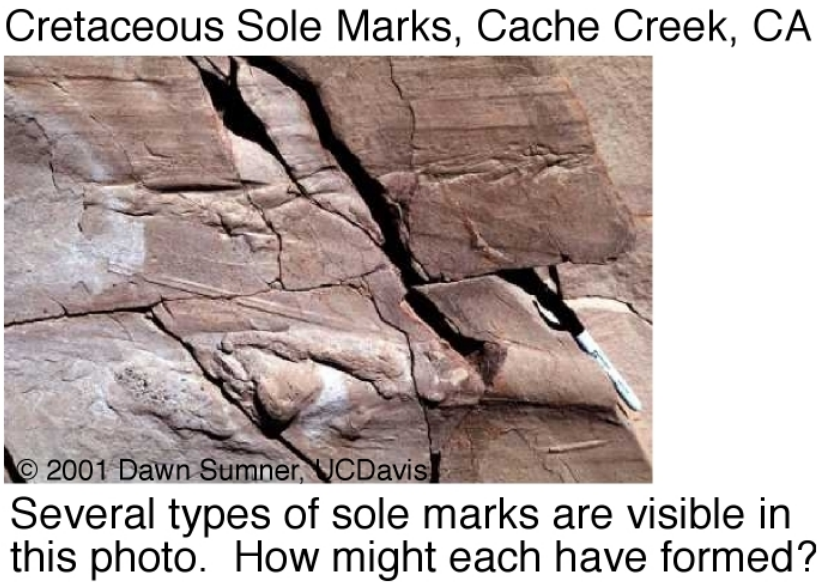


Figure 6.2.6.2***:*** *Sole Marks*

Cretaceous Sole Marks, Cache Creek, CA



Figure 6.2.6.3***:*** *Sole Marks*

Permian Glacial Pavement on Archean Ventersdorp Lava, South Africa



This glacial pavement was eroded on the surface of 2.8 Ga lavas during Permian time. The glaciers polished this surface and left striae marking the direction of ice flow. They are visible here running from the bottom to the top of the photo.

Figure 6.2.6.4***:*** *Scratch Marks on a Glacial Pavement*



Figure 6.2.6.5***:*** *Glacial striae from the last glacial maximum on the slope of the old Mt. Tehama*

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Burrows



Figure 6.2.6.6***:*** *Burrows*

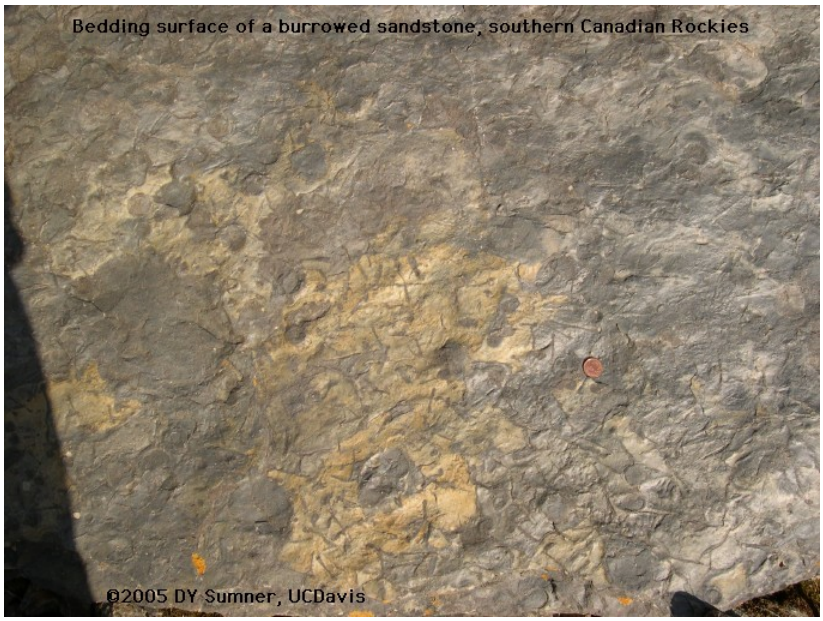


Figure 6.2.6.7***:*** *Burrows*



Figure 6.2.6.8***:*** *Burrows*

Return to Sedimentary Structures



Figure 6.2.6.9***:*** *Rain marks on glacial flour that look a lot like "wrinkle structures", usually interpreted as microbial fossils.*

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6.2.7: Subaqueous Bedforms and Cross Stratification

I have divided these by type of bedform and cross stratification. The examples are both fluvial and marine.

Planar Cross Stratification

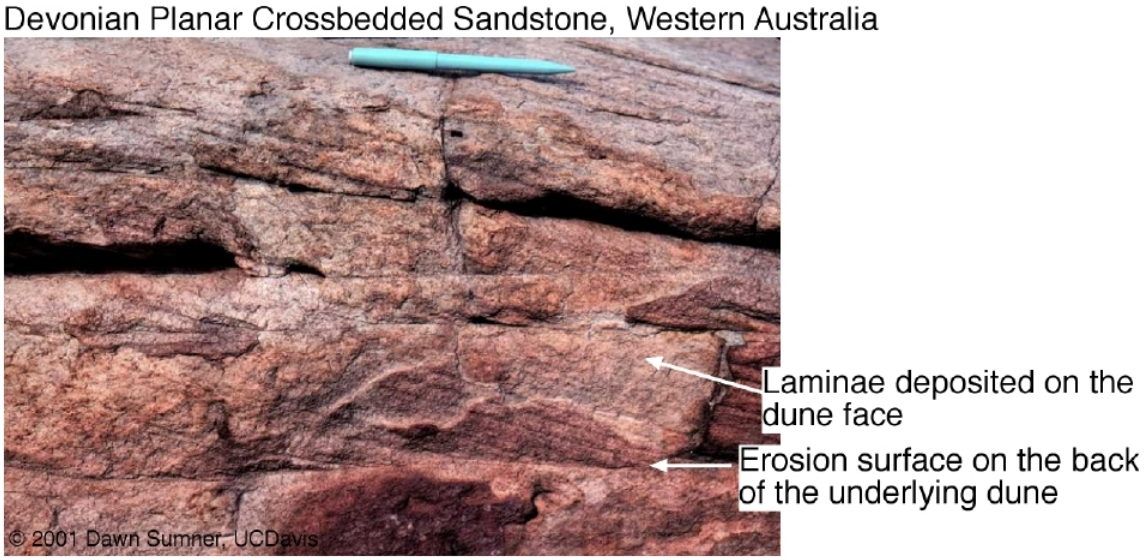


Figure 6.2.7.1***:*** *Ancient Planar Cross Stratification*

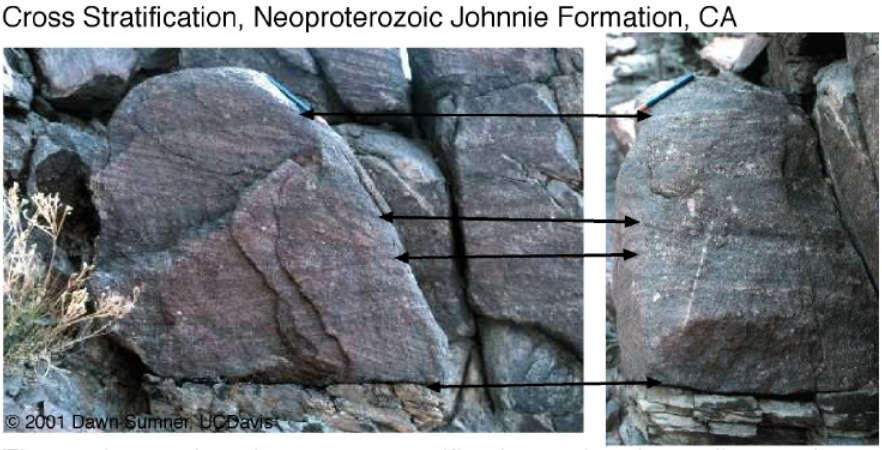


Figure 6.2.7.2***:*** *Ancient Planar Cross Stratification*

Red Rock State Park, CA

Stratification deposited as a bar migrated in a river channel. The larger geometry of the sandstone bed (not visible here) demonstrates that the stratification is due to bar migration rather than dune migration. Note the clay layer below the base of the channel (black arrow). It was probably deposited on the flood plane.

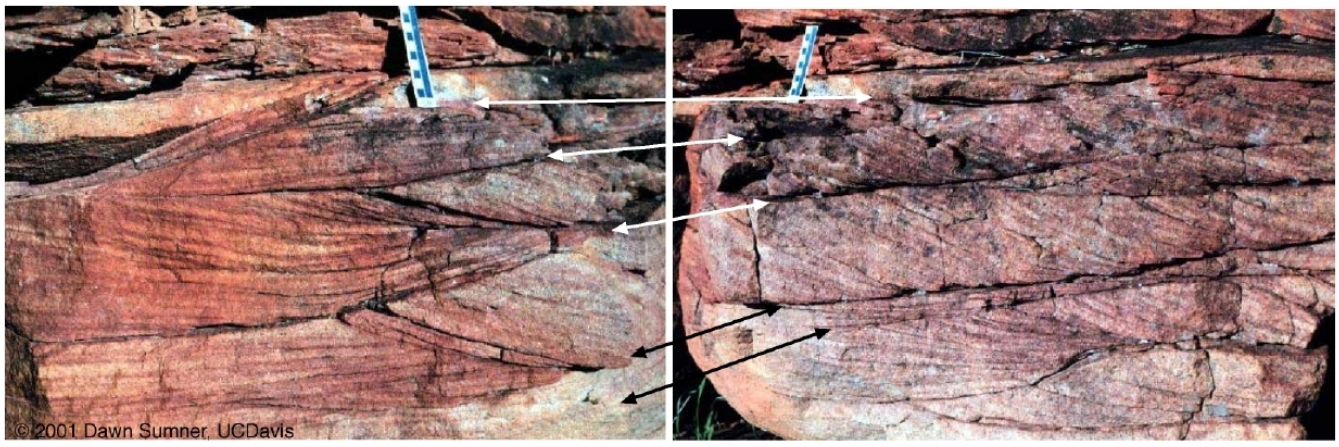


Figure 6.2.7.3***:*** *Single set of cross strata in a planar bed*

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Trough Cross Stratification

Ancient Trough Cross Stratification, Western Australia



These photos show two views of trough cross stratification. The scale bar is at the same place in both photos and shows centimeters. Which direction was water flowing? Try to match the pattern of cross stratification to one of the USGS bedform movies. What might the geometry of the bed forms have been?

Figure 6.2.7.4***:*** *Ancient Trough Cross Stratification*

Trough Cross Stratification

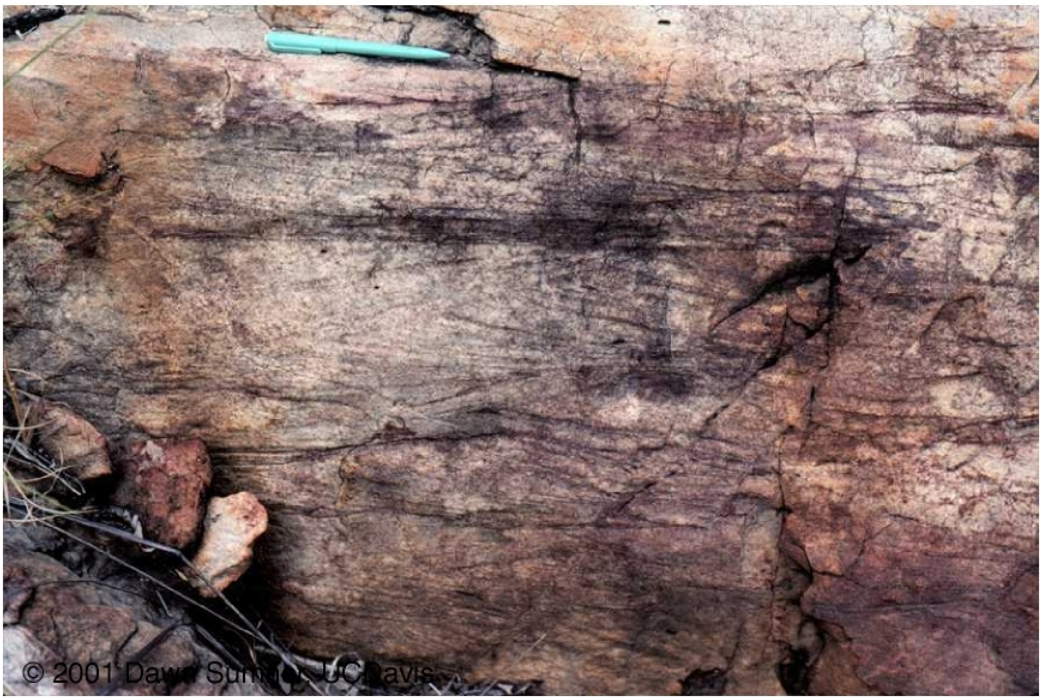


Figure 6.2.7.5***:*** *Ancient Trough Cross Stratification*



Trough Cross Stratification, Ricardo Group, Redrock Canyon State Park

Figure 6.2.7.6***:*** *Ancient Trough Cross Stratification*

Plan View of Fluvial Trough Cross Stratification, Western Australia



The paleoflow direction was from the bottom left of the photo to the top right.

Figure 6.2.7.7***:*** *Plan or Map View of Ancient Trough Cross Stratification*

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Herringbone Cross Stratification

Herringbone Cross Stratification, Eco Beach, Australia



Which surfaces are the erosional surfaces on the backs of migrating dunes? Which direction was water flowing for each set of laminae?

Figure 6.2.7.8***:*** *Herringbone cross stratification*

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Hummocky Cross Stratification

Hummocky Cross Stratification, Johnnie Formation, CA



Figure 6.2.7.9***:*** *Hummocky cross stratification*

Hummocky cross stratification in a fractured carbonate, Belt Supergroup, southern Canadian Rockies



Figure 6.2.7.10***:*** *Hummocky cross stratification*

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Cross Stratification from Bar Migration

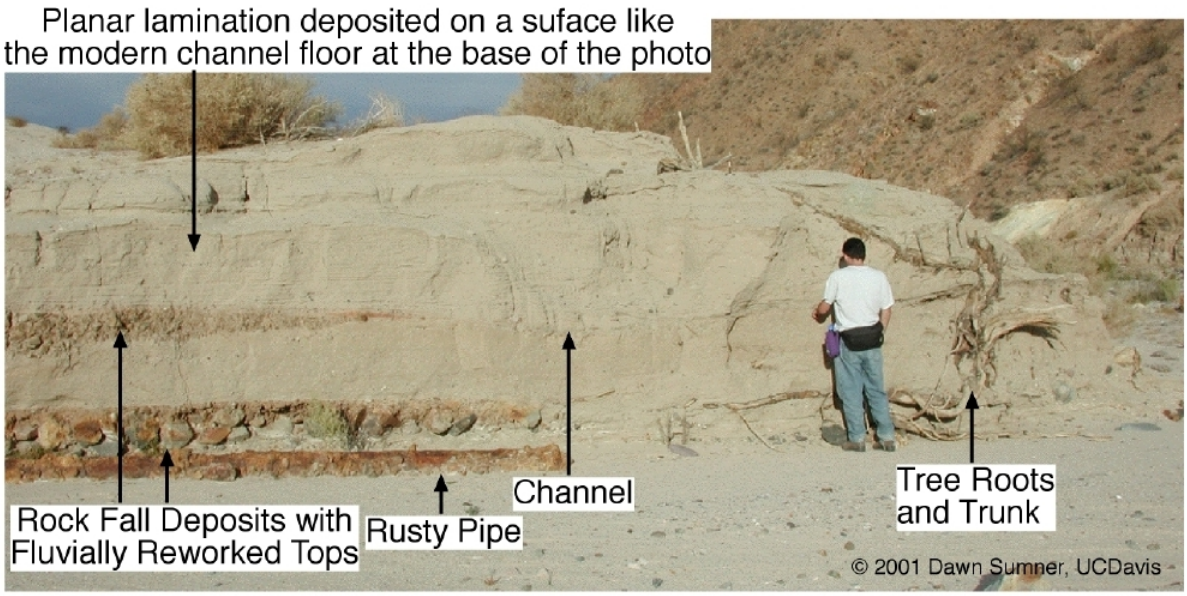


Figure 6.2.7.11***:*** *Recent Alluvial Deposits (Terrace at Redrock State Park, CA)*

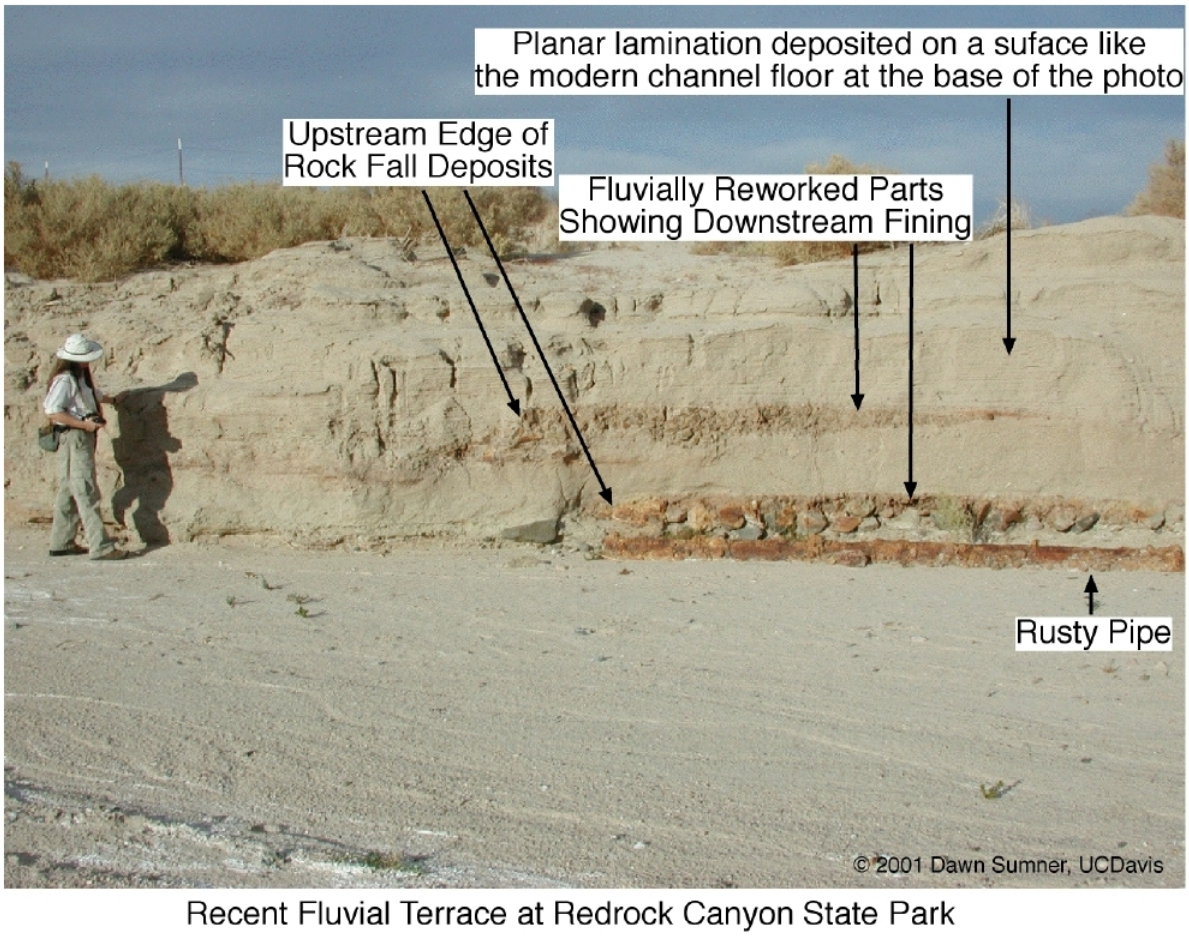


Figure 6.2.7.12***:*** *Recent Alluvial Deposits (Terrace at Redrock State Park, CA)*

Alsek River, Alaska (photo taken by Jeff Mount)
The sediment in this river bank was deposited by either migrating river bars or subaqueous dunes. Note the variations between higher-angle cross strata (black arrows) and the overlying lower-angle strata (above the erosional surface marked by the green arrow). A bounding surface between two sets of cross stratification is marked by a red arrow.

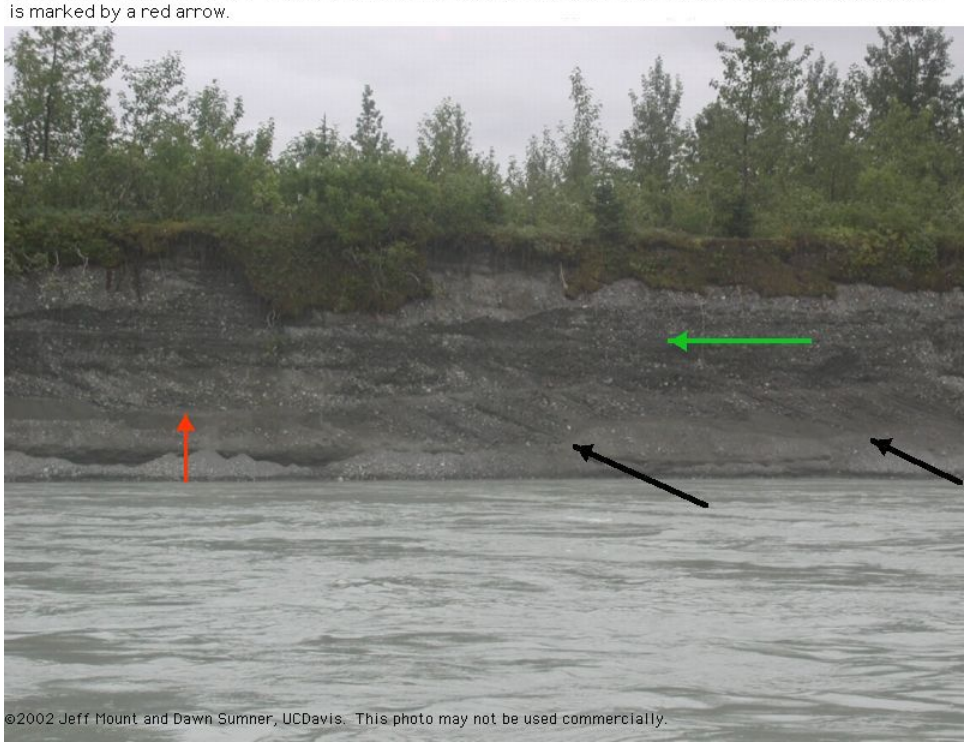


Figure 6.2.7.13***:*** *Recent Fluvial Deposits (Alsek River, Alaska)*

Fluvial cross stratification due to channel bar migration. The marmot is about 25 cm in diameter. Southern Canadian Rockies.



Figure 6.2.7.14***:*** *Stratification Due to Bar Migration*

Fluvial cross stratification due to bar migration and channel fill, southern Canadian Rockies. Marmot is about 30 cm tall at the shoulder.



Figure 6.2.7.15***:*** *Same outcrop as above, but also showing channel fill deposits above the sandstones deposited by the bar.*

Quarry Near Oberlin, OH

This quarry wall contains fluvial sandstones. The vegitated bounding surfaces (black arrows) were the bases of channels that were filled by migration of river bars. The green arrow points to some bar stratification.



Figure 6.2.7.16***:*** *Quarry wall showing fluvial cross stratification, probably due to channel migration and bar accretion.*

Quarry Near Oberlin, OH
This quarry wall contains fluvial sandstones. The vegitated bounding surfaces (black arrows) were the bases of channels that were filled by migration of river bars. The green arrow points to some bar stratification.



Figure 6.2.7.17***:*** *Extension of the same quarry wall as above*

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Dune Cross Stratification

(that does not fit nicely into a specific category)

Quarry Near Oberlin, OH

These sandstones were deposited by a river. This photo shows a climbing dune that migrated to the right. It was part of a river bar that infilled a river channel. Black arrow points to the dune; green arrow to base of channel.



Figure 6.2.7.18***:*** *Climbing Dunes*

Pennsylvanian to Permian Bird Spring Formation, CA



Remnants of the toe of a subaqueous dune are preserved in grey carbonate and reddish quartz sand.

Figure 6.2.7.19***:*** *Ancient Dune Cross Stratification*



Figure 6.2.7.20***:*** *Cross Stratified Gravel*

Vasquez Formation, Transverse Ranges, CA

Note the sharp contact between the underlying shale and the overlying coarse, graded bed. Faint cross stratification is present in the coarser bed and overlying sand. This style of deposition is consistent with fluvial deposition, which is the broader interpretation of the Vasquez Formation.



Figure 6.2.7.21***:*** *Graded bedding with faint cross stratification deposited in a fluvial channel*

Pebble Beach near Pescadero, CA

Coarse sand to pebble cross stratification filling a submarine fan channel in the Cretaceous Pigeon Point Formation. The pitted weathering (black arrow) is due to differential cementation and reflects diagenetic processes rather than depositional processes.



Figure 6.2.7.22***:*** *Cross stratification in a channel fill in a subaqueous turbidite fan*

Pebble Beach near Pescadero, CA

Coarse sand to pebble cross stratification filling a submarine fan channel in the Cretaceous Pigeon Point Formation. The pitted weathering (black arrow) is due to differential cementation and reflects diagenetic processes rather than depositional processes.



***Figure** 6.2.7.23**:** Cross stratification in a channel fill in a subaqueous turbidite fan*

Return to Sedimentary Structures

The following photographs are of large-scale cross stratification that was deposited by the migration of giant dunes and/or large fluvial bars. Detailed analysis of the regional characteristics of these deposits would be required to distinguish between dune and bar deposition in many cases, and both might be present.

Park near Oberlin, OH

This large-scale cross stratification was deposited by migration of a river bar. It had ripples migrating across its surface as demonstrated by the small-scall cross lamination, visable here as undulating laminae (arrows).



***Figure** 6.2.7.24**:** Large Cross Stratification*

Park near Oberlin, OH

This large-scale cross stratification was deposited either by migration of a large subaqueous dune or migration of a river bar. If it was deposited on a bar, no smaller dunes were present as demonstrated by the lack of smaller-scale cross stratification. Arrow points to a bounding surface.



Figure 6.2.7.25***:*** *Large Cross Stratification*

Quarry near Oberlin, OH

These fluvial sandstones were deposited by a migrating river bar. Note that the layers in the bar (black arrow) continue to the channel floor (red arrow). Dune cross stratification is also present at the base of the photo (green arrow). (One of two photos of this bar.)

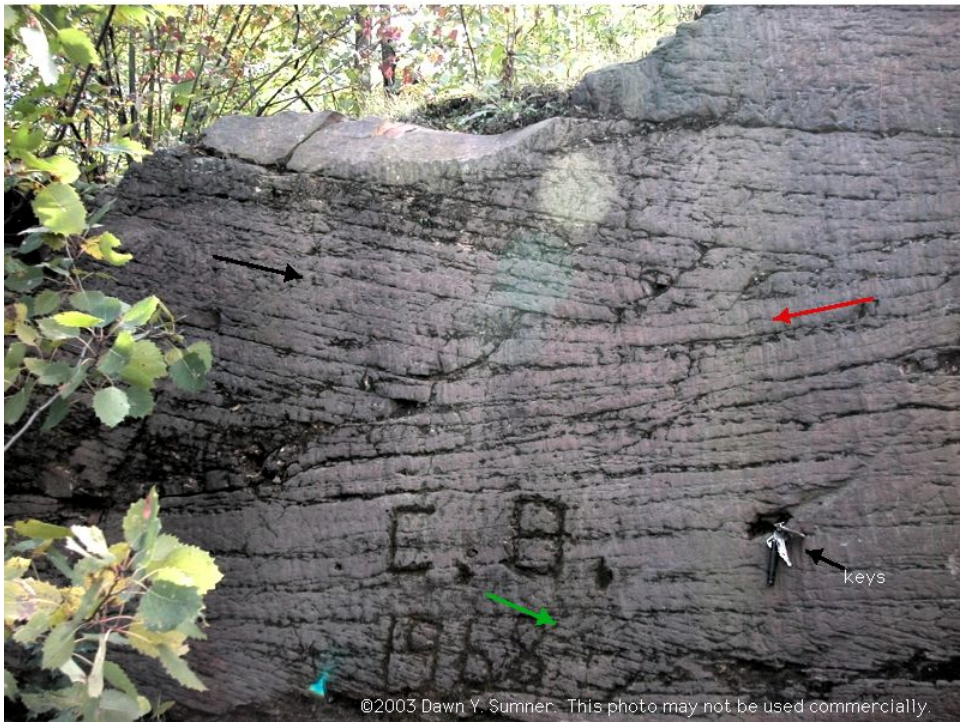


Figure 6.2.7.26***:*** *Cross stratified sediment deposited by a migrating bar based on the abundance of more planar laminae that would be characteristic of a channel bottom.*

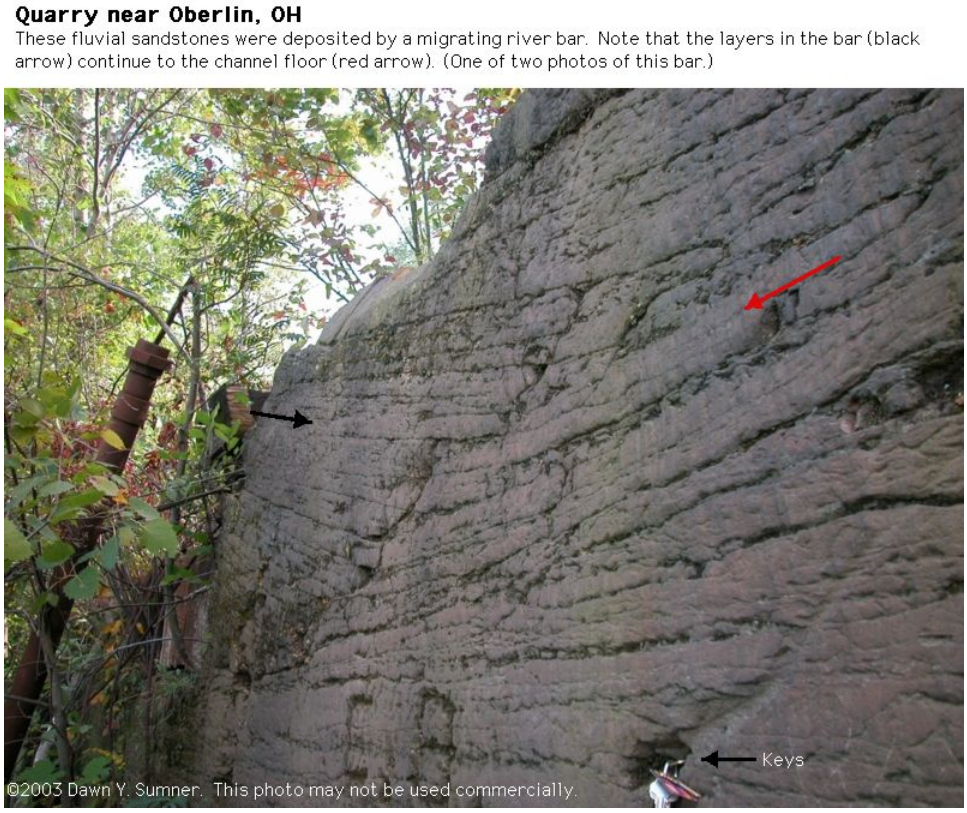


Figure 6.2.7.27***:*** *Different view of the bedform in the previous photo*

Return to Sedimentary Structures

The following photographs were taken by Jeff Mount during his Roy Shlemon Course in Applied Watershed Science class trip down the Copper River, Alaska and Yukon (see the Shlemon class web page). The river shown below was dammed by ice from the toe of a glacier, which created a very large lake. The ice dam broke catastrophically, producing a huge flood. The flood waters transported very large volumes of sediment in huge dunes. After normal river processes resumed, the river eroded into the flood deposits, exposing the cross stratification in these impressive dunes.

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
The Kaskawulsh River was temporarily dammed during rapid advance of a glacier. The glacial ice created the dam and a large lake formed. This photograph shows beach terraces from the ancient lake (black arrows).



Figure 6.2.7.28***:*** *Lake shoreline terraces from the lake*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
The Kaskawulsh River was dammed by ice from a glacier, which created a large lake. Beach ridges are visible in the middle of this photo (green arrows). When the ice dam broke, sediment was transported downstream very rapidly in large dunes. The cross stratification (black arrows) in the river bank may have been deposited by migration of these dunes. The high on the bank may be a remnant of a dune crest (red arrow).

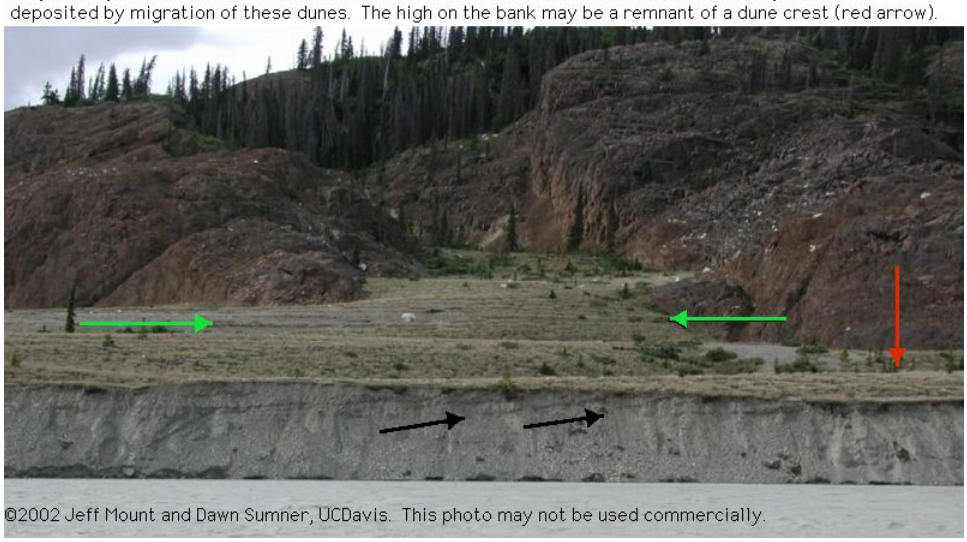


Figure 6.2.7.29***:*** *Lake shoreline terraces from the lake and cross stratification in the river bank. This cross stratification may have been deposited by the flood waters.*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
When an ice dam on the river broke, the lake water flowed extremely rapidly downstream, eroding and then depositing large volumes of sediment. The remnants of very large dunes are preserved both as large cross stratification and as bedforms, which are visible on this island in the river. Green arrows point to troughs.

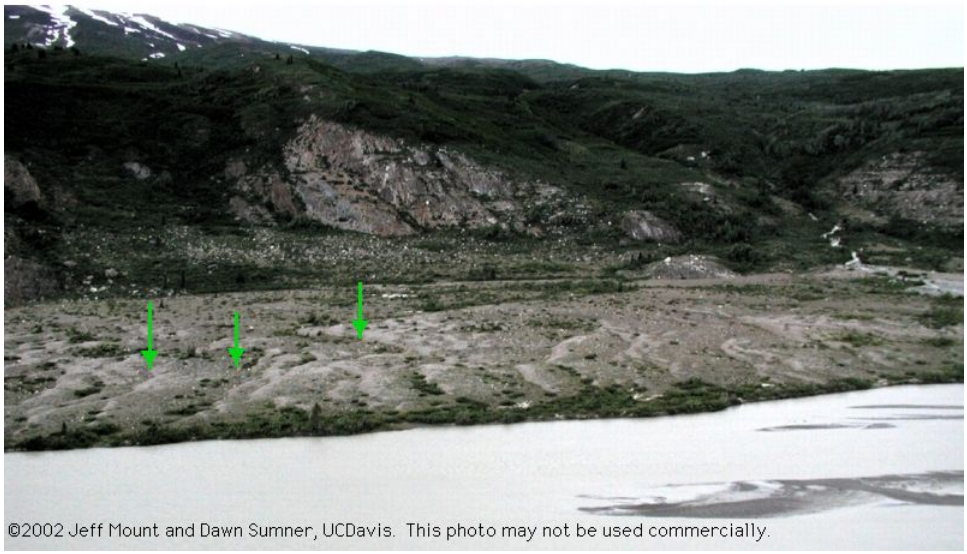


Figure 6.2.7.30***:*** *Remnants of giant dunes that migrated during the flood*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)
During a flood due to the breaking of an ice dam, very large dunes deposited the sediments in this river bank. Cross strata extend almost the full height of the bank (black arrow). The remnants of large bedforms are present (green arrows indicate troughs), but they are much shorter than the maximum height of the dunes.



Figure 6.2.7.31***:*** *Large dune cross stratification and remnants of giant dunes*

Kaskawulsh River, Yukon (photo taken by Jeff Mount)

When an ice dam on the river broke, large dunes deposited the sediment in the river terrace. The remnants of the bedforms can be seen at the top of the bank (green arrows indicate troughs).

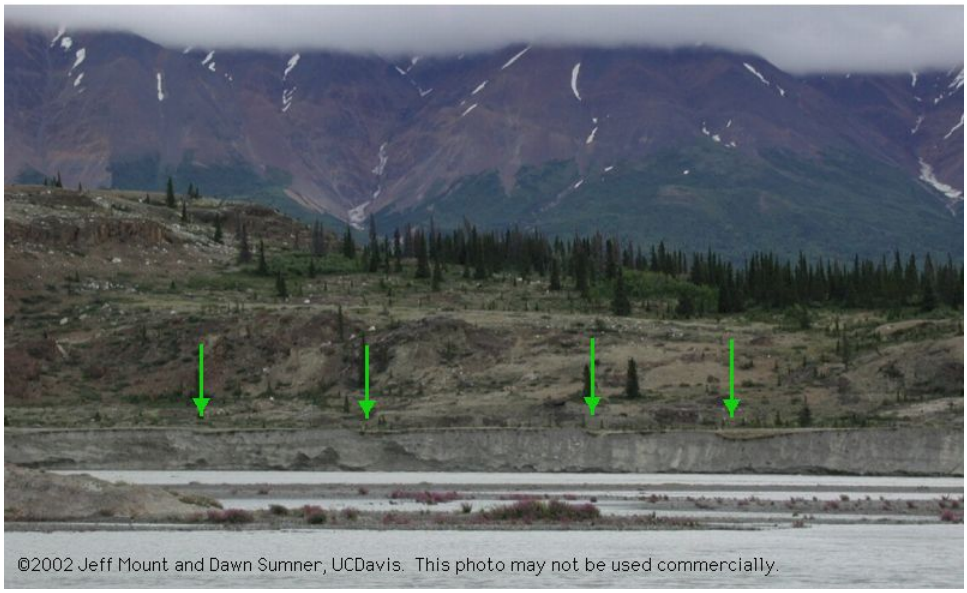


Figure 6.2.7.32***:*** *Large dune cross stratification and remnants of giant dunes*

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6.2.8: Subaqueous Ripples and Cross Lamination

Current Ripples

Pescadero Beach, CA

Current ripples formed when creek flow was amplified by tidal run-off from the Pescadero estuary. Which direction was the current flowing? How irregular was the flow?



Figure 6.2.8.1***:*** *Modern Current Ripples*

Current Ripple Laminations



Where are the depositional laminae?
Where are the erosional surfaces on the upstream sides of the ripples?
Which direction was the water flowing?

Figure 6.2.8.2***:*** *Current Ripple Lamination*

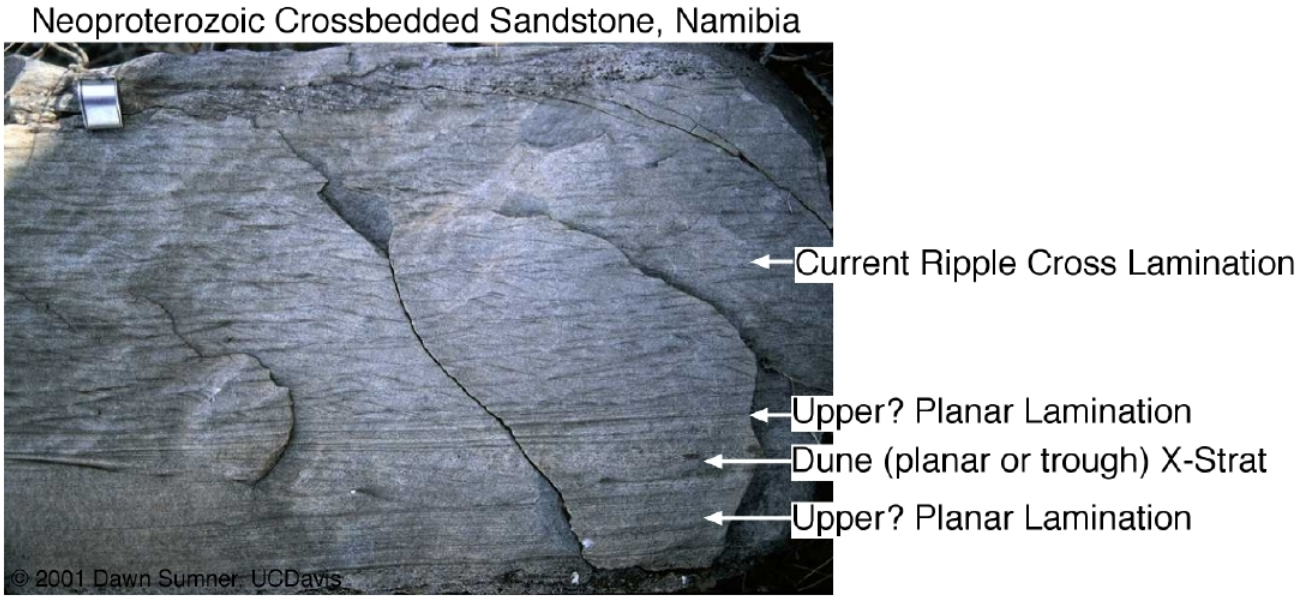


Figure 6.2.8.3***:*** *Ancient Current Ripple and Planar Lamination*

Pebble Beach near Pescadero, CA

Slightly deformed current ripple lamination deposited from a turbidite and preserved in the Cretaceous Pigeon Point Formation. A few burrows are also present (black arrows).



Figure 6.2.8.4***:*** *Ancient current ripple lamination that is slightly deformed*

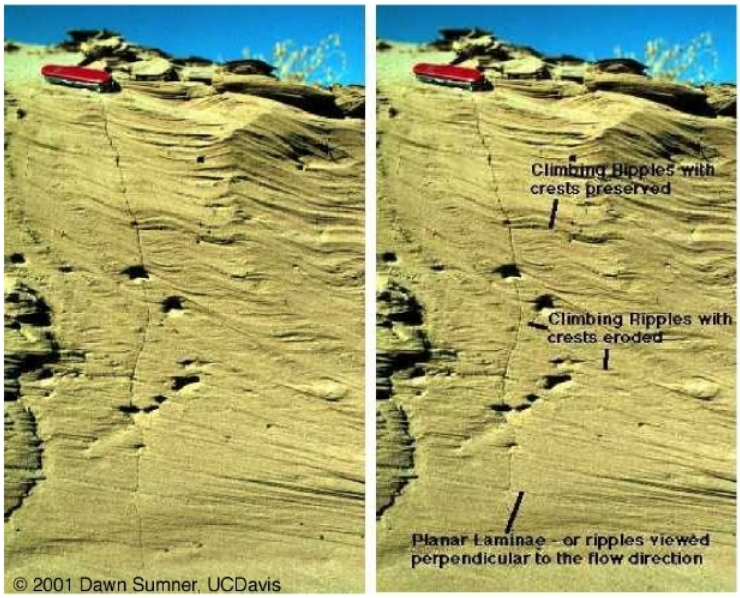
Pebble Beach near Pescadero, CA

Slightly deformed current ripple lamination deposited from a turbidite and preserved in the Cretaceous Pigeon Point Formation. Bioturbation is locally abundant (black arrow).



Figure 6.2.8.5***:*** *Ancient current ripple lamination that is slightly deformed and burrowed*

Modern Climbing Ripples, Fish River Canyon, Namibia



These ripples were probably deposited by a high water flow at the bend in the river. A small spring cut through this unconsolidated sand exposing the ripples.

Figure 6.2.8.6***:*** *Climbing Ripple Lamination*

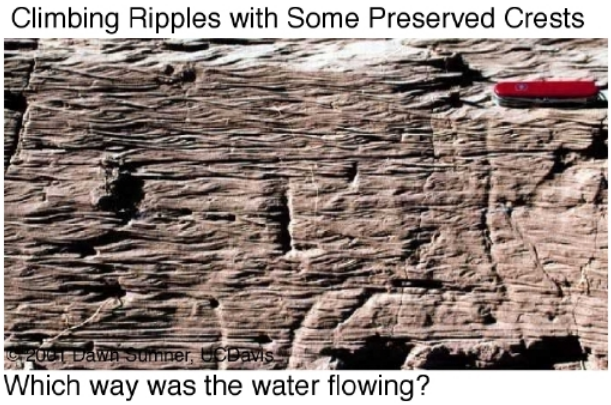


Figure 6.2.8.7***:*** *Climbing Ripple Lamination*

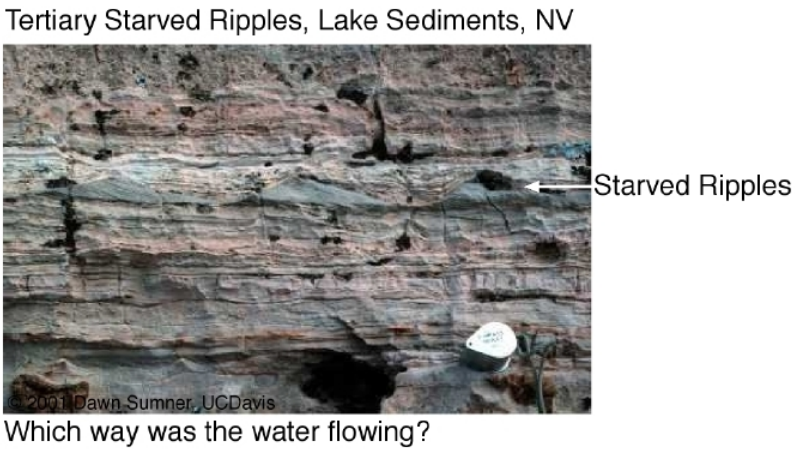


Figure 6.2.8.8***:*** *Starved Ripples*

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Modern Wave Ripples, Broome Town Beach, Western Australia



Ripple crests were flattened as the water drained off the tidal flat.

Figure 6.2.8.9***:*** *Modern Wave Rippples - Broome Beach*

Modern Wave Ripples, Broome Town Beach, Western Australia



Figure 6.2.8.10***:*** *Modern Wave Rippples - Broome Beach*

Modern Wave Ripples, Broome Town Beach, Western Australia



Ripples are disrupted by crab bioturbation (mounds of sand).

Figure 6.2.8.11***:*** *Modern Wave Rippples - Broome Beach*

Waves and resulting wave ripples, Lake Louise, southern Canadian Rockies. Note the difference in wavelength between the waves and the ripples. Ripple size depends on flow speed and grain size at the sediment surface.



Figure 6.2.8.12***:*** *Modern Wave Ripples and Waves - Lake Louise*

Very small wave ripples, Lake Louise, southern Canadian Rockies



Figure 6.2.8.13***:*** *Small Modern Wave Ripples - Lake Louise*

Eocene Ripples on a Lake Bedding Surface, CA



These ripples are probably wave ripples based on their almost symmetric crest profile and their linear extent. However, slightly steeper sides towards the top of the photo suggest final sediment transport was in that direction.

Figure 6.2.8.14***:*** *Ancient Wave Ripple Crests*

River flowing over much older sandstone near Oberlin, OH

The sandstones are rippled. The upper layer has interference ripples. Their small size suggests that the water was very shallow when they formed. The lower layer has wave ripples, which are also moderately small. Both were deposited in a lake or near-shore marine environment. (The modern river would produce current rippples.)



Figure 6.2.8.15***:*** *Ancient Wave Ripple Crests and Interference Ripple Crests*



Figure 6.2.8.16***:*** *Ancient Interference Ripple Crests*

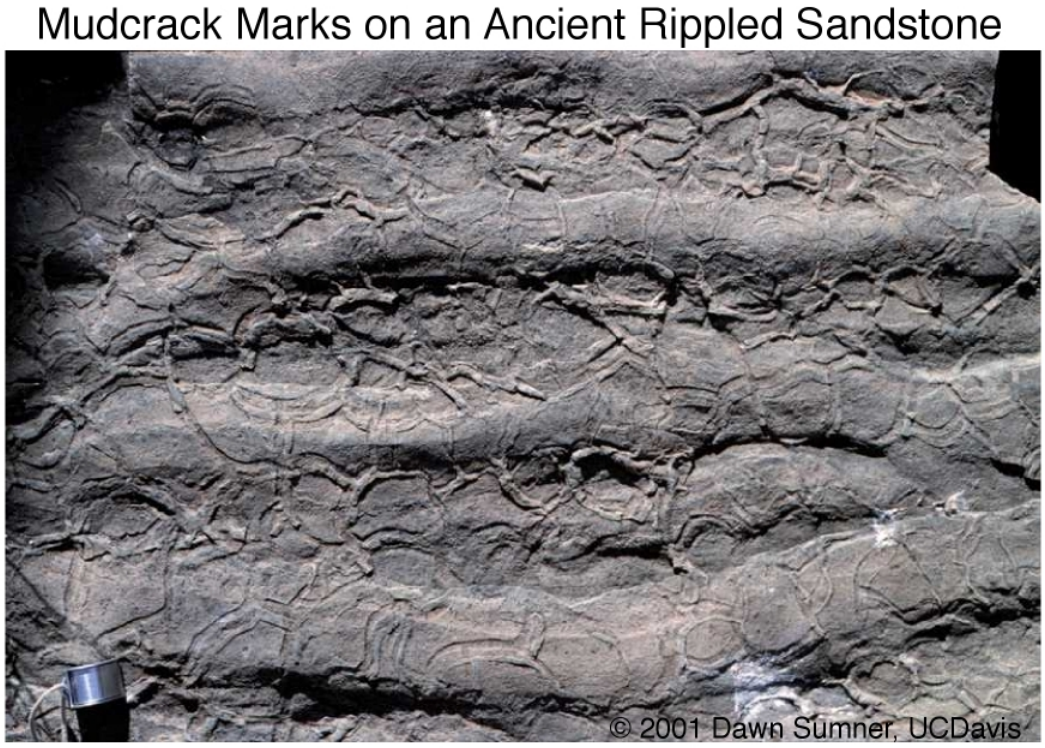


Figure 6.2.8.17***:*** *Ancient Wave Ripple Crests with Mud Cracks*

Archean Wave Ripples, Malmani Supgroup, South Africa



The symetric crests and laminae dipping in both directions demonstrates that these are wave ripples, as opposed to current ripples.

Figure 6.2.8.18***:*** *Ancient Wave Ripple Lamination*

Sandstones Near Oberlin, OH

Cross lamination in this sandstone is typical of wave ripple migration and aggredation.



Figure 6.2.8.19***:*** *Ancient Wave Ripple Lamination*

Wave rippled sandstone interbedded with shale and sandstones with mud chips; Belt Supergroup, southern Canadian Rockies.



Figure 6.2.8.20***:*** *Ancient Wave Ripple*

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Current and Wave Cross Lamination

Sandstones Near Oberlin, OH

Cross lamination in near-shore marine to fluvial sandstones showing indications of both current ripple migration and wave ripple aggredation near the base of the bed. Which is which? Hand lens is 2 cm across.



Figure 6.2.8.21***:*** *Ancient Ripple Lamination*



Figure 6.2.8.22***:*** *Ancient Wave Ripple Lamination and Hummocky Cross Stratification*

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6.2.9: Turbidites

Turbidites in the Cretaceous Pigeon Point Formation

Pebble Beach near Pescadero, CA

This photo shows some turbidites deposited on a submarine fan in the Cretaceous Pigeon Point Formation. An erosional surface (black arrow) is overlain by a normally graded bed. Ripple lamination is visible in a lower bed (green arrow).



Figure 6.2.9.1***:*** *Various Parts of the Bouma Sequence*

Pebble Beach near Pescadero, CA

These turbidites, in the Cretaceous Pigeon Point Formation, show faint current ripple cross laminations (black arrow), flame structures (green arrow), planar lamination (red arrow), and contorted ripple(?) laminae (white arrow).

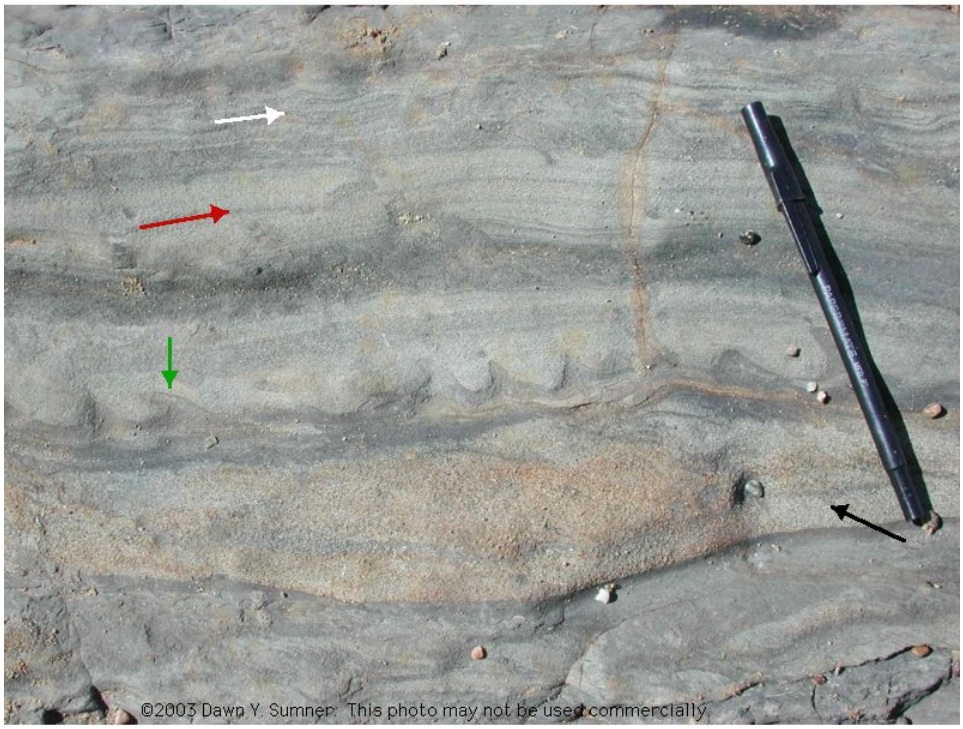


Figure 6.2.9.2***:*** *Thin Turbidites*

Pebble Beach near Pescadero, CA

These sands to shales are part of a turbidite fan in the Cretaceous Pigeon Point Formation. In this photo, sand-filled burrows (black arrows) are abundant, and flame-structures formed at the base of the upper sand layer (green arrow).

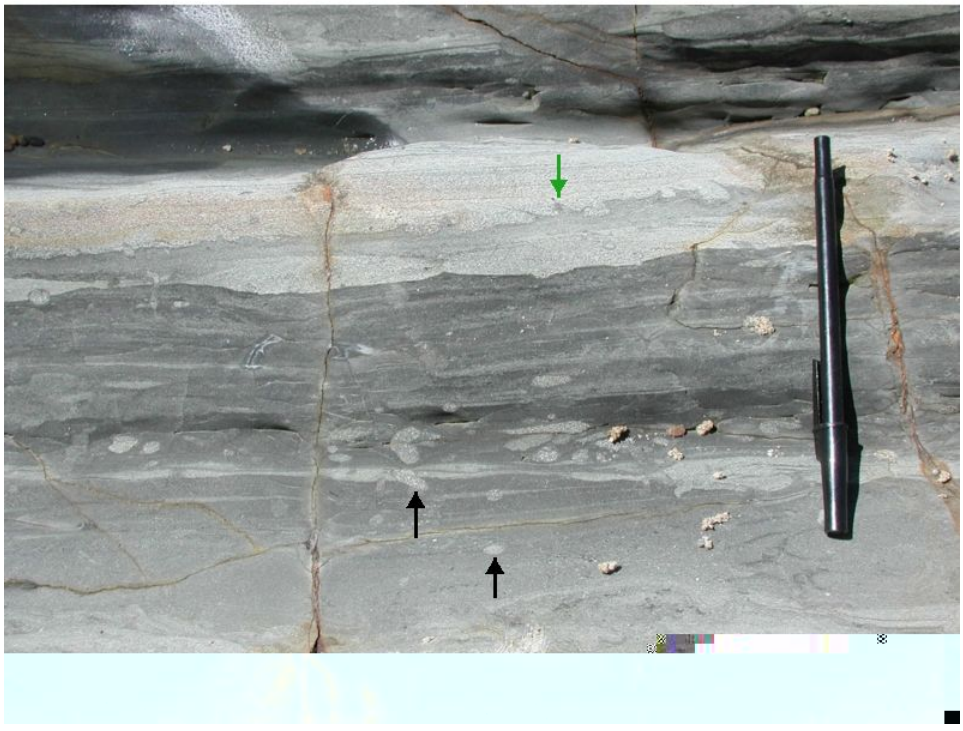


Figure 6.2.9.3*: Coarser Sediment Overlying Shale*

Pebble Beach near Pescadero, CA

These flame structures formed where turbidites were deposited over shaley layers in the Cretaceous Pigeon Point Formation.



Figure 6.2.9.4*: Turbidites*

Pebble Beach near Pescadero, CA

This is a small channel in the Cretaceous Pigeon Point Formation. A turbidite current eroded the channel (base indicated by the black arrow), and as the flow slowed, it deposited the granules to coarse sands that infilled the channel.



Figure 6.2.9.5***:*** *A small channel in a more proximal part of the turbidite fan*

Pebble Beach near Pescadero, CA

In this photo of turbidites in the Cretaceous Pigeon Point Formation, flame structures are abundant where sandstones were deposited over shale (black arrow). Larger load structures formed where very coarse to granular sand was deposited over medium sand (white arrow). A closer photo of the flame structures is also available on this web site.



Figure 6.2.9.6***:*** *Granular sized sediment at the base of a turbidite*

Pebble Beach near Pescadero, CA

Pebbles were deposited in channels in the submarine turbidite fan preserved in the Cretaceous Pigeon Point Formation. Thier presence demonstrates that rapid flows were common in this part of the fan, probably due to steep, tectonically active slopes.



Figure 6.2.9.7***:*** *Pebbles in the base of a turbidite*

Pebble Beach near Pescadero, CA
Granular sandstone with large shale clasts were deposited on an erosional surface in a submarine fan in the Cretaceous Pigeon Point Formation. Black arrow points to a shale clast.



Figure 6.2.9.8***:*** *Mud clasts and pebbles in the base of a turbidite*

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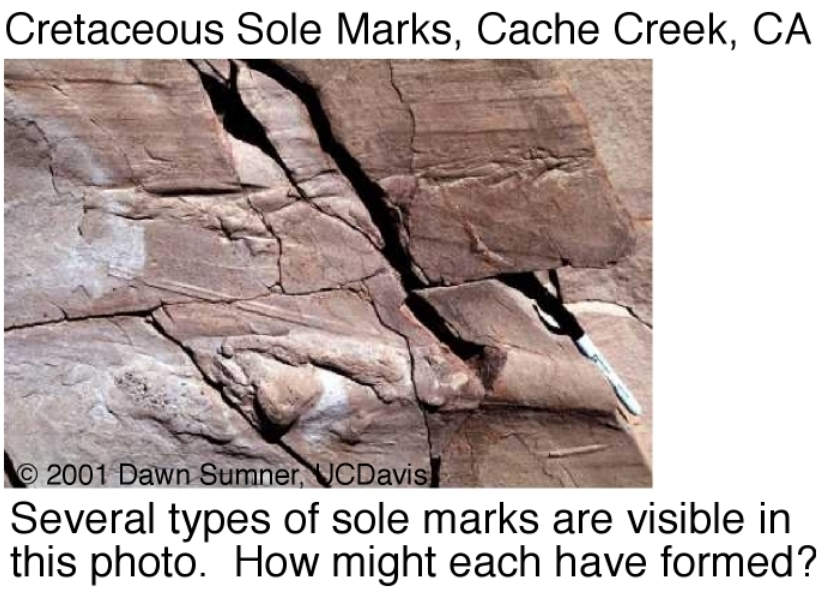


Figure 6.2.9.9***:*** *Sole Marks on the base of a turbidite*



Figure 6.2.9.10***:*** *Sole Marks on the base of a turbidite*

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6.2.10: Wave Ripples in Sediment

Waves and resulting wave ripples, Lake Louise, southern Canadian Rockies. Note the difference in wavelength between the waves and the ripples. Ripple size depends on flow speed and grain size at the sediment surface.



Figure 6.2.10.1: Waves and resulting wave ripples forming in Lake Louise, British Columbia.

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6.2.11: Wave Ripple Cross Lamination



Figure 6.2.11.1: The upper surface of this bed has preserved ripple crests that are almost symmetrical. Within the ripple, laminae dip both to the right and left. The dip of laminae in both directions within the preserved ripple, plus the nearly symmetrical shape, indicate that this ripple was formed by waves.

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6.2.12: Wind Transported Bedforms and Cross Stratification

Modern Coarse-grained Wind Ripples, Brazil



Strong winds produced these coarse wind ripples on a Brazilian beach. Which characteristic (besides location) allowed me to identify them as wind ripples? Which way was the wind blowing?

Figure 6.2.12.1***:*** *Modern coarse-grained wind ripples*

Modern Coarse-grained Wind Ripples, Brazil



In this close view, you can more clearly see the difference in grain size between the troughs and the crests.

Figure 6.2.12.2***:*** *Modern coarse-grained wind ripples*

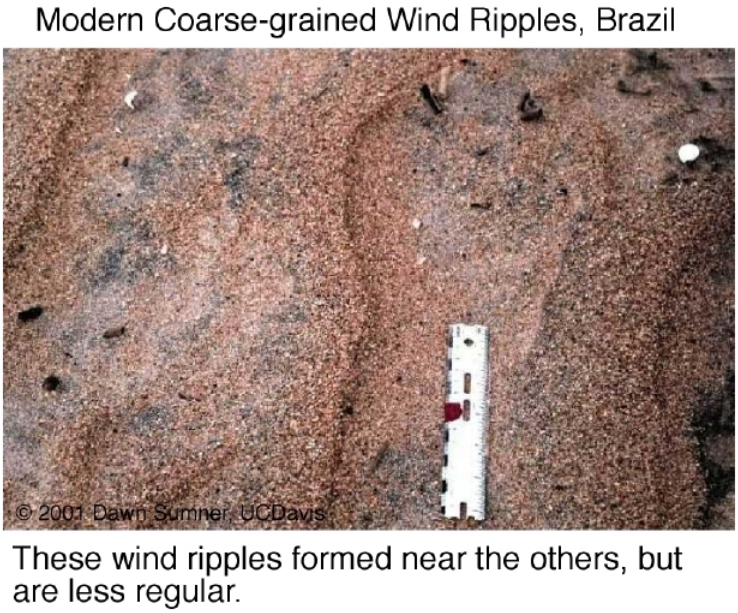


Figure 6.2.12.3***:*** *Modern coarse-grained wind ripples*

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CHAPTER OVERVIEW

7: Lab Materials

7.1: Broome Town Beach Sample Descriptions

7.2: Lake Wanaka Area Samples

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7.2.2: Samples 5-7

7.2.3: Samples 8 and 9

7.3: Sedimentary Structures

7.3.1: USGS Bedform Movie Explanation

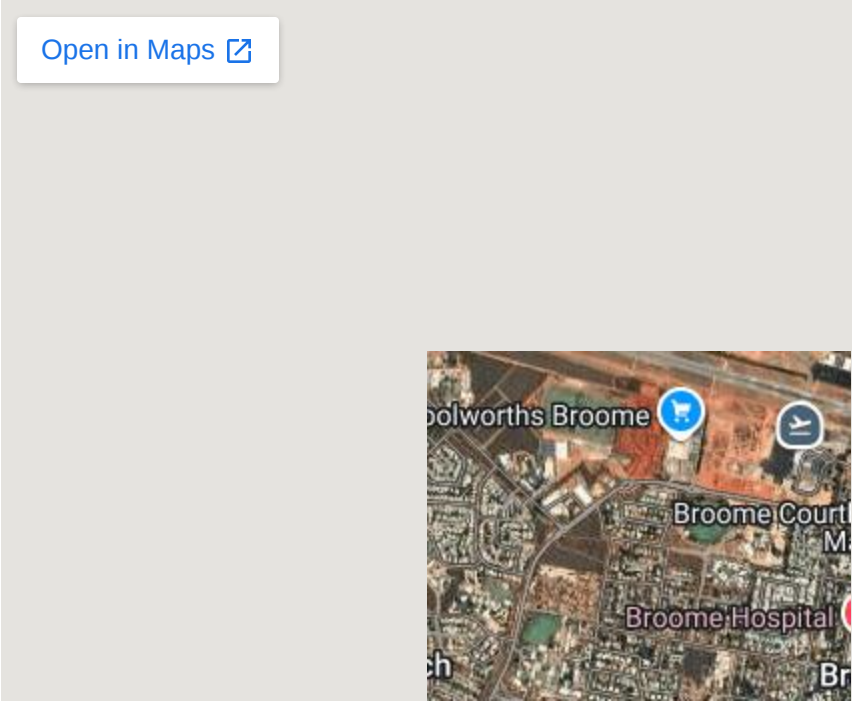
7.4: Carbonates

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7.1: Broome Town Beach Sample Descriptions

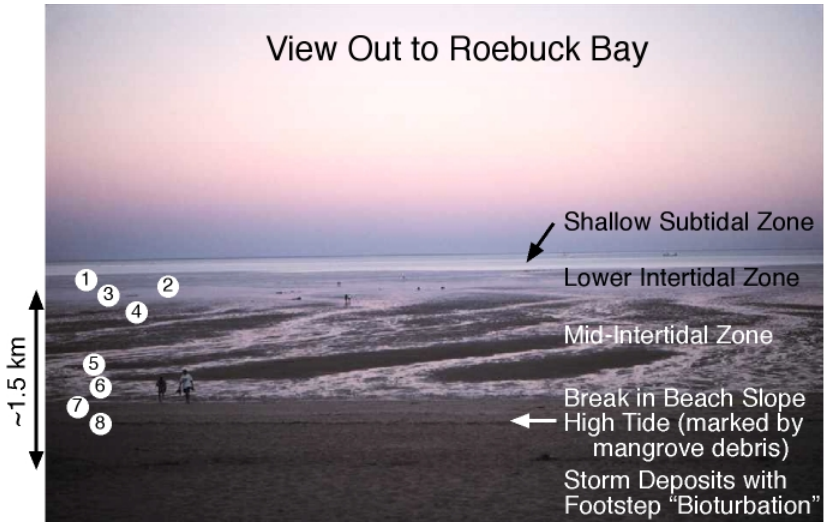
Interpretation of Broome Town Beach Samples

The town of Broome is located in Western Australia (Maps from http://ebroome.com/tourism/).

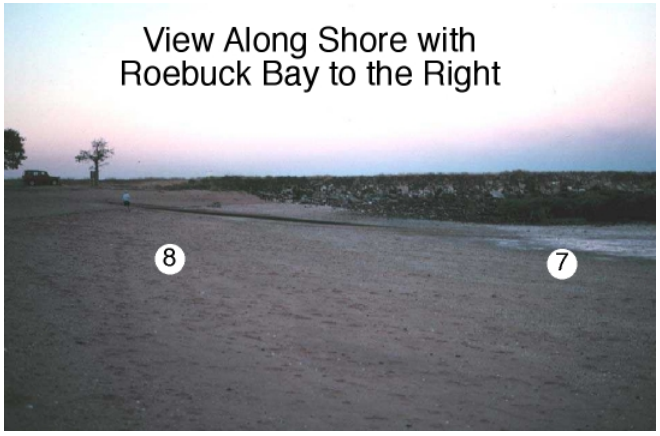


View Larger Map

I collected a suite of samples for your lab from the Town Beach at a very low tide. They are marked by the circled numbers in the photograph, and the depositional environments are also labeled.



The tidal range on this beach is about 10 m, and it has very small waves because it is protected on one side by a spit and the other by a grove of mangroves that extends into the water. A view of the shore-ward end of the spit also shows the slope of the beach face where waves break at high tide.



Sediment dispersal on the steep part of the beach is dominated by waves swashing back and forth (plus summer storms - but these photos and samples were taken during their winter). Sedimentation in the flatter parts of the beach are dominated by tidal currents, the back-and-forth currents produced by small waves impinging on the sediment surface at high tide, and the run-off of water in irregular channels at low tide. The waves produce wave ripples from near the break in slope in the shelf to more than 1.5 km off shore across a nearly flat intertidal zone. The speed of these currents is lower in deeper water, so the ripples tend to be smaller and the grain sizes finer farther off shore where the water is deepest at high tide. The following thumbnail photos show these ripples at different distances from shore.



This is a view of the tidal flat at about sample 4. Note that the ripples are linear and flat-topped. Their linear character is due to a consistent wave direction. Their tops were flattened when the water drained off the flat as the tide fell. At high tide, they would have had peaked crests.



This photo shows both current ripples (in front) and wave ripples (in back). It was taken looking across a shallow channel with water flowing from the shore to the bay at low tide across the mid-intertidal zone.



This is a closer view of the wave ripples in the mid-intertidal zone. Their tops are only slightly rounded. Note the dark line on the right side of each ripple. It marks the edge of sand that slipped down the ripple slope and indicates that the last sand transport on the ripple was to the right. The larger chuncks sitting on the sand and the white areas are shells of organisms that live in this environment. Their shells are too big and heavy for the slight wave currents to wash them out of this environment. The "crators" in the ripples are probably crab burrows and the line running across the top of the photo is another trace fossil.



These ripples, which are transitional between wave and interference ripples, are near the lower intertidal zone. The texture of the shoe prints preserves the sole texture, which suggests a large fraction of mud is present in the sediment. The "crators" are crab

burrows.

Sample Descriptions from the Field

Sample BR7-00-1

- Sed Structures: interference ripples
- Fauna: abundant worms with feathery feeding apendages (1-3 cm in diameter), chitinous tube worms, some snails, some crabs, abundant tracks on the sediment surface

Sample BR7-00-2

- Sed Structures: in slow-moving tidal channel with current ripples; sediment outside of channel is similar to sediment of sample BR7-00-1
- Fauna: worms with feathery feeding apendages (1-3 cm in diameter), chitinous tube worms, snails, crabs, some sea anenomies

Sample BR7-00-3

- Sed Structures: not recorded - flat surface?; sediment felt soft underfoot
- Fauna: u-shaped worms that lie burried in the sediment and squirt water, abundant chitinous tube worms, abundant and active snails and crabs

Sample BR7-00-4

- Sed Structures: wave ripples; sediment felt coarser underfoot (I was barefoot). This site marks the first distinct coarsening of grain size towards shore.
- Fauna: common agglutinated 1 cm-diamter tube worms, abundant crabs, u-shaped worms present and decrease in abundance shoreward

Sample BR7-00-5 (collected about 200m from high tide mark)

- Sed Structures: wave ripples
- Fauna: agglutinated tube worms

Sample BR7-00-6 (collected about 5m seaward of break in beach slope)

- Sed Structures: wave ripples
- Fauna: not recorded - none observed?

Sample BR7-00-7 (in breaker zone at high tide)

- Sed Structures: smooth surface dipping seaward
- Fauna: not recorded - non observed?

Sample BR7-00-8 (collected at the high tide mark)

- Sed Structures: bioturbation by human footsteps (plus a few dog and bird footprints)
- Fauna: none observed (besides humans, dogs, and birds)

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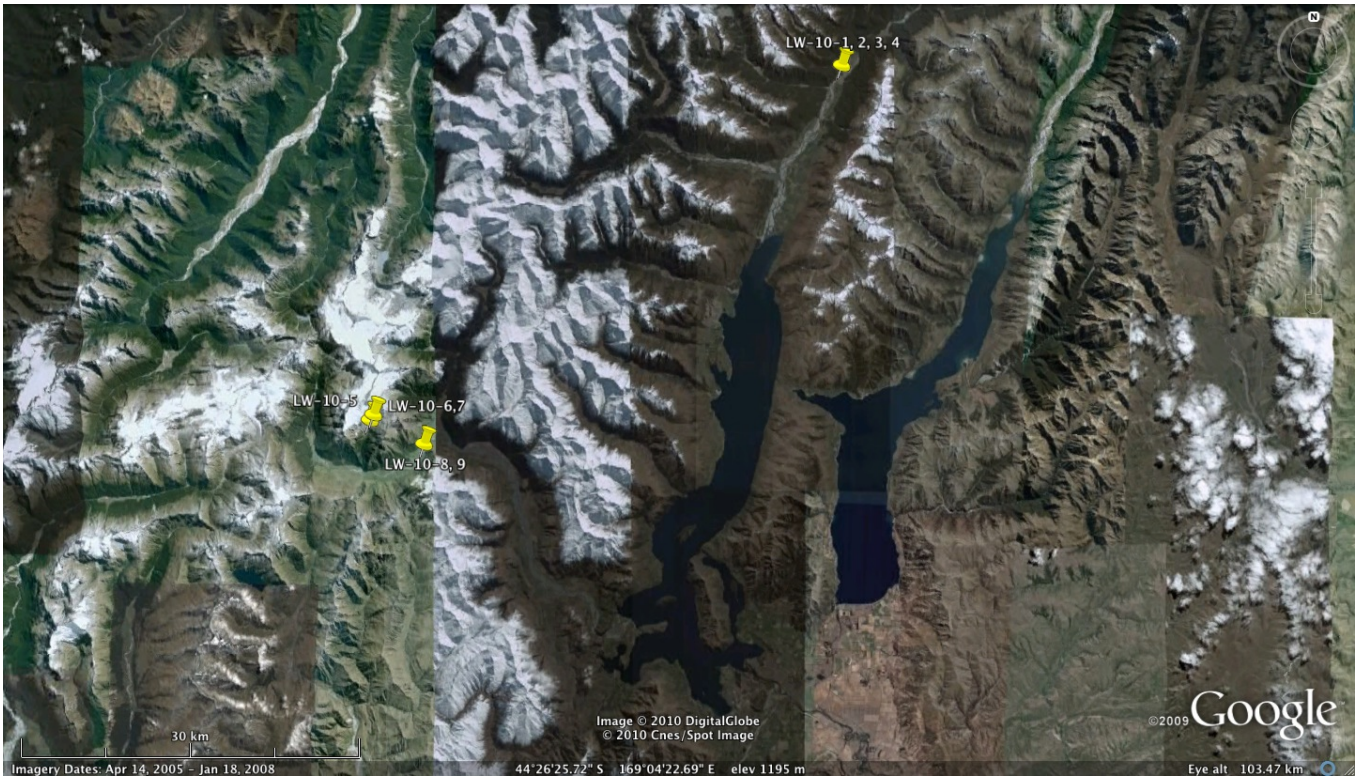
7.2: Lake Wanaka Area Samples

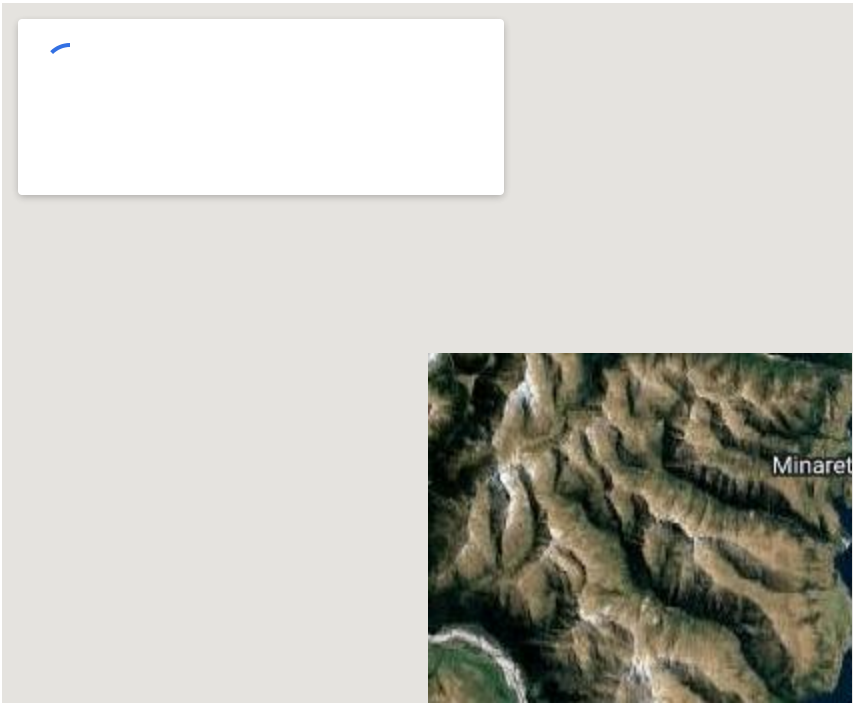
Interpretation of Lake Wanaka Area Samples

I collected a suite of samples for your lab from the Lake Wanaka area, New Zealand. This is a mountainous area with glaciers, mountain streams, braided rivers, and Lake Wanaka. The samples came from stream and river bars, with the exception of sample LW-10-5, which came from either a glacier morraine or a landslide deposit. It represents typical source sediment that is being eroded by the rivers (but includes only grains small enough to fit into the sample container). The following links provide context information for the samples.

- Samples 1-4
- Samples 5-7
- Samples 8, 9

Sample locations:





View Larger Map

You may find this video on Sediment Provenance helpful in answering some of the lab questions.



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7.2.1: Samples 1-4

Lake Wanaka Sample Descriptions for LW-10-1, LW-10-2, LW-10-3, and LW-10-4

Samples LW-10-1, LW-10-2, LW-10-3, and LW-10-4 were collected in the Makarora River, which drains the Southern Alps (GoogleEarth kmz file to download with location shown here).



It is a very large river with a large watershed and a substantial sediment supply. The high concentration of bedload sediment causes it to have a braided river morphology when the valley is wide enough. Sediment is supplied by the many tributary creeks as well as erosion of the valley walls. Here are some examples of the sediment supplied by erosion of the valley walls:



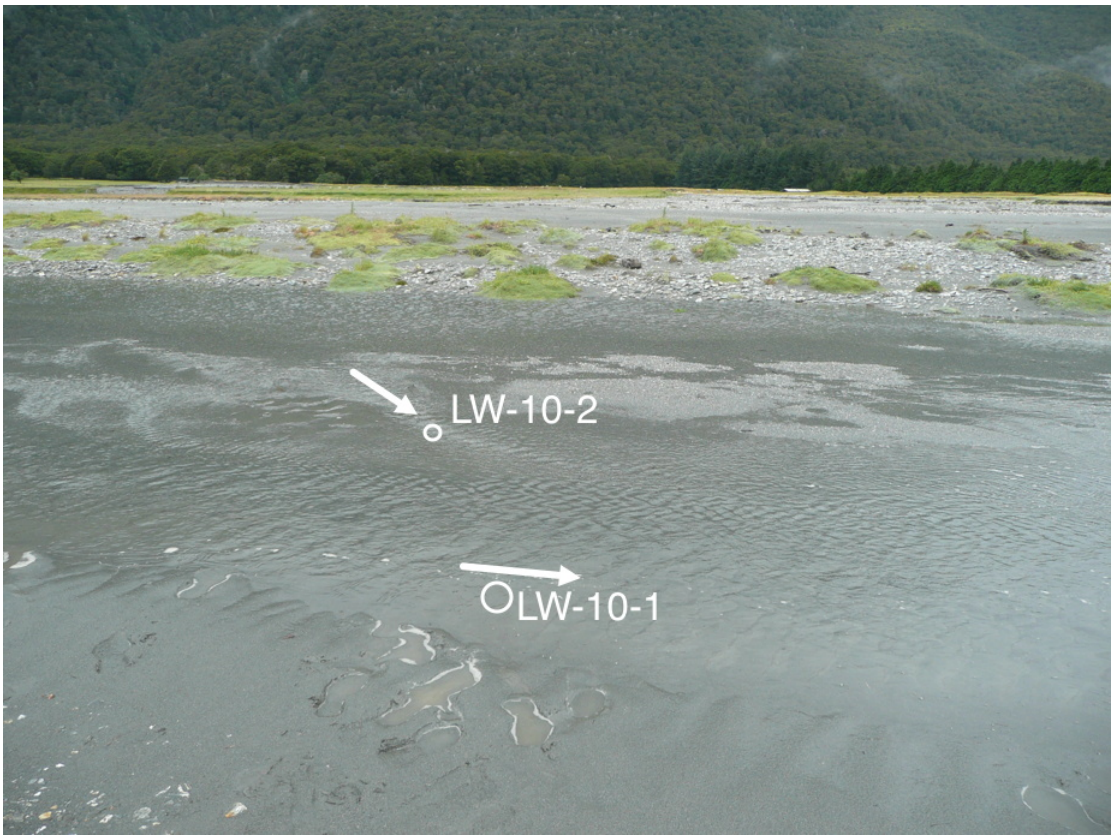
Some of this sediment falls directly into the river. There is a large difference in the rounding of sediment transported by the river and that recently supplied from the valley walls:





Newly introduced sediment joins that in the river. The lab samples were collected a few hundred meters downstream of the area shown in the last two images.

Samples LW-10-1 and LW-10-2 were collected on a river bar in an area with shallow flow of variable speed. White arrows show the flow direction.



Sample LW-10-1 was collected in an area with current ripples. The sand was barely being transported over the crests of the ripples. Pen for scale.



Sample LW-10-2 was collected in an area with a flat bed and higher flow speed than LW-10-1. Sand was being transported by the flow, and it was accumulating in shallower water areas with slower flow such as right at the pen. It may also have been accumulating in the downstream flow shadows of larger grains. Larger grains moved occassionally in the flow, but not frequently. Pen for scale.



Sample LW-10-3 was collected in an area with even higher flow speeds, between the two arrows indicating flow direction. Here, sand and finer grains were in suspension in the flow. Note how brown the water looks due to that suspended sediment. In several minutes of watching the flow, I saw only 2 cobbles move, so I do not think the flow was fast enough to have transported these grains into this location. Rather, they were probably deposited when the local flow speed was higher. Pen for scale.



Sample LW-10-4 was collected in an old channel that was partially blocked by migration of a coarse-grained bar, seen in the background of the next photo. The old channel had ponded water in it when the sample was collected. However, the grain size of the sample is too coarse to have been deposited in this environment. Thus, I interpret it to have been transported to this location when the water was flowing, with the possible addition of silt and clay-sized grains after the water stopped flowing. Pen for scale.



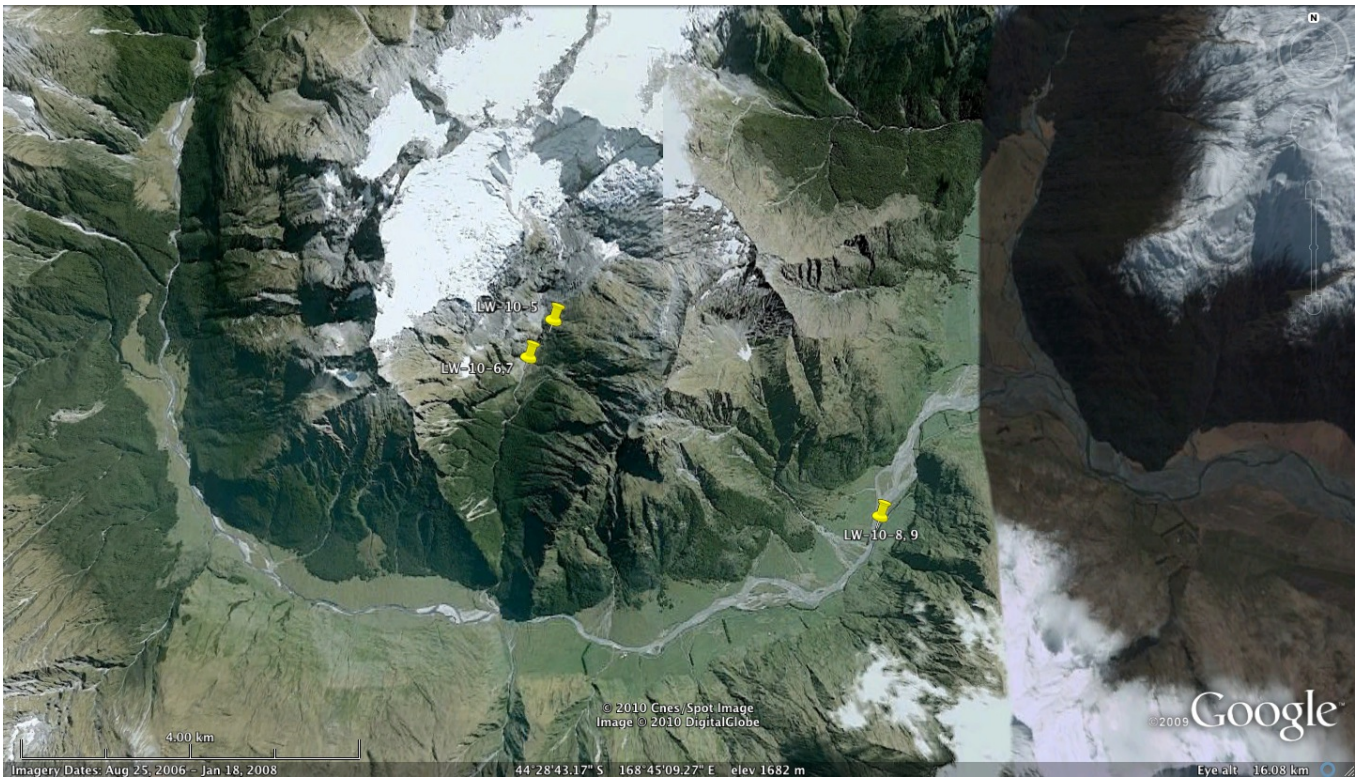
Return to Lab 1: Lake Wanaka Area Samples

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7.2.2: Samples 5-7

Lake Wanaka Sample Descriptions for LW-10-5, LW-10-6, and LW-10-7

Samples LW-10-5, LW-10-6, and LW-10-7 were collected near the headwater and in Rob Roy Stream (GoogleEarth kmz files for LW-10-5 and LW-10-6 and 7 as shown here).





The water comes from melting glaciers, and the water erodes sediment created by the glaciers, landslides, or weathering processes.

Sample LW-10-5 was collected on a very steep slope in an area with glaciers as well as landslides.





The sample consists only of the grains that could fit in the sample container; grains up to boulder-size were present in the deposit. There are two characteristics of this sample that you should note in your lab descriptions that indicate that the grains were neither transported nor deposited by flowing water. Rather, these two characteristics suggest that the sediment was transported by either a glacier or a landslide (debris flow?) and deposited as either the ice melted or the landslide stopped. This sediment is characteristics of the source area for sediment in Rob Roy Stream. Pen for scale.



Samples LW-10-6 and LW-10-7 were collected from the edge of Rob Roy Stream. The contrast in the grain size of these two samples suggests a change in flow speed through time. Field relationships (the grains from LW-10-7 overlie those of LW-10-6) suggest that sediment in LW-10-6 was deposited prior to that in LW-10-7. Changes in flow speed are very common in mountain streams. Also note how opaque the water is from a high concentration of suspended sediment. Pen between the two circles for scale in the first image. It is in the same location in the second image.





Also compare the level of rounding in LW-10-6 to that in sample LW-10-5. It is visible even in the photographs and even though the samples were collected only a few hundred meters apart.

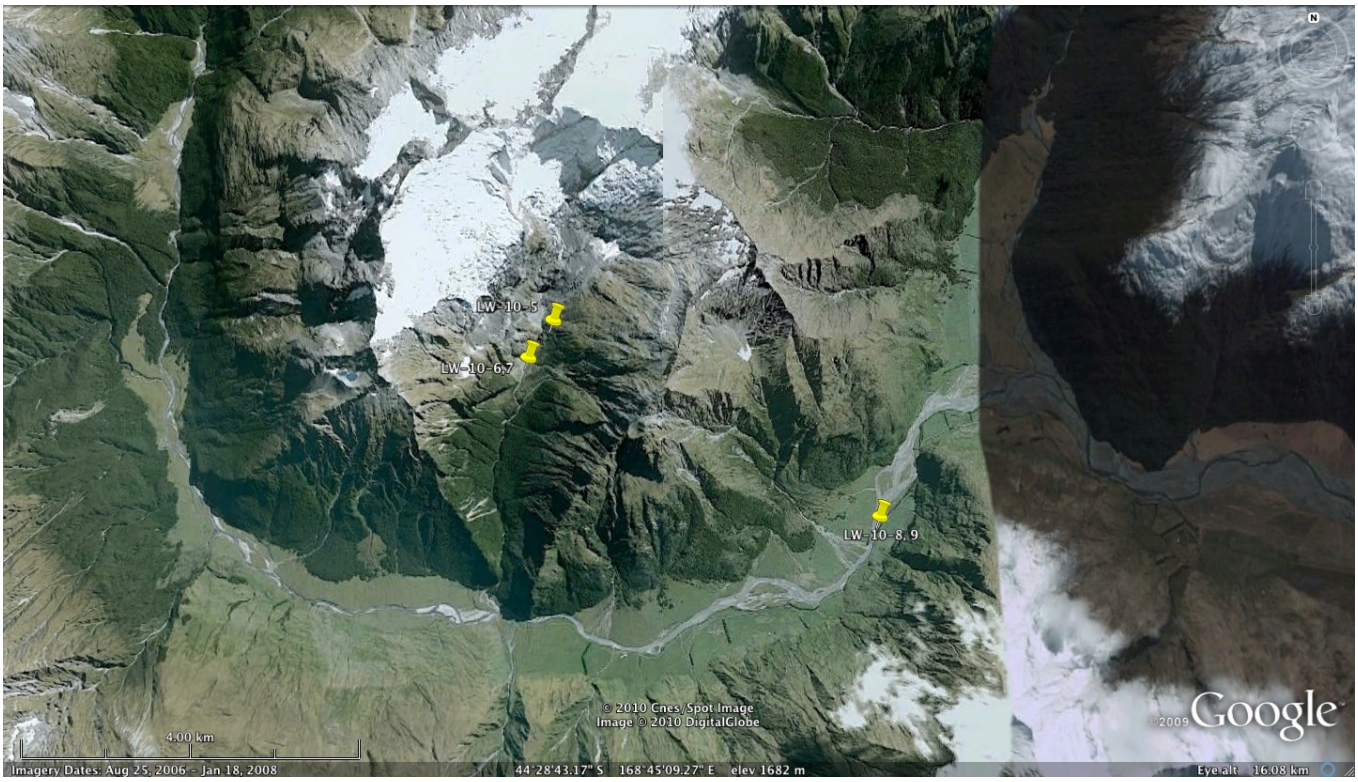
Return to Lab 1: Lake Wanaka Area Samples

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7.2.3: Samples 8 and 9

Lake Wanaka Sample Descriptions for LW-10-8 and LW-10-9

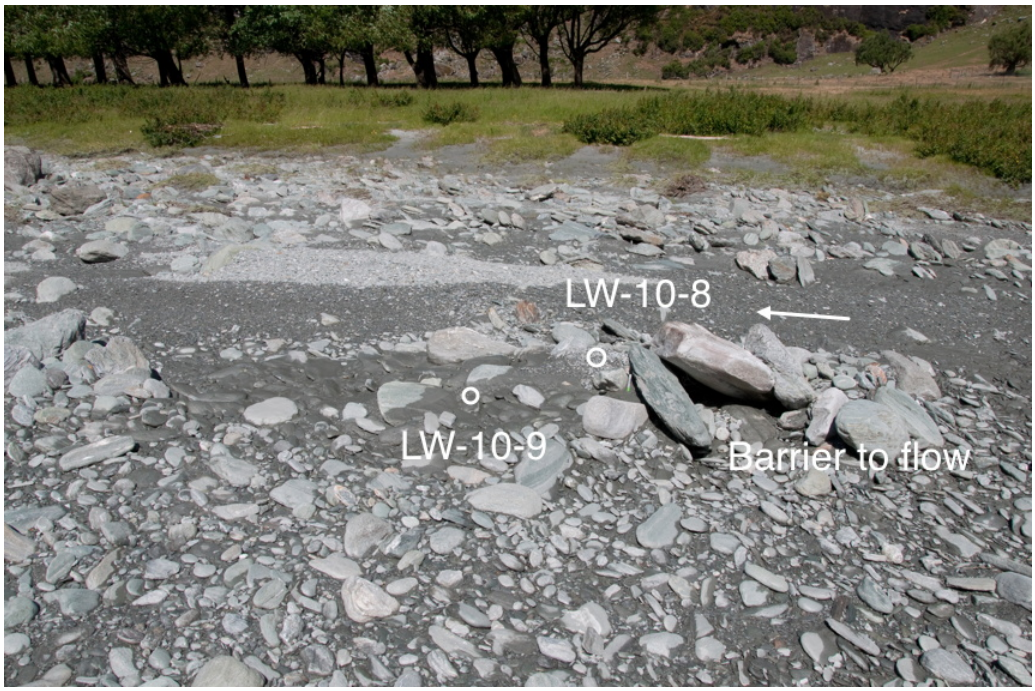
Samples LW-10-8 and LW-10-9 were collected on a bar in the Matukituki River (GoogleEarth kmz file for LW-10-8 and 9 as shown here).





Both samples were down stream of a pile of boulders that created a significant flow shadow. Arrows show the flow direction. Pen for scale, but hard to see in the first two images. It is in the same place in the third image.





Sample LW-10-8 was collected immediately downstream of the boulders, above and to the left of the pen. I interpret the grains to have been transported over the boulders by a very fast flow and deposited as the flow slowed down immediately after it passed the boulders. Sample LW-10-9 was scraped off the tops of the cobbles that look coated and wet downsteam of the boulders. This sediment is present only downstream of these boulder piles, and its grainsize requires a very low flow speed for deposition.



Based on its grain size and distribution, I interpret LW-10-9 to represent sediment that is normally transported in suspension, but the flow was so slow in the shadow of the boulders that some of it could settle out on top of the cobbles. Other interpretations might be possible, such as water was somehow ponded here.

Return to Lab 1: Lake Wanaka Area Samples

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7.3: Sedimentary Structures

Exploration of Cross Stratification and Bedforms

Cross stratification and cross lamination (same thing, but on a smaller scale) form as dunes and ripples (bedforms) migrate, leaving behind some of the sediment. The style of cross stratification that is preserved in a rock depends on the shape of the bedform, which direction it is migrating, and the amount of sediment left behind (deposited). You have a number of different examples of cross stratification in the lab samples. Here, you can use some movies and look at photos of additional samples to interpret the types of bedforms that created the cross stratification in your samples.

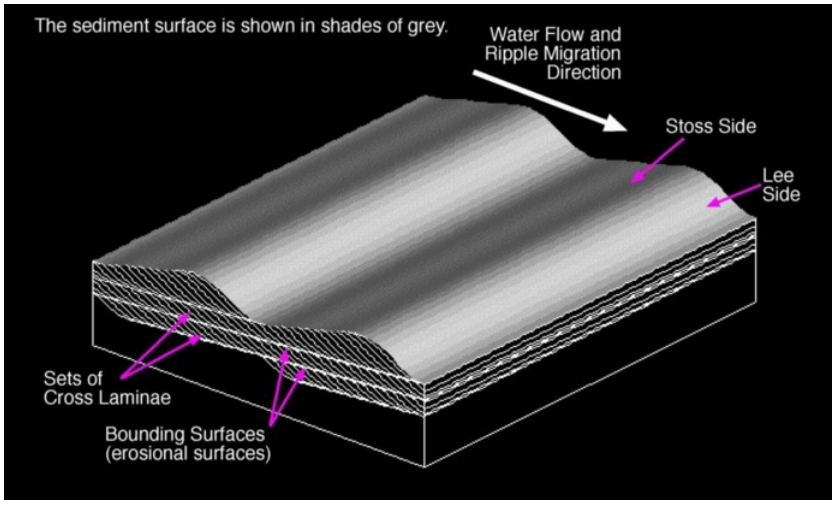
The three resourses that will help the most with your lab are: 1) the lab text, Sedimentology in the Field; 2) the photos of sedimentary structures and 3) Bedform migration movies from the USGS Bedform Sedimentology web site.

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7.3.1: USGS Bedform Movie Explanation

David M. Rubin, from the USGS Western Region Coastal and Marine Geology Program at Menlo Park, CA, published a book called Cross-Bedding, Bedforms, and Paleocurrents, which is available from SEPM and online at http://walrus.wr.usgs.gov/seds/bedforms/. He has posted some movies on the web site which demonstrate how various types of cross stratification are created. We will use these movies in lab to help interpret various styles of cross stratification.

First, here is an explanation of what you see in the movies:



The computer model that generated these movies starts with a bedform shape, which is constant throughout the movie. It is defined by the grey shaded surface. "Laminae" are deposited by moving the surface downstream and slightly up for each time step. Deposited laminae are represented by white lines. If the surface intersects the laminae, they are eroded, just like if laminae are exposed to an erosive current, they are eroded. Thus, the laminae change length and geometry as the "bedform" (surface) migrates.

All the movies associated with the publication are all listed at http://walrus.wr.usgs.gov/seds/bedforms/animation-toc.html. They are categorized by the shapes of the bedforms and photographs of real bedforms are also included. This is an EXCELLENT resource.

Start with a movie of real current ripples in an experimental flume. This will give you a sense of how irregular ripples can be. (Drag the marker at the bottom of the movie to go back to a specific place. Click on the play button to rerun the movie.)

Here is a model-produced version of the migration of a linear ripple or dune: http://walrus.wr.usgs.gov/seds/bedforms/movie_pages/movie5.html

Here is a model-produced version of the migration of a sinuous ripple or dune: http://walrus.wr.usgs.gov/seds/bedforms/movie_pages/movie34a.html This movie ends with the top surface of the ripples/dunes getting eroded flat. The white lines represent the laminae that intersect the upper surface. Note how complexly shaped they are. Next the cross stratification is rotated to show how different surfaces show different cross stratification styles. Drag the marker at the bottom of the movie back and forth to explore these variations. Note how important it is to have a 3-D view of the cross stratification to interpret bedform geometry even when it is relatively simple!

One goal of the modeling effort is to reproduce complex cross stratification that is observed in the field. The following movie produces a simplified version of cross stratification observed in a river bar. Here is movie that shows how the model can fit complicated structures observed in the field: http://walrus.wr.usgs.gov/seds/bedforms/morphs/fig46l-54morphMOVIE.mov.

> *This movie begins with a computer-animated sequence showing the origin of compound crossbedding. After the computer-generated structure is constructed and rotated through a variety of outcrop orientations, the image morphs into a natural outcrop of the same kind of structure. The natural example was*

> *photographed on a horizontal surface that was excavated into a fluvial bar in Grand Canyon. This movie is the best one for illustrating the origin of moderately complicated crossbedding.*

Lots of other movies are available to explore as you wish. There are also LOTS of photos of different model-produced stratification styles and some outcrop photos associated with the online book. The USGS web site also provides software to make your own movies by defining a bedform geometry. Have fun! (Note there are a few problems with the input files. To get them to run, make sure each number has a comma after it, and remove the tab characters. I did figure it out, so ask me if you are interested.)

Return to the Sedimentary Structures Lab Page

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7.4: Carbonates

Bahamas Lab

Organisms produce a large volume of carbonate sediments, so it is important to know what is living in different carbonate environments. James Bishop has assembled these links to the organisms he observed in areas where he collected the Bahamian sediments you look at in this lab. Use these photos to help you interpret the sediments.

Organisms found in modern carbonate environments (e.g., the Bahamas)

- Mollusk (snail) (right photo)
- Mollusk (clam) **Scroll to the bottom of the page. The last four photos of shells are examples of this type of organism.
- This is a living (or recently living) coral with dark spots disease. This coral is colonial, with a coral animal living inside each little cup-like polyp on the surface. Coral sediment often appears porous due to these little calcareous cups or polyps.
- This site has some lovely photos of corals (the 3rd, 4th, and 5th photos).
- Diadema are black sea urchins which have calcareous spines that can be reworked into sand. Diadema themselves also excavate into hard surfaces, breaking down reefs and hardgrounds into sand.
- Homotrema rubrum is an encrusting foraminifera. It can be reworked into carbonate sand grains which are often colored pink. Scroll down to Figure 3. There is also other useful information on this page about reef-forming organisms.
- Branching coralline (or calcareous) red algae
- Halimeda is a calcareous green algae which is rooted into the sediment and disaggregates into carbonate sand
- The following 4 photos links are for calcareous green algae which are rooted into the sediment and disaggregate into carbonate mud.
  - 1. Penecillus looks a bit like a paintbrush.
  - 2. Rhipocephalus looks a bit like a pine cone.
  - 3. Udotea
  - 4. Acetabularia attaches itself to firm substrates, such as hardgrounds and reefs.
- Seagrass meadows (here comprised of Thalassia) can baffle wave energy, allowing for the deposition of muds and creating environments favored by foraminifera, snails, and clams.
- This sea fan is a soft coral or Gorgonid, which has neither a calcareous skeleton, nor photosymbionts. Gorgonids like to attach to firm substrates with high energy, such as reefs.

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CHAPTER OVERVIEW

8: Old or Lost Pages

1.9: 9. Deltas, Estuaries, Marine Processes Part 1
3.1.01: Bagnold Dunes - Introduction
3.1.4: Downwind Toe of a Linear Dune- Ogunquit Beach
4.1: Gale Crater, Mars
4.1.1: Walther's Law for an Alluvial Fan
8.1: Alluvial Fans
8.1.1: Glacial Environments
8.2: Arid Environments
8.3: Beaches
8.3.1: Virtual field trip
8.3.1.3: Salmon Creek Beach
8.3.1.3.1: Aeolian Processes
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8.7: Weathering and Erosion

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1.9: 9. Deltas, Estuaries, Marine Processes Part 1

Marine Deposition

Most of Earth is covered with oceans, there is abundant life in the oceans, most sediments eventually get transported into the oceans, and shallow marine deposits are the most abundant in the in sedimentary record due to their large volume and the low erosion rates in shallow marine environments. You need tectonics to uplift them above sea level to get significant erosion. This happens commonly, so that we can also see them exposed.

Processes

Several processes are unique to shallow marine deposition (and some large lakes): Waves, storms, and tides

Waves

Waves have oscillating current directions every few seconds. The flow in both directions is equal in deep water, but not necessarily near shore. Draw a picture of wave water motion. (Water at the top of the wave moves in the direction the waves move.)

Wave Ripples - Wave ripples are different from current ripples because that they experience transport in both directions over the time scale of seconds. Draw a picture with the laminar boundary layer, etc. Wave ripples can be recognized in rocks by their symmetric shape (if flow in each direction is the same speed) and most importantly, the presence of cross-laminations dipping in two directions. This is the truly distinctive feature and can be present even if the ripples are not very symmetric. At low flow, the boundary layer doesn't have enough speed or momentum to remove the crest of the ripple and the grains that are moved are deposited right on the upper part of the lee slope. Thus, crests are sharp. At higher flow, the crests erode and deposition occurs farther down the lee slope. Thus, high flow ripples have rounded crests.

In shallow water, currents from the waves can be strong enough to flatten out the ripples, but they are not consistent enough in one direction to form dunes; the flow switches directions too frequently for dunes to build up. Thus, where flow speeds are too fast to form ripples, the sedimentary surface tends to be planar or broadly scalloped as the waves are focused into certain areas. This produces a flat lamination (not upper planar lamination) where waves are in very shallow water relative to their height, e.g. from the breaker zone towards the shore.

KEY POINT FOR WAVES: Bi-directional flow every few seconds

Storms

Storms produce both large waves and strong, irregular currents. Combined waves and currents produce unique deposits that can be used to recognize ancient storms in a marine sequence. Storms generally start far from shore and get stronger at the shoreline through time. Then they either die out or move on. Thus, near shorelines, storms tend to start out with low energy flows, increase in flow speed until they are erosional (if strong enough) and then decrease back to lower energy flows. For example, sharp crested wave ripples might mark the start of a storm, then transition into round crested wave ripples, followed by cross stratification due to large waves and strong currents, followed by erosion. As the storm wanes, the coarsest sediment would be deposited, then finer sand deposited by waves and currents, and then wave ripples, e.g. the reverse of the sedimentary structures seen as the storm approaches. There is usually little sediment being deposited at the beginning of a storm because not much sediment has been eroded yet and flow speeds are increasing through time. Thus, there is usually no record of the first half of a storm sequence in the rock record. It is only the second half that gets preserved. Storm deposits almost always consist of an erosion surface with sediment of decreasing grain sizes upward - like turbidites, but with different sedimentary structures.

HCS - The cross stratification that is deposited as a combination of strong currents and large waves is unique to storms (and is found only in medium to fine sands). It is called hummocky cross stratification (HCS) and swaley cross stratification. When currents are washing eroded sand into an area with strong oscillatory flow from waves, rounded mounds or hummocks of sand develop on the sea floor separated by lows (swales). These mounds are a few to 10 cm high and 10's of cm across. See Figures 14.3 and 4 in Nichols. Variations in current strength cause erosion locally, and the locations of the hummocks and swales change through time. This produces erosional surfaces which truncate the older laminae (note that Fig 14.2 has the wrong laminae truncated). HCS is characterized by low angle laminae truncated by low angle surfaces. There are abundant concave and convex up laminae and many fewer flat laminae.

Storm Sequence - A sample stratigraphic column consists of: Mud, scoured surface, sole marks, (gravel at base), normally graded, HCS, flat laminae or wave rippled top, return to suspension settling. Contrast this to a turbidite - I will ask you to do this!

KEY POINT FOR STORMS: Multi-directional flows over seconds, low to high to low energy in deep water

Tides

Two key characteristics that are unique to tides: 1) flow changes direction 1 or 2 times per day; and 2) The speed of flow is cyclical with flow going onshore, stopping at hight tide, then flowing offshore, and stopping at low tide. There is lots of variability in tides depending on geography. Flow speeds vary, producing different sedimentary structures. In the Bay of Fundy, which has the highest tides recorded in the world (up to 16 m - a 5 story building), the water moves up to 15 km/hr (417 cm/sec) which is fast enough to transport boulders. At the low end, tidal currents are essentially non-existent. Also, there are times of slack tides when the water is essentially still or wave-dominated. Thus, the range of sedimentary structures is wide, including dunes (often called tidal bars when very large) and ripples. The main characteristic to look for, though, is variations in flow speed and DIRECTION.

Tidal sedimentary structures - Due to changing flow directions, two sediment transport directions are common, one for onshore flow and one for offshore flow. Often the onshore and offshore flows are not in the same location, but they shift around. This gives rise to current ripples showing transport in two directions and dune migration in two directions producing herringbone cross stratification. See figures 11.6 and 11.7 in Nichols. If the dunes are small and sedimentation rates are very high, you can get ***herringbone cross stratification*** in one tidal cycle in a modern environment. It is usually not preserved in the geological record because it is eroded prior to lithification. It is almost always the longer term changes in current locations that gives rise to preserved herringbone cross stratification. Dunes migrate in one direction for a while, and then currents patterns change and they migrate in the other direction. Herringbone cross stratification is almost always due to tidal processes, although it is not all that common in the sedimentary record. Commonly, one tidal current is much stronger than the others or the flow locations aren't systematically shifting, so tabular cross stratification is more common. It is not unique to tidal environments, however.

Reactivation Surfaces - Reactivation surfaces form when flow in one direction is stronger than the other, but the other flow is strong enough to modify the bedform shape. See figures 11.6 and 11.9 in Nichols. Reactivation surfaces are erosion surfaces within the sets of cross stratification. They look like irregular surfaces that are similarly oriented to the foresets, but usually do not dip quite as steeply. Also, the foresets above and below the reactivation surface commonly have a slightly different orientation. Reactivation surfaces indicate varying flow directions, which is very common in tidal environments.

Mud Drapes - Flow speeds are also cyclical. During slack tides (low or especially high), fine grained sediment can fall out of suspension draping tidal bedforms with mud. Because mud is cohesive, it does not necessarily erode during the next tidal flow, particularly in the separation zone where flow is slow, e.g. at the bases of ripples and dunes. Thus, sand foresets coated with mud are very common in tidal environments as well. See figures 11.6 and 11.8 in Nichols.

KEY POINT FOR TIDAL PROCESSES: Bi-directional flow with varying speeds over hours

Deltas and Estuaries - Introduction

When rivers reach standing water such as a lake or the ocean, the flow speed slows down dramatically. And when flows slow down, sediment is deposited. Almost all of the sediment transported in a river is thus deposited close to the river mouth, with the exception of grains that are fine enough to remain in suspension. Lacustrine and marine processes can rework the deposited sediment to distribute it along shorelines.

Deltas form at the mouths of rivers that transport enough sediment to build outward. (*Building outward* is a key component of the definition of a delta. In contrast, ***estuaries*** are present where the ocean or lake waters flood up into the river valley.) Deltas require substantial accumulation of sediment, in contrast to estuaries which do not build outward. Sedimentary facies are similar to other depositional environments, but the association of subenvironments are recognizable as deltas. Some of the sub environments include: river facies with all the associated sub environments; shore line deposits including beaches, marshes/swamps, etc.; submarine shelf and slope facies, including storm deposits and turbidites; etc.

I will draw cross section and map views of a delta showing the delta plane, delta slopes, and prodelta. Rivers flow through delta planes and slow when reaching water, producing a mouth bar. Grain size decreases with distance away from the river mouth.

Progradation

Because deltas are sites of sediment building outward from the coast, they are progradational; the landward depositional environments move seaward over more marine/lacustrine deposits. Thus, delta sequences in the rock record start with deep water, marine (or lacustrine), fine grained sediments and grade upward into shallower water, possible more freshwater, coarser grained sediments. This is one of the distinguishing aspects of deltas that let you define them in the sedimentary record. These changes in grain size and environment typically occur over 1's to 100's of meters in the rock record and include many beds.

Sediment Transport Type

All deltas (by definition) have their sediment transported to the delta by rivers. Thus, fluvial deposits are always associated with them. In addition, depending on marine (or lacustrine) conditions, waves and tides can redistribute the fluvial sediment changing the morphology and facies of deltas. There are three main end member categories of deltas when characterized by processes: 1) River dominated; 2) Wave influenced; and 3) Tide influenced. We will come back to these delta types after discussing the marine processes.

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3.1.01: Bagnold Dunes - Introduction

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3.1.4: Downwind Toe of a Linear Dune- Ogunquit Beach

This page has the images to make the mosaic of our field stop, which I'll eventually add to this page.

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SECTION OVERVIEW

4.1: Gale Crater, Mars

Topic hierarchy

4.1.1: Walther's Law for an Alluvial Fan

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4.1.1: Walther's Law for an Alluvial Fan

Let’s look at an alluvial fan in Gale Crater, Mars: http://tinyurl.com/be39pmv

Where are there differences in environment laterally? If the fan grew through time, how would you predict the deposits to change vertically?

For more information on ancient stream flows on Mars, see:

http://mars.jpl.nasa.gov/msl/news/whatsnew/index.cfm?FuseAction=ShowNews&NewsID=1360

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8.1: Alluvial Fans

Flash Flood Deposits

When it rains in deserts, it often floods because there is little vegetation to trap water in soils and slow the runoff. Two environment types dominated by flash flood sediment transport are common: valleys with ephemeral rivers (wadis) and alluvial fans. Alluvial fans form in areas with a steep gradient from a drainage catchment to the basin floor whereas wadis in valleys form where the gradients are much lower. Tectonic activity it typically required to maintain steep slopes because they erode to lower slopes through time. The Basin and Range Province in eastern California and Nevada is an area with abundant examples of alluvial fans. Less structurally active deserts where deposition is dominated by flash floods, such as eastern Egypt, tend to have wadis (which is an Arabic word).

- Alluvial fans in Death Valley: http://g.co/maps/n2udd
- A wadi in Egypt: http://g.co/maps/369c4

Alluvial fans - Alluvial fans are cone shaped accumulations of coarse sediment deposited at the transition from confined flow in a canyon to unconfined flow in a basin. This also corresponds to a break in slope. As the slope shallows and the flows spread out, the flows slow down and deposit much of the sediment that they were able to transport in the canyon. (Think about the Hjulstrom diagram.) Fan geometry is determined by the rate of deposition. At the canyon mouth, it is steeps (up to 15°) due to rapid deposition of coarse sediment. It shallows to about 5° over the main part of the fan and shallows even more to 1-2° at the toe. Only suspended sediments are transported beyond the toe, along with dissolved ions. If the water can pond, the fine grains settle out and the water evaporates forming minerals like gypsum and halite, and creating playa lake deposits. Deposition on a given alluvial fan is very rare - one event occurs about every 300 years on most fans in the southwestern US.

Wadis - Wadis are similar to braided river deposits, which we will talk about next week. They have a high sediment load for the amount of water.

Flow types - Three types of flows are common: 1) debris flows, 2) sheet flows, and 3) channelized flows.

Debris flows are slurries of mud, rock debris, and just enough water to make the sediment into a viscous flow. Due to the high viscosity, the flow is laminar, like a glacier, and like a glacier, there is no significant sorting of grain sizes. Debris flows can transport very large blocks. Debris flows continue to move until the internal friction of the flow due to viscosity exceeds the flow's momentum when it freezes into place. This can occur due to either the loss of water or lower slope. The resulting deposits show little sorting and would be classified as a mud supported breccia or a diamictite. (Diamictites are defined as very poorly sorted sedimentary rocks with no grain size sorting within them. They are characteristics of laminar flow deposits.) In most cases, debris flow deposits are unsorted and lack any form of stratification. They are laterally restricted because they do not spread out too much, and they are commonly an even thickness throughout, with steep edges to the flows.

Sheet flows are turbulent flows with significantly more water and less mud than debris flows. Since the flows are turbulent, there is significant grain sorting and normally graded, fining upward deposits are common. Once a flow reaches the mouth of the canyon, the flow spreads out and the coarsest rocks are deposited first. Finer grains are deposited later and farther down the fan and later in time. This produces normally graded beds, but deposition is very rapid and the grading is commonly poor. The suspended load may make it to the toe of the fan if the water doesn't filter into the fan first. Sheet flood deposits produce broad deposits that are clast supported, with some imbrication of clasts. Unlike a debris flow, sheet flows commonly cover 1/3 to 1/2 of a fan surface.

Channelized and other types of flows - A number of other flow types are also common on fans. For example, if there is insufficient rain to produce a sheet flow, ephemeral rivers can flow down the surface of the fan - which is more common. This produces braided river type deposits, which we will talk about later. There is also a significant gradation between debris flows and sheet floods. They represent two end members, and there are lots of variations in mud content and water content which variously affect the viscosity of the flow and thus the resulting sedimentary deposits.

Alluvial Fan Facies

1. Poorly sorted beds (diamictites) that are of an approximately uniform thickness but of limited lateral extent, deposited by debris flows;
2. Moderately to well sorted sandstone beds, often normally graded with pebbles at the base deposited in ephemeral channels; these show some cross stratification due to turbulent flow dynamics;
3. Normally graded sandstone beds that are laterally extensive deposited by sheet flows;
4. Average grain size decreases down slope and the abundance of debris flow deposits decreases down slope.

Side note about facies: Each of list items 1-3 above could be described as a subfacies of the Alluvial Fan Facies, with its own grain sizes, characteristics, sedimentary structures, etc. Each of those could also be considered a facies, and the overall alluvial fan deposit could be assigned to an “Alluvial Fan Facies Assemblage”. If I was studying the sedimentation in all of Death Valley, I would probably be most interested in distinguishing between alluvial fan facies, playa deposits, and eolian deposits, so I would use the “Alluvial Fan Facies” I defined above. In contrast, if I wanted to highlight variations in the depositional processes on one fan in Death Valley, I would probably define the different types of alluvial fan deposits as different facies, so that my facies would emphasize the differences in debris flows, sheet flows, and channelized flows. I would then have an “Alluvial Fan Facies Assemblage” that would be distinct from my “Playa Facies”.

Contributors

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8.1.1: Glacial Environments

Glacial environments are defined as those where ice is a major transport process. Liquid water and wind can also transport sediment in these environments. Wind transport is common when there is little vegetation. Liquid water transport occurs when the ice melts.

As you all remember, the high viscosity of ice makes all ice transport of sediment laminar. Thus, grain sizes are not sorted. All of the sediment is transported together, with the ice, and it is deposited when the ice melts. There are several features that are characteristic of glacial environments, including the process of erosion.

Erosion

Erosion in glacial environments is dominated by physical processes:

1. ice freezing in cracks in rocks, breaking them up
2. flow of glaciers “plucking” rocks up from the base of the flow
3. grinding of rocks against each other and against the floor of the glacial valley as the ice flows

These processes produce some distinctive sedimentary features including:

1. facetted clasts, e.g. rocks with smoothed off faces from dragging against other rocks
2. striations and grooves in rocks from dragging against other rocks
3. flat valley floors called glacial pavements that are smoothed off due to glacial flow
4. rock flour, which is clay size lithic grains formed from the bits of rock that are abraded off as facets, striations, grooves, and glacial pavements form.

There is often little chemical weathering in glacial environments because temperatures are cold.

Deposition

Ice flows are laminar because they have very high viscosity. This can be seen in the ice cliffs along the edges of glaciers in Taylor Valley, Antarctica. The ice is particularly cold and is so viscous that it does not flatten out on the time scale of at least dozens of years. Because the flow is laminar, when the ice melts or sublimates, it dumps all grain sizes into one deposit, forming a diamictite. If one knows that the diamictite was deposited by ice, it is then called till or tillite. If the glacier melts on land, it leaves piles of till in moraines. If it melts over water, the debris is deposited into the water, commonly forming a till sheet. If only a few large clasts are deposited in the water, they are called “drop stones”. These commonly are deposited by melting ice bergs that carry large grains out over lakes or the ocean, where they are deposited in (nearly) standing water.

As glaciers melt over land, melt water commonly reworks glacial till into braided river deposits. In arid environments, much less reworking of the sediment takes place.

Glacial Facies Assemblage

For illustrative purposes, I am describing the glacial facies as an assemblage of other facies.

Morraine Facies

1. Composed of diamictite; no sedimentary structures.
2. Diamictite in mounds.
3. Clast composition mostly lithic fragments, including silt and clay-sized rock flour.
4. Clasts mostly angular, some with facets and striations.

Till Sheet Facies

1. Composed of diamictite; sedimentary structures suggestive of turbidites in rare sandstone interbeds.
2. Diamictite in sheets with rare shale and sandstone interbeds.

3. Clast composition mostly lithic fragments, including silt and clay-sized rock flour.
4. Clasts mostly angular, some with facets and striations.

Distal Glacial-Lacustrine/Marine Facies

1. Shale with isolated large clasts and sandstone interbeds with sedimentary structures suggestive of turbidites.
2. Clast composition mostly lithic fragments.
3. Clasts mostly angular.
4. Frequency of large clasts decreases away from the glacier.

Braided River Facies
We will describe these later.

The parts of the glacial facies assemblage that are observed depends on whether the glacier ends on land or in standing water. Thus, the way I have described the facies here are particularly good for studying the environment for the glacier. If one wanted to determine how ice sheets around Antarctica have advanced and retreated through time, one would want to subdivide the Till Sheet Facies and Distal Glacial-Marine Facies into smaller groupings that would help locate the edge of the ice sheet. In contrast, if one wanted to distinguish between alluvial fan deposits and glacial deposits in Owens Valley, CA, one would want to pay particular attention to the geometry of the diamictites because they form in both environments, but the geometry of the deposition are different.

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8.2: Arid Environments

Review of Details of Cross Lamination/Stratification Formation

There are several important details of cross lamination formation that I'd like to emphasize before the midterm. First, the geometry of the laminae within the cross stratification reflects the geometry of the surface during deposition. A layers of sediment is deposited on a surface, and the geometry of the bottom of the layer preserves the geometry of the depositional surface. If there is a change in slope on the surface, there will be a change of slope at the bottom of the laminae that mimics the surface. However, layers can vary in thickness. On the lee size of a ripple or dune crest, there is often more deposition on the steep slope because that is where the sediment lands when it is washed over the crest. It is the high depositional rate here that makes the slope steep. If the slope gets too steep, the grains avalanche downslope, and it is no longer quite as steep. The geometry of the ripple or dune is directly related to the distribution of deposition.

The geometry of laminae on the downstream side, e.g. where they merge with the erosion surface that forms on the stoss side of the next ripple/dune downstream, is also interesting. The laminae thin to zero thickness right where they "downlap" onto this surface. If deposition occurs beyond the steep slope of the ripple/dune, the laminae curve and gradually thin. If deposition only occurs on the steep slope, the laminae end more abruptly again the erosional surface. The geometry of the laminae tells you very precisely where deposition occurred relative to the ripple/dune trough.

These videos review these concepts:

- http://youtu.be/r62qIKNBkos
- http://youtu.be/0Zanh17ulXs
- http://youtu.be/ogM-UqcYIfU

Arid Environments

Aridity - Aridity defines a desert, not temperature. An arid region gets less than 250 mm of rain/year. Our average in Davis is about 480 mm. That puts us barely in a semi-arid climate, which has 250-500 mm of rain/year on average. Arid environments are characterized by little vegetation.

Types of Deposits Typical of Arid Environments - 1) Wind blown sand (well sorted, texturally mature medium or finer sand); 2) Flash flood deposits (poorly sorted breccia, including debris flows); and 3) Playa lake deposits (silt, mud and evaporites). There are also very cold desert environments, such as the McMurdo Dry Valleys, Antarctica. These environments have glacial deposits left by glaciers that flow in from areas with higher precipitation (e.g. higher elevations) or the ice cap.

Flash Flood Deposits - When it rains in deserts, it often floods because there is little vegetation to trap water in soils and slow the runoff. Two environment types dominated by flash flood sediment transport are common: valleys with ephemeral rivers (wadis) and alluvial fans. Alluvial fans form in areas with a steep gradient from a drainage catchment to the basin floor whereas wadis in valleys form where the gradients are much lower. Tectonic activity it typically required to maintain steep slopes because they erode to lower slopes through time. The Basin and Range Province in eastern California and Nevada is an area with abundant examples of alluvial fans. Less structurally active deserts where deposition is dominated by flash floods, such as eastern Egypt, tend to have wadis (which is an Arabic word).

- Alluvial fans in Death Valley: http://g.co/maps/n2udd
- A wadi in Egypt: http://g.co/maps/369c4

Alluvial fans - Alluvial fans are cone shaped accumulations of coarse sediment deposited at the transition from confined flow in a canyon to unconfined flow in a basin. This also corresponds to a break in slope. As the slope shallows and the flows spread out, the flows slow down and deposit much of the sediment that they were able to transport in the canyon. (Think about the Hjulstrom diagram.) Fan geometry is determined by the rate of deposition. At the canyon mouth, it is steeps (up to 15°) due to rapid deposition of coarse sediment. It shallows to about 5° over the main part of the fan and shallows even more to 1-2° at the toe. Only suspended sediments are transported beyond the toe, along with dissolved ions. If the water can pond, the fine grains settle out and

the water evaporates forming minerals like gypsum and halite, and creating playa lake deposits. Deposition on a given alluvial fan is very rare - one event occurs about every 300 years on most fans in the southwestern US.

Wadis - Wadis are similar to braided river deposits, which we will talk about next week. They have a high sediment load for the amount of water.

Flow types - Two types of flows are common: 1) debris flows and 2) sheet flows.

Debris flows are slurries of mud, rock debris, and just enough water to make the sediment into a viscous flow. Due to the high viscosity, the flow is laminar, like a glacier, and like a glacier, there is no significant sorting of grain sizes. Debris flows can transport very large blocks. Debris flows continue to move until the internal friction of the flow due to viscosity exceeds the flow's momentum when it freezes into place. This can occur due to either the loss of water or lower slope. The resulting deposits show little sorting and would be classified as a mud supported breccia or a diamictite. In most cases, debris flow deposits are unsorted and lack any form of stratification. They are laterally restricted because they do not spread out too much, and they are commonly an even thickness throughout, with steep edges to the flows.

Sheet flows are turbulent flows with significantly more water and less mud than debris flows. Since the flows are turbulent, there is significant grain sorting and normally graded, fining upward deposits are common. Once a flow reaches the mouth of the canyon, the flow spreads out and the coarsest rocks are deposited first. Finer grains are deposited later and farther down the fan and later in time. This produces normally graded beds, but deposition is very rapid and the grading is commonly poor. The suspended load may make it to the toe of the fan if the water doesn't filter into the fan first. Sheet flood deposits produce broad deposits that are clast supported, with some imbrication of clasts. Unlike a debris flow, sheet flows commonly cover 1/3 to 1/2 of a fan surface.

Other types of flows - A number of other flow types are also common on fans. For example, if there is insufficient rain to produce a sheet flow, ephemeral rivers can flow down the surface of the fan - which is more common. This produces braided river type deposits, which we will talk about later. There is also a significant gradation between debris flows and sheet floods. They represent two end members, and there are lots of variations in mud content and water content which variously affect the viscosity of the flow and thus the resulting sedimentary deposits.

Characteristics of Alluvial Fan Deposits

1. Poorly sorted beds that are of an approximately uniform thickness but of limited lateral extent, deposited by debris flows;
2. Moderately to well sorted beds, often normally graded with pebbles at the base deposited in ephemeral channels; these show some cross stratification due to turbulent flow dynamics;
3. Normally graded beds that are laterally extensive deposited by sheet flows;
4. Average grain size decreases down slope and the abundance of debris flow deposits decreases down slope.

Eolian Environments

The viscosity of air is low so it is typically a turbulent flow ($Re=ul\rho/\mu$). Density is also low, but viscosity is a larger effect. Think back to the Bernoulli Effect. The lift force has to overcome gravity, but it also depends on the difference in density between the fluid and the grains. The lower the density of the fluid, the harder it is to lift the grains against gravity. Thus, wind speeds must be very high to transport grains, and wind tends to lift only medium sand or smaller grains into saltation or suspension even at 30 m/s (about 60 miles/hour). Larger grains can only roll along the ground, mostly due to impacts from saltating grains.

Saltation - Wind transports sand as bedload (traction and saltation) and in suspension, like water. The traction and saltation transport are slightly different, however, because the impacts between grains are more forceful. Water dampens the impacts by limiting grain speed by friction between the water and grains and the effects of viscosity. Air does much less so because of both lower density and much lower viscosity. Thus, impacts when saltating grains land are very forceful. This has 2 effects: 1) more grains are launched into the saltating layer than the fluid could lift. This leads to a positive feedback - once saltation starts, the number of saltating grains increases rapidly. 2) The landing grains push the grains they hit, leading to surface creep of grains. This

processes can push much bigger grains up slopes than could be transported by the wind alone, even with traction transport.

Ripple Formation - As in water ripples, wind ripples form as an initial pile of grains once saltation has started. However, the mechanisms of growth are different. There is no separation of a laminar flow sublayer or back eddy as seen in water ripples, in part because air flow is very turbulent. Rather, the impacts from saltating grains push coarser grains up the back sides of ripples to the crests where they eventually avalanche off the lee slope. Most of the smaller grains get transported off the crests where wind speeds are the greatest. Some small grains may also accumulate in troughs, especially between the larger grains. This leads to one of the rare cases of reverse grading: The larger grains are more concentrated at the tops of ripples and smaller grains are more concentrated at the bases. If there is significant accumulation of sand, thin reversely graded layers can be preserved in the rock record and are indicative of aeolian transport.

Cross Lamination - Migration of ripples occurs due to erosion on the windward side and deposition on the leeward side, as in water ripples. However, cross lamination is rare because the sand in dunes tends to be well sorted, especially the sand that gets transported down the lee slope - which is where sediment accumulates. Sometimes cross lamination is preserved due to fluctuations in wind speed resulting in different grain sizes being deposited at different times.

Dunes and Draas - Larger bedforms also form due to wind transport of sand. Unlike water transported sand, dunes and draas (huge bedforms really observable only from the air) commonly have abundant smaller bedforms developed on them. Basic sand transport on both is the saltation of sand up their windward sides and avalanching down their leeward sides. Cross stratification is common and large scale. Meter-thick beds are common even though the tops of the bedforms are not preserved.

Sand Characteristics - Another aspect of strong collisions between grains is that they are commonly rounded very quickly and commonly have frosted surfaces due to collision damage. The collisions also break down softer grains, particularly lithic fragments. Thus, most dune sand consists of well rounded, well sorted quartz sand. Rare exceptions, such as the gypsum sands at White Sands National Park can persist due to a lack of hard dense grains to abrade the softer gypsum grains.

Characteristics of Eolian Deposits -

1. Well sorted, rounded grains;
2. Little clay or silt sized grains;
3. Large bedforms, thus thick sets of cross strata;
4. Ripple stratification is rare;
5. Some reversely graded laminae (not beds);

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SECTION OVERVIEW

8.3: Beaches

Topic hierarchy

8.3.1: Virtual field trip

8.3.1.3: Salmon Creek Beach

8.3.1.3.1: Aeolian Processes

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SECTION OVERVIEW

8.3.1: Virtual field trip



Above is an arial photograph of the field trip site.

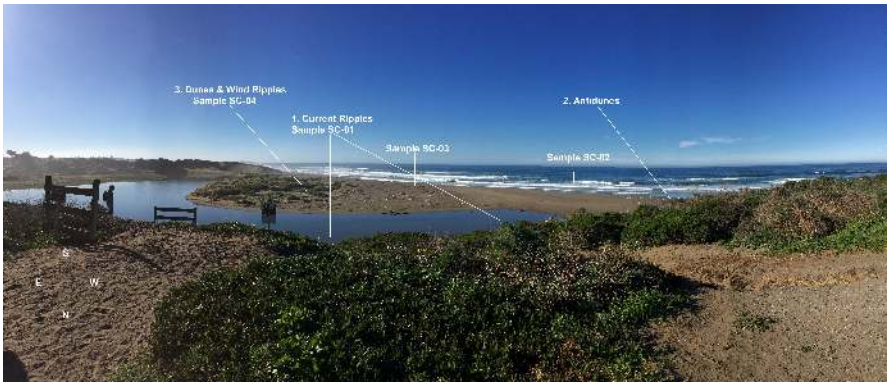
Topic hierarchy

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8.3.1.3: Salmon Creek Beach







Welcome to Salmon Creek Beach located in beautiful Sonoma County, California! This site was visited, along with several others in Bodega Bay, on January 31, 2015 in order to observe active sedimentary processes and to document spacial trends in sediments within an environmental context. Salmon Creek Beach consists of an estuary that is fed by Salmon creek that originates from the surrounding coastal hills and empties into the Pacific Ocean. Depending on the time of the year and the meteorological conditions, the estuary may or may not fully reach the ocean; however, on the day the site was visited, the Pacific Ocean and Salmon creek were connected. Looking at the left, southern side of the **above** image, the back of the estuary is lined with dunes and is a very low-energy environment where flow velocities are very low. In the images **below**, we see an increase in energy and flow velocity as water moves through a smaller, narrower area and bends around to where it meets with the Pacific Ocean. We can also see the cut bank of where the channel water level used to be at higher tides as it meanders on the beach toward the ocean. The most prominent sedimentary structures that were observed at Salmon Creek Beach were current ripples, antidunes, dunes, and wind ripples, along with the bioturbation (human and wildlife footprints).





1. Current Ripples

The first observed sedimentary structures were current ripples. These type of ripples indicate present unidirectional flow moment, which was initially determined to be north and then west closer to the bed of the ocean. The direction of the ripples changed where the flows of Salmon creek and the Pacific Ocean began to meet. The flow direction can be concluded by the direction of the Lee side, or grain attachment point. This side is where the grains being transported go from being suspended in the flow to depositing "down" to the bed again. The process of lamination is where such grains begin to repeat the process and produce wavy surface

features known as ripples. The ripples seen at the beginning of Salmon creek, **bottom images**,were in between sinuous and linear and were measured to have a wavelength (from crest to crest) of 30mm with a flow direction going north. This small wavelength was suggestive of calm flow speeds, allowing fine sediment to be deposited.



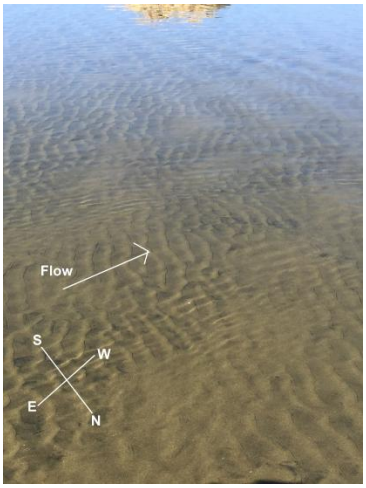
(penny for scale) (footprint for scale)

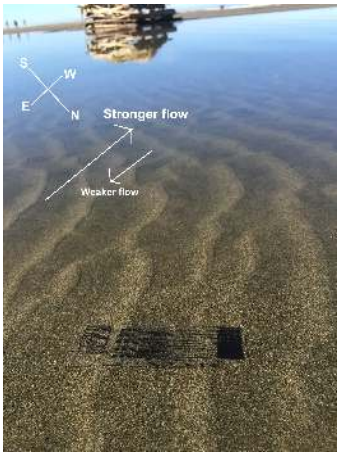


Sample SC-01 was collected here and was later analyzed. The sample contains well-sorted very fine to fine sand consisting of quartz, lithics, and occasional pieces of glass and shells. The sediments here overall are well-rounded to rounded and spheroidal which suggests the grains are texturally and compositionally mature, meaning they are far away from the source of sediments.

(Sample SC-01)

Closer to the ocean as the channel meanders, ripples are still observed however they change in magnitude and direction. Given the flow is directed towards the ocean, the ripples change to that direction (west), **bottom left**. As the channel nears the ocean, ripple wavelengths were observed to get longer and sand grains became coarser. Wavelengths were now measured to be up to 90mm, consisting of the same sediments. These sediments were coarser and didn't share the uniform spherocity of the grains up the creek. The reason for this change in ripple characteristics was a result of flow differences. The flow had increased here and was able to carry more coarse sediments. The changes in flow allowed for the formation of reactivation surfaces, **bottom right**.





Reactivation surfaces occur from bidirectional flow where a one flow direction dominates and creates the ripple structure while an opposing weaker flow erodes the top of the ripple.

Aside from the current ripples observed, an area by the bend of the channel had interference ripples. Unlike the unidirectional ripples formed by current flow, these ripples indicate bidirectional flow. This means that at some point in tide fluctuations there were two different flow directions. These directions were from the creek to the ocean and from the ocean to the creek, or east to west. Indicative features of interference ripples are visible in the picture **below**, where sinuous ripples cross one another.



(penny for scale)

2. Antidunes

Along the stream connecting the lagoon and the ocean was observable a sedimentary bedform recognized as antidunes. These formations are possible when Froude's number of a flow is close to one so standing waves may form on the surface of the water before steepening and breaking in an upstream direction. As a result, the sand on the bed develops a bedform surface parallel to the standing wave; therefore, as the flow steepens, sediment accumulates on the upstream side of the bedform creating these unique structures. In the video recorded at Salmon Creek, we find that the fluvial environment present has the flow velocity needed to form the antidunes.



Video taken at Salmon Creek Beach showing the antidunes that formed in the shallow stream with a high flow rate.

Further down from where the antidunes were seen where the channel meets the swash zone, Sample SC-02 was taken. Sample SC-02 was analyzed to be coarser than SC-01 and consisted of well-sorted fine to medium sands primarily composed of quartz and lithics. Sediments in the swash zone are exposed to medium energy processes which gives us the medium sized grains as opposed to those finer grains found in the breaker and surf zone. The main sedimentary structures associated with Sample SC-02 would be bioturbation and faint lines of longshore drift.





Sample SC-03 was collected about halfway towards the dunes (going east) from the swash zone of the ocean past the antidunes. (See pictures at top of page for exact location). This sample contains moderately-sorted very fine sand to granule-sized grains that are composed of quartz, lithics, and shells. In this area, bioturbation as well as ripples were observed in the area. Coarser grains were concentrated on top of finer grains.

3. Aeolian Dunes and Ripples

Other sedimentary structures present were dunes and wind ripples. Dunes, also recognized as “megaripples,” are bedforms distinctly larger than ripples. These bedforms are usually known as hills of sand that are produced by either water flow or wind. Dunes vary in size and are formed as sediments are pushed up the stoss side and are deposited on the lee side. At Salmon Creek Beach, we find that the dunes are primarily shaped by wind activity and are primarily comprised of the very fine-grained sediments transported and deposited by wind. These Aeolian dunesraneg from about 3 meters to 600 meters in wavelength and are between 10 cm and 100 meters high. Again, the migration of sediments, saltation, up the stoss side to the crest form structures like Aeolian ripples.

Aeolian Ripples are formed as grains migrate across a bed of sand creating patches of piled up grains. These “piles” of grains are due to irregularities on the surface of the sand that then pile in a perpendicular fashion equally spaced apart; therefore, the crests formed produce these aeolian ripples comprised of very fine to medium sized grains. The direction of these ripples are dependent on the direction of the wind which carries different sized grains depending on the strength of the blowing wind. The coarser grains in any given wind current are concentrated on the crests where the finer grains continue being transported by the wind. As the crests develop, the grains avalanche down the lee side into the rough forming cross-laminations.



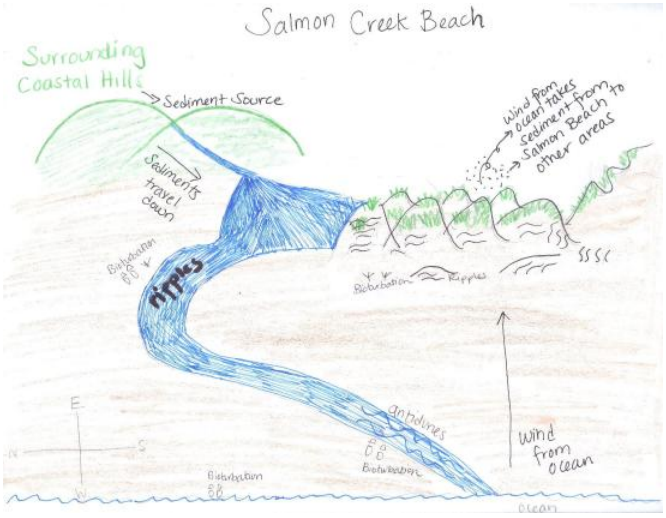
In the figure above, we can notice the aeolian ripples formed by the wind blowing in the southward direction. Each ripple is equally spaced out and is comprised, more or less, of the same fine sized grains.



Sample SC-04 was collected in this area and is consisted of well-sorted medium to very-fine quartz and lithic sands. The sedimentary structures associated with this sample are bioturbation (human and animal footprints), wind ripples, and dunes.

Interpretation

This coastal location has experienced an immense amount of sediment allocation from different sources. Methods including air and water have deposited the sediments seen today. The most dominant sediment redistributing source is water, carrying sediments during tidal fluctuations. At low tide, which was observed the day of the trip, all of the sedimentary structures described were able to be seen. At high tide, some structures would have been destroyed or altered due to water movement. With tides comes wind, which can also transport sediment. Both dunes and ripples at Salmon creek were created and sediment was transported out of the area to Bayside Park and further south as a result of these transport mechanisms.



Learning Modules

Ripples: https://www.youtube.com/watch?v=VAcr...ature=youtu.be

Preface- Ripples were present at Salmon Creek and Bayside Park. Of course, they differ in some ways but are also similar. At both sites one is able to see grain size, composition, and angularity extremely up close. Both stops were at low tide which allowed for this. Given they have water flow fluctuations, one is able to see these ripples. Salmon Creek, however, had a slightly higher energy level than Bayside Park. At the creek ripples can be seen above and below a water surface. At Bayside Park, only ripples above a water surface are visible. This lead to the conclusion that although ripples are formed at both sides, different flow conditions influence their form and location on the bed.

Contributors

- Marcelle d'Almeida
- Rebeca Ontiveros
- Robert Torres

Works Cited

1. Sedimentology and Stratigraphy 2nd Edition, Gary Nichols, 2009. Print

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8.3.1.3.1: Aeolian Processes



Dunes : a wind deposited sand body A sand storm over Iraq in 2005. Wind sediment transportation in suspension

Aeolian Processes are related to wind activity and how wind can erode, transport, and deposit sediments.

Throughout the different sites visited during the Bodega Bay field trip on January 31, 2015, there were several sources of evidence observed of Aeolian processes taking place. In Salmon Beach Creek, dunes and wind ripples were present which are both types of wind-deposited structures. The grain size in the area where these structures were observed were analyzed to be well-sorted, well-rounded, medium to very fine sands composed primarily of quartz, lithics, and shells which are very characteristic of Aeolian deposits. In Bayside Park, the sediments are almost identical to those in Salmon Creek Beach where grain sizes range from coarse silt-sized to very fine. These sediments overall are well-sorted and consist of mostly quartz and lithics with the exception of larger calcite grains from the shells of organisms inhabiting the area. Due to the great similarity between the grains from Salmon Creek Beach and Bayside Park, it was concluded that the main source of grains in Bayside Park were from Salmon Creek Beach as a result of wind transportation.

In the other sites towards the southern part of Bodega Bay, Horseshoe Cove and Bodega Head, the sediment sizes observed were much coarser, ranging from coarse sand to cobble-sized grains. The main difference between these four areas is that the source of sediments is significantly closer at Bodega Head and Horseshoe Cove than at Bayside Park and Salmon Creek Beach. The northern areas (Salmon Creek and Bayside) receive their sediments from the coastal hills around Salmon Creek and through wind transportation, while Bodega Head and Horseshoe Cove gain their sediments from high wave energy eroding the granite diorite and surrounding rocks right along the coast and on shore. Even though aeolian processes weren't directly observed at Bodega Head and Horseshoe Cove, on the drive down to these sites dunes were observed which shows how sediment from Salmon Creek Beach could have been transported and deposited through wind closer to these areas.

For complete audio of this section, click here: */@api/deki/files/152/Aeolian_processes.m4a*

Aeolian Transport

Just like in water flow, wind or air can transport grains in *bedload* and *suspended load* depending on the flow velocity and grain size/density.

Bedload refers to grains that are transported along the bed surface. Two types of sediment transport in *bedload* are called *traction/rolling* and *saltation*. See my video on *saltation* and *traction* below!



Suspended load refers to grains that become entrained in the flow and are transported this way until flow velocity slows down enough to deposit them. In Aeolian transportation, usually only medium to very fine sands are transported in suspension while larger grains travel by rolling and saltation. The transportation of sediment in suspension in air flow can be dangerous as well as disruptive as it can create dust storms, like the Phoenix Dust Storm of 2014.

Sediment from Salmon Creek Beach to Bayside Park was most likely transported in combination through bedload and suspended load in wind.

For complete audio of this section, click here: /@api/deki/files/153/Aeolian_Transport.m4a

Aeolian Deposits



Aeolian deposits are sedimentary deposits of grains transported by wind. The picture on the **right** shows dunes at Salmon Creek Beach along with overlying wind ripples which are both two main types of wind deposits. Dunes and ripples are differentiated by wavelength and amplitude. Dunes have a wavelength of 60cm or greater, while ripples have wavelengths that are less than 60cm. These two structures are formed by the interaction of air flow with the sediments. Once sediments begin to pile up, dunes and ripples form. Aeolian Ripples are formed as grains migrate across a bed of sand creating patches of piled up grains. These “piles” of grains are due to irregularities on the surface of the sand that then pile in a perpendicular fashion and begin to create flow separation. Flow then reattaches below and past the "pile" and begins to erode and move grains up the the "stoss" side of the ripple. Once enough grains accumulate, the grains then avalanche down the "lee" side of the ripple and form cross-laminations The direction of these ripples are dependent on the direction of the wind which carries different sized grains depending on its strength. Ripples with sharper peaks are formed more from grains that roll, while rounded and more elongated ripples are formed from saltating grains. The ripples in the picture on the **right** were formed more from rolling grains rather than saltating. Dune shapes can vary between linear, crescentic, star, and parabolic while ripple shapes can very between linear and sinuous and isolated depending on flow speed.

To learn more about aeolian deposits and the different shapes they form, click here.

To learn more about ripples, watch my classmate, Rebeca's, video here!

For complete audio of this section, click here: */@api/deki/files/158/Aeolian_Deposits.m4a*



A quick video taken by Guthrie Nutter in Death Valley, California of dunes forming.

Wind Erosion

Wind can erode the surface of the Earth through *wind abrasion* and through *deflation. Wind abrasion* is the physical weathering of a rock from strong, turbulent winds, while *deflation* refers to wind actively removing loose particles. Wind erosion has a huge impact on shaping the Earth's surface as well as affecting our lives. It can affect crops and soils greatly disrupting agriculture and can also impact the air quality.

For complete audio of this section, click here: */@api/deki/files/159/Wind_Erosion.m4a*

Contributor

- Marcelle d'Almeida

Works Cited

Title Images:

- http://en.wikipedia.org/wiki/Aeolian_processes#mediaviewer/File:Sandstorm_in_Al_Asad,_Iraq.jpg
- http://skywalker.cochise.edu/wellerr...s/image001.jpg

Sources for information:

- http://www.nature.nps.gov/geology/mo.../geomon-01.pdf
- http://skywalker.cochise.edu/wellerr...an/aeolian.htm
- http://www.seddepseq.co.uk/SEDIMENTOLOGY/Sedimentology_Features/Ripples/Ripples.htm

Sand Dune video by Guthrie Nutter:

- https://www.youtube.com/watch?v=OKkRF2sdXb8

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8.4: Chronostratigraphy

The idea behind chronostratigraphy is to correlate rocks that formed at the same time. This is useful for reconstructing events and depositional environments in earth history as well as finding resources like oil. There are several techniques that can be used for chronostratigraphy, including: event stratigraphy, magnetostratigraphy, chemostratigraphy, biostratigraphy, and sequence stratigraphy. Here, I will address event stratigraphy, magnetostratigraphy, and biostratigraphy. Sequence stratigraphy is very powerful, and lots of resources on it can be found at: http://sepmstrata.org/

Event Stratigraphy

Event stratigraphy involves identifying the sedimentary effects of an unusual event in multiple stratigraphic columns. If one can demonstrate the the effects were all produced by the same even, one can reasonably interpret the effects to have happened at the same time in the different columns. For example, if a volcano erupts and deposits ash over a broad region, that ash is preserved in the stratigraphy, and a geologist can demonstrate that the ash in multiple sections came from the same eruption, then the geologist can create a chronostratigraphic correlation among the sections. Other events that are useful for event stratigraphy can include impact debris layers (for example at the Cretaceous-Tertiary boundary), tsunami deposits, and sometimes large storms.

There are some shortcomings of event stratigraphy. First, there has to be an event that affects the stratigraphy. For it to be useful, it needs to be something that affects multiple depositional environments in a way that produces a distinctive set of features that can be distinguished from the normal depositional processes. Second, for a specific event to be useful for correlations, it has to have affected the stratigraphy at the sites of interest. For example, a tsunami that affected the west coast of North America might help one correlate Pleistocene coastal deposits in Oregon and Washington. However, it would not be helpful for correlating Pleistocene rocks in Florida because it did not influence them. Third, if there are multiple events, the geologist has to sort out which correlate with each other. For example, if there are multiple volcanic eruptions at different times, the geologist needs to evaluate which eruptions the ash beds might represent. It can become complicated to correlate many events. Sometimes correlations are more reliable if there are fewer events, but then there are not as many potential temporal ties between the stratigraphic columns. Even with these complications, event stratigraphy is a very valuable tool. When the events are volcanic, the ash beds can often be dated, providing a precise age for a segment of the stratigraphic column.

Magnetostratigraphy

Magnetostratigraphy uses preserved magnetization of rocks for correlation. The magnetization comes from the alignment of magnetic minerals in sedimentary rocks (and other types of rocks) with the earth's magnetic field. Small magnetic minerals, especially clay-sized minerals, align like little magnets, and when the sediment is lithified, that magnetization can be preserved. Under the right conditions, samples can be collected and the direction of magnetization measured. Data can be used to reconstruct the direction of the earth's magnetic field. This magnetic field can reverse directions due to the dynamics of circulation in the core. In other words, sometimes the magnetic field is aligned such that magnets point north (as they do now, and called "normal" in the scientific literature) and sometimes it is aligned such that magnets point south (called "reversed"). The earth's magnetic field changes at close to the same time globally, so the effects are seen everywhere. Paleomagnetists have studied well dated sedimentary and volcanic rocks and have mapped out the times in earth history where the magnetic field was normal and reversed (see: http://www.geosociety.org/science/timescale/). This provides a reference that can help correlate other stratigraphic sections.

To correlate a suite of stratigraphic sections using magnetostratigraphy, one would collect samples, measure their magnetic properties using a variety of techniques, and evaluate whether or not they have been remagnetized. If they have not been remagnetized, changes in the direction of earth's magnetic field can often be interpreted from the results. If a geologist has multiple sections that were deposited at the same time, they can interpret the changes in the direction of earth's magnetic field to have happened at the same time. Unfortunately, however, one can not necessarily independently tell the many normal intervals apart from each other nor the many reversed intervals apart. Thus, the geologist needs additional information to make reliable chronostratigraphic correlations.

Biostratigraphy

Biostratigraphy is an extremely powerful tool for chronostratigraphic correlation. Life evolves through time, with new species emerging and other species going extinct. For time intervals and species that are well studied, the process of evolution provides a detailed temporal framework for correlating stratigraphic columns. The basic idea is for the geologist to identify fossils in the stratigraphic columns, compare them to the ranges of those organisms know from previous studies, and then interpret the age of the rocks from documented extinction and species origination events. This is an extremely powerful approach to correlating stratigraphic columns because each species is unique and changes through time. However, not all organisms are useful for biostratigraphy.

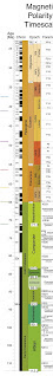
Good biostratigraphic species:

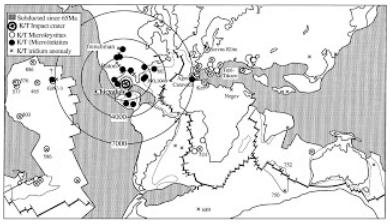
1. have short geological ranges, e.g. they did not live for millions of years, and evolved quickly;
2. were distributed over a large region of the earth;
3. were easily preserved; and
4. were abundant. They also need to be well studied.

Zones of well documented species with distinct origination and extinction times can be defined a number of ways. A zone could consist of the total time of existence of a fossil, it could consist of the time where two or more fossils coexist, it could be defined as the time between the origination of one fossil and the extinction of a different fossil, etc. An example of a biostratigraphic zone chart, combined with magnetostratigraphic reversals can be found at: http://www-odp.tamu.edu/publications/189_IR/chap_02/c2_f6.htm

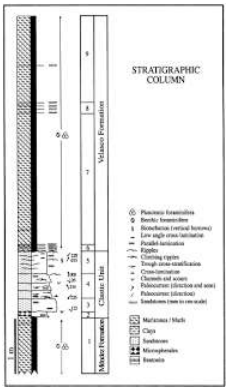
Cretaceous-Tertiary Boundary Example

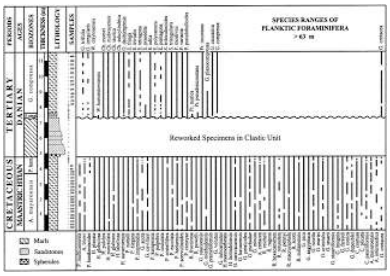
The end of Cretaceous time is marked by a major extinction, a meteorite impact, and reversals in the Earth's magnetic field. The following are some figures we'll use in class. I'll update the notes and reference the figures after class (my computer just crashed and I lost what I'd written - save often!)

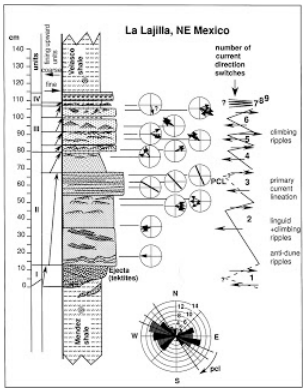


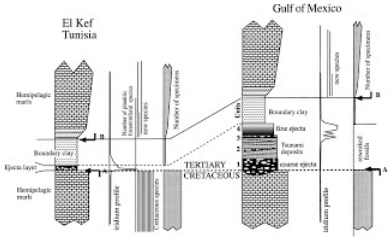


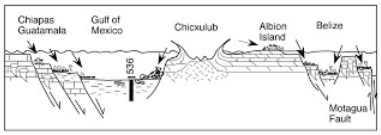


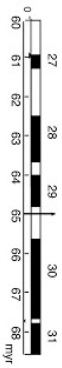

STRATIGRAPHIC COLUMN
Velasco Formation
Clastic Unit
Midway Formation

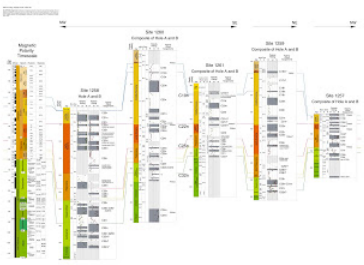

SPECIES RANGES OF PLANKTIC FORAMINIFERA
Reworked Specimens in Clastic Unit
TERTIARY
CRETACEOUS
Marls
Sandstones
Spherules


La Lajilla, NE Mexico
number of current direction switches
climbing ripples
primary current lineation
linguid +climbing ripples
anti-dune ripples
Ejecta (shilites)
Velasco shale
Mexcala group


El Kef
Tunisia
Gulf of Mexico
Hemipelagic marls
Boundary clay
Ejecta layer
TERTIARY
CRETACEOUS
fine ejecta
coarse ejecta
Tsunami deposits
rare species
Number of specimens
Cretaceous species
iridium profile


Chiapas
Guatamala
Gulf of Mexico
Chicxulub
Albion Island
Belize
Motagua Fault





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8.5: Exploring Cross Stratification

Overview

By working through this page, you will gain a deeper understanding of how cross stratification reflects the geometry of migrating bedforms. We will use information from David M. Rubin, who published a book called Cross-Bedding, Bedforms, and Paleocurrents, which is available from SEPM with free online movies. His great movies demonstrate how various types of cross stratification are created. You can use these movies to help interpret various styles of cross stratification.

Goal

The insights you gain from working through this page will help you predict the type of cross stratification a ripple or dune is creating as well as interpret the ancient flows that produced cross stratification you see in rocks.

Straight Bedforms

A computer model generated these movies. Each starts with a bedform shape, which is constant throughout the movie. It is defined by the grey shaded surface. "Laminae" are deposited by moving the surface downstream and slightly up for each time step. Deposited laminae are represented by white lines. If the surface intersects the laminae, they are eroded, just like if laminae are exposed to an erosive current, they are eroded. Thus, the laminae change length and geometry as the "bedform" (surface) migrates.

All the movies associated with the publication are all listed at http://walrus.wr.usgs.gov/seds/bedforms/animation-toc.html. They are categorized by the shapes of the bedforms and photographs of real bedforms are also included. This is an EXCELLENT resource.

First, watch a model-produced version of the migration of a linear ripple or dune. Note that the crests of the ripples or dunes are straight. They produce dipping surfaces on the lee side of the bedform (where sediment is deposited and shown by tan lines). These are preserved if the crest migrates upward through time, e.g. sediment accumulates. Note that the laminae look flat when viewed looking directly upflow or downflow, as in the image here.

Questions to Ask Yourself:

- How does the geometry change looking at different angles? (Watch carefully between 30 and 50 sec in the video.)
- What is the geometry of the laminae on top of the deposit? (Watch after 50 sec.)

Curved Bedforms

Watch a movie of ripples or dunes with curved crests. After migration of the bedforms, the cross stratification is rotated to show how different surfaces show different cross stratification styles. Drag the marker at the bottom of the movie back and forth to explore these variations. Note how important it is to have a 3-D view of the cross stratification to interpret bedform geometry even when it is relatively simple! The movie ends with the top surface of the ripples/dunes getting eroded flat. The tan lines represent the laminae that intersect the upper surface. Note how complexly shaped they are.

Questions to Ask Yourself:

- How is the geometry of the cross stratification different than that of bedforms with linear crests when viewed perpendicular to the flow direction?
- How is the geometry of the cross stratification different than that of bedforms with linear crests when viewed looking directly upflow or downflow?
- How does the geometry change at intermediate angles?
- How is the geometry of the top look different? Which lines represent the laminae and which represent the bounding surfaces?

Real Ripples

Next, watch a movie of real current ripples in an experimental flume. This will give you a sense of how irregular ripples can be. https://cmgds.marine.usgs.gov/data/seds/bedforms/extras/movies/ripple_flume.html In nature, sometimes ripples are this variable, and sometimes they are more linear.

Make a Prediction:

- Predict the geometry of the cross stratification produced by the bedforms in the flume!

Sediment Accumulation

The amount of sediment that accumulates as a ripple or dune migrates past changes whether or not sediment accumulates. Compare these two movies: No sediment accumulation and very abundant sediment accumulation. The amount of sediment that accumulates depends on how the sediment transport capacity of the flow is changing. If the flow is speeding up or getting deeper, its transport capacity is increasing, and erosion will occur. If the flow is staying exactly the same, all the sediment that is moving will bypass the sediment surface, and nothing will be preserved. If the flow is slowing down or getting shallower, it has to reduce the amount of sediment that it is carrying, so sediment remains behind and preserves the passage of the bedform.

Questions to Ask Yourself:

- If there is no sediment accumulation, will there be any record of the bedform passing?
- How is the geometry of the cross stratification different when there is so much sediment accumulating that there is no erosion on the stoss side of the bedform than when there is?
- What types of conditions promote the accumulation of sediment and thus the preservation of the bedform passing? Where are these conditions likely to occur?

What's Next

One goal of the modeling effort is to reproduce complex cross stratification that is observed in the field. The following movie produces a simplified version of cross stratification observed in a river bar. Here is movie that shows how the model can fit complicated structures observed in the field. This movie begins with an image of cross stratification from the Colorado River. Then it shows a computer-animated sequence that generates compound crossbedding. "After the computer-generated structure is constructed and rotated through a variety of outcrop orientations, the image morphs into a natural outcrop of the same kind of structure. The natural example was photographed on a horizontal surface that was excavated into a fluvial bar in Grand Canyon. This movie is the best one for illustrating the origin of moderately complicated crossbedding." (Dave's description)

Lots of other movies are available to explore as you wish. There are also LOTS of photos of different model-produced stratification styles and some outcrop photos associated with the online book (see https://walrus.wr.usgs.gov/seds/bedforms/animation-toc.html). The USGS web site also provides software to make your own movies by defining a bedform geometry. Have fun!

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8.6: Rivers

Transport Capacity

Erosion by water occurs when water is flowing across a surface and the flow is capable of transporting more sediment than is currently moving as bedload. This is called the sediment transport “capacity”. A certain number of grains of a certain size can be picked up by the Bernouli effect for a given flow. If there are too many grains, they start colliding and the characteristics of sediment transport change. Grains are directed back toward the bed and up into the flow. Eventually, more go back to the bed and are deposited, leaving fewer grains in the flow even at high flow speeds because there are more grains than the transport capacity of the flow.* In contrast, if there is a shortage of grains of a size that can be moved by the flow, e.g. the flow is moving all of grains present, any new grains will be eroded off the bed as soon as they are available. The flow then has excess transport capacity.

* Think about dumping a truck load of fine sand into a fast moving river, it takes time to move all that sediment even if the flow speed is theoretically fast enough to erode fine sand.

One of the most common times for a flow to have excess transport capacity is when the flow is speeding up. We know from the Hjulstrom diagram that faster flows transport larger grains. They can also transport more grains. Thus, water flowing downhill commonly speeds up, has excess capacity and erodes sediment. When it slows down, sediment is deposited. In floods, the water speeds up, erodes sediment, and transports it. As the flood ends, the water slows down and deposits the excess sediment. In general, erosion occurs when flows are speeding up or when they go from an environment with low sediment (e.g. a dam spillway) to an environment with more sediment (e.g. a river bed).

Rivers

Rivers are responsible for most sediment transport from mountains to lowlands and the oceans. They do the most to even out the topography that tectonic processes create. Rivers consist of channel, bank and overbank or floodplain deposits. Most of the sediment and many river characteristics are controlled by the highest common flow speeds.

River Types -
Straight (rare, except for ones humans have modified)
Meandering (high sinuosity)
Braided (many branches within a channel)
Anastomosing (rivers with branching and merging channels)

The form of the river is controlled by the gradient of the river bed (steep = braided, gently dipping = meandering), local vegetation that stabilizes banks and limits the number of channels, sediment grain size, particularly the ratio of suspended versus bedload sediment, and sediment volume. A high bedload gives rise to abundant bars, which promotes formation of braided rivers.

Braided Rivers

Braided rivers develop when the proportion of bed load sediment is high, which produces abundant bedforms and promotes the development of bars, and thus, the braided character of the river. The sediment is commonly coarse, which requires fast flow and steep gradients for the sediment to be transported. Much of the geometry of braided rivers is shaped by the highest flows, e.g. spring floods, when the bars are covered in water. Many braided rivers have exposed bar tops for much of the year.

Flow speeds and transport capacity vary dramatically within a braided river. Friction with the riverbed tends to slow down the flow, particularly where the flow is shallow. Thus, the Reynolds number in shallow areas is relatively low (but still high enough that the flow is turbulent) and the transport capacity is low. In contrast, the transport capacity and Reynolds number are much higher in the deeper middles of channels in the river. Thus, the coarsest sediment is transported here, whereas finer sediment gets deposited in shallow areas. Also, bars block the flow on the upstream sides, and like dunes, the upstream sides tend to erode. Areas of low flow and eddies form on the downstream sides of bars, and they are usually sites of net deposition. Thus, bars migrate downstream through time. If we summarize the processes:

Sediment Transport

1. The coarsest sediment is transported in the middle of the flow where the Reynolds number is highest.
2. Bars are eroded upstream where the bars deflect the flow. Sediment is deposited on downstream side of bars and some on the flanks of bars where flow is slower, particularly on the insides of bends.
3. Secondary bedforms, i.e. planar beds, dunes, and ripples, form as a result of sediment transport on the bars and in the channels.

Sedimentary structures include:

1. trough x-bedding in channels, due to the migration of irregular dunes
2. coarsest sediment may be lower flat laminated if flow speeds are not fast enough to form coarse grained dunes
3. sediment on the edges of bars fines upward because the flow is shallower and slower, e.g. has a lower Reynolds number. Sedimentary structures can include anything from upper flat to ripple laminations.

Braided River Facies

Channels migrate back and forth leaving a sheet of sand with abundant cross stratification. These sheets of sand tend to fine upward. General characteristics of braided river deposits include:

1. Scoured surface at the base of a channel
2. Gravel lag at base of channel
3. Trough x-bedded sands deposited just off the center of channels
4. Occasional tabular x-stratification from migrating bars
5. Sand deposited at slower speeds (ripple cross lamination possible)
6. Overbank deposits from floods mostly composed of sand and silt, with some mud

The large scale geometry of the deposits includes sheets of sand with various grain sizes representing bar migration separated by floodplain deposits.

Template:ExampleStart

Example of a braided river in Alaska: http://g.co/maps/wrk9n It is cutting through glacial morraines deposited as a glacier retreated up the valley. Follow the river downstream (to the north and east) to http://g.co/maps/q5kq7. How does the channel geometry change?
Template:ExampleEnd

Meandering Rivers

Meandering rivers have a low gradient and thus slower flow, and usually have a high proportion of suspended sediment relative to the amount of bedload. A meandering river channel has curves that meander back and forth on a gently sloping floodplain. The flow speed in the channel varies with the geometry of the meanders. Water has to travel faster on the outside of bends than on the insides of bends. We know from the relationships between Reynolds number and bed shear stress that higher flow speeds mean that more and coarser sediment can be transported at higher flow speeds. Thus, we can predict that:

1. there is more erosion on the outsides of bends
2. the sediment moving near the outsides of bends and in the deepest parts should include the coarsest sediment available
3. sediment will accumulate on the insides of bend and this sediment will be finer grained.

If we look at a channel in cross section, it is asymmetric, representing the sites of erosion and deposition. Variation in flow speed also produce different sedimentary structures. Upper planar lamination and dune cross stratification are common where Re is highest, and ripple cross lamination is common where Re is lower.

The main parts of the channel include eroding bank, the thalweg (the deepest point of the flow) and the point bar (on the inside of the bend where most sediment is accumulating). As the channel migrates due to erosion and deposition, a distinctive suite of sedimentary structures accumulate. The deepest part is coarser and has upper planar lamination or dune cross stratification. This is overlain by finer sediment with current ripple lamination.

As meandering rivers migrate, the meanders tend to increase. Eventually, the channel forms almost a circle, and the meander gets

cut off, often during a flood. This straightens the channel temporarily and produces an ox bow lake in the abandoned meander. The lake accumulates mud and organic matter.

Watch this cartoon of a meander migration in France: http://faculty.gg.uwyo.edu/heller/SedMovs/Meander_Alliers.htm

Levees and Floodplains - When a river floods, it goes from a confined flow in the channel which is very rapid to a widespread flow across the floodplain. It slows down very quickly and the water becomes shallower, both of which cause a decrease in Re. Thus, the water can not transport as much sediment on the floodplain as it does in the channel. Thus, finer sands that may be in suspension during a flood are transported as bedload or rapidly deposited once the river tops its banks. This produces levees. The finer silts and especially clays remain in suspension much longer and settle out on the floodplain as the flood waters dry up.

Watch this model of a meandering river flood: http://faculty.gg.uwyo.edu/heller/SedMovs/RhineFlood.htm

Over time, the levees build up and provide a higher bank for the channel than the level of the floodplain. Thus, the channel bottom can aggrade (fill in) until the bottom of the channel is as high or higher than the floodplain. When the next flood comes along, the river avulses and does not go back into its old channel which is higher than a new one on the floodplain. This results in the downstream part of the channel being completely abandoned.

Meandering River Channel Facies

1. Scoured base of flow
2. Lag deposit with mud rip-up clasts and the coarsest grains being transported
3. Fining upward sands with trough cross stratification
4. Rippled sands
5. Sigmoidal cross stratification from migrating point bars

Floodplain Facies

1. Fine sand with climbing ripples
2. Mudstone/shale with mud cracks
3. Soils
4. Root casts

Ox Bow Lake Facies

1. Mudstone/shale without mud cracks
2. Organic-rich deposits, including coal
3. Anoxic water indicators (especially in fossils and absence of trace fossils)

Differences between braided and meandering river deposits

1. Braided river deposits are commonly coarser grained
2. Meandering rivers contain abundant suspended sediment, which is deposited in ox bow lakes and on floodplains.
3. Overbank deposits are better developed and finer grained in meandering river systems.
4. Bar migration is much more regular in direction in meandering rivers because there is a well defined, single thalweg towards which the bars migrate. In contrast, braided river bar migration occurs in multiple directions. Thus, meandering rivers produce a more regular geometry of tabular cross bedding, when preserved.

General Characteristics of Fluvial Sediments

1. On a large scale, river deposits consist of sheets and lenses of sand deposited in channels associated with flat laminated shales and silts with rare rippled sand beds deposited on floodplains.
2. Fining upward sequences of beds in the sands with sedimentary structures that indicate decreasing flow speeds.
3. Abundant cross stratification in well sorted sands, particularly trough cross stratification.
4. Cut banks at the edges of channels - these are good indicators of a migrating river channel, but can be hard to see in outcrop since they are rarely preserved

5. Soil development in associated shales deposited in the floodplain environment.

Look at pictures of fluvial rocks at http://mygeologypage.ucdavis.edu/sumner/gel109/SedStructures/Fluvial.html

Template:Summer

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8.7: Weathering and Erosion

Sediment comes from the break down of rocks into smaller, transportable components. This occurs via two processes: **physical weathering** and **chemical weathering**. Physical weathering consists of breaking apart rocks and crystals. The results of physical weathering are smaller components of the same material that is being weathered. There is no change in composition. In contrast, chemical weathering consists of changing the composition of at least some components of the rock that is weathering. The sediment does not have the same composition as the original rock.

Physical Weathering

Physical weathering occurs via:

1. Freeze-thaw action. Water in cracks expands when it freezes, putting force on the cracks. The cracks grow, and eventually crystals and pieces of rock break off into smaller components. Obviously, this process is most important in environments where temperatures cycle across the freezing point of water.
2. Salt crystal growth. When water evaporates, salts precipitate. If this happens in fractures in rock, the growth of the salt crystals can put pressure on the cracks, causing them to grow. This process is most important near oceans where rocks are exposed to lots of salt water spray and in arid environments where water evaporates rapidly.
3. Temperature changes. Minerals contract and expand as temperature decreases and increases, respectively, and different parts of the rock are heated different amounts. Those in direct sunlight expand as they heat, whereas the interiors and shaded areas do not. Differential expansion and contraction produces stresses which can result in cracks and physical weathering. This process is most important when temperatures change dramatically from day to night, a characteristic of many desert environments.

Physical weathering tends to produce mostly sand-sized sediment and larger grains because most of the fracturing occurs along mineral boundaries. Physical weathering of fine grained or finely crystalline rock can produce abundant very fine grains, but most of the sediment from these rock types consists of rock fragments (called lithic clasts).

Figure : Image of physically weathered rocks in New Zealand:



Chemical Weathering

Chemical weathering occurs via:

1) Dissolution of minerals. Some minerals like halite and other evaporites dissolve very easily in water. Other minerals, particularly silicates, do not dissolve easily. Carbonates are in between and dissolve in acidic waters. (Rain water has a pH of ~5.7 due to dissolved CO_2, even without “acid rain” pollution.) The results of dissolution are ions in water that are transported downstream. Ions are not deposited until the water evaporates, they react with other minerals, or organisms use them to make shells. Often, only part of a rock dissolves, leaving sediment that can be transported by wind, water, etc.

Alteration of minerals. Silicates do not dissolve very easily, but they do react with water to form new minerals. Feldspars react with water to form clay minerals and ions, olivine reacts with water and O_2 to form oxides, clay minerals and ions, pyrite reacts with water and O_2 to form oxides and sulfate ions. Iron oxides, such as hematite, are commonly red, giving weathered rocks a rusty hue. Alteration of minerals is one of the main sources of clay minerals and mud-sized grains.

Image of chemically weathered rocks in New Zealand:



This outcrop originally had the same composition as the rock shown in the previous photograph, but has been exposed to much more water as well as plant-assisted soil processes.

Mineralogy of Weathered Rocks

Sediments that have been subjected primarily to physical weathering have a mineralogy that is similar to that of the parent rock. If the sediments have been subject to extensive chemical weathering, it is much harder to characterize the source rocks because the composition has changed extensively. Overall, the composition of the resulting sediment depends on the mineralogy of the rock, how it is transported, and the weathering environment.

Some minerals alter more quickly than others. Quartz is difficult to dissolve and is hard, so it commonly lasts through both chemical and physical weathering and is the most common mineral in sand on Earth. In contrast, minerals like Ca-feldspar and olivine react to form new minerals quickly. They are substantially less common in sediments. Thus, mafic rocks (which contain Ca-feldspar, olivine and pyroxenes) tend to alter to clay minerals very easily and produce little sand and abundant mud. In contrast, granites (quartz, K-feldspar, Na-feldspar, mica) contains minerals that react more slowly and tend to produce sand-sized grains, especially quartz.

The following list includes minerals from most reactive (rarely found in sediments) to least reactive (common in sediments): Olivine, Ca-feldspar, Pyroxene, Amphibole, Na-feldspar, Biotite, K-feldspar, Muscovite, and Quartz

The other main control on sediment mineralogy is the hardness of the grains. During transport, grains hit each other. Softer grains tend to be damaged when they collide with harder grains, and this damage can cause them to break into smaller grains. Thus, soft grains become smaller very quickly when they are transported with hard grains. Quartz is the most common mineral in sandstones because it is hard and unreactive. Clay minerals are also very common because they are too small to damage much during collisions and they are the product of the alteration of other minerals.

Controls on Weathering

The extent and style of weathering is mainly controlled by climate. **Water** is extremely important, even for physical weathering. The more water present, the faster weathering occurs. **Temperature** is also important, as discussed for physical weathering. Warmer temperatures also promote faster reactions, so chemical weathering is more effective in warm climates. Thus, warm, humid climates tend to have the most rapid weathering (and poor outcrop). Finally, **vegetation** has a strong influence on weathering. Plants tend to increase the extent of chemical weathering by producing organic acids that help break down rocks into soil through both dissolution and alteration. They also help soil retain moisture, increasing the availability of water for weathering, and their roots can help widen cracks.

Erosion

Once sediment is produced by weathering, it is available for transport. The two main forces in erosion are fluid flow and gravity.

Fluid flow is what we talk about most, e.g. glacial erosion of sediment, wind blown sediment, and mostly water flow. Flowing water is the biggest influence in erosion because it is very common and effective at transporting sediment.

Erosion by water occurs when water is flowing across a surface and the flow is capable of transporting more sediment than is currently moving as bedload. This is called the sediment transport “capacity”. A certain number of grains of a certain size can be picked up by the Bernouli effect for a given flow. If there are too many grains, they start colliding and and the characteristics of sediment transport change. Grains are directed back toward the bed and up into the flow. Eventually, more go back to the bed than are lifted into the flow, and sediment is deposited. Sediment can be deposited even at high flow speeds when there are more grains than the transport capacity of the flow.* In contrast, if there is a shortage of grains that are small enough to be transported by the flow, e.g. the flow is moving all of grains present, any new grains will be eroded off the bed as soon as they are available. The flow then has excess transport capacity.

* Think about dumping a truck load of fine sand into a fast moving river, it takes time to move all that sediment even if the flow speed is theoretically fast enough to erode fine sand.

One of the most common times for a flow to have excess transport capacity is when the flow is speeding up. We know from the Hjulstrom diagram that faster flows transport larger grains. They can also transport more grains. Thus, water flowing from a shallower slope to a steeper slope commonly speeds up, has excess capacity and erodes sediment. When it slows down, the transport capacity decreases, and sediment is deposited. In floods, the water speeds up, erodes sediment, and transports it. As the flood ends or flood waters extend over larger areas, the water slows down and deposits the excess sediment. In general, erosion occurs when flows are speeding up or when they go from an environment with low sediment (e.g. a dam spillway) to an environment with more sediment (e.g. a river bed).

Gravity Transport of Sediment

Gravity pulls sediment down steep slopes through creep, rock or debris falls, landslides and slumps. These processes are really important for the hills in coastal California where there is enough water for extensive weathering, but there is little runoff of water most of the time.

Here are some videos of debris flows, mud flows, landslides, etc.:

Usually, the concentration of sediment is very high in gravity flows, which means that the grains collide with each other frequently. Grain collisions can help keep the flow moving. The collisions also keep the different grain sizes from being sorted out, and many of gravity flow deposits are poorly sorted. If lots of mud-sized sediment is present, the viscosity of the flow is high, and the flows can be laminar, which produces very poorly sorted deposits. These are often called mud flows or debris flows. Watch the videos again, and predict the characteristics of the sediment that would be deposited by the different processes.

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9.1.1: Importance of Sediment

Sediments, sedimentology, and stratigraphy all play important roles in shaping Earth history as well as in human societies.

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9.1.1: Importance of Sediment

Why Sedimentology Matters

Sediments and sedimentary rocks cover most of Earth, and weathering is occurring on the rest of it. The reshaping of the surface of the Earth has had a huge influence on the planet, affecting everything from the evolution of life to the tectonics of mountain ranges. Sediments and sedimentary rocks record the events and processes that shaped the surface of Earth – and other rocky planets. They provide the temporal framework that connects processes within the Earth to those at the surface. They are important for:

1. Earth history. Sedimentary rocks contain features that allow us to interpret ancient depositional environments, including the evolution of organisms and the environments they lived in, how climate has changed throughout Earth history, where and when faults were active, etc.
2. Economic resources. Petroleum reservoirs have organic-rich, sedimentary source rocks that produced the petroleum when heated, most oil and gas migrates through sedimentary rocks, and most of the reservoirs are hosted in sedimentary rocks. Water aquifers are dominantly found in sedimentary rocks (although some are in fractured metamorphic and igneous rocks). The composition of the rocks strongly influences water quality due to water-rock interactions. (Why does Davis water taste bad?) Sedimentary rocks also host economic minerals such as gold and diamonds, which are eroded from other rocks and concentrated to specific areas during sediment transport.
3. Environmental geology. Sediments cover 2/3 of the continents and essentially all of the ocean floor, which totals 89% of the surface of Earth. They host the biosphere, and they are most of the rocks we interact with directly and indirectly. Our actions as humans have an extremely strong effect on sedimentation and erosion. Understanding our impact on the environment - and the environment's impact on us - must include deep appreciation for sediments and sediment transport.

Case Study: Oroville Dam and Sediment Transport

Applications of Sedimentological Analysis to Problems of Interest

Environmental Geology

Examples with photos or diagrams

Natural Hazards

Examples with photos or diagrams

Natural Resources

Examples with photos or diagrams

Reconstructing Ancient Earth

Examples with photos or diagrams

Evolution and the Fossil Record

Examples with photos or diagrams

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9.3: Sediments and Strata

Sedimentology is the study of sediment transport processes and sedimentary rocks, and it is the focus of most of this course. It covers scales ranging from a single grain to entire planets. Sedimentology focuses on processes. Stratigraphy is the study of the distribution of sediments and sedimentary rocks in space and time. It is essential for understanding Earth history, reservoir properties, etc. Sedimentological interpretations are placed into a stratigraphic context for detailed interpretations of changes in environments over time.

Principle of Uniformitarianism

Sedimentology and stratigraphy are about as old as mineralogy as a field of study. Leonardo da Vinci provided one of the first environmental interpretations from sediments; he interpreted fossils in the Italian Apennines as evidence of an ancient ocean. He used the logic behind what we now call the **Principle of Uniformitarianism**: Similar organisms produce similar shells. The logic is, "If you see shells on the tops of mountains that look like those from organisms that live in the ocean today, the shells on the mountain tops were probably once in the ocean, too." (Did the mountains go up or did the ocean go down? That is a question that was not thoroughly answered until we understood plate tectonics!) Here is a more formal statement of the Principle of Uniformitarianism:

> **Key Concept:** The characteristics of sedimentary rocks can be used to determine the environmental conditions under which they were deposited, and the environmental conditions allow you to predict the characteristics of sediments that are likely to be deposited. The processes that formed ancient deposits are the same as those that form modern deposits.

Here are some videos and images that connect these ideas:

Current Ripples:

- Current ripples forming in a flume (video): http://youtu.be/rSzGOCo4JEk
- Modern Current Ripple Image: https://en.Wikipedia.org/wiki/Ripple_marks#/media/File:Ebbe.jpg
- Current Ripple Cross Lamination

Wave Ripples:

- Wave ripples forming in a flume (video): http://youtu.be/MBDadRqSHOc
- Modern Wave Ripple Images
- Ancient Wave Ripple Images

In the much more recent past, for example in the 1970's, the Principle of Uniformitarianism was interpreted by some as requiring continuous, incremental processes and as excluding dramatic, rapid events. For example, a meteorite impact was seen as a non-uniformitarian event. However, my view of uniformitarianism can encompass rare events. The basic idea is that catastrophic events also produce characteristic features. For example, a meteorite impact produces similar deposits no matter when it occurs in time. We can recognize impact spherules from Archean sedimentary rocks that formed and were deposited in essentially the same way as those from the Cretaceous impact that killed the dinosaurs. Or an impact on Mars will produce features similar to those produced by an impact on Earth.

> *Brief summary of how geologists identified the K-T impact from Prof. Eliza Richardson, Penn State*

The key point is that **similar processes produce similar products**. All processes are not active at all times (large meteorites are not continuously bombarding Earth!), and some, like burrowing by worms for example, did not occur at specific times, e.g. before the evolution of worms. However, if a feature is present that is characteristic of a specific process, e.g. a thin tube-shaped area in a siltstone with a slightly different color and a specific geometry, it is reasonable to interpret that process, e.g. burrowing by a worm, as having produced the feature. This is how we extract Earth history from rocks, e.g. the absence of worm burrows before 540 Ma allows us to state with confidence that worms did not exist before 540 Ma. However, it is often challenging to identify which processes produce which features. There is rarely an exact correlation between features and processes that one would wish for. For example, a specific color variation in a rock could reflect a burrow or a water flow path or both if the burrow influenced water flow. One needs to understand the uncertainties in geological interpretations.

Right now, I am using the Principle of Uniformitarianism as a scientist on the NASA Mars Science Laboratory (MSL; http://Mars.jpl.nasa.gov/msl) - a mission that is using the rover Curiosity to investigate ancient environment in Gale Crater on Mars. The team is looking at grains and rocks, trying to understand what the ancient environments were like. The only way they can do this is to assume that sedimentary processes on Mars produce the same features they would produce if they occurred on Earth. There may be some processes on Mars that are very rare or do not occur on Earth, and these might produce features we do not recognize. However, if we see a current ripple, we can infer that there was flowing water on Mars. The details of the flow speed, water depth, etc. might have been different (and we can calculate that), but the basic process was similar.

> *Summary of the Principle of Uniformitarianism (Video link)*



Original Horizontality and Younger-Over-Older

There are two other really important concepts that were first articulated in the 1660's that we use on both Earth and Mars: The **Principle of Original Horizontality** and the fact that **younger sediments overlie older sediments** (also called superposition). Nicolas Steno was the first to write down the idea that strata (or sedimentary rock layers) are deposited in a nearly horizontal position, an idea called the **principle of original horizontality**. Some layers are deposited exactly flat, but most layers follow the tilt of the depositional surface, which is not exactly horizontal. However, most sedimentary layers are sufficiently close to horizontal for our purposes here. If layers are no longer horizontal, later deformation must have changed their orientation.

Images of "horizontal" and tilted strata:

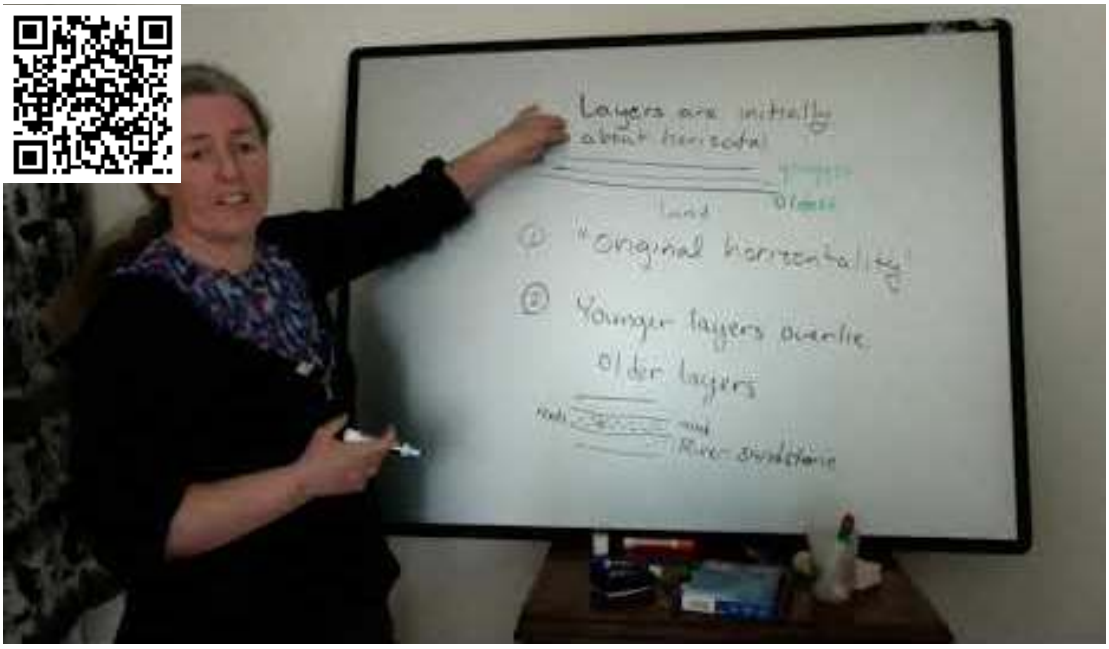
- Grand Canyon "horizontal" strata
- Rainbow Basin tilted and folded strata

This idea is intimately associated with the idea of time in rocks.

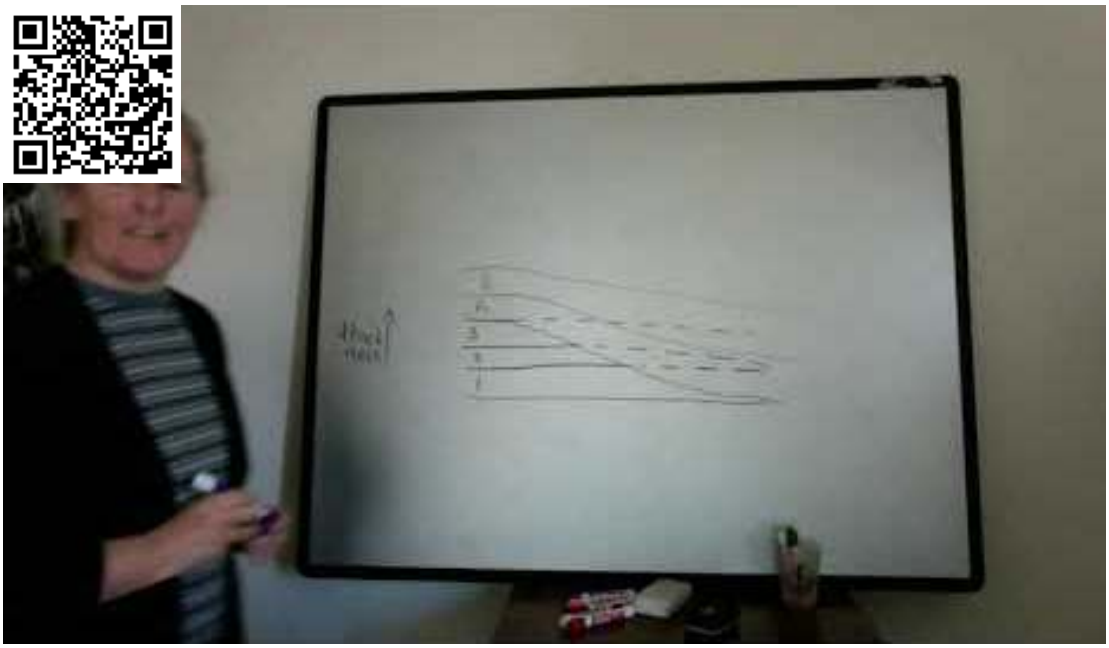
- **Key Concept:** Younger sediments overlie older sediments (unless faulting and folding have turned them upside down).

Steno first wrote this down in 1667. The relative ages of sedimentary rocks gives us time. We can interpret changes in processes through time using the principle of uniformitarianism combined with the relative age (or stratigraphic succession) of rock layers. Steno's work provided the intellectual framework for understanding relative time in a local areas. It was not until much later that the idea of "faunal succession" (articulated by William Smith, early 1880's) provided a global time scale. Smith (and other geologists at the time) recognized that fossil organisms succeed one another in the stratigraphic record in an orderly, recognizable fashion. They were learning about a key component of evolution, although they did not yet have the intellectual framework of evolution by natural selection. They formulated the basic ideas that if organisms evolve through time, rocks containing similar organisms are approximately the same age.

Discussion of original horizontality and superposition (Video link)



Broad-scale discussion of the distribution of time in sedimentary rocks (video link)



Discussion of the distribution of time in sedimentary rocks at the grain scale, including a discussion of the differences in ages of grains versus layers (Video link)



NASA's Mars Science Laboratory team is using these ideas to interpret the time history of events in Gale Crater, Mars. One of the reasons we chose to go to this landing site was that Mt. Sharp, which is a 5 km-high mountain in the crater, contains layers of rock. These layers record a history of processes and events that occurred in Gale Crater; they contain clues to what Mars was like about 3 billion years ago. We do not yet know very much about the rocks. However, we do know that the earliest history is in the rocks at the bottom, and changes in the rocks going upward reflect changes through time. In other words, the history book starts at the bottom.

Strata in Mt. Sharp taken by the Curiosity rover, Gale Crater, Mars

On Earth, geologists have studied the time succession of rocks to create the Geological Time Scale. This time scale is largely based on fossils (for rocks younger than mid-Neoproterozoic time), with radiometric ages providing absolute time and refinements on our understanding of evolution. Continual refinements in the time scale provide insights into the process and history of Earth that are core to geology. In many ways, the geological time scale documents our substantial understanding of Earth. In contrast, the Martian Geological Time Scale is just being built. We know very little about the history of Mars, and right now, we can only use how old rocks look - the number of craters or how many other rocks are on top of them - to get relative ages. Some planetary scientists have noted a correlation between apparent age and mineralogy, with the oldest rocks having more clay minerals, medium aged rocks having more sulfate minerals, and the youngest rocks being mostly wind deposits. On average, this may be true, and this model provides a testable hypothesis, one that we are testing with the Curiosity rover. Rocks in Mt. Sharp show spectral signatures of both clay and sulfate minerals. Using Curiosity, the team is analyzing the mineralogy of these rocks, in the context of their sedimentary structures, grain size, etc. to interpret the environments in which they formed and their relative ages.

It was the similar study of rocks in England by early geologists that led to the definition of Cambrian, Ordovician, etc. Comparisons of the spatial distribution of similar features leads to many important insights. Da Vinci recognized that fossils can be used to interpret ancient rocks; he interpreted similar environments because the shells he saw were essentially identical to those in the modern oceans. To Smith and other English geologists, similar fossils suggested the rocks were similar ages.

These two ideas reflect the two key components of stratigraphy: rock types vary in both space and time, but the same type of rock can be deposited in different places at different times. These changes in rock type can be organized based on how different environments are distributed.

Walther's Law

> **Key Concept:** (Walther's Law) Depositional environments vary in space and time such that "The facies [rock types] that occur conformably* next to one another in a vertical section of rock will be the same as those found in laterally adjacent depositional environments" (Johannes Walther, 1894).

(**Conformably* means that there is neither a break in sedimentation nor erosion between the two environments, e.g. there is no unconformity between them. Jumps in depositional environment can occur if the rocks do not provide a complete record of the environmental changes that occurred; rock types in a vertical succession separated by an unconformity do not necessarily represent neighboring environments.)

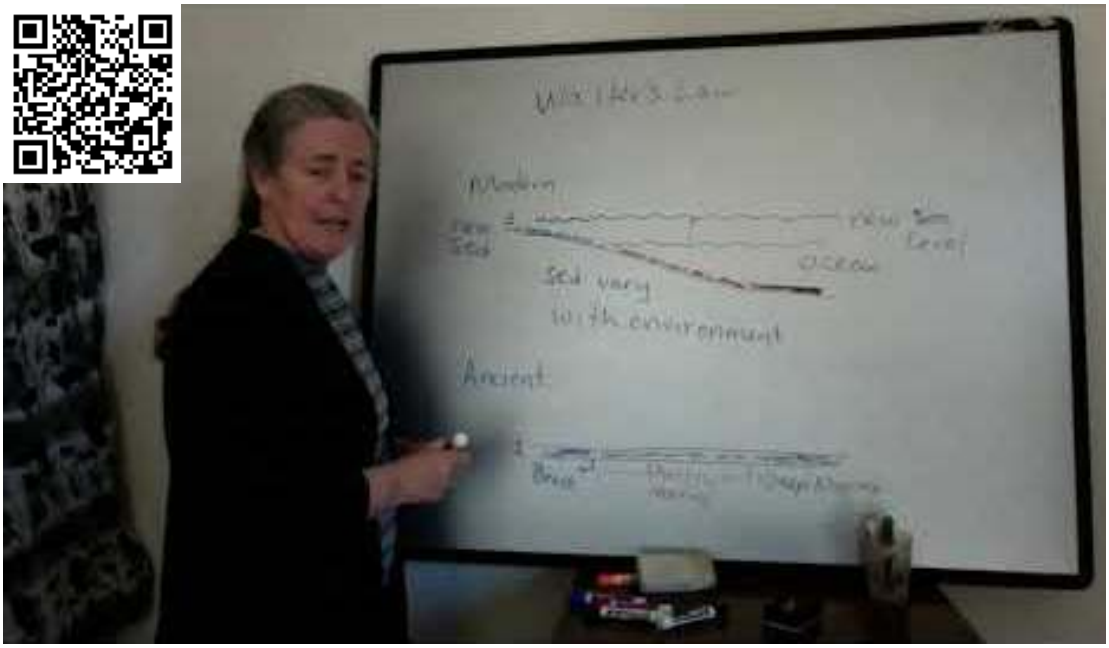
- *Images of environments and Google Earth tours: To view these files, you can open them with a number of GIS programs. Alternatively, you can go to http://earth.google.com, create a new project, and import the kmz file.*
  - *Environments from Davis to San Francisco*

- Tidal environments near Derby, Western Australia

One of the most important implications of Walther's Law is that rocks of the same type are not necessarily deposited at the same time. There is a BIG difference between correlating rocks based on having the same lithology and rock being deposited at the same time. This is a critical conceptual idea that we will focus on throughout the class.

Thought question: What does this suggest for the martian time scale, which is based on mineral compositions?

Summary of Walther's Law (video link)



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9.4: Fluid Flow

Sediment Transport

Most sediment transport is due to gravity. Things fall down hill in slumps, debris flows, and mudflows, and are transported downhill by fluids, like water, ice, and air. In some cases, processes like waves, currents, and wind transport sediment up a slope such as on a beach or mountain slope. This transport goes against gravity and is driven by the processes of fluid dynamics. Fluid dynamics is the main topic of today's and the next lectures. We will come back to mass wasting processes when we talk about erosion. Mass wasting is important for transporting large volumes of sediment short distances, but fluid transport is required to move sediments long distances and is responsible for most sediment transport. To understand sediment transport, it is essential to understand the mechanics of fluid flow.

Fluid Flow

There are two end member ways fluids flow: 1) laminar flow and 2) turbulent flow. There is a wide gradation between these two end members, specifically "transitional" flows.

Laminar Flow- In laminar flow, water molecules move in straight, parallel lines down current. If you add a dye to water that is in the laminar flow regime, the dye would not mix into the water; it would streak out in an approximately straight line. Laminar flow is characteristic of very slow moving, shallow water, which is uncommon in nature. It is also characteristic of flows in "fluids" that are very viscous, like glacial ice or mud flows that have little water. (https://youtu.be/_dbnH-BBSNo)

Turbulent Flow- In contrast, turbulent flow is characterized by complex motion of water (or other) molecules. Molecules move in all directions in bursts of upward, downward, and forward motion, and even some backward movement. There is abundant mixing in the flow because neighboring molecules move in different directions, and an added dye mixes into the water very quickly. Most water and air flows are turbulent, at least to some degree. Turbulence is important for sediment transport in water and air because it makes grains easier to transport and tends to keep them moving longer. (https://youtu.be/LSi_2fw6ySY)

Transitional Flow– Transitional flows have some characteristics of laminar flow and some of turbulent flow. For example, dye may take some time to mix into the flow, but it does mix. (https://youtu.be/XOLl2KeDiOg)

Movies of Laminar and Turbulent Flow: YouTube Fluid Dynamics Playlist



The image to the left is of two rivers in Costa Rica mixing turbulently. The suspended sediment in the brown river is mixed into the clear water of the other river downstream.

The image to the right is of a glacier in Pearse Valley, Antarctica. Is the flow in glaciers laminar or turbulent? How can you tell? What properties of ice make it behave differently than water in terms of the amount of turbulence?



Reynolds Number

The Reynolds number predicts the extent of turbulence in a fluid based on how fast the fluid is flowing, the geometry of the flow (how deep and wide it is, etc.), and the density and viscosity the of the fluid.

Viscosity is a measure of the resistance of a material to flow, i.e. how “thick” and easily deformed it is. Viscosity is sort-of like the amount of friction within a substance. Walking through air is easy, because there is not much friction between air molecules. Air has a low viscosity. Swimming is more difficult because the water drags on your body. This is due to the “friction” between adjacent water molecules, i.e. higher viscosity. Ice is more viscous and impossible to move through because of the crystal bonds between the water molecules. It flows, but it does so slowly. It has a high viscosity relative to water and air (but low compared to most rock).

Back to the Reynolds number. The variables for the Reynolds number (**Re**) are: flow velocity (**u**), characteristic length (**l**) which represents flow geometry, say river depth, fluid density (**ρ**), and fluid viscosity (**μ**). The book uses **μ/ρ = v** (kinematic viscosity). **Re**

= (fluid inertial forces)/(fluid viscous forces) = **l*u*ρ/μ**. The units for this equation are typically (length)*(length/time)*(mass/length^3)/(mass/(length*time)). These all cancel out to form a unitless number, if you choose the same set of units for each variable, which you should always do.

Re can be viewed as inertial forces divided by viscous forces. Inertia is the resistance to change in motion, and inertial forces tend to make a bit of the fluid keep flowing in its own direction if it is misdirected from the main flow direction. Thus, high inertial forces tend to cause more turbulence. In contrast, viscous forces tend to suppress turbulence by damping out variations in motion through friction. Thus, a flow with a high viscosity (ice) tends to have less turbulence than a low viscosity flow (air).

The magnitude of **Re** gives an idea of whether the flow is turbulent or laminar. Turbulent flow has **Re greater than 2000** and laminar flow has **Re less than 500**.* Flow with **Re** between 500 and 2000 is transitional and has some characteristics of laminar flow, but some turbulence as well. In most cases, water and air flows have high Re because **l** is large, **u** is high and **μ** is low. Rivers and wind storms are good examples of turbulent flow. In contrast, ice has a high **μ** and flows slowly (**u** is low), so it is usually laminar. Also, very thin, slow flows of water, such as water flowing off a smooth cement parking lot, have low **Re** because **l** and **u** are small. Thus, it can be laminar. Laminar flow also occurs locally in turbulent flows right at the contact between the fluid and a smooth surface because **u** becomes very slow. This is really important for sediment transport, and we'll talk more about it in a few minutes.

* There are a number of different ways to define a Reynolds number. For example, a flow in a pipe has more surface interactions than a flow in a wide channel, and the radius of the pipe is used rather than the flow depth. When the Reynolds number is defined differently, the numbers where flow transitions from turbulent to transitional to laminar are different. For this class, we will always use these numbers as the boundaries, but they will be different for other applications, such as in hydrology and civil engineering.

It is useful to think about which variables are important for different comparisons. When comparing ice and water, the main difference is viscosity; the viscosity of ice ranges from about 10^3 kg/(m*s) up to more than 10^{20} kg/(m*s) depending on temperature. In contrast, the viscosity of water is about 10^{-3} kg/(m*s). The density of both is very close to 1000 kg/m^3. Thus, ice is almost always laminar but water is usually turbulent, although it can be laminar. When considering water flows, the flow speed and water depth are both very important. The viscosity and density change a little bit with temperature, but variations in flow speed and water depth are typically much larger effects.

For air, both the density and viscosity are low, so does **Re** tend to be high or low? The density of dry air at 1 atm at 15°C is 1.225 kg/m^3, and its viscosity is $1.8\text{x}10^{-5}$ kg/(m*s), giving an inverse "kinematic viscosity" of **ρ/μ**=$6.8\text{x}10^5$ s/m^2 for air versus $1.0\text{x}10^6$ s/m^2 for water. Thus, air would have a slightly lower value for Re than water for the same flow depth and speed. However, the thickness of typical air flows (meters to 100's of meters) promotes turbulence. **ρ/μ** for ice is 1 to 10^{-17} s/m^2, which is why it is essentially always in a laminar flow regime.

Here is a video of a gust of wind that probably has a maximum **u** somewhere around 40 m/s: http://www.youtube.com/watch?v=iXlYEJaJ66A That's me putting rocks on the fly of the tent. Note the turbulence and the snow transport.

Boundary Layer

Video of a boundary layer in a flume: https://youtu.be/cUTkqZeiMow

There is boundary layer at the edge of every flow, and it is illustrated in the video above. Flows have an average speed in the middle, but friction with immobile surfaces slows down the speed of the flow right at the surface. This creates a boundary layer that has different flow characteristics than the rest of the flow. Right at the surface, the water does not move, but as you go higher into the flow it starts to move more like the average flow. The area of the flow that has a reduced speed is called the boundary layer. The thickness of the boundary layer depends on **Re** (i.e. the amount of turbulence) and the roughness of the surface the flow is moving past. If the main water flow is very turbulent, it changes the velocity distribution because more of the high speed water is mixed down into the lower speed areas. Thus, the boundary layer tends to be thin. In less turbulent flow, there is little mixing of water from the center of the flow toward the edge of the flow, so the boundary layer tends to be thicker.

Viscous/Laminar Sublayer - Within the boundary layer, right next to the surface, there is a laminar sublayer. **Re=u*l*ρ/μ** - remember this defines the difference between laminar and turbulent flow. Because **u** (water speed) is very low at the base of the boundary layer, the **Re** is low there and the flow is laminar. The laminar flow part of the boundary layer is called the viscous or laminar sublayer, "viscous" because the viscous properties of the fluid are more important than the inertial effects. The fluid is

NOT more viscous here; rather, the inertia of the fluid is lower because **u** is lower, and the viscous properties dominate the behavior of the fluid. Farther up in the flow, **u** is higher, so the inertial properties of the flow dominate, and the flow is typically turbulent. If grains do not extend above the top of the laminar sublayer, they do not "see" much turbulence, and they are less likely to be transported. If they do stick up beyond the laminar sublayer because the laminar sublayer is thin or the grains are large, the grains feel the force of the turbulent flow.

Bed roughness or the characteristics of the surface also affect the boundary layer by affecting the amount of water that interacts with the surface. A very smooth bed, say one made of mud, does not deflect the water at all, so there is less mixing and less turbulence. There is a well developed laminar sublayer. In contrast, a bed with pebbles or boulders disrupts the direction of water flow in the boundary layer. The water gets deflected around the pebbles. Water from above tends to take its place. Since it is moving faster, the average water speed in the boundary layer increases. Thus, a rough bed reduces the thickness of the boundary layer much like a more turbulent flow does. A rough bed also disrupts the laminar sublayer by forcing the flow to move around objects. The laminar sublayer is developed locally, but in general, rough beds increase the amount of turbulence in a flow.

Sediments and Flow

Key Concept: The boundary layer strongly affects the amount of "Bed Shear Stress" which corresponds to the forces that tend to roll particles along the bed and the pressure differences above and below grains, which tend to lift them off the bed.

Bed Shear Stress - Sediments are affected by the difference in flow speeds from the bottom to the top of the boundary layer, gravity, and friction with the ground. Bed shear stress is a measure of these differences; it is the differential force that a grain feels from top to bottom. In a thick boundary layer, the speed of water flow at the top of the grains is not much different from the bottom, so bed shear stress is lower, and sediment is less likely to move. In a thin boundary layer, bed shear stress is much higher, and grains are likely to roll down flow. Thus, more turbulent flow (with a thinner boundary layer) results in more sediment transport. Bed shear stress increases with increasing fluid density, slope, and turbulence (water depth and flow speed). For example, water is better at moving sediment than air because it has a higher density and exerts a larger bed shear stress than air can. Deep, fast rivers move more sediment than shallow, slow rivers because of more turbulence and higher flow speeds in the boundary layer in fast rivers.

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9.5: Sediment Transport

The Bernoulli Effect

A higher pressure above grains than below them can “pull” grains off the bed into the flow. The pressure difference comes from a difference in water (or air) speed above and below the grain. As water flows faster, there are fewer collisions between the water and the surface it flows over than there are between standing water and a similar surface. Pressure is due to collisions. Thus, fewer collisions means lower pressure. The upstream side of a grain experiences the most collisions because the water is flowing into it. The downstream side experiences the fewest collisions, and the sides of the grain experience fewer collisions where flow is faster and more where the flow is slower. The net result is a low pressure zone above and slightly downstream of a grain. If the force exerted by this pressure difference is larger than the force of gravity, the grain will lift off the bed. This lift due to the pressure difference is the Bernouli Effect.

Which Grains Move?

Which grains get entrained in the flow depends on their size and density (how much they weigh) because that determines the force of gravity holding them down. It also depends on the shape of the grain. A grain with a large area to experience the low pressure (like a plate) will be more susceptible to being picked up than a round grain of the same mass (although flat grains may see a smaller flow difference from top to bottom if the boundary layer is thick, and thus flat grains may experience a lower Bernoulli Effect per unit area.) The other thing that really matters is the position of a grain relative to surrounding grains. If a grain is sandwiched between larger grains, i.e. in their flow shadows, it will not experience as big a pressure difference as if it is on a flat surface. Also, if a grain is upstream of a big grain, it has to be lifted over it, so it has to experience enough force to lift it high into the flow. Thus, things can be complicated if you are trying to predict the behavior of a specific grain. However, experiments and theory provide statistically meaningful predictions for how grains behave on average.

Bedload and Suspended Load Transport



Two things can happen once a grain is lifted into the flow: 1) it can fall back down or 2) it can stay there. It depends on how quickly the grain settles out versus how turbulent the water is (back to **Re**...). **Bedload** refers to the grains that are transported along the sedimentary bed, e.g. grains that are rolling and being lifted off the bed, but they fall back quickly. The name bedload comes from the fact that the grains moving by traction and saltation never get too far from the bed and “load” is an engineering term for the amount of sediment transported by a river. Rolling grains are in **traction**. Grains that are pulled off the bed with the Bernoulli effect but are large enough that gravity causes them to fall “quickly” back to the bed are said to be **saltating**. (The word saltating refers to the way salt from a salt shaker bounces when it is shaken onto a hard surface. The word is derived from a Latin word meaning dance.) Bedload grains are the ones that form sedimentary structures in flowing water.

Here is a playlist with movies related to sediment transport: Sumnerd’s Sed Transport Playlist

Suspended sediment consists of grains that are light or small enough that they do not settle out of the water; the turbulent bursts of water keep them in the flow (see brown water in the photo). The more turbulence in the water, e.g. the higher the Reynolds number, the larger the grains in suspension will be. The upward motions of turbulent flow are faster than the rate these grains settle, so gravity is counteracted and they stay “floating” in the water even though they are denser than the water. Very small grains do not settle out of flows unless the Reynolds number is low, which means that the flows need to be either have a very low flow speed or be very shallow.

YouTube video of white clay in a turbulent flow in a flume: http://tinyurl.com/78kg3z The pulsing in the flow is (probably) due to the pump that is making the water flow.

The video below shows both suspended and bedload transport. The water is cloudy due to suspended grains, and pebbles can be seen rolling on the bed.



Video 9.5.1: Observing bedload in a braided river

Hjulstrom Diagram

The flows that are required to pick up grains of certain sizes have been extensively studied in experiments and the results are plotted in Hjulstrom (or Shields) diagrams. Hjulstrom diagrams show grain entrainment on a plot of log grain size versus log flow speed. This diagram shows the areas where grains of different sizes are left on the bed, where they get moved sometimes (this is the gray zone), and where they get lifted up often and eroded away. Note that larger grains require higher flows - in general. The water speed that is required to transport a grain is call the *critical velocity*. This is important. If there is gravel in a sedimentary deposit, you can say that the water flow had to be above the *critical threshold* for it to get there! That might require a fast flowing river or strong wave action, and thus, a large part of narrowing down the depositional environment has already been done!

Here is the Hjulstrom Diagram we will use (or the one in the Nichols text, which has additional information on it):

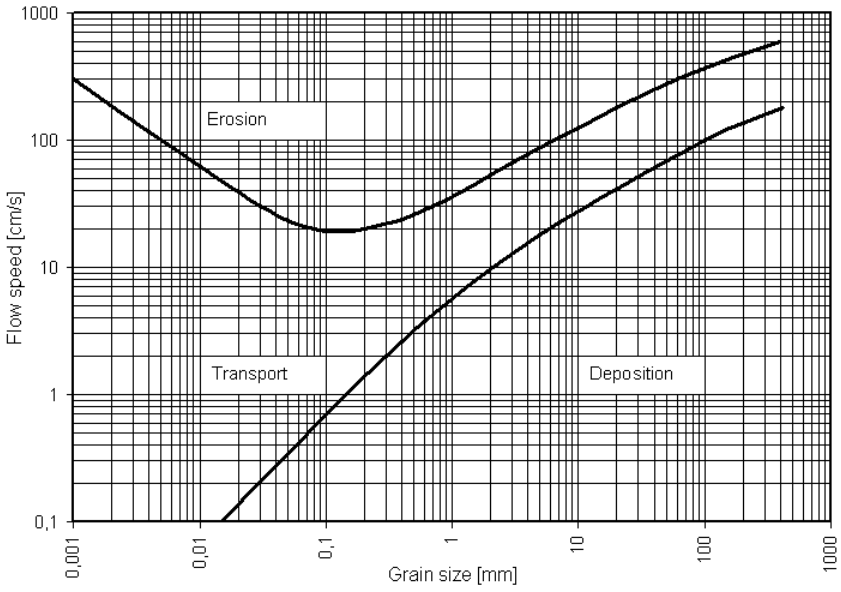


Figure 9.5.1: A Hjulstrom chart, describing transport, deposition and erosion in streaming water. The vertical axis is flow speed in cm/s and the horizontal axis is grain size in mm; note that both axes are on a log scale. This diagram is for a flow depth of 1 m. (CC BY-SA 3.0 Unported; Karrock via Wikipedia)

If the flow speed and grain size are in the field labeled "Deposition", grains of this size will not be lifted into the flow, and if they are already moving, they will be deposited onto the sediment surface. If the flow speed and grain size are in the field labeled "Transport", grains in motion are likely to continue in motion. A few grains will be deposited and a few grains will be eroded, but there will not be a significant change in the number of grains that move. If the flow speed and grain size are in the field labeled "Erosion", more grains will be transported than deposited until the flow is transporting as many grains as it can, e.g. it is at its "carrying capacity" for sediment.

The boundaries for deposition, transport and erosion shift with changing flow depth. For example, deeper flows can move larger grains at the same flow velocity because they are more turbulent:

$$Re = \frac{l \times u \times \rho}{\mu} \tag{3.1}$$

and l is larger. This is because deeper flows can have larger variations in flow speed and the laminar flow layers are very thin. They can have bursts of very rapid flow relative to the average flow speed and these bursts can pick up larger grains.

Caution

Actual flow characteristics are much more complex in detail than just Hjulstrom diagrams, which summarize a lot of characteristics into two axes. However, like a lot of people, we will use the diagram anyway, because it is very useful as a rule of thumb. Just remember that it does not accurately represent what will happen in detail - it represents a reasonable guess.

Silt and Clay Transport

Notice that for the small end of grain size, the speed of flow required for erosion actually increases. One reason small grains are hard to erode is that they tend not to stick up through the laminar sublayer; they are just too small. Thus, thinner boundary layers are necessary to roll them or for the pressure differences to pick them up off the bed. Also, the surfaces of clay minerals tend to be charged and the grains stick together. This is most obvious when big clumps of mud stick to your shoes. That just does not happen with sand (unless there is something gross in it). The stickiness of the clay grains makes them difficult to erode, so faster water flows (a greater pressure difference or larger turbulent burst down to the sediment surface) are required to move them. The smaller the grains, the more surface charges stick the grains together, thus the stronger the flow needed to erode them. The stickiness of the clay grains also depends on the amount of water between them and the mineralogy, so there is a big gray zone where a clay may or may not erode.

In the Hjulstrom diagram, there is an interesting area where the flow is not strong enough to move any of the particles on the bed, but those that are in the suspended load do not settle out either. This zone includes many of the waters on the surface of the Earth. In flows with any velocity or that are very deep, Re is high enough to keep some clay in suspension. Clay deposition usually occurs very slowly, e.g. when the rate of settling is just slightly faster than the average rate at which turbulence moves clay particles upward or when the clays clump together to form larger grains (which is common when fresh and salty waters mix).

Miscellaneous Notes

A few more words about saltation: Saltation is a very interesting and important process in sediment transport, because the force of the impact when the grains land tends to knock new grains up into the flow even if the flow is not fast enough to lift them with the Bernoulli Effect. These new grains can kick up more grains when they land, etc. This increases the rate of sediment transport above the amount the flow can lift grains off of the bed. This is one of the causes of the gray zone in the Hjulstrom diagram at larger grain sizes. Once saltation starts, it can trigger sediment transport that would not otherwise occur.

Deposition: Deposition is the accumulation of grains. If a flow starts slowly and gains speed, it will start to move larger and larger grains. As it slows down, it can only move the smaller ones. Deposition happens when a flow slows down and starts to leave grains on the bed. The combination of changing average flow speeds and local variations in flow speed caused by topography on the bed give rise to very informative sedimentary structures – including cross stratification - which are extremely useful for interpreting depositional environments.

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9.6: Bedforms

A Few Definitions:

1) *"Stratification" - layers in rocks*; stratified rocks are those organized into beds



Figure (above): Beds in the Grand Canyon, AZ.

2) *"Beds" are separated by "bedding planes"* - cm to m thick units of sedimentary rock that were deposited approximately horizontally (beds) and are separated by approximately horizontal planes (bedding planes); the rocks typically weather more along these planes. Beds are usually fairly uniform or change gradationally in composition. Bedding planes usually represent breaks in sedimentation or changes in grain size. In other words, they usually represent changes in flow characteristics.



Figure (above): Turbidite beds and bedding planes along the road near Cache Creek, CA. They were originally deposited about horizontally and were tilted due to tectonic activity.

3) "*Laminae" are color, composition, or grain size variations defining surfaces within a bed*. They typically represent variations in flow velocity, sediment supply, sediment composition, etc. *Planar Laminae* are parallel to bedding, e.g. planar and deposited approximately horizontally.

4) *"Cross Lamination", "Cross Stratification" or "Cross Bedding" are laminations or layers that are oriented obliquely to bedding.* They truncate older laminae and are truncated by younger laminae. The erosional surfaces that separate "sets" of similarly oriented laminae are called "bounding surfaces". There are lots of subdivisions of cross stratification; different types represent different types of bedforms and different flow conditions.

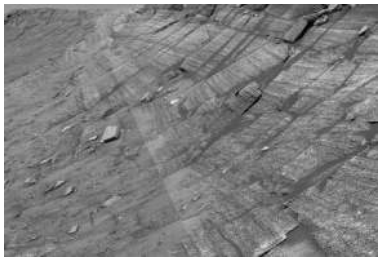


Figure (above): Burns Cliff on Mars photographed by the rover Opportunity: The upper part of the image has planar lamination, and the lower part to the far left has cross lamination or stratification. (The very straight line running diagonally from top to bottom is a seam where two images were merged together.)

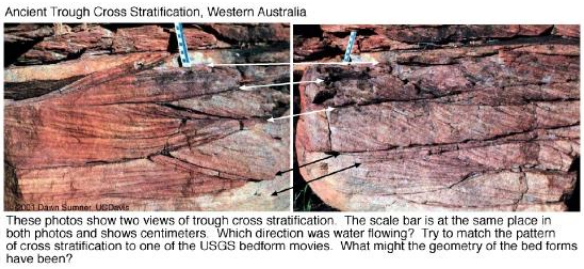


Figure (above): Trough cross stratification in sandstone. The photos show two views of the same rock with the scale bar at the same place in both photos. Note how the geometry of the layers is different in the two views. (Bars in scale represent 1 cm each.)

Other examples of dune cross stratification can be found here.

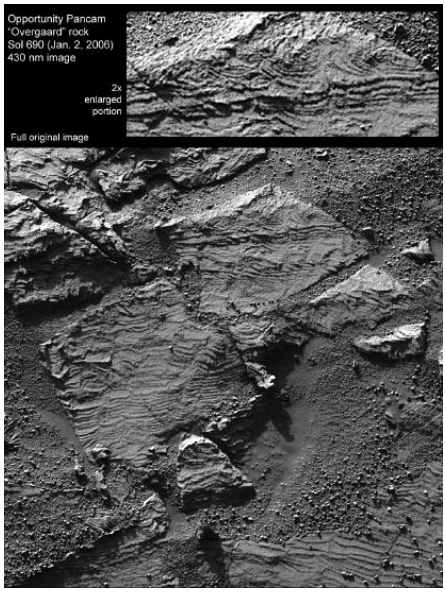


Figure (above): Ripple cross lamination on Mars, taken by NASA's Opportunity Mars Exploration Rovers team.

Bedforms

When sediments get deposited from turbulent flows, the sediment interacts with the geometry of the flow. Depending on the flow speed, turbulence, and sediment characteristics, different structures or bedforms develop.

Bed Geometry and Flow Separation

Until now, we have been implicitly assuming that the bases of beds are flat and smooth, but if sediment is present, they are not. If you start with a smooth bed of sand and increase water speed above it, irregularities form from irregularities in the flow. Irregularities in sand develop into ripples if the flow speed is appropriate. First, a few grains pile up. Once the height of the pile is several grains high, there is a flow shadow down stream of them, and the laminar sublayer detaches from the base of the flow. The water has enough momentum that it does not hug the bed surface and instead, goes shooting out over the top. This point is called the separation point. The water flows forward and downward and reconnects with the bed at the attachment point. At the attachment point, water is flowing directly towards the sediment with a lot of force. This force moves the grains and causes erosion. In contrast, the area between the separation point and the attachment point has a very low flow speed. In fact, there can be back eddies, where the flow is moving upstream. Thus, sediment transport is very irregular along the bedding surface at a local scale.

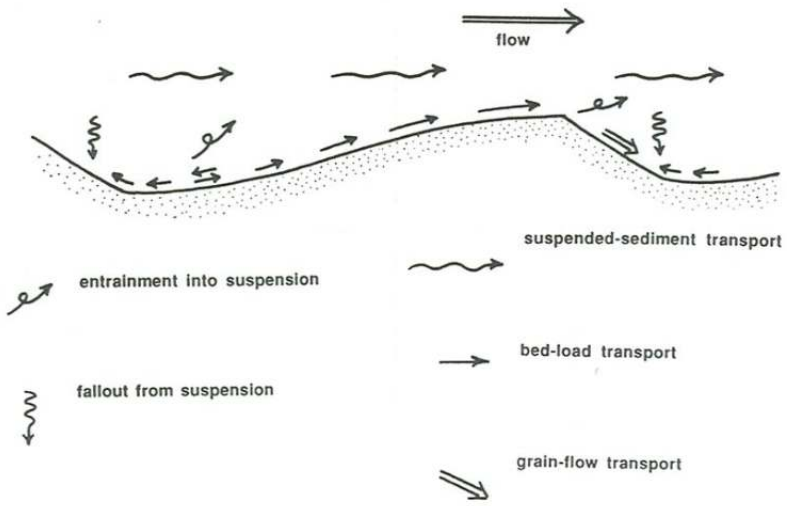
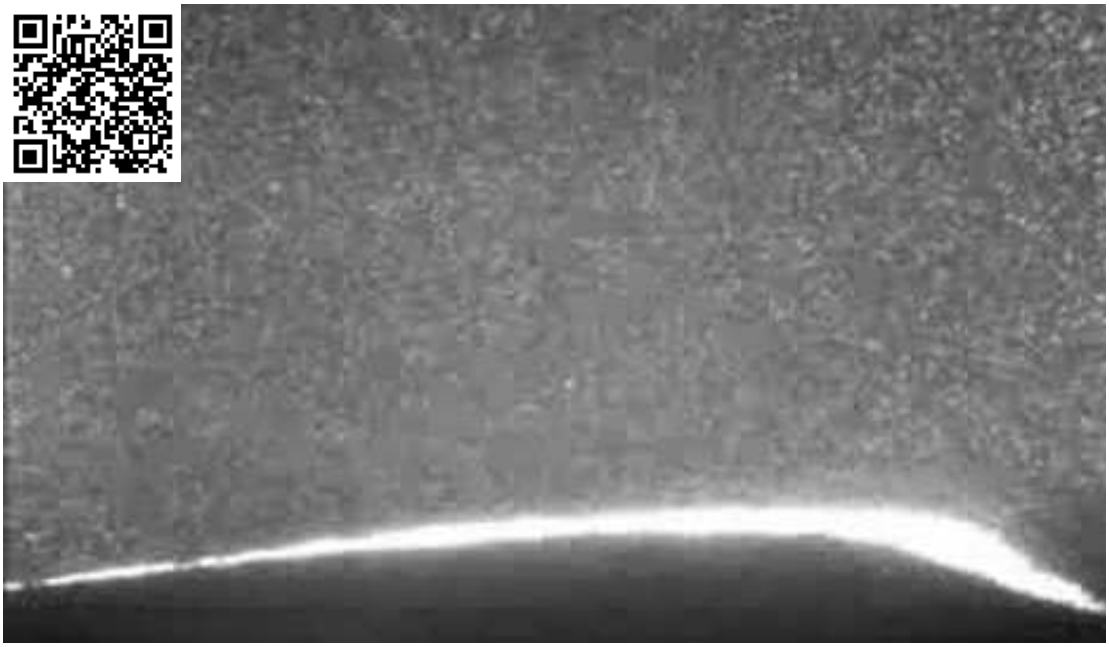


Figure (above): Sketch of fluid flow and sediment transport over a ripple or dune. Note that the suspended sediment does not influence the formation of the bedform. Only bedload (rolling/traction and saltating) grains do. (From Southard, LibreTexts)

The video below shows sediment transport over a ripple.



Sediment Transport Over a Ripple

Sediment grains are mobilized at the attachment point - more so than in normal flow because the water is shooting directly into the sediment - and the grains are moved downstream by saltation and traction. As the flow becomes parallel to the sediment surface again, its ability to transport sediment decreases. Thus, the grains tend to pile up and a new mound forms. This gives a periodic chain of mounds - the beginnings of ripples. As flow continues, grains roll and saltate up the stoss (upcurrent) side of the ripples. Once they pass the crest, they reach the low flow on the lee side of the ripple. The larger grains settle out and roll partway down the slope; this is the site of net deposition. As the process of deposition on the lee side and erosion on the stoss side continues, the ripples migrate downstream. If there is net deposition of sediment, the ripples leave behind distinctive dipping layers between two erosional surfaces that can be preserved in the rock record. These layers slope downstream and are one type of cross lamination.

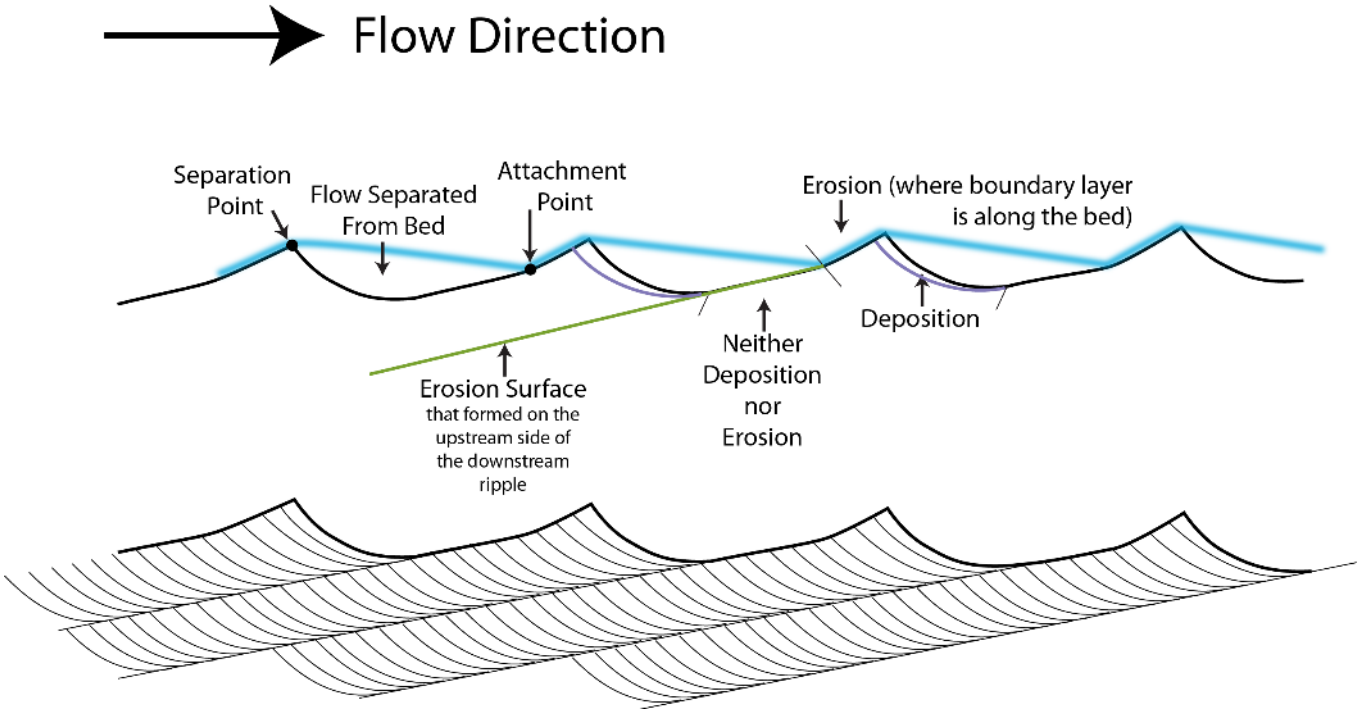


Figure (above): A sketch of a ripple or dune showing the locations of deposition and erosion relative to the geometry of the flow and its connection to cross lamination.

The geometry of the flow tracks the separation and attachment points. Erosion can only occur where there the bed shear stress is high enough to move sediment. In other words, the the main flow must be near the sediment surface. Sediment accumulates into a deposit in the flow shadow downstream of the ripple or dune crest; sediment accumulates in the flow detachment zone. Laminae are visible where deposition occurs due to variations in flow speed which cause variations in grain sizes transported and deposited.

Sets of laminae are separated by erosion surfaces which form on the upstream side of the ripples or dunes. They represent deposition on the downstream side. The shape of the laminae reflects the shape of the depositional surface and the geometry of sediment accumulation. If the depositional surface is curved, the base of the laminae is curved. Laminae thicken into areas with higher deposition rates. Also, the maximum distance between erosion surfaces is less than the maximum height of the ripple or dune; since the erosion surfaces form on the upstream sides, they are closer to the underlying erosion surfaces than the ripple/dune crests. Thus, the maximum separation of erosion surfaces represents a minimum height for the ripple or dune.

Watch the USGS bedform movies described at: Sedimentary Structures Lab and Homework Resources

The video below shows migration of a ripple in a flume.



Bedforms and Flow Velocity

The size and shape of subaqueous bedforms depends on flow strength and grain size and can be used to interpret ancient flow characteristics in a depositional environment from looking at sedimentary rocks. The relationships between flow speed and bedforms have been determined in flume experiments. This is the sequence of structures seen in relatively shallow flows:

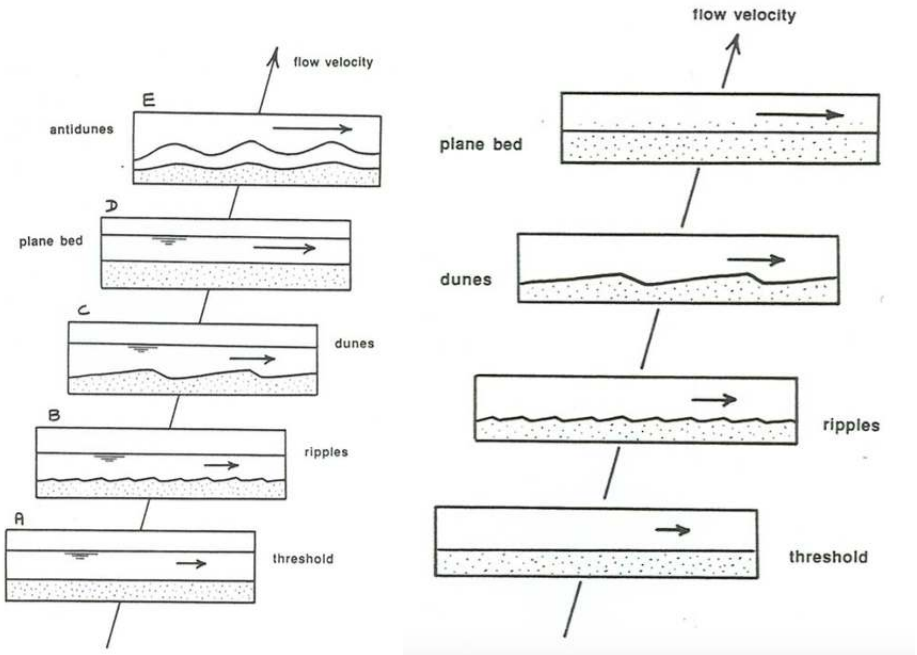
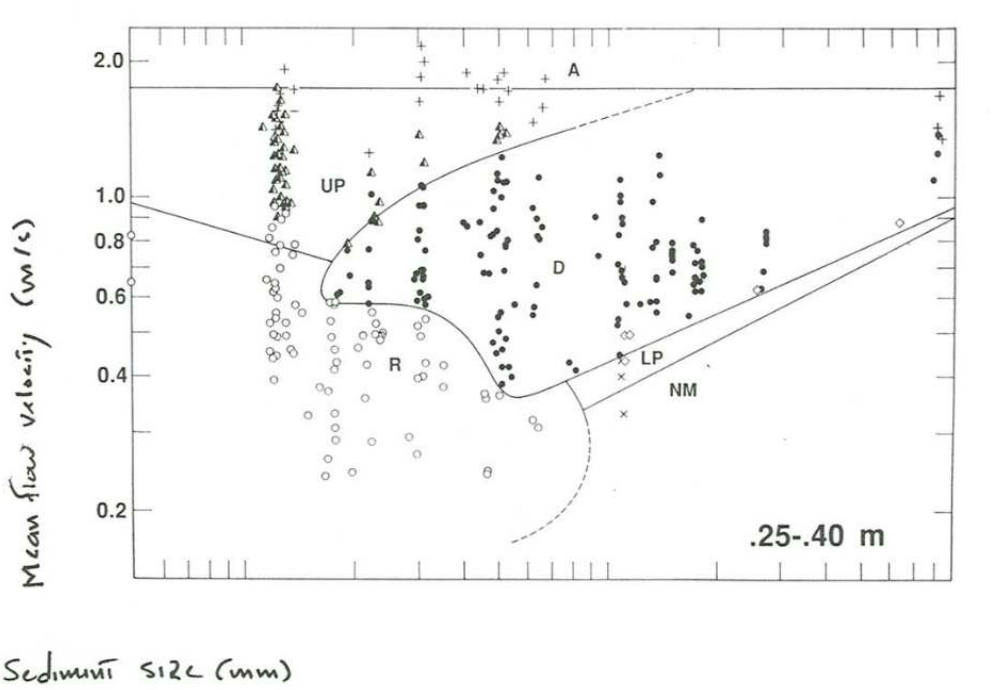


Figure (above; from Southard-LibreTexts): Sketchs showing the sequence of bed features in a flume with increasing flow speed over medium sand in a shallow flow (left) and a flow with a top that keeps the upper water surface flat (right). Antidunes only form when the surface of the flow can interact with the bed (left). If the water is too deep, only plane (or planar) bedding forms (right).

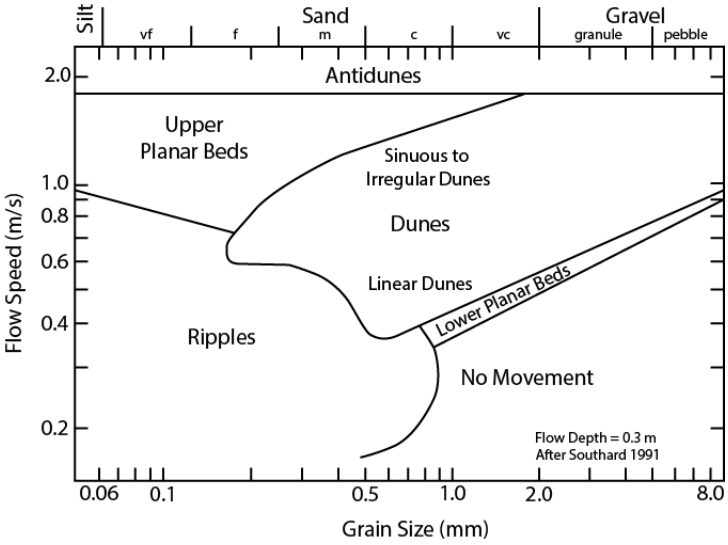
The video below shows the evolution of a flat bed into ripples and then dunes. Note the two distinct bedform sizes, particularly later in the video where small ripples are forming on the backs of the larger dunes.



The bedforms that develop in any given flow-sediment combination depend on the Reynolds Number as well as the grain size. Bedforms require bedload transport of sediment to form; suspended grains do not create them. Thus, they form in grain sizes of silt and larger, as long as the flow speed is not so large that the grains are mostly transported in suspension. In addition, they depend on both flow speed and flow depth. Most of the experiments have been done in flows that are < 1 m in depth for practical reasons. However, we will use plots that show only grain size and flow speed. This creates a disconnect between the bedform diagram below and the Hjulstrom Diagram. The average Reynolds Number for the bedform diagram is lower than that in the Hjulstrom Diagram because the flow depths are lower.



https://geo.libretexts.org/@go/page/10737



Figures **Top**: (from Southard-LibreTexts; note that he wrote the axis labels by hand).The type of bedform varies with both the size of the grains and the average flow speed. The circles, triangles, crosses, etc. mark conditions that were tested in flume experiments. These data were used to create the diagram. Note that right near the boundaries, experiments can give slightly different results due to variations in the flows. Fluctuations are common, and right at the boundaries, the bed geometry is often unstable. For practical reasons, all experiments were performed in flows with a depth of less than 1 m. This means that the flow speed for no movement is different than it is in the Hjulstrom Diagram. Southard provides data on how the bedforms change with flow depth in this chapter. **Bottom**: A summary of the bedforms at different flow speeds and grainsizes (redrawn by Sumner after Southard, 1991).

Ripples

(crest-to-crest distance - or wavelength - of less than 50 cm and heights of less than 4 cm)

The minimum flow for ripples is determined by the minimum velocity for sediment transport. Once this flow speed is reached, ripples form if the grains are sufficiently fine and are transported as bedload. The formation of ripples is controlled by the characteristics of the boundary layer. In particular, the laminar sublayer is a key component at these flow speeds. At grain sizes of coarse sand (~0.8 mm) and larger, the bed roughness increases, which disrupts the laminar sublayer. Thus, ripples do not form in coarser grained sediments (See Figure below).

At the lowest transport speeds for grains that form ripples, ripple crests tend to be linear. At higher flow speeds, irregular crests develop, with some parts of the ripples moving faster than others. This creates variations in the ripple cross lamination geometry. Eventually, too much erosion occurs at the crests of the ripples and the ripples flatten out. Dunes or upper planar beds develop, depending on the grain size.

Dunes

(60 cm-100’s m wavelength and 10’s of cm to meters in height)

Dunes and ripples behave similarly at the level of detail that I have been describing them. Their cross stratification geometries are similar. However, dunes are larger than ripples; there is a distinct break in size between the two. In addition, dunes form in grain sizes ranging from fine sand to pebbles, whereas ripples form in silt to coarse sand. Dunes do not form in finer grained sediment because the grains tend to be transported in suspension if they are lifted above the laminar sublayer in the flow.

For grain sizes of fine sand (~0.15 mm) and coarser, dunes develop as ripples flatten out. Turbulence in the flow creates large scale irregularities grow into dunes. The basic ideas of dune and ripple formation are the same. The difference is that the area of flow separation is much larger and more turbulent for dunes. Roller vortexes (e.g. upstream flows along the lee sides of dunes) are common, and the upstream flow can be strong enough to form ripples that migrate upstream on the lee side of dunes. As flow speeds increase, the dunes change morphology. The wavelength or spacing between dunes increases, and they go from having straight crests ("2D" bedforms) to sinuous crests (or even irregular crests, "3D bedforms"). These changes in morphology reflect changes in the structure of turbulence in the flows.

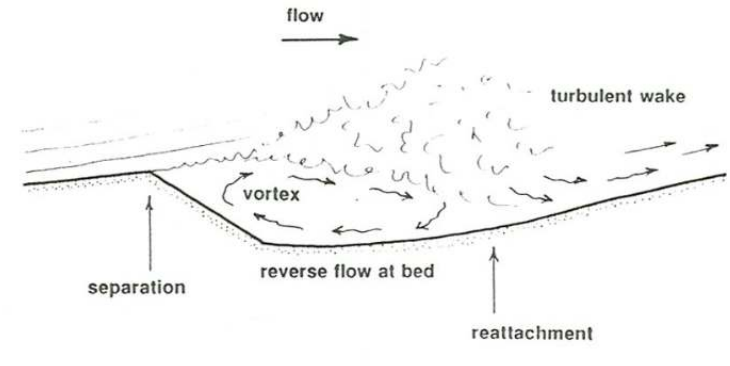


Figure (above; from Southard-LibreTexts): Sketch of a roller vortex on the lee side of a dune.

As the flow speed increases even more, the stoss sides of dunes experience so much erosion that they flatten out to form planar beds.

Planar/Flat Lamination

Planar lamination forms when the flow is strong enough that the beds flatten out. The momentum of the transported grains and fluid are high enough that they tend to move horizontally, eroding any irregularities in the bed. This zone of planar lamination is called “upper flow regime”. (Why “upper”? - there is a zone of planar lamination in coarse grained sediment at low flow velocities.)

Antidunes

Antidunes form at flow speeds greater than planar lamination when shallow water moves very quickly (Putah Creek in flood; tidal channels; creeks flowing across beaches). Irregularities form on the planar beds, but there is no flow separation. Instead, the water surface mimics the bedding surface. On the down flow side of the antidunes, there is a very strong erosional force (from the Bernoulli Effect) and sediment gets plastered onto the upstream side. Thus, antidunes produce laminae that dip upstream, and they migrate upstream (anti normal dune behavior). Sediment is still transported downstream; it is just the peak of the dune itself that moves upstream. At even higher flow, the waves on the surface of the water break, and the dunes flatten out. Antidunes are rarely preserved in the rock record because they are unstable bedforms and are reworked into other sedimentary structures as the flow speed decreases.

Scott Creek Beach, CA

Antidunes are common in creeks flowing across beaches. Here, 7 can be identified by the waves on the surface of the water. They were migrating upstream. When the eroding sand bank collapsed, the antidunes were disrupted and took 10's of seconds to reform. Faint beach stratification can be seen in the bank.



Figure (above): Photograph of antidunes in a creek flowing across Scott Creek Beach in a channel. The surface of the water has waves in it that are associated with antidunes on the sediment surface.

Variations in Geometry and Bedform

Dunes and ripples are often irregular in plan view. This affects the geometry of the cross stratification/lamination. The laminae are always approximately parallel to the dip on the lee sides of the ripples or dunes. If the direction that these dip varies, the orientation of the laminae also varies. When looking at deposited cross stratification/lamination, these variations appear as variable dips in the laminae because you are viewing them at different angles.

Watch the USGS bedform movies described at Sedimentary Structures Lab and Homework Resources for examples of how bedform morphology affects the geometry of the resulting cross stratification.

Distinguishing Between Ripple Cross Lamination and Dune Cross Stratification

If the distance between erosion surfaces defining cross sets is greater than a few centimeters, the cross stratification has to be from a dune. Ripples are only a few centimeters tall, and they cannot create laminae that are higher than the ripple crest-to-trough distance. Thus, if cross sets are greater than a few centimeters high, the cross stratification must be from dunes. However, if the cross sets are only one centimeter high, the cross stratification could be due to either ripples or dunes. It is possible for ALL sediment to be eroded as a dune migrates, leaving no cross stratification. If only a small amount of sediment accumulates, the cross sets might be only a centimeter high, much like ripples. In the field, grain size variations and changes in cross stratification along an outcrop can help you distinguish between ripples and dunes in a case like this. For example, you could look for an instance where the cross stratification is more than a few centimeters high. If you did not find one, that might suggest ripple cross lamination rather than dune cross stratification. Or maybe the grain size is wrong for one or the other.

Other Types of Flows

Not all flows are uniform in one direction. For example, waves move water back and forth, transporting sand back and forth. Because the transport direction varies through time, the orientation of cross laminations vary through time. Note that wave ripple lamination dips in two directions and the ripple crests are symmetric rather than steeper on the lee slope than the stoss slope. Flows can also be irregular due to combinations of currents and waves, etc. Some of these flows are very characteristic of specific environments, for example, storm-influenced beaches. The structures they produce are very useful for interpreting ancient rocks, and we will highlight them as we discuss different sedimentary environments.

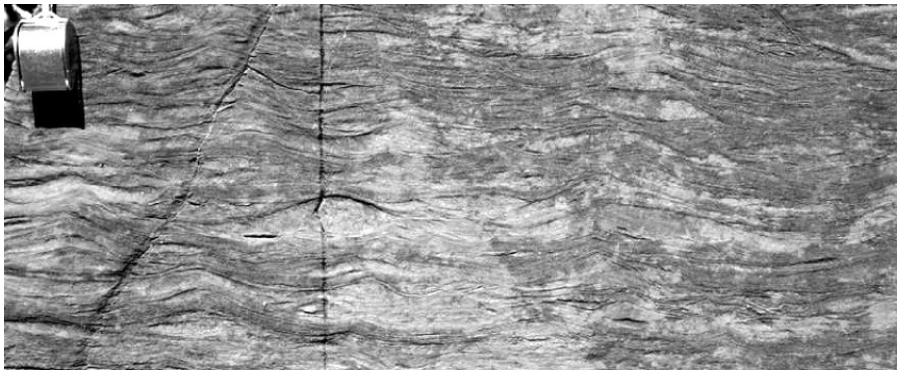
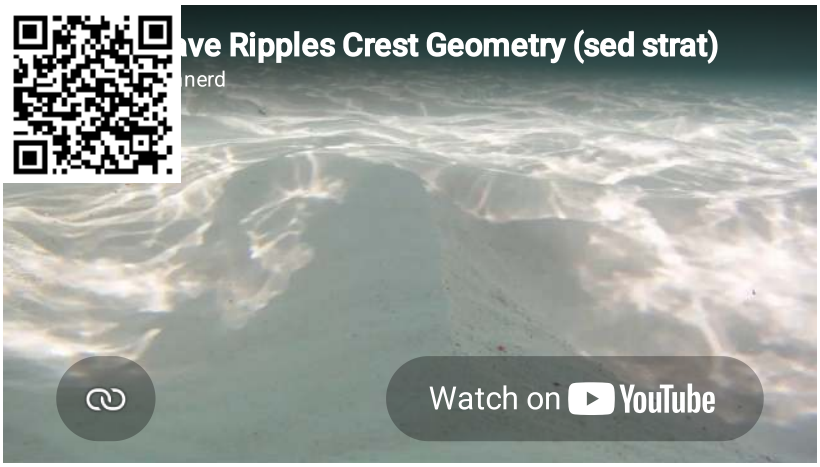
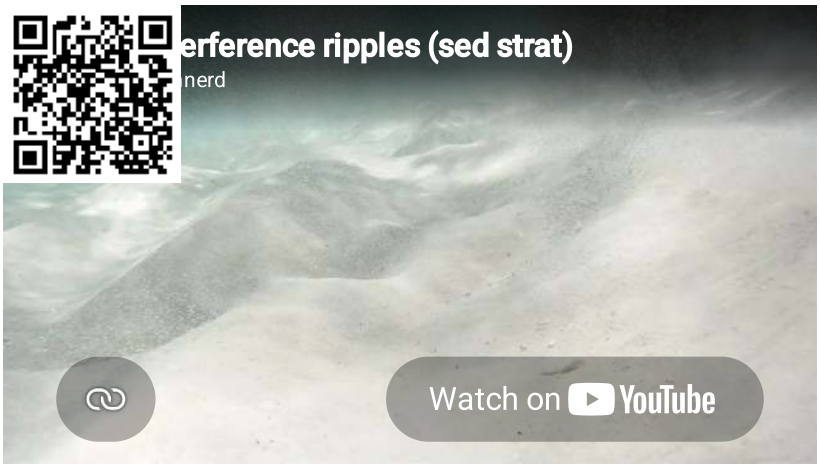


Figure (above): Wave ripple cross lamination in an Archean carbonate. Note that laminae dip in both directions. Some ripple crests are preserved. The hand lens is about 1.5 cm across.

The first video below shows transport across the crest of a wave ripple. It is easier to see the darker grains move. When they move just past the crest and stop, most of the grains are rolling (in traction) and the crest tends to have a sharp peak. In contrast, when larger waves come by, more grains are transported via saltation (and suspension) and the crest is more rounded.



The video below shows "interference" ripples. They form in places that have waves moving in multiple directions. In this case, the waves are going around stromatolites (the darker blobs). The suspended sediment shows that the flow is in multiple directions, and the amount of sediment varies depending on the size of the waves.



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9.6.2: Exploring Cross Stratification

Overview

By working through this page, you will gain a deeper understanding of how cross stratification reflects the geometry of migrating bedforms. We will use information from David M. Rubin, who published a book called Cross-Bedding, Bedforms, and Paleocurrents, which is available from SEPM with free online movies. His great movies demonstrate how various types of cross stratification are created. You can use these movies to help interpret various styles of cross stratification.

Goal

The insights you gain from working through this page will help you predict the type of cross stratification a ripple or dune is creating as well as interpret the ancient flows that produced cross stratification you see in rocks.

Straight Bedforms

A computer model generated these movies. Each starts with a bedform shape, which is constant throughout the movie. It is defined by the grey shaded surface. "Laminae" are deposited by moving the surface downstream and slightly up for each time step. Deposited laminae are represented by white lines. If the surface intersects the laminae, they are eroded, just like if laminae are exposed to an erosive current, they are eroded. Thus, the laminae change length and geometry as the "bedform" (surface) migrates.

All the movies associated with the publication are all listed at http://walrus.wr.usgs.gov/seds/bedforms/animation-toc.html. They are categorized by the shapes of the bedforms and photographs of real bedforms are also included. This is an EXCELLENT resource.

First, watch a model-produced version of the migration of a linear ripple or dune. Note that the crests of the ripples or dunes are straight. They produce dipping surfaces on the lee side of the bedform (where sediment is deposited and shown by tan lines). These are preserved if the crest migrates upward through time, e.g. sediment accumulates. Note that the laminae look flat when viewed looking directly upflow or downflow, as in the image here.

Questions to Ask Yourself:

- How does the geometry change looking at different angles? (Watch carefully between 30 and 50 sec in the video.)
- What is the geometry of the laminae on top of the deposit? (Watch after 50 sec.)

Curved Bedforms

Watch a movie of ripples or dunes with curved crests. After migration of the bedforms, the cross stratification is rotated to show how different surfaces show different cross stratification styles. Drag the marker at the bottom of the movie back and forth to explore these variations. Note how important it is to have a 3-D view of the cross stratification to interpret bedform geometry even when it is relatively simple! The movie ends with the top surface of the ripples/dunes getting eroded flat. The tan lines represent the laminae that intersect the upper surface. Note how complexly shaped they are.

Questions to Ask Yourself:

- How is the geometry of the cross stratification different than that of bedforms with linear crests when viewed perpendicular to the flow direction?
- How is the geometry of the cross stratification different than that of bedforms with linear crests when viewed looking directly upflow or downflow?
- How does the geometry change at intermediate angles?
- How is the geometry of the top look different? Which lines represent the laminae and which represent the bounding surfaces?

Real Ripples

Next, watch a movie of real current ripples in an experimental flume. This will give you a sense of how irregular ripples can be. https://cmgds.marine.usgs.gov/data/seds/bedforms/extras/movies/ripple_flume.html In nature, sometimes ripples are this variable, and sometimes they are more linear.

Make a Prediction:

- Predict the geometry of the cross stratification produced by the bedforms in the flume!

Sediment Accumulation

The amount of sediment that accumulates as a ripple or dune migrates past changes whether or not sediment accumulates. Compare these two movies: No sediment accumulation and very abundant sediment accumulation. The amount of sediment that accumulates depends on how the sediment transport capacity of the flow is changing. If the flow is speeding up or getting deeper, its transport capacity is increasing, and erosion will occur. If the flow is staying exactly the same, all the sediment that is moving will bypass the sediment surface, and nothing will be preserved. If the flow is slowing down or getting shallower, it has to reduce the amount of sediment that it is carrying, so sediment remains behind and preserves the passage of the bedform.

Questions to Ask Yourself:

- If there is no sediment accumulation, will there be any record of the bedform passing?
- How is the geometry of the cross stratification different when there is so much sediment accumulating that there is no erosion on the stoss side of the bedform than when there is?
- What types of conditions promote the accumulation of sediment and thus the preservation of the bedform passing? Where are these conditions likely to occur?

What's Next

One goal of the modeling effort is to reproduce complex cross stratification that is observed in the field. The following movie produces a simplified version of cross stratification observed in a river bar. Here is movie that shows how the model can fit complicated structures observed in the field. This movie begins with an image of cross stratification from the Colorado River. Then it shows a computer-animated sequence that generates compound crossbedding. "After the computer-generated structure is constructed and rotated through a variety of outcrop orientations, the image morphs into a natural outcrop of the same kind of structure. The natural example was photographed on a horizontal surface that was excavated into a fluvial bar in Grand Canyon. This movie is the best one for illustrating the origin of moderately complicated crossbedding." (Dave's description)

Lots of other movies are available to explore as you wish. There are also LOTS of photos of different model-produced stratification styles and some outcrop photos associated with the online book (see https://walrus.wr.usgs.gov/seds/bedforms/animation-toc.html). The USGS web site also provides software to make your own movies by defining a bedform geometry. Have fun!

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9.7: Sedimentary Facies

Environments and Facies

Scott Creek Beach, CA

Antidunes are common in creeks flowing across beaches. Here, 7 can be identified by the waves on the surface of the water. They were migrating upstream. When the eroding sand bank collapsed, the antidunes were disrupted and took 10's of seconds to reform. Faint beach stratification can be seen in the bank.



Look at the photo of Scott Creek Beach above. Note that the antidunes are forming in one part of a creek. The middle of the creek has upper planar lamination flow speeds, and the closest part is very shallow and has some antidunes again. (I know some of this from being there more than from looking at the photo.) Note that there is a faint lamination present in the eroding bench on the far side of the creek. This lamination mimics the beach surface. It is lamination from the waves swashing and transporting sediment on the beach. If all sediment transport stopped immediately, one would see a suite of sedimentary structures: Antidunes and upper planar laminae next to each other in the creek, an erosional surface overlying planar stratification that undulates like a beach. The association of these features would tell you that the sediment was deposited in an environment with a variety of flow conditions.

The suite of structures forms a **facies**. A facies (Latin for aspect or appearance) is a body of rock (i.e. a sequence of beds) or sediment marked by a particular combination of compositional, physical and biological structures that distinguish it from bodies of rock/sediment above, below and adjacent to it. A sedimentary facies has a characteristic set of properties that makes it distinctive, which the geologist defines. Usually facies are defined based on a suite of characteristics in rocks/sediment.

Facies vs Environments - By grouping characteristics of the rocks into facies, the depositional environments can be more easily compared and interpreted. It is important to remember that the sedimentary environment is the combination of physical, chemical and biological processes that influence sediment deposition, whereas sedimentary facies are the characteristics of the rocks/sediments after deposition. It is the difference between a water flow speed of 20 cm/sec and high angle cross stratification; the stratification is the result of high flow speed, but they are not the same.

Example Facies

Facies are groupings of rock types based on similar features. We use these groupings to generalize individual properties into useful, genetically related categories. Some examples include:

Facies based on grain size:

- Coarse-grained sandstone with 1-5% pebbles (suggests high flow speeds)
- Fine-grained, well-sorted sandstone (suggests low flow speeds with either only one size sediment source or a consistent flow speed)
- Mudstone (suggests standing water)

Facies based on sedimentary structures:

- Fine-grained sandstone with current ripple cross lamination
- Fine-grained sandstone with upper planar lamination
- Fine-grained sandstone lacking cross stratification, but with abundant burrows

Facies based on grain composition:

- Coarse-grained sandstone with 25% lithic fragments, 25% feldspar, and 50% quartz
- Coarse-grained sandstone with 80% quartz, 10% mica, and 10% feldspar
- Coarse-grained sandstone with 99% quartz and trace gold flakes

Beach Facies

What features do we see in the photo of the beach? How should we divide those into facies? We can compare them to what we would see in the rock record. Take a look at photos of Scott Creek Beach stratification again: mygeologypage.ucdavis.edu/sumner/gel109/sedstructures/Beach.html. Describe some of the facies.

Turbidites - Success of a Facies Model

Turbidites provide a good summary of the ideas we have been talking about, e.g. facies and sedimentary structures related to flows. Turbidites are deposited from slurries of sediment and water in any standing body of water (lakes, oceans). (photos of turbidites)

1. Turbidity flows start with slope failure in soft sediment. Slopes become oversteepened where sedimentation rates are very high, such at the mouths of rivers. Because flow speeds are very low in standing water, the sediment does not get washed downslope. Rather, it builds up until there is a subaqueous slope failure. Earthquakes can trigger these slides, too.
2. Sediment and water mix creating a “fluid” that is denser than the surrounding water because of the entrained sediment. Thus, it flows downhill even if the slope is very low (1°).
3. The base of the flow is commonly erosional on steep slopes, so more sediment is entrained in the flow.
4. Enough sediment is entrained that erosion stops. Deposition begins as the slope gets shallower or the flow starts to slow down. Initially, the coarsest grains are deposited (remember the Hjulstrom diagram) and then finer grains, so the sediment is “graded”. However, the sediment is usually poorly sorted because the flow is a slurry of water and sediment so hydraulic sorting is reduced. (Facies = Bouma a)
5. Sediment concentration decreases with deposition, so one gets more hydraulic sorting. The flow is very fast so the sediment has upper planar lamination. (Facies = Bouma b)
6. As the flow slows more, grain size decreases and ripples start to form. Dunes do not usually form for two reasons: a) often only fine sand and finer grains are left in the flow by this point; and b) dunes do not have time to develop. (Facies = Bouma c)
7. Eventually, the flow slows to the point that bedload transport stops and deposition is mostly settling of silt and then clay. The progressive settling of coarser and then finer grains produces a faint lamination, but it is not as strong as the planar laminations in Bouma b. (Facies = Bouma d)
8. Mud settles out producing shale. This can look identical to background settling of clays brought into the lake/ocean as suspended sediment. (Facies = Bouma e)

Bouma divisions a-d can take hours or a day or so to be deposited. However, division e, which is usually the thinnest, commonly accumulates over months or longer (e.g. hundreds of years) depending on how frequent turbidites are in the area.

Changes in Character Downslope

The parts of turbidites that are deposited change downslope and usually only a few of the subdivisions are preserved. In the most proximal (upslope) environments, divisions a and b are most common. In the more distal areas, all of the coarser sediment has

already been deposited upstream, so divisions d and e are most common. Generally, there are also channels which fan out producing variations in rock types that change in space and through time.

Turbidite Facies Models

Over the decades, sedimentologists have described and interpreted sedimentary rocks and defined generalized facies and facies associations that are characteristic of different depositional environments. These generalized facies and associations are called Facies Models. Each depositional environment or system has its own facies model. This is a VERY powerful tool for interpreting ancient environments. See my video summary: http://www.youtube.com/watch?v=G05juwK2OTI



A nice, hour long lecture on turbidites in the Monterrey Bay canyon, CA, can be found at: http://online.wr.usgs.gov/calendar/2010/jun10.html The actual lecture starts about 5 minutes into the video.

History of Turbidites and Their Interpretation

Turbidite facies analysis and the resulting facies model led to the discovery of a new process. Sedimentologists had characterized turbidites all over the world. They all had the same flow characteristics consisting of a very strong erosive flow, deposition of a normally graded bed which was massive, followed by upper plane bedding, rippled finer sands, coarsely laminated silts, then shales. Comparisons with known flows showed that this sequence of deposits must come from a fast initial flow that slowed through time to still water. And this repeated again and again. The associated facies and the succession of different facies in these sequences suggested that the deposits had to be in deep water. For example, the fossils were all characteristic of deep water, shales were abundant and are characteristic of still water (shallow or deep), and they were sometimes associated with deep water storm deposits. Thus, the sedimentologists proposed slope failure and turbid currents flowing down slope and called them turbidity currents. A process like this had not been observed in modern depositional environments, so the idea was controversial. Many geologists did not believe that you could generate strong enough currents underwater to get those flow characteristics. Eventually in 1964, two geologists Heezen and Drake realized that an event in 1929 provided strong evidence for turbidity currents. In 1929, which is long before there were satellites, under water telegraph cables were strung from Newfoundland to Europe. In November, about 30 cables broke in order from farthest north and shallowest to farther south and deeper water. At the time, people did not know why they broke, but Heezen and Drake suggested that a turbidity current was triggered by an earthquake and the cables broke as the turbidity current passed over them (they are strong flows!). Because they were continuously used for communication, the time each cable broke was precisely known. Heezen and Drake calculated that the front of the flow traveled at 250 km/h (36,000 cm/s) when the turbidite first formed and then slowed to around 20 km/h (7000 cm/s) by the time the last cables broke 500 km from the source. This was a fast, strong flow and may be typical of turbidites. These flow speeds are very erosive. It is only after the turbidite slows down even more that you get deposition. The characteristics of the flow seen by the breaking cables fit the flow characteristics proposed by the sedimentologists, and now turbidity currents and the facies model developed for turbidites are widely accepted and often treated as a good example of rocks that closely reflect flow characteristics. Turbidites and their interpretation are almost an ideal example of a good Facies Model.

Extra on Dense Sediment Flows

Sometimes with slope failures on land or under water, much more sediment can be put into motion than the flow would normally erode. Depending on the amount of water mixed with the sediment, the flow characteristics are different. When abundant water is present, the sediment can form a thick slurry with a higher density (ρ) than sediment-free water, commonly leading to a higher Re and more turbulent flow:

$$Re = \frac{u \times l \times \rho}{\mu} \tag{9.7.1}$$

Also, collisions between grains become extremely important. Both of these tend to keep the sediment moving. Grain-to-grain collisions also make sorting much less efficient, and the sediment that gets deposited tends to consist of whichever grains make it to the base of the flow and are not kicked back up again. Usually, the largest grains are part of this first deposit because they weigh more, but small grains are also present. As the amount of sediment decreases, the flow becomes more like typical water flows. Turbidites are subaqueous flows that start out with a very high sediment load and decrease in time to more normal flows. They have characteristic sedimentary structures associated with them that reflect these changes.

If there is very little water associated with a clay-rich sediment flow, the flow can be very viscous due to the charge attraction among clay particles. The high viscosity reduces Re (Equation 9.7.1). Debris flows with lots of cohesive mud can even be laminar. In laminar flows, there is no mixing of the water or grains (or ice) and there is no sorting of grain sizes. Thus, the sediment remains mixed up with large grains, sometimes boulders, “floating” in mud. They flow down slopes pulled by gravity until the flow seizes up and stops. This can be due to too low a slope or loss of water. Underwater debris flows can also be diluted by water that gets incorporated at the edges of the flow and become less viscous and more turbulent through time.

There also are dry sediment flows in which air is present between grains. For example, rock avalanches and some pyroclastic flows from volcanoes lack water. For these to move significant distances, large amounts of energy from either gravity or explosions are necessary to keep the sediment in motion.

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9.8: Introduction to Stratigraphy

Stratigraphy and Time

Stratigraphy is the study of sedimentary rocks in space and time. It is the basis of interpreting what happened in the past. We use facies to interpret depositional environments from the rocks. Changes in facies both vertically and horizontally allow us to interpret changes in ancient landscapes and processes.

Example: Beach Facies. Beach environments grade laterally into each other. The offshore areas grade into the swash zone of the foreshore. The foreshore grades into the berm (the highest point of the beach) and backshore (if present). Eolian (wind) dunes, marshes or erosional cliffs can be present landward of the beach. Rock facies similarly grade into each other because they were deposited in different depositional environments. If the depositional environments stay in exactly the same place through time, a stratigraphic column in each place would consist of a uniform facies, but each stratigraphic column would have a different style of rock (facies). However, depositional environments tend to migrate back and forth as sea level rises or falls, basins fill in with sediment, etc. Thus, facies in stratigraphic columns tend to change upward. They also vary laterally. See figure 19.8 on pg. 308 of Nichols.

Changes in sea level and depositional environment lead to variations in stratigraphic columns both laterally and vertically. If you compare different stratigraphic columns, there are several ways you might "correlate" them. If you correlate different rock types, e.g. **lithostratigraphy**, you are marking regions with similar characteristics, but the sediments in each unit were not necessarily deposited at the same time. In contrast, if you correlate rocks that were deposited at the same time, e.g. **chronostratigraphy**, each unit often consists of more than one facies. This is obvious when you look at the distribution of depositional environments now. Different areas are accumulating different types of sediment at the same time.

Lithostratigraphic correlations are relatively easy because you can directly observe rock type. These correlations are very useful for studies of reservoir properties, where one might want to identify a porous sand that acts as a water or hydrocarbon reservoir. However, these correlations do not help you interpret ancient depositional environments because they do not represent an ancient landscape. Chronostratigraphic correlations tell you the most about depositional environments and their distribution through time, but they can be VERY difficult because you have to have a time marker that tells you which deposits were synchronous. Sometimes volcanic ash beds or other depositional events allow you to directly observe which rocks were deposited at the same time, but these events are rare. Often, chronostratigraphic correlations require detailed facies analysis and an understanding of how depositional environments change through time.

Walther's Law

Walther's Law is key for understanding the differences between lithostratigraphy and chronostratigraphy. Walther's Law states that environments that are adjacent to each other are represented as vertical successions of facies in the rock record **if there is no break in sedimentation** (no unconformity). If sea level is rising relative to the shore line, the different depositional environments are migrating inland. This leads to different facies accumulating progressively inland as well. The most landward deposits are river deposits and alluvial plain deposits, followed by marsh and then marine deposits. Vertically, you see the facies representing those depositional environments in the same order. At any given time, rocks are being deposited in all of the different environments.

Chronostratigraphy

Chronostratigraphy enhances the interpretation of the stratigraphic record in terms of Earth history. Even when one has a detailed map of the distribution of depositional environments, it is difficult to say exactly how to correlate section in terms of time. In real rocks, there are a number of tools that you can use to get correlations of various accuracy. These include: fossils (biostratigraphy); magnetic properties (magnetostratigraphy); absolute ages of interbedded volcanic ash beds and basalt flows; some chemical properties such as elemental isotope ratios in carbonates; geological instantaneous depositional events such as huge storms, meteorite impacts, etc.; and unconformities due to sea level falls and the geometry of sedimentary deposits (sequence stratigraphy). We will get back to all of these in more detail throughout the quarter, particularly near the end.

Distribution of Rock and Time

One might think that sections can be correlated based on assuming that the same amount of sediment gets deposited in all places in the same amount of time. This is a BAD assumption, although many researchers are forced to use it. It is important to understand that the preserved rock does not represent all of time. In other words, time is not evenly represented by rock thickness. For example, with turbidites, the sandstones may have been deposited in a couple hours to a day at most, whereas the shales (Bouma E) represent 100’s to 1000’s of years of fine grains settling out. Thus, most of the "time" is represented in the much thinner shales. In addition, there is erosion at the base of some of the turbidites. Thus, there is a significant amount of time that is only represented by an erosional surface which produces a gap in the rock record. Generally, sedimentation is thought of as a continuous processes. This is NOT true. Sedimentation is episodic and there are unconformities in the stratigraphic record spanning all time ranges from minutes to millions of years. Gaps of minutes might occur in a river if there is a burst of strong flow that is erosive rather than depositional. Gaps of hours occur at low tides when the intertidal zone is exposed. Gaps of years to thousands of years can occur in land environments where there is no source of sediment or the topography is too high to collect sediment. Gaps of millions of years also occur in terrestrial environments, especially if there is erosion. The longer time gaps usually represent regional changes in deposition and can be very useful for correlating rocks chronostratigraphically. Also, different depositional environments accumulate sediment at different rates: thickness does not equal time!

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9.10: Glacial Environments

Glacial environments are defined as those where ice is a major transport process. Liquid water and wind can also transport sediment in these environments. Wind transport is common when there is little vegetation. Liquid water transport occurs when the ice melts.

As you all remember, the high viscosity of ice makes all ice transport of sediment laminar. Thus, grain sizes are not sorted. All of the sediment is transported together, with the ice, and it is deposited when the ice melts. There are several features that are characteristic of glacial environments, including the process of erosion.

Erosion

Erosion in glacial environments is dominated by physical processes:

1. ice freezing in cracks in rocks, breaking them up
2. flow of glaciers “plucking” rocks up from the base of the flow
3. grinding of rocks against each other and against the floor of the glacial valley as the ice flows

These processes produce some distinctive sedimentary features including:

1. facetted clasts, e.g. rocks with smoothed off faces from dragging against other rocks
2. striations and grooves in rocks from dragging against other rocks
3. flat valley floors called glacial pavements that are smoothed off due to glacial flow
4. rock flour, which is clay size lithic grains formed from the bits of rock that are abraded off as facets, striations, grooves, and glacial pavements form.

There is often little chemical weathering in glacial environments because temperatures are cold.

Deposition

Ice flows are laminar because they have very high viscosity. This can be seen in the ice cliffs along the edges of glaciers in Taylor Valley, Antarctica. The ice is particularly cold and is so viscous that it does not flatten out on the time scale of at least dozens of years. Because the flow is laminar, when the ice melts or sublimates, it dumps all grain sizes into one deposit, forming a diamictite. If one knows that the diamictite was deposited by ice, it is then called till or tillite. If the glacier melts on land, it leaves piles of till in moraines. If it melts over water, the debris is deposited into the water, commonly forming a till sheet. If only a few large clasts are deposited in the water, they are called “drop stones”. These commonly are deposited by melting ice bergs that carry large grains out over lakes or the ocean, where they are deposited in (nearly) standing water.

As glaciers melt over land, melt water commonly reworks glacial till into braided river deposits. In arid environments, much less reworking of the sediment takes place.

Glacial Facies Assemblage

For illustrative purposes, I am describing the glacial facies as an assemblage of other facies.

Morraine Facies

1. Composed of diamictite; no sedimentary structures.
2. Diamictite in mounds.
3. Clast composition mostly lithic fragments, including silt and clay-sized rock flour.
4. Clasts mostly angular, some with facets and striations.

Till Sheet Facies

1. Composed of diamictite; sedimentary structures suggestive of turbidites in rare sandstone interbeds.
2. Diamictite in sheets with rare shale and sandstone interbeds.
3. Clast composition mostly lithic fragments, including silt and clay-sized rock flour.
4. Clasts mostly angular, some with facets and striations.

Distal Glacial-Lacustrine/Marine Facies

1. Shale with isolated large clasts and sandstone interbeds with sedimentary structures suggestive of turbidites.
2. Clast composition mostly lithic fragments.
3. Clasts mostly angular.
4. Frequency of large clasts decreases away from the glacier.

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9.11: Rivers

Rivers are responsible for most sediment transport from mountains to lowlands and the oceans. They do the most to even out the topography that tectonic processes create. Rivers consist of channel, bank and overbank or floodplain deposits. Most of the sediment and many river characteristics are controlled by the highest common flow speeds.

River Types

1. Straight (rare, except for ones humans have modified)
2. Braided (many branches within a channel)
3. Meandering (high sinuosity)
4. Anastomosing (rivers with branching and merging channels)

The form of the river is controlled by the gradient of the river bed (steep = braided, gently dipping = meandering), local vegetation that stabilizes banks and limits the number of channels, sediment grain size, particularly the ratio of suspended versus bedload sediment, and sediment volume. A high bedload gives rise to abundant bars, which promotes formation of braided rivers.

Braided Rivers

Braided rivers develop when the proportion of bedload sediment is high, which produces abundant bedforms and promotes the development of bars, and thus, the braided character of the river. The sediment is commonly coarse, which requires fast flow and steep gradients for the sediment to be transported. Much of the geometry of braided rivers is shaped by the highest flows, e.g. spring floods, when the bars are covered in water. Many braided rivers have exposed bar tops for much of the year.

Flow speeds and transport capacity vary dramatically within a braided river. Friction with the riverbed tends to slow down the flow, particularly where the flow is shallow. Thus, the Reynolds number in shallow areas is relatively low (but still high enough that the flow is turbulent) and the transport capacity is low. In contrast, the transport capacity and Reynolds number are much higher in the deeper middles of channels in the river. Thus, the coarsest sediment is transported here, whereas finer sediment gets deposited in shallow areas. Also, bars block the flow on the upstream sides, and like dunes, the upstream sides tend to erode. Areas of low flow and eddies form on the downstream sides of bars, and they are usually sites of net deposition. Thus, bars migrate downstream through time. If we summarize the processes:

Sediment Transport

1. The coarsest sediment is only transported in the middle of the flow where the Reynolds number is highest. (All grain sizes that can be moved are transported where Re is high.)
2. Bars are eroded upstream where the bars deflect the flow. Sediment is deposited on downstream side of bars and some on the flanks of bars where flow is slower, particularly on the insides of bends.
3. Secondary bedforms, i.e. planar beds, dunes, and ripples, form as a result of sediment transport on the bars and in the channels.

Sedimentary Structures

1. Trough x-bedding in channels, due to the migration of irregular dunes
2. Coarsest sediment may be lower flat laminated if flow speeds are not fast enough to form coarse grained dunes
3. Sediment on the edges of bars fines upward because the flow is shallower and slower, e.g. has a lower Reynolds number. Sedimentary structures can include anything from upper planar to ripple laminations.

Braided River Facies

Channels migrate back and forth leaving a sheet of sand with abundant cross stratification. These sheets of sand tend to fine upward because the channels migrate due to bar migration, and sediment is finer grained higher up on the bars. General characteristics of braided river deposits include:

1. Scoured surface at the base of a channel
2. Gravel lag at base of channel
3. Trough x-bedded sands deposited just off the center of channels
4. Occasional tabular x-stratification from migrating bars

5. Sand deposited at slower speeds (ripple cross lamination possible)
6. Overbank deposits from floods mostly composed of sand and silt, with some mud

The large scale geometry of the deposits includes sheets of sand with various grain sizes representing bar migration, with sand sheets separated by floodplain deposits.

Example of a braided river in Alaska: http://g.co/maps/wrk9n It is cutting through glacial morraines deposited as a glacier retreated up the valley. Follow the river downstream (to the north and east) to http://g.co/maps/q5kq7. How does the channel geometry change?

Meandering Rivers

Meandering rivers have a low gradient and thus slower flow, and usually have a high proportion of suspended sediment relative to the amount of bedload. A meandering river channel has curves that meander back and forth on a gently sloping floodplain. The flow speed in the channel varies with the geometry of the meanders. Water has to travel farther on the outside of bends than on the insides of bends, so flow speeds are higher on the outsides of bends. We know from the relationships between Reynolds number and bed shear stress that higher flow speeds mean that more and coarser sediment can be transported at higher flow speeds. Thus, we can predict that:

1. There is more erosion on the outsides of bends.
2. The sediment moving near the outsides of bends and in the deepest parts of the channel should include the coarsest sediment available.
3. Sediment will accumulate on the insides of bends, and this sediment will be finer grained.

If we look at a channel in cross section, it is asymmetric, representing the sites of erosion and deposition. Variation in flow speed also produce different sedimentary structures. Upper planar lamination and dune cross stratification are common where the Reynolds number (Re) is highest, and ripple cross lamination is common where Re is lower.

The main parts of the channel include eroding bank, the thalweg (the deepest point of the flow) and the point bar (on the inside of the bend where most sediment is accumulating). As the channel migrates due to erosion and deposition, a distinctive suite of sedimentary structures accumulate. The deepest part is coarser and has upper planar lamination or dune cross stratification. This is overlain by finer sediment with current ripple lamination.

As meandering rivers migrate, the meanders tend to increase in size. Eventually, the channel forms almost a circle, and the meander gets cut off, often during a flood. This straightens the channel temporarily and produces an ox bow lake in the abandoned meander. The lake accumulates mud and organic matter since the flow speed is close to zero.

Levees and Floodplains

When a river floods, it goes from a confined flow in the channel, which is very fast, to a widespread flow across the floodplain. The flow slows down very quickly and the water becomes shallower, both of which cause a decrease in Reynolds number. Thus, the water can not transport as much sediment on the floodplain as it does in the channel. Thus, finer sands that may be in suspension during a flood are transported as bedload or rapidly deposited once the river overflows its banks. This sediment deposition produces levees. The finer silts and especially clays remain in suspension much longer and settle out on the floodplain as the flood waters dry up.

Over time, the levees build up and provide a higher bank for the channel than the level of the floodplain. Thus, the channel bottom can aggrade (fill in) until the bottom of the channel is as high or higher than the floodplain. When the next flood comes along, the river avulses and does not go back into its old channel which is higher than a new one on the floodplain. This results in the downstream part of the channel being completely abandoned.

Meandering River Facies

Meandering rivers produce suites of facies that vary depending on the subenvironment. Channel facies different from floodplain and ox bow lake facies because the flow characteristics and sediment supplies are different.

Channel Facies

1. Scoured base of flow
2. Lag deposit with mud rip-up clasts and the coarsest grains being transported by the flow
3. Fining upward sands with trough cross stratification
4. Rippled sands
5. Sigmoidal cross stratification from migrating point bars

Floodplain Facies

1. Fine sand with climbing ripples near channels
2. Mudstone/shale with mud cracks
3. Soils
4. Root casts

Ox Bow Lake Facies

1. Mudstone/shale without mud cracks (unless the lake dries out)
2. Organic-rich deposits, including coal
3. Anoxic water indicators (especially in fossils and absence of trace fossils)

Differences between braided and meandering river deposits

1. Braided river deposits are commonly coarser grained
2. Meandering rivers contain abundant suspended sediment, which is deposited in ox bow lakes and on floodplains.
3. Floodplain deposits are better developed and finer grained in meandering river systems.
4. Bar migration is much more regular in direction in meandering rivers because there is a well defined, single thalweg towards which the bars migrate. In contrast, braided river bar migration occurs in multiple directions at the same time. Thus, meandering rivers produce a more regular geometry of tabular cross bedding, when preserved.

General Characteristics of Fluvial Sediments

1. On a large scale, river deposits consist of sheets and lenses of sand deposited in channels associated with flat laminated shales and silts with rare rippled sand beds deposited on floodplains.
2. Fining upward sequences of beds in the sands with sedimentary structures that indicate decreasing flow speeds.
3. Abundant cross stratification in well sorted sands, particularly trough cross stratification.
4. Cut banks at the edges of channels - these are good indicators of a migrating river channel, but can be hard to see in outcrop since they are rarely preserved
5. Soil development in floodplain deposits, with root casts common if the rocks are Devonian or younger (and on Earth).

Look at pictures of fluvial rocks at mygeologypage.ucdavis.edu/sum...s/Fluvial.html

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9.12: Marine Deposition

Marine Depositional Processes

Most of Earth is covered with oceans, there is abundant life in the oceans, most sediments eventually get transported into the oceans, and shallow marine deposits are the most abundant in the in sedimentary record due to their large volume and the low erosion rates in shallow marine environments. You need tectonics to uplift them above sea level to get significant erosion. This happens commonly, so that we can also see them exposed.

Several processes are unique to shallow marine deposition (and some large lakes): Tides, waves, and storms

Deltas, Estuaries, and Other Shorelines

When rivers reach standing water such as a lake or the ocean, the flow speed slows down dramatically. And when flows slow down, sediment is deposited. Almost all of the sediment transported in a river is thus deposited close to the river mouth, with the exception of grains that are fine enough to remain in suspension. Lacustrine and marine processes can rework the deposited sediment to distribute it along shorelines.

Deltas form at the mouths of rivers that transport enough sediment to build outward. (*Building outward* is a key component of the definition of a delta. In contrast, ***estuaries*** are present where the ocean or lake waters flood up into the river valley.) Deltas require substantial accumulation of sediment, in contrast to estuaries which do not build outward. Sedimentary facies are similar to other depositional environments, but the association of subenvironments are recognizable as deltas. Some of the sub environments include: river facies with all the associated sub environments; shore line deposits including beaches, marshes/swamps, etc.; submarine shelf and slope facies, including storm deposits and turbidites; etc.

Because deltas are sites of sediment building outward from the coast, they are progradational; the landward depositional environments move seaward over more marine/lacustrine deposits. Thus, delta sequences in the rock record start with deep water, marine (or lacustrine), fine grained sediments and grade upward into shallower water, possible more freshwater, coarser grained sediments. This is one of the distinguishing aspects of deltas that let you define them in the sedimentary record. These changes in grain size and environment typically occur over 1’s to 100’s of meters in the rock record and include many beds.

All deltas (by definition) have their sediment transported to the delta by rivers. Thus, fluvial deposits are always associated with them. In addition, depending on marine (or lacustrine) conditions, waves and tides can redistribute the fluvial sediment changing the morphology and facies of deltas. There are three main end member categories of deltas when characterized by processes: 1) River dominated; 2) Wave influenced; and 3) Tide influenced. We will come back to these delta types after discussing the marine processes.

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9.12.1: Tidal Flows and Facies

Tides

Two key characteristics that are unique to tides: 1) flow changes direction 1 or 2 times per day; and 2) The speed of flow is cyclical with flow going onshore, stopping at hight tide, then flowing offshore, and stopping at low tide. There is lots of variability in tides depending on geography. Flow speeds vary, producing different sedimentary structures. In the Bay of Fundy, which has the highest tides recorded in the world (up to 16 m - a 5 story building), the water moves up to 15 km/hr (417 cm/sec) which is fast enough to transport boulders. At the low end, tidal currents are essentially non-existent. Also, there are times of slack tides when the water is essentially still or wave-dominated. Thus, the range of sedimentary structures is wide, including dunes (often called tidal bars when very large) and ripples. The main characteristic to look for, though, is variations in flow speed and DIRECTION.

More information on tidal flows and what causes them

Tidal Sedimentary Structures

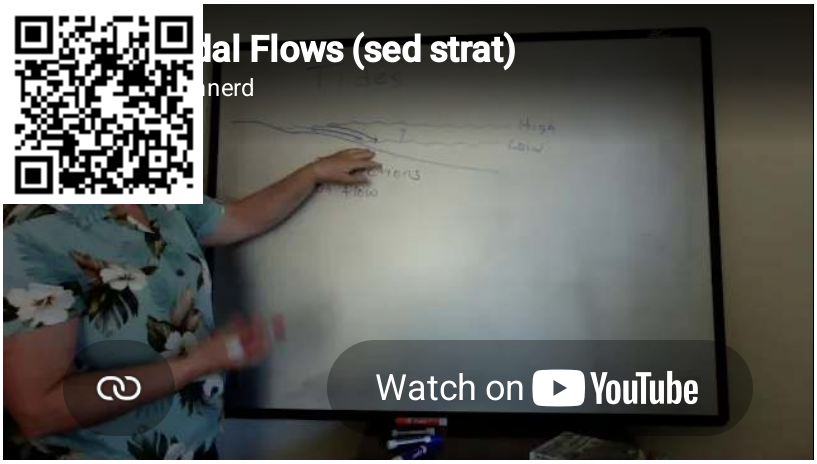
Due to changing flow directions, two sediment transport directions are common, one for onshore flow and one for offshore flow. Often the onshore and offshore flows are not in the same location, but they shift around. This gives rise to current ripples showing transport in two directions and dune migration in two directions producing herringbone cross stratification. See figures 11.6 and 11.7 in Nichols. If the dunes are small and sedimentation rates are very high, you can get ***herringbone cross stratification*** in one tidal cycle in a modern environment. It is usually not preserved in the geological record because it is eroded prior to lithification. It is almost always the longer term changes in current locations that gives rise to preserved herringbone cross stratification. Dunes migrate in one direction for a while, and then currents patterns change and they migrate in the other direction. Herringbone cross stratification is almost always due to tidal processes, although it is not all that common in the sedimentary record. Commonly, one tidal current is much stronger than the others or the flow locations aren't systematically shifting, so tabular cross stratification is more common. It is not unique to tidal environments, however.

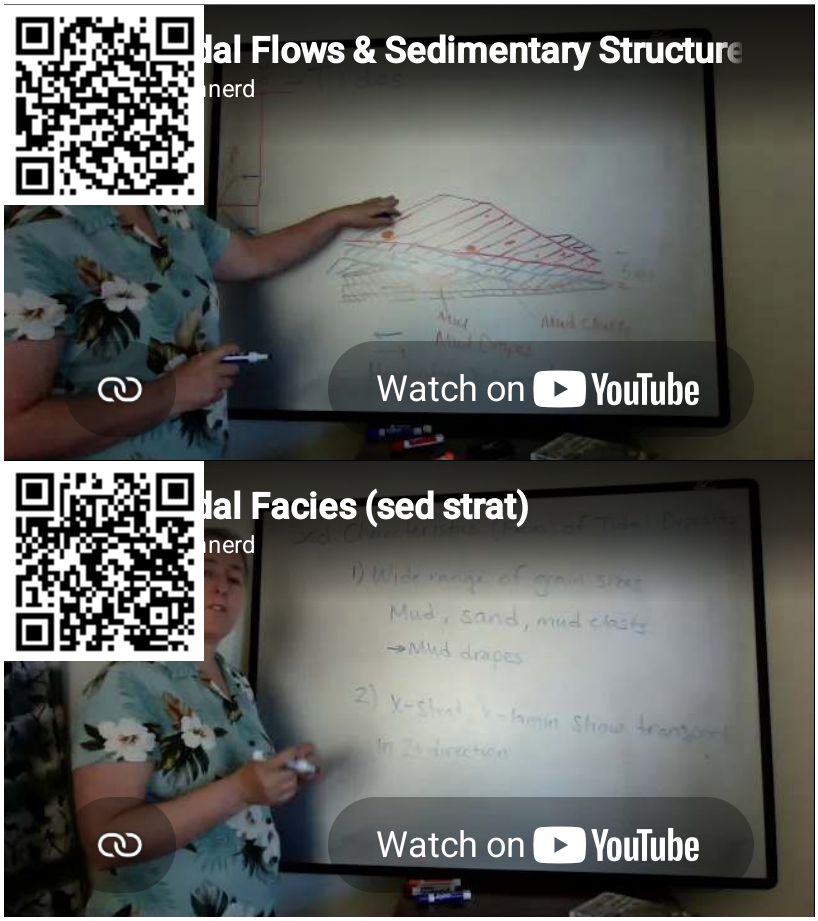
Reactivation Surfaces - Reactivation surfaces form when flow in one direction is stronger than the other, but the other flow is strong enough to modify the bedform shape. See figures 11.6 and 11.9 in Nichols. Reactivation surfaces are erosion surfaces within the sets of cross stratification. They look like irregular surfaces that are similarly oriented to the foresets, but usually do not dip quite as steeply. Also, the foresets above and below the reactivation surface commonly have a slightly different orientation. Reactivation surfaces indicate varying flow directions, which is very common in tidal environments.

Mud Drapes - Flow speeds are also cyclical. During slack tides (low or especially high), fine grained sediment can fall out of suspension draping tidal bedforms with mud. Because mud is cohesive, it does not necessarily erode during the next tidal flow, particularly in the separation zone where flow is slow, e.g. at the bases of ripples and dunes. Thus, sand foresets coated with mud are very common in tidal environments as well. See figures 11.6 and 11.8 in Nichols.

KEY POINT FOR TIDAL PROCESSES: Bi-directional flow with varying speeds over hours

Videos





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9.12.2: Waves and Beaches

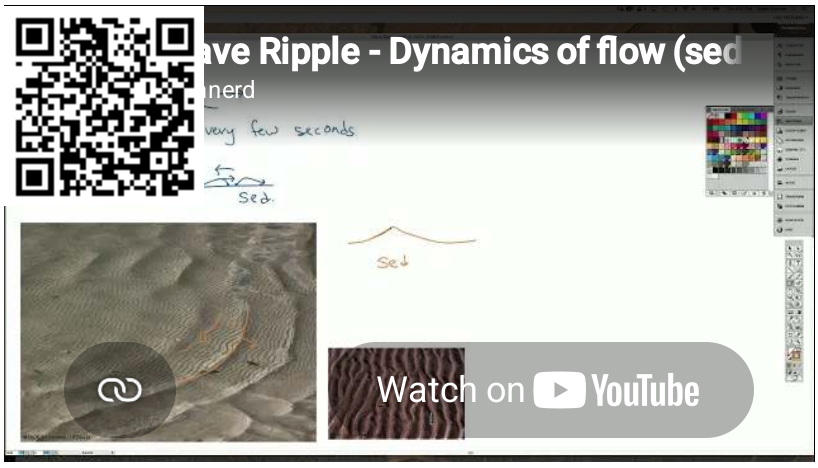
Waves

Waves have oscillating current directions every few seconds. The flow in both directions is equal in deep water, but not necessarily near shore.

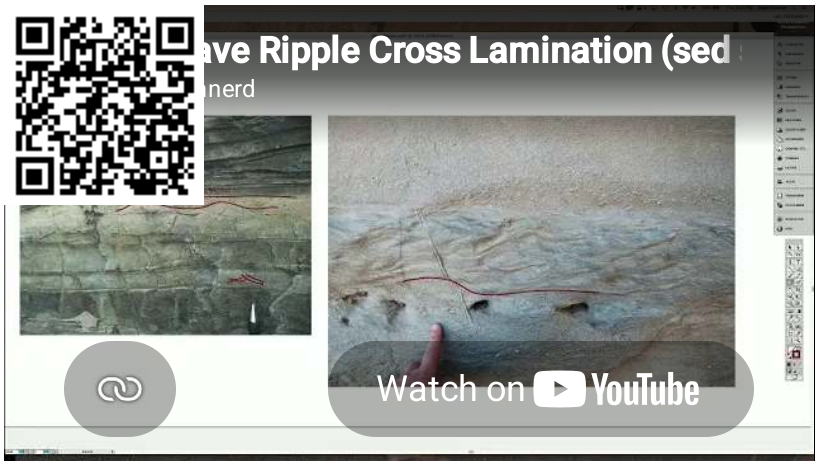
More information on waves and their interactions with shorelines

Wave Ripples

Wave ripples are different from current ripples because that they experience transport in both directions over the time scale of seconds.



Wave ripples can be recognized in rocks by their symmetric shape (if flow in each direction is the same speed) and most importantly, the presence of cross-laminations dipping in two directions. This is the truly distinctive feature and can be present even if the ripples are not very symmetric. At low flow, the boundary layer doesn't have enough speed or momentum to remove the crest of the ripple and the grains that are moved are deposited right on the upper part of the lee slope. Thus, crests are sharp. At higher flow, the crests erode and deposition occurs farther down the lee slope. Thus, high flow ripples have rounded crests.



In shallow water, currents from the waves can be strong enough to flatten out the ripples, but they are not consistent enough in one direction to form dunes; the flow switches directions too frequently for dunes to build up. Thus, where flow speeds are too fast to form ripples, the sedimentary surface tends to be planar or broadly scalloped as the waves are focused into certain areas. This produces a flat lamination (not upper planar lamination) where waves are in very shallow water relative to their height, e.g. from the breaker zone towards the shore.

KEY POINT FOR WAVES: Bi-directional flow every few seconds

Beaches

Waves create beaches with the constant washing back and forth of sediment.



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9.12.3: Storms

Storms

Storms produce both large waves and strong, irregular currents. Combined waves and currents produce unique deposits that can be used to recognize ancient storms in a marine sequence. Storms generally start far from shore and get stronger at the shoreline through time. Then they either die out or move on. Thus, near shorelines, storms tend to start out with low energy flows, increase in flow speed until they are erosional (if strong enough) and then decrease back to lower energy flows. For example, sharp crested wave ripples might mark the start of a storm, then transition into round crested wave ripples, followed by cross stratification due to large waves and strong currents, followed by erosion. As the storm wanes, the coarsest sediment would be deposited, then finer sand deposited by waves and currents, and then wave ripples, e.g. the reverse of the sedimentary structures seen as the storm approaches. There is usually little sediment being deposited at the beginning of a storm because not much sediment has been eroded from shallower water yet and flow speeds are increasing through time. Thus, there is usually no record of the first half of a storm sequence in the rock record. Only the second half usually gets preserved. Storm deposits almost always consist of an erosion surface with sediment of decreasing grain sizes upward - like turbidites, but with different sedimentary structures.

Hummocky Cross Stratification (HCS)

The cross stratification that is deposited as a combination of strong currents and large waves is unique to storms (and is found only in medium to fine sands). It is called hummocky cross stratification (HCS) and swaley cross stratification. When currents are washing eroded sand into an area with strong oscillatory flow from waves, rounded mounds or hummocks of sand develop on the sea floor separated by lows (swales). Variations in current strength cause erosion locally, and the locations of the hummocks and swales change through time. This produces erosional surfaces which truncate the older laminae. These mounds are a few to 10 cm high and 10’s of cm across. HCS is characterized by low angle laminae truncated by low angle surfaces. There are abundant concave and convex up laminae and many fewer flat laminae.

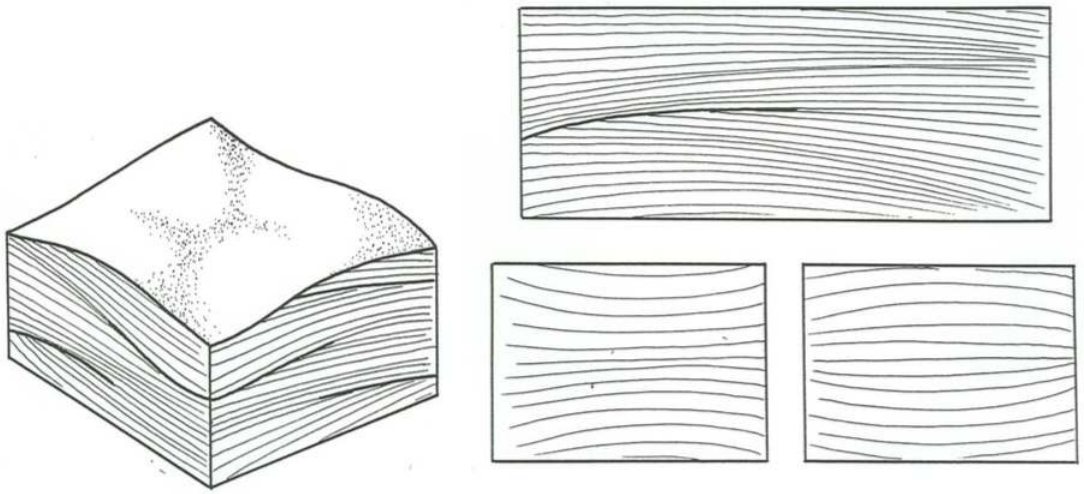


Figure (above): Sketch of hummocky cross stratification in three dimensions and three panels showing important laminae geometries in HCS. The thinner lines represent laminae in the rock, and the darker lines represent erosional surfaces that truncated underlying laminae. The stippled parts on the top surface represent lows (swales). Note that both sides of the block diagram look similar to each other. There is no obvious flow direction because the flow shifted in many directions during accumulation of the sand. The top panel on the right shows a "low-angle" truncation, characteristic of HCS. The two lower panels show pinching and swelling laminae, patterns that form with changes in deposition without intervening erosion. (from Southard's Text)



Figure (above): A hummocky surface in a quarry in Mesoproterozoic carbonates of the Chhattisgarha Basin, India. The modern gravel tends to settle into the swales on the surface.



Figure (above): Hummocky cross stratification in Mesoproterozoic carbonates of the Chhattisgarha Basin, India. Note the low angle truncations of laminae in the bed near the pencil eraser and the pinching and swelling of laminae in the bed near the pencil top.

Storm Sequence

A sample stratigraphic column consists of: Mud, scoured surface, sole marks, (gravel at base), normally graded, HCS, flat laminae or wave rippled top, return to suspension settling. The details of the storm deposits vary with water depth.



Figure (above): Wave-rippled bedding plain in Mesoproterozoic carbonates of the Chhattisgarha Basin, India. This surface likely represents the end of a storm deposit. The waves shaping the surface were large, as reflected in the long wavelength of the wave ripples. Scale in middle of photo shows cm and inches.



Figure (above): Wave ripples and hummocky cross stratification in Mesoproterozoic carbonates of the Chhattisgarha Basin, India. The best wave ripple cross laminae are below the scale bar. The other beds show mostly hummocky cross stratification. It is likely that each prominent layer represents a different storm deposit. There is very little mudstone between these beds because the flux of mud into this basin was very low during this interval.

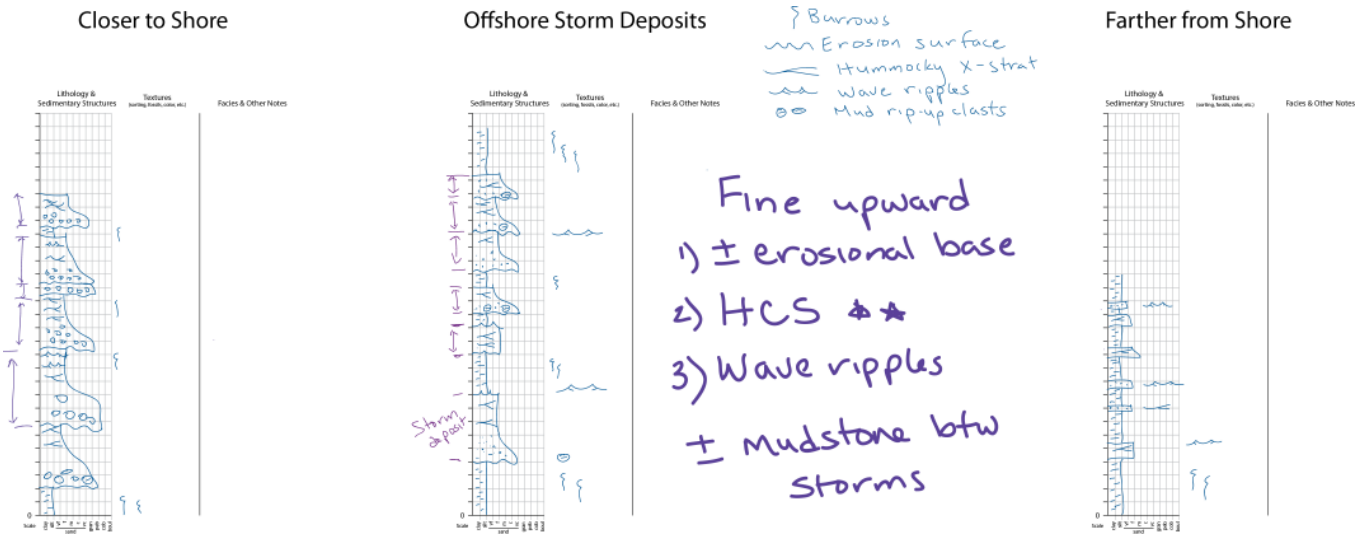
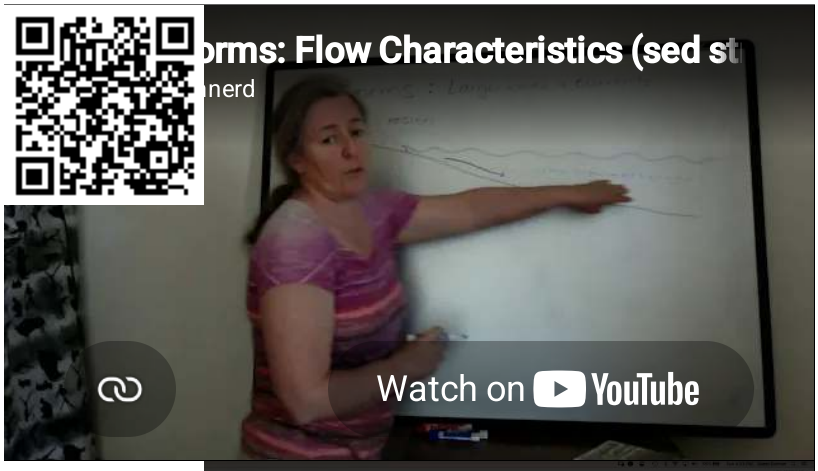


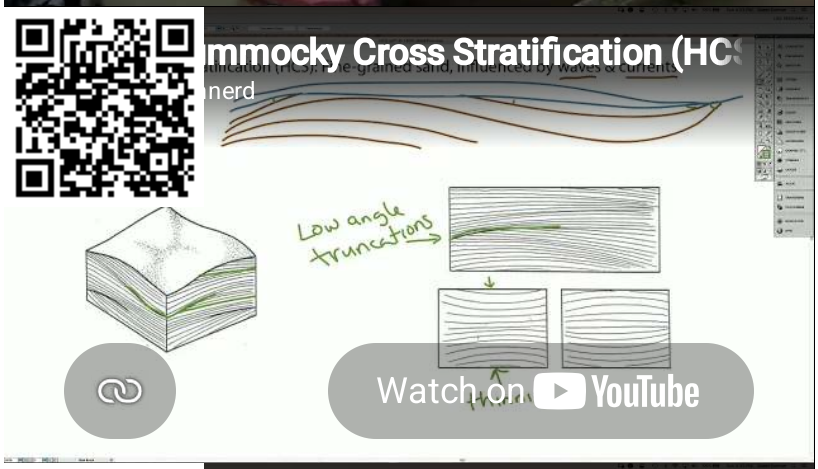
Figure (above): Example storm deposits with variations from closer to farther from store.

KEY POINT FOR STORMS

Multi-directional flows over seconds, low to high to low energy in deep water

Videos







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9.12.4: Deltas and Estuaries

Introduction

When rivers reach standing water such as a lake or the ocean, the flow speed slows down dramatically. And when flows slow down, sediment is deposited. Almost all of the sediment transported in a river is thus deposited close to the river mouth, with the exception of grains that are fine enough to remain in suspension. Lacustrine and marine processes can rework the deposited sediment to distribute it along shorelines.

Deltas form at the mouths of rivers that transport enough sediment to build outward. In contrast, estuaries are present where the ocean or lake waters flood up into the river valley. The key difference between the two is where the sediment transported by the river is deposited. It accumulates seaward or lakeward of the average shoreline for a delta and within the river valley for an estuary. Whether any specific river-sea/lake interface is an estuary or a delta depends on the balance between the supply of sediment, the rate at which the sediment is transported away from the river mouth, and changes in sea/lake level.

Deltas require substantial accumulation of sediment at the river mouth, which can happen when the river supplies a large amount of sediment, transport processes in the sea/lake are relatively slow, and/or the sea or lake level is going down through time. In each of these cases, the river extends farther out into the standing body of water through time. River valleys are flooded, creating **estuaries**, when the sediment supply is low, significant amounts of sediment are transported away from the shoreline by tides and storms, and/or sea level or lake level is going up faster than sediment is accumulating.

The sedimentary rocks deposited in deltas and estuaries are similar, consisting of a mixture of fluvial, shoreline, and shallow marine facies. However, the association of subenvironments and their vertical sequence through time are different.

Video:



Deltas

Distribution of Depositional Environments

I will draw cross section and map views of a delta showing the delta plane, delta slopes, and prodelta. Rivers flow through delta planes and slow when reaching water, producing a mouth bar. Grain size decreases with distance away from the river mouth.

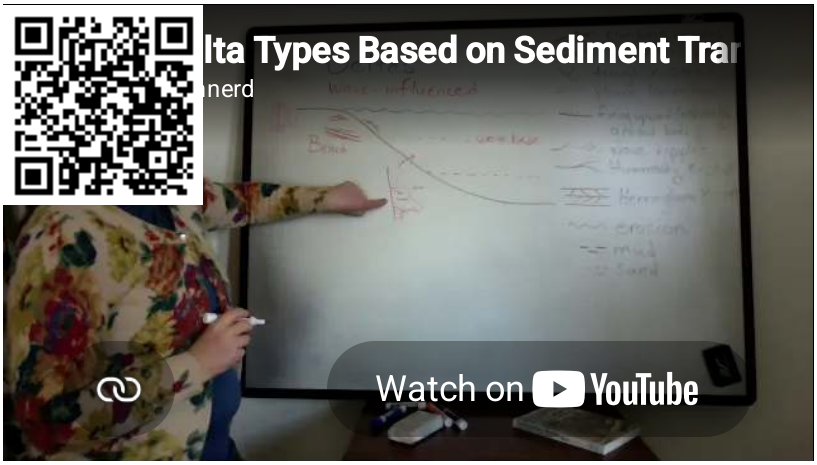
video:



Sediment Transport Processes

General description from river to sea/lake floor, with variations among river-dominated deltas, wave-influenced deltas, and tide-influenced deltas

Video:



Delta Type

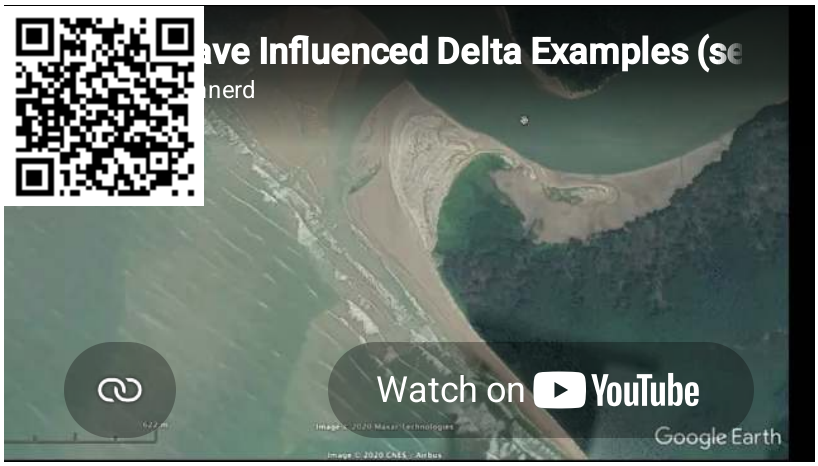
All deltas (by definition) have their sediment transported to the delta by rivers. Thus, fluvial deposits are always associated with them. In addition, depending on marine (or lacustrine) conditions, waves and tides can redistribute the fluvial sediment changing the morphology and facies of deltas. There are three main end member categories of deltas when characterized by processes: 1) River dominated; 2) Wave influenced; and 3) Tide influenced.

Videos:

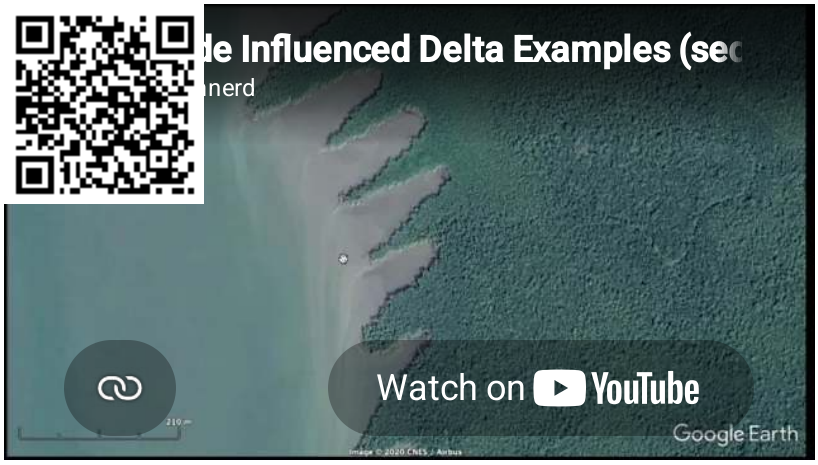
River-dominated examples:



Wave-influenced examples:

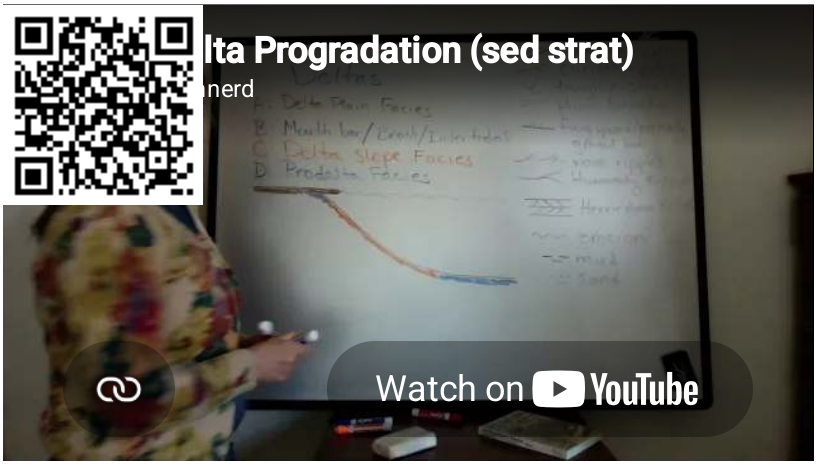


Tide-influenced examples:



Progradation Through Time

Because deltas are sites of sediment building outward from the coast, they are progradational; the landward depositional environments move seaward through time, and are deposited over deeper marine/lacustrine deposits. Thus, delta sequences in the rock record start with deep water, marine (or lacustrine), fine grained sediments and grade upward into shallower water, possible more freshwater, coarser grained sediments. This is one of the distinguishing aspects of deltas that let you define them in the sedimentary record. These changes in grain size and environment typically occur over 1's to 100's of meters in the rock record and include many beds.



Estuaries

Distribution of Depositional Environments

Fluvial into marsh or tidal environments, with land on either side.

Sediment Transport Processes

Fluvial, settling from suspension, plus or minus tidal currents. Shallow water depositional environments.

Waves rare except at the seaward/lakeward end of the estuary because the shallow environments and narrow valley.

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9.12.5: Estuaries

Introduction

Estuaries are river valleys that are flooded by seawater. They form when sea level rises relative to the mouth of a river, and the shoreline retreats landward, up the river valley. This usually happens when the river is not transporting enough sediment to keep the shoreline in place. Estuaries commonly have fluctuating water chemistry. When the river flow is high and the tide is low, they have a high influx of fresh water. When the river flow is low and the tide is high, seawater extends much farther into the river valley, and the water is saltier. Due to the higher density of seawater relative to freshwater, sometimes estuaries have a layer of fresh water that overlies seawater. The waters often mix, creating brackish water. These significant changes in water salinity help shape the ecosystems in estuaries, favoring organisms that are tolerant of frequent changes in water chemistry.

Estuaries form when sea level increases relative to the mouth of the river. Rivers carve into a shoreline when sea level is low, creating valleys of various widths depending on the sediment transport capacity of the river, the ease with which the near-shore rocks or sediments can be eroded, and the duration of the low sea level. When sea level starts to rise, the river gradient is lower near the shoreline, so sediment is deposited before the river gets to the former shoreline. If the sediment supply is low or the rate of sea level rise is high, seawater will start to intrude up the former river valley, creating the estuary.

Like in all coastal environments, tides and waves can redistribute sediment within an estuary. In environments with waves, a set of barrier islands usually develops near the former shoreline, defining a bay or lagoon into which the river flows. In environments with strong tides, estuaries develop tidal islands and bars, similar to those in tide-influenced deltas.

Distribution of Depositional Environments

The landward-side of all estuaries is dominated by fluvial processes and deposits. The boundary between the river and the estuary is usually defined as the farthest upstream area influenced by seawater. Seaward of this area, the influence of marine processes increases, both in terms of water chemistry and sediment transport. Similarly, the influence of the river decreases. Environments eventually become so dominated by marine processes that the influence of the river is difficult to identify. These marine processes include all of those we've discussed before.

The lateral boundaries of estuaries usually consist of exposed land. These areas can be eroding away, developing soil, or accumulating eolian deposits. In places where the topographic gradient is low, marshes can stretch from these areas of land to a main channel that accommodates the river (and tide) flows.

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9.14: Interpreting Stratigraphic Columns

Step 1: Diagnostic Sedimentary Structures

Look for sedimentary structures that are characteristic of a specific environment or process

Examples:

- hummocky cross stratification - waves plus currents (storms)
- wave ripples (vs current ripples) - waves (standing water)
- herringbone cross stratification - bidirectional flow over hours or longer (tides)
- reactivation surfaces - reshaping of bedforms due to changes in flow (tides)
- mud drapes in sandstone - flow stops (tides)
- bouma sequence - rapid flow slowing down (turbidity current)
- mud cracks - mud contracts (exposed to air)
- root casts - from plants, usually land plants (land)
- faint ripple cross lamination with reverse grading - (eolian ripples)
- meter-high dunes in fine sand - (eolian dunes)
- diamictites - laminar flow - (debris flows, mud flows, melting ice)
- diamictites with facetted clasts and striations - (glacial)
- lone (or drop) stones in laminated shale - large grains rafted over quiet environment (icebergs; trees possible)

Step 2: Tentative Environmental Interpretation

Evaluate how these distinctive sedimentary structures relate to each other in the stratigraphic column.

- Are there several indicators of waves or storms?
- Are there several indicators of tides?
- Are there several indicators of wind-deposited sediment?
- Are there several indicators of glacial activity?

Evaluate the environment(s) in which these processes occur most commonly to develop a tentative environmental interpretation (or an environmental hypothesis).

Step 3: Consistency with Other Features

Compare your environmental hypothesis to the characteristics implied by other sedimentary structures in the column and evaluate whether they are consistent with your tentative environmental interpretation.

- Examples of other sedimentary structures:
  - Trough cross stratification
  - Planar cross stratification
  - Current ripple cross lamination
  - Planar lamination

Evaluate whether or not your tentative environmental interpretation is consistent with the presence of these other sedimentary structures. If it is not consistent, evaluate how you can revise your environmental hypothesis to take these other features into account.

Example: Turbidites vs River Channel Deposits

If you hypothesized that set of a fining upward sandstones were turbidites (which have planar lamination and current ripple cross lamination), but there is also trough cross stratification in a number of the beds, ask yourself if there is a way for trough cross stratification to form in turbidites. The answer is that trough cross stratification is VERY rare to absent, which is why trough cross stratification is not part of the Bouma sequence of facies defined for turbidites.) You would then look for another environment that includes sandstones with planar lamination and current ripples. Fluvial channels often have those features. Turbidites and fluvial

channels do not form in neighboring environments (see Step 5 below), so it is unlikely that both are present. You will thus want to go back to steps 1-3 to identify a more consistent tentative environmental interpretation.

Example: Turbidites vs Storm Deposits

If you hypothesized that set of a fining upward sandstones were turbidites (which have planar lamination and current ripple cross lamination), but there are also wave ripples in a number of beds, ask yourself if there is a way for wave ripples to form in turbidites. The answer is no because turbidites are unidirectional flows. However, waves and storms can influence the sediment in the same environments that produce turbidity currents. For example, lakes and the ocean can have both in environments above storm wave base. Thus, the presence of wave ripples in some beds that contain mostly turbidite features suggests that waves were ALSO present in that environment. Thus, your environmental interpretation does not need to be significantly revised. Rather, it can be expanded to include both turbidites and waves.

Step 4: Vertical Evaluation

Evaluate how the vertical sequence of sedimentary structures changes to refine or correct your environmental interpretations.

- Do structures occur in a distinctive pattern that suggests a depositional environment?
  - Is there an erosion surface followed by dune stratification followed by ripple lamination followed by a rooted horizon? (Then it might be migrating river channels or tidal channels if there are indicators of tidal currents.)
  - Do the structures suggest an environment that shallows from deep quiet water upward into a river system? (Then it might be a delta building out into standing water.)

Sometimes the main sedimentary transport characteristics change through time. For example, a storm influenced environment can become more dominated by tides through time as the geometry of the shoreline changes, as climate changes, or as relative sea level changes. All three of these can change at once, too, because climate and sea level are tightly linked to each other, and shorelines respond to the changing sediment transport processes.

Step 5: Walther's Law

Use Walther's Law to refine your environmental interpretations and to test whether or not they are reasonable. There are two ways to approach this: testing your hypothesis by starting with your predictions, or starting with the data from the stratigraphic column and seeing if you get reasonable environments next to each other.

Test your environmental hypothesis

If you have a good mental image of your hypothetical environments, this is a useful process:

1. Draw a cross section or map view (or both) that includes all of your hypothesized environments. Make sure that it is a reasonable landscape, e.g. something that would be reasonable to see in a satellite image. In other words, do not draw rivers flowing uphill or lakes on mountain peaks, etc.
2. Indicate things like the relative water depth and the characteristics of sediment transport in each area. Include the sedimentary structures that you predict will form.
3. Compare these environments to your stratigraphic column. Start with the interval of the column that you have the most confidence in for your environmental interpretation. Mark that environment on your cross section or map. Then go up (or down) in the column to the next facies (rock type) and mark the environment it represents on your cross section or map.
4. Evaluate whether the two points are consistent with Walther's law. Draw a line from the first environment to the second one. Does that line cross any depositional environment that is absent from your stratigraphic column? If the answer is yes:
   - How can you reconcile the missing environment?
   - Are there features that you missed in the stratigraphic column that could have been deposited in that environment?
   - Is there an erosion surface between the two facies in the stratigraphic column?
5. Revise your interpretation of either your depositional environment or the facies in your stratigraphic column until they are consistent with each other. Do not, however, ignore the sedimentary structures in the stratigraphic column because they are the data that will lead to an appropriate interpretation. Revise your cross section or map appropriately.

6. Repeat steps numbers 3-5 until you have marked every facies in your stratigraphic column on your cross section or map, and all inconsistencies are resolved. Sometimes there are remaining uncertainties because the rock record does not record everything and we miss features when we are collecting the data. If there are still inconsistencies, record them and why you could not resolve them. For example, if there is one set of trough cross stratification in a sequences that otherwise consists of turbidites and storm deposits, you could make a note of where it occurs and provide a tentative interpretation for why, e.g. maybe the flow speed was consistent enough for long enough to produce dunes even though that rarely happens in turbidity currents.

Recreate environments from your strat column

If you are having trouble creating a mental image of your hypothesized environments, this is a useful process:

1. Start with the interval of the strat column that you have the most confidence in for your environmental interpretation. Draw that environment on a map or in a cross section. For example, if there are interbedded sandstones and mudstones, and the sandstones have features consistent with the Bouma sequences, draw a standing body of water with a slope on one side.
2. Indicate things like the relative water depth and the characteristics of sediment transport in each area. Include the sedimentary structures that you predict will form.
3. Next, go up (or down) in the column to the next facies (rock type) and draw the environment that it represents on your cross section or map, again indicating the relative water depth, sediment transport processes, and sedimentary structures indicated by the stratigraphic column data.
4. Evaluate whether the two environments are consistent with Walther's law. Are they typically next to each other in a landscape? If the answer is yes, go the the next facies in the strat column (go back to 3). If the answer is no, evaluate whether any of these are possible:
    - Did you miss an environment represented in your stratigraphic column? Is that environment between the two you drew in your cross section or map?
    - Is there an unconformity in your stratigraphic column that would mean that Walther's Law does not apply? Could erosion have been caused by the flows in the "missing" environment?
    - Is one of your environmental interpretations wrong? What else could it be?
5. Revise your interpretation of either your depositional environment or the facies in your stratigraphic column until they are consistent with each other. Do not, however, ignore the sedimentary structures in the stratigraphic column because they are the data that will lead to an appropriate interpretation. Revise your cross section or map appropriately.
    - **Example**: Say you interpreted interbedded mudstones and sandstones with current ripples as turbidites. However, there are also sandstones with an erosional base, thick sections of trough cross stratification fining up into current ripples at the top that you interpret as river point bar deposits. If those two rock types are next to each other vertically, they would violate Walther's Law since turbidites form in lakes and oceans, whereas river channels form on land. You need a shoreline between the two. Possible resolutions to this "illegal" interpretations could include: a) there is an interval between the two with climbing ripples that you missed in the stratigraphic column that could represent a river mouth bar, providing a transition from the standing body of water into the river channel; b) there is an unconformity that is more significant than the erosion at the base of a fluvial channel in the stratigraphic column, and thus there are no rocks preserved that reflect the changes in environments between the standing water and the river channel; or c) the interbedded mudstones and sandstones actually represent floodplain deposits rather than turbidites. You would then go back to the stratigraphic column and evaluate which change in interpretation is best supported by the data in your column.
6. Repeat steps numbers 3-5 until you have marked every facies in your stratigraphic column on your cross section or map, and all inconsistencies are resolved. Sometimes there are remaining uncertainties because the rock record does not record everything and we miss features when we are collecting the data. If there are still inconsistencies, record them and why you could not resolve them. For example, if there is one set of trough cross stratification in a sequences that otherwise consists of turbidites and storm deposits, you could make a note of where it occurs and provide a tentative interpretation for why, e.g. maybe the flow speed was consistent enough for long enough to produce dunes even though that rarely happens in turbidity currents.

Summary

Often, there is some ambiguity about the depositional environment(s) represented in real rocks. By going through this process, you can reach a reasonable interpretation that is well supported by the data. You will also understand where the ambiguities are. This is

particularly helpful if it is your own data and you can make more observations by doing more field work. You will be able to focus your efforts on resolving the ambiguities, leading to a more accurate environmental interpretation.

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9.9: Weathering and Erosion

Introduction

Weathering is the process of larger rocks breaking down into smaller pieces. It is the first step in transforming bedrock into sediment through diverse physical and chemical processes. The importance of each process varies depending on the environmental conditions and the rock type.

As the bedrock breaks down into smaller pieces, the grains are more easily transported. When transport occurs depends on the air, water, or ice flows in the area or a potential collapse of a slope to produce a gravity flow. The initial transport processes vary significantly depending on the environment and local topography.

Sedimentary grains continue to weather as they are transported through various depositional environments and after they are deposited. The weathering processes vary depending, again, on the environmental conditions and the composition of the grains.

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9.9.1: Weathering

Weathering

Sediment comes from the break down of rocks into smaller, transportable components. This occurs via two processes: **physical weathering** and **chemical weathering**. Physical weathering consists of breaking apart rocks and crystals. The results of physical weathering are smaller components of the same material that is being weathered. There is no change in composition. In contrast, chemical weathering consists of changing the composition of at least some components of the rock that is weathering. The sediment does not have the same composition as the original rock.

Physical Weathering

Physical weathering occurs via:

1. **Freeze-thaw action**. Water in cracks expands when it freezes, putting force on the cracks. The cracks grow, and eventually crystals and pieces of rock break off into smaller components. Obviously, this process is most important in environments where temperatures cycle across the freezing point of water.
2. **Salt crystal growth**. When water evaporates, salts precipitate. If this happens in fractures in rock, the growth of the salt crystals can put pressure on the cracks, causing them to grow. This process is most important near oceans where rocks are exposed to lots of salt water spray and in arid environments where water evaporates rapidly.
3. **Temperature changes**. Minerals contract and expand as temperature decreases and increases, respectively, and different parts of the rock are heated different amounts. Those in direct sunlight expand as they heat, whereas the interiors and shaded areas do not. Differential expansion and contraction produces stresses which can result in cracks and physical weathering. This process is most important when temperatures change dramatically from day to night, a characteristic of many desert environments.

Physical weathering tends to produce mostly sand-sized sediment and larger grains because most of the fracturing occurs along mineral boundaries. Physical weathering of fine grained or finely crystalline rock can produce abundant very fine grains, but most of the sediment from these rock types consists of rock fragments (called lithic clasts).

Image of physically weathered rocks in New Zealand:



Chemical Weathering

Chemical weathering occurs via:

1. **Dissolution** of minerals. Some minerals like halite and other evaporites dissolve very easily in water. Other minerals, particularly silicates, do not dissolve easily. Carbonates are in between and dissolve in acidic waters. (Rain water has a pH of ~5.7 due to dissolved CO_2, even without “acid rain” pollution.) The results of dissolution are ions in water that are transported downstream. Ions are not deposited until the water evaporates, they react with other minerals, or organisms use them to make shells. Often, only part of a rock dissolves, leaving altered grains that can be transported by wind, water, etc.
2. **Alteration** of minerals. Silicate minerals do not dissolve very easily, but they do react with water to form new minerals. Feldspars react with water to form clay minerals and ions, olivine reacts with water and O_2 to form oxides, clay minerals and ions, pyrite reacts with water and O_2 to form oxides, acidity and sulfate ions. Iron oxides, such as hematite, are commonly red, giving weathered rocks a rusty hue. Alteration of minerals is one of the main sources of clay minerals and mud-sized grains.

Image of chemically weathered rocks in New Zealand. This outcrop originally had the same composition as the rock shown in the previous photograph, but has been exposed to much more water as well as plant-assisted soil processes.

Mineralogy of Weathered Rocks

Sediments that have been subjected primarily to physical weathering have a mineralogy that is similar to that of the parent rock. If the sediments have been subject to extensive chemical weathering, it is much harder to characterize the source rocks because the composition has changed extensively. Overall, the composition of sediment depends on the mineralogy of the original rock, how it is transported, and the weathering environment.



Some minerals alter more quickly than others. Quartz is difficult to dissolve and is hard, so it commonly lasts through both chemical and physical weathering and is the most common mineral in sand on Earth. In contrast, minerals like Ca-feldspar and olivine react to form new minerals quickly. They are substantially less common in sediments. Thus, mafic rocks (which contain Ca-feldspar, olivine and pyroxenes) tend to alter to clay minerals very easily and produce little sand and abundant mud. In contrast, granites (quartz, K-feldspar, Na-feldspar, mica) contain minerals that react more slowly and tend to produce sand-sized grains, especially quartz.

The following list includes minerals from most reactive (rarely found in sediments) to least reactive (common in sediments): Olivine, Ca-feldspar, Pyroxene, Amphibole, Na-feldspar, Biotite, K-feldspar, Muscovite, and Quartz

The other main control on sediment mineralogy is the hardness of the grains. During transport, grains hit each other. Softer grains tend to be damaged when they collide with harder grains, and this damage can cause them to break into smaller grains. Thus, soft grains become smaller very quickly when they are transported with hard grains. Quartz is the most common mineral in sandstones because it is hard and unreactive. Clay minerals are also very common because they are too small to damage much during collisions and they are the product of the alteration of other minerals.

Controls on Weathering

The extent and style of weathering is mainly controlled by climate. **Water** is extremely important, even for physical weathering. The more water present, the faster weathering occurs. **Temperature** is also important. Warmer temperatures promote faster reactions, so chemical weathering is more effective in warm climates. Thus, warm, humid climates tend to have the most rapid weathering (and poor outcrop). Finally, **vegetation** has a strong influence on weathering. Plants tend to increase the extent of chemical weathering by producing organic acids that help break down rocks into soil through both dissolution and alteration. They also help soil retain moisture, increasing the availability of water for weathering. Their roots can help widen cracks, increasing physical weathering.



Some of the big questions we have about Mars right now are about the extent and timing of chemical weathering. There is no vegetation. Right now, the climate is very cold and very dry, so the rate of chemical weathering now is extremely low. However, most of the rocks on the surface of Mars (that we have characterized) are basalts, which have glass and mafic minerals that should alter “quickly” if they come in contact with water. (The image to the right is wind-blow sand in Gale Crater, Mars.)

What do you expect a chemically weathered basalt to produce? What should we look for as evidence of past chemical weathering on Mars? How might products from basalt weathering look different if one looks at the weathered basalt itself or at sediment that was eroded from weathered basalt? (Basalt is mostly plagioclase (calcium feldspar) and pyroxene, with or without olivine, as well as glass. It has less than 20% quartz.)

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9.9.2 Erosion

Erosion

Once sediment is produced by weathering, it is available for transport. The two main forces in erosion are fluid flow and gravity. Fluid flow is what we talk about most, e.g. glacial erosion of sediment, wind blown sediment, and mostly water transport. Flowing water is the biggest influence in erosion on Earth because it is very common and effective at transporting sediment.

Transport Capacity

Erosion by water occurs when water is flowing across a surface, and the flow is capable of transporting more sediment than is currently moving as bedload. This is called the sediment transport "capacity". A certain number of grains of a certain size can be picked up by the Bernouli effect for a given flow. If there are too many grains, they start colliding and the characteristics of sediment transport change. Grains are directed back toward the bed and up into the flow. Eventually, more go back to the bed than are lifted into the flow, and sediment is deposited. Sediment can be deposited even at high flow speeds when there are more grains than the transport capacity of the flow.* In contrast, if there is a shortage of grains that are small enough to be transported by the flow, e.g. the flow is moving all of grains present, any new grains will be eroded off the bed as soon as they are available. The flow then has excess transport capacity.

* Think about dumping a truck load of fine sand into a fast moving river, it takes time to move all that sediment even if the flow speed is theoretically fast enough to erode fine sand.

One of the most common times for a flow to have excess transport capacity is when the flow is speeding up. We know from the Hjulstrom diagram that faster flows transport larger grains. They can also transport more grains. Thus, water flowing from a shallower slope to a steeper slope commonly speeds up, has excess capacity and erodes sediment. When it slows down, the transport capacity decreases, and sediment is deposited. In floods, the water gets deeper, speeds up, erodes sediment, and transports it. As the flood ends or flood waters extend over larger areas, the water slows down and deposits the excess sediment. In general, erosion occurs when flows are speeding up or when the water goes from an environment with low sediment (e.g. a dam spillway) to an environment with more sediment (e.g. a river bed).

There was a dramatic demonstration of excess sediment transport capacity when the Oroville Dam Auxilliary Spillway became active due to excessive rainfall in 2017. Flow over the spillway caused extremely rapid erosion that risked the integrity of the dam (figure below). More details are available here.



Figure: Aerial view of the Oroville Dam Auxilliary Spillway after water flowed over the cement barrier at the top of the dam, seen running diagonally across the image. The broken-up grey band to the right was a 2 lane road leading to a dam viewing area. Note the very large construction trucks in the upper part of the image. The grey rock in that area was moved in to rebuild the road so that equipment could get to areas of the dam that needed repairing.

Gravity Transport of Sediment

Gravity pulls sediment down steep slopes through creep, rock or debris falls, landslides and slumps. These processes are really important for the hills in coastal California where there is enough water for extensive weathering, but there is little runoff of water most of the time.

Here is a video of gravity-transported sediment:



Usually, the concentration of sediment is very high in these flows, which means that the grains collide with each other frequently. Grain collisions can help keep the flow moving but the grains increase the viscosity of the flow (decreasing the Reynolds number). These collisions and higher viscosity keep the different grain sizes from being sorted out, and most gravity flow deposits are poorly sorted. If lots of mud-sized sediment is present, the viscosity of the flow is high, and the flows can be laminar (Reynolds number < 500), which produces very poorly sorted deposits. These are often called mud flows or debris flows. Watch the videos again, and predict the characteristics of the sediment that would be deposited by the different processes.

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Textbook Construction

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Taryn Lausch			Turbidites
Andrew Powell			Chemical Weathering

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Alluvial fans

Introduction

When it rains in arid environments, such as deserts, it often floods because there is little vegetation to trap water in soils and slow the runoff. Alluvial fans form in areas with a steep gradient from a drainage catchment to the basin floor. Tectonic activity is typically required to maintain steep slopes because they erode to lower slopes through time. The Basin and Range Province in eastern California and Nevada is an area with abundant examples of alluvial fans.

Alluvial fans are cone shaped accumulations of coarse sediment deposited at the transition from confined flow in a canyon to unconfined flow in a basin. This also corresponds to a break in slope. As the slope shallows and the flows spread out, the flows slow down and deposit much of the sediment that they were able to transport in the canyon. (Think about the Hjulstrom diagram). Fan geometry is determined by the rate of deposition. At the canyon mouth, it is steep (up to 15°) due to rapid deposition of coarse sediment. It shallows to about 5° over the main part of the fan and shallows even more to 1-2° at the toe. Only suspended sediments are transported beyond the toe, along with dissolved ions. If the water can pond, the fine grains settle out and the water evaporates forming minerals like gypsum and halite, and creating playa lake deposits. Deposition on a given alluvial fan is very rare - one event occurs about every 300 years on most fans in the southwestern US.



Figure 1: Alluvial fan deposited in a glacial valley. Note the conical shape and surficial flows actively depositing sediment.

Alluvial fans in Death Valley: http://g.co/maps/n2udd

- The fluids involved are water, usually in the form of precipitation.
- Three types of flows are common: 1) debris flows, 2) sheet flows, and 3) channelized flows.

Sediment Transport Processes

Debris flows are slurries of mud, rock debris, and just enough water to make the sediment into a viscous flow. Due to the high viscosity, the flow is laminar, like a glacier, and like a glacier, there is no significant sorting of grain sizes. Debris flows can transport very large blocks and continue to move until the internal friction of the flow due to viscosity exceeds the flow's momentum when it freezes into place. This can occur due to either the loss of water or lower slope. The resulting deposits show little sorting and would be classified as a mud supported **breccia** or a **diamictite**. (Diamictites are defined as very poorly sorted sedimentary rocks with no grain size sorting within them. They are characteristics of laminar flow deposits.) In most cases, debris flow deposits are unsorted and lack any form of stratification. They are laterally restricted because they do not spread out too much, and they are commonly an even thickness throughout, with steep edges to the flows.



Figure 2: The front of a debris flow of sediment containing very large blocks. Note that most of the flow is restricted to the channel and the lateral variability in grain size due to energy loss on the flow boundary.

Sheet flows are turbulent flows with significantly more water and less mud than debris flows. Since the flows are turbulent, there is significant grain sorting and normally graded, fining upward deposits are common. Once a flow reaches the mouth of the canyon, the flow spreads out and the coarsest rocks are deposited first. Finer grains are deposited last as they require the least amount of energy to keep in suspension. This produces normally graded beds, but deposition is very rapid and the grading is commonly poor. The suspended load may make it to the toe of the fan if the water doesn't filter into the fan first. Sheet flows produce broad deposits that are clast supported, with some imbrication of clasts. Unlike a debris flow, sheet flows commonly cover 1/3 to 1/2 of a fan surface.

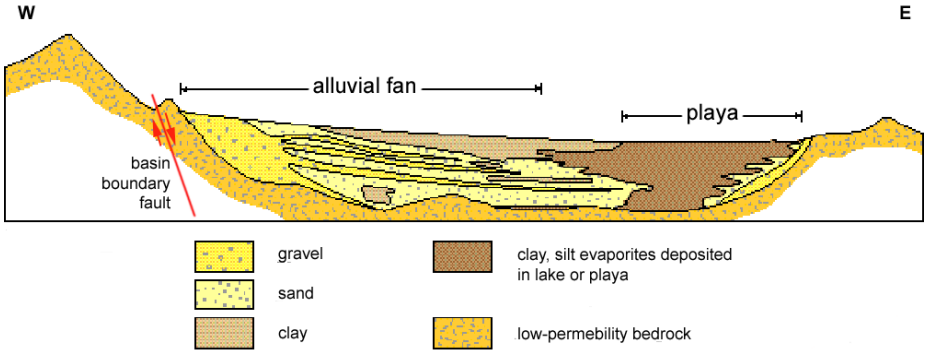


Figure 3: Example of what a sheet flow may look like. This example is not on an alluvial fan; however, it does demonstrate the idea that sheet flows are not restricted to channels and typically flow over large surface areas.

Channelized and other types of flows - A number of other flow types are also common on fans. For example, if there is insufficient rain to produce a sheet flow, ephemeral rivers can flow down the surface of the fan - which is more common. This produces braided river type deposits, which we will talk about later. There is also a significant gradation between debris flows and sheet floods. They represent two end members, and there are lots of variations in mud content and water content which variously affect the viscosity of the flow and thus the resulting sedimentary deposits.



Figure 4: Braided streams cut into the alluvial fan deposit sediments. Larger channels may form episodically, resulting in fluctuating grain size distributions in a typical vertical facies.



https://pubs.usgs.gov/ha/ha730/ch_b/B-text2.html

Figure 5: Representation of what to expect in vertically in an alluvial fan deposit. Note the episodic gravel deposits between thicker, more consistent sand deposits. As mentioned before, the finer sediments are deposited most distally away from the inlet of the alluvial fan. (Public Domain, redrawn from Thompson, D.G., 1929, The Mohave Desert region, California, a geographic, geologic, and hydrologic reconaissance: U.S. Geological Survey Water-Supply Paper 575, 759

Characteristics of Deposited Sediment

Characteristics of Alluvial Fan Deposits

1. Poorly sorted beds (diamictites) that are of an approximately uniform thickness but of limited lateral extent, deposited by debris flows;
2. Moderately to well sorted sandstone beds, often normally graded with pebbles at the base deposited in ephemeral channels; these show some cross stratification due to turbulent flow dynamics;
3. Normally graded sandstone beds that are laterally extensive deposited by sheet flows;
4. Average grain size decreases down slope and the abundance of debris flow deposits decreases down slope.

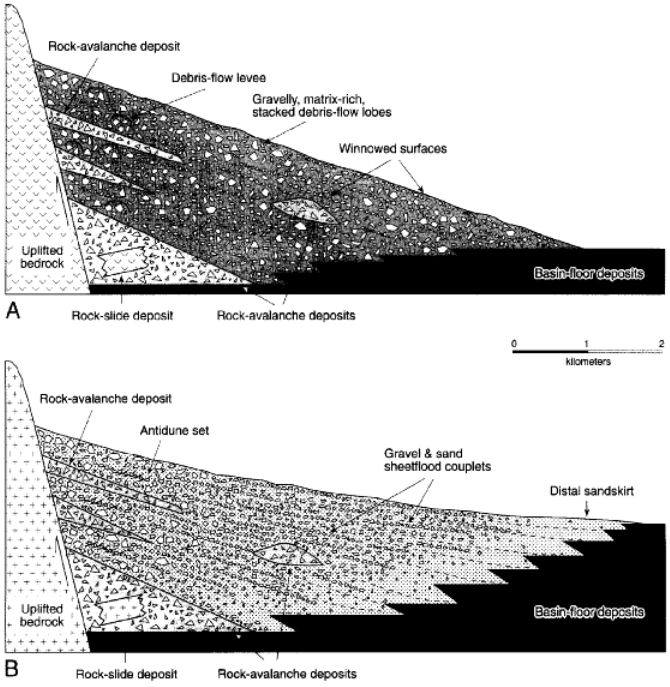
Side note about facies: Each of list items 1-3 above could be described as a subfacies of the Alluvial Fan Facies, with its own grain sizes, characteristics, sedimentary structures, etc. Each of those could also be considered a facies, and the overall alluvial fan deposit could be assigned to an “Alluvial Fan Facies Assemblage”. If I was studying the sedimentation in all of Death Valley, I would probably be most interested in distinguishing between alluvial fan facies, playa deposits, and eolian deposits, so I would use the “Alluvial Fan Facies” I defined above. In contrast, if I wanted to highlight variations in the depositional processes on one fan in Death Valley, I would probably define the different types of alluvial fan deposits as different facies, so that my facies would

emphasize the differences in debris flows, sheet flows, and channelized flows. I would then have an “Alluvial Fan Facies Assemblage” that would be distinct from my “Playa Facies”.

Types of Deposits Typical of Arid Environments

- Wind blown sand (well sorted, texturally mature medium or finer sand)
- Flash flood deposits (poorly sorted breccia, including debris flows)
- Playa lake deposits (silt, mud and evaporites). There are also very cold desert environments, such as the McMurdo Dry Valleys, Antarctica. These environments have glacial deposits left by glaciers that flow in from areas with higher precipitation (e.g. higher elevations) or the ice cap.

Typical Vertical Sequence of Facies Representing this Environment



(A) is a debris flow dominated alluvial fan (B) is a sheet flood dominated alluvial fan.

Key Words

- **Aridity** - Aridity defines a desert, not temperature. An arid region gets less than 250 mm of rain/year. Our average in Davis is about 480 mm. That puts us barely in a semi-arid climate, which has 250-500 mm of rain/year on average. Arid environments are characterized by little vegetation.

References

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Introduction

Lagoons:

Lagoons are bodies of water that are separated from larger bodies of water by a natural barrier, such as barrier islands, sandbars, and reefs. The word comes from the Italian word 'laguna' meaning pond or lake. There are two main types of lagoons: coastal and atoll. (11)

1. Coastal lagoons: Shallower lagoons separated from the ocean typically by a barrier island, reef or sandbank. (11)

800px-Venice_Lagoon_December_9_2001.jpg

Figure 1: Coastal Lagoon

The Venetian Lagoon

The city of Venice, Italy is located on the large orange island in the center of the lagoon. (20)

It is separated from the ocean half by a peninsula (top barrier) and half by a barrier island (bottom barrier), as seen in the image.

2. Atoll lagoons: These form due to the erosion of an extinct seamount or volcano with a fringing coral reef that continues to grow upward forming a barrier for the lagoon. (11)



Figure 2: Atoll Lagoon

Wake Island

The green water surrounded by land and reef is an atoll lagoon. Quick Historical Fact: Wake Island is used as a US Air Force Base, and was simultaneously attacked by the Japanese along with Pearl Harbor in WWII. (19)

This page will focus on coastal lagoons that are separated from the ocean by barrier islands.

Lagoons are areas of quiet water and generally sites of mud deposition (either carbonate or siliciclastic). Coarser sediments are washed in during storms and are oftenwave rippled. Tidal channels commonly cut into lagoonal deposits as the location of concentrated flow migrates back and forth. Lagoons have extremely variable water chemistry depending on climate. If the climate is humid, they contain a mix of fresh and salt water (brackish). If the climate is dry and a river does not flow into it, they tend to be evaporitic and hypersaline. The types of organisms living in the lagoon is a good indicator of local climate, (21). Around lagoons where evaporation exceeds water inflow, salt flats, and sand dune fields may develop at or above the high tide line, (4). If the lagoon is fed by a river it is considered to be a part of an estuary system.

Go on a Virtual Field Trip to a Lagoon at Bayside Park here!

Barrier Islands:

A barrier island is an island that runs parallel to the coastline. These islands protect the coast from storms, and provide the separation from the ocean to allow a lagoon to form in between it and the coast. (9)

The Four Requirements to form a Barrier Island:

1. Barrier island formation requires a large source of sand, either from coastal sand deposits or marine sand deposits called shoals. It must be enough to exceed the amount of sand loss due to erosion.
2. The coastline must have a shallow slope or else the barrier deposits could fall away.
3. The area must have waves, currents, and tides strong enough to move the sand, however, the tides must be weaker than the waves. In strong tidal areas, the flow speed through an inlet is not large enough for barrier formation.
4. Slow rising sea levels, which can flood a coastal plain, creating a lagoon. It must be slow or else the barrier island would become submerged; it would not have adequate time to build up enough sand to stay above water. (1 and 9)

Over time, sand builds up at the far reach of the waves forming a high called a berm. Storm surges wash over the berm and deposit sediment on the landward dipping surface. They can also erode the berm. When a beach develops offshore of exposed land, it creates a barrier island. These islands are very dynamic, shifting in location, growing, and eroding as storms reshape them. If the area behind the berm is a lagoon or estuary, the berm forms a barrier island (or peninsula) that protects the area from the full force of marine processes, i.e. waves and storms, (21). The islands often form as the result of sediment moving offshore through river discharge, while wave action works to push the sediment back towards the shore. The resulting sediment buildup is then stretched into long barrier islands by longshore transport. (8)

Barrier islands themselves have several depositional environments within them. On the seaward side, beaches form that are shaped by the incoming waves, tides, and currents. Sand dunes form behind the beach. On the coastal side of the sand dunes is the back-barrier, bordering the lagoon. The back-barrier can include vegetation growth, washover fans, marshes, and tidal flats. The low lying tidal flats can grow vegetation that increases sediment deposition. (8)

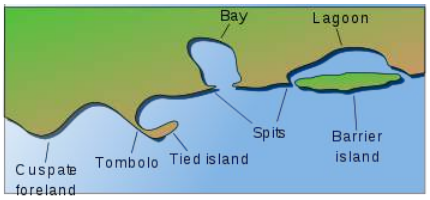


Figure 3: Geography of the Environment

(3)

Diagram of a barrier island and subsequent lagoon.

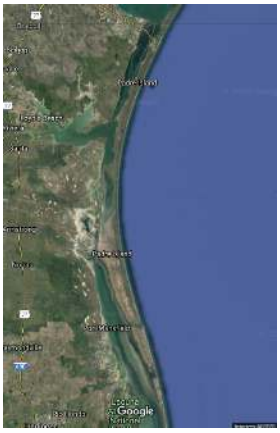


Figure 4: Barrier Island and Lagoon Satellite View

Padre Island, TX

The longest Barrier Island in the world, separating Laguna Madre (a hypersaline lagoon) from the Gulf of Mexico (18)

Image screenshotted from Google Maps

Barrier Islands and Lagoons are typically found together in the following sequence of depositional environments: Coast, lagoon, barrier island, open ocean.

Sediment Transport Processes



Figure 5: Sub-Environments

This figure diagrams locations of different barrier island sub-environments from Reinson, G. E. (1979). Take note of the barrier island beach, dune ridges, back-barrier (the section of the barrier island landward of the dunes, washover fan, lagoon, and the main shoreline. The main shoreline is made up of marshes and tidal flats here, but beaches are also possible.

Sediment transport in lagoons:

Within the lagoon, tides go in and out carrying smaller sediments. These tides enter and exit the lagoon through inlets, small openings connecting the lagoon to the ocean. From the landward side, rivers and streams if present carry and deposit smaller suspended particles into the lagoon. Organic material growing around the lagoon may also end up in the lagoon, (Nichols Sedimentology and Stratigraphy). If the barrier protecting the lagoon experiences overwash, coarser-grained material from the barrier can be deposited into the lagoon (contributing to barrier migration). Wind can also blow sand from the barrier dunes into the lagoon. (1)

Sediment transport within the Barrier Island:

Barrier islands have several transport processes on them since they have several depositional environments. The seaward side is eroded by waves, currents, and tides which can both transport sediment out to sea and onto the beach. Sediment is transported from the beach to the dune portion of the island by wind and typically push the dunes landward. The back-barrier is mostly influenced by tides. The back-barrier is also important to the migration of the barrier island. When large storms hit, sediment from the dune section is blown and carried by water down into the back-barrier and lagoon. This creates washover fans. This process shifts the sediment on the island, and over time washover deposits build up and the island moves towards the shore. (8, 9, 10)

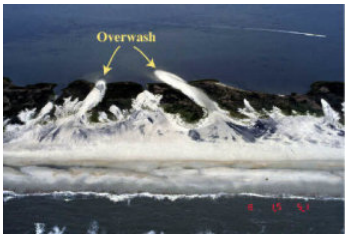


Figure 6: Washover in Action

A wave overtopping a barrier island, this leads to the migration of the island coastward as sediments are moved from the seaward to landward side of the island. This process creates washover fans in the back-barrier and brings coarse material into the lagoon.

Photo: (6)

Deposited Sediment

Lagoons are low to moderate energy environments with little transport. As a result, lagoons typically contain mud with some sand (Nichols). In tropical locations, the deposited sediments are often carbonates and laminated mud, (4 and 5). They can also have chemical deposits resulting from evaporation (7). When the sediments undergo diagenesis they become shale (4).

Barrier islands typically have sand in the beach zone and dune field, and mud in the back-barrier. Overwash deposits sand in the back-barrier. Conglomerates can also be found on barrier islands but are rarer (1).

Lateral Variation and Facies:

Starting from the coast laterally, one can expect to see coastline, lagoon, back-barrier, dune, beach, and marine facies. The coastline facies are described in other sections of this book, and can be beaches, estuaries, marshes, and tidal flats. Next is the lagoon facies, consisting of bioturbation, organic-rich laminated mud, some wave ripples, and some sand. After the lagoon facies, the barrier

island facies begins with the back-barrier. The back-barrier will include mudcracks, bioturbation, mud-sized sediments, sand from overwash deposits, and cross-stratification dipping towards the coast. The dune field will consist of sand sized particles with bioturbation, wind ripples, trough cross-bedding, and of course, dunes. The seaward beach of the barrier island will contain sand sized particles displaying wave ripples, herringbone cross-stratification, and cross-stratification dipping towards the sea. Finally, the marine facies, consisting of bioturbation fine sands, and mud. (1,3,4,12)

Marine fossils are found in the lagoons (1), and fragmented marine fossils may be present in the barrier island, (2).

Photos of Sedimentary structures:

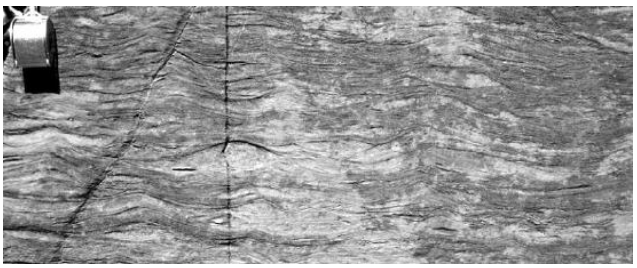


Figure #7: Wave Ripples (13)

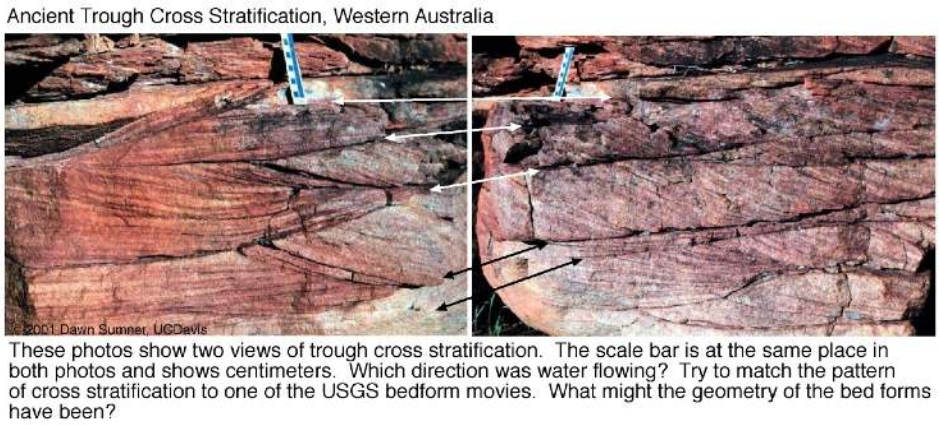


Figure #8: Trough Cross-Stratification (13)



Figure #9: Herringbone Cross-Stratification (15)

Modern Coarse-grained Wind Ripples, Brazil



Strong winds produced these coarse wind ripples on a Brazilian beach. Which characteristic (besides location) allowed me to identify them as wind ripples? Which way was the wind blowing?

Figure #10: Wind Ripples (14)

Modern Mudcracks in a Canyon Floor, Namibia



Figure 11: Mudcracks (16)



Figure 12: Eolian Dune Cross-Stratification (17)

Vertical Facies Sequence

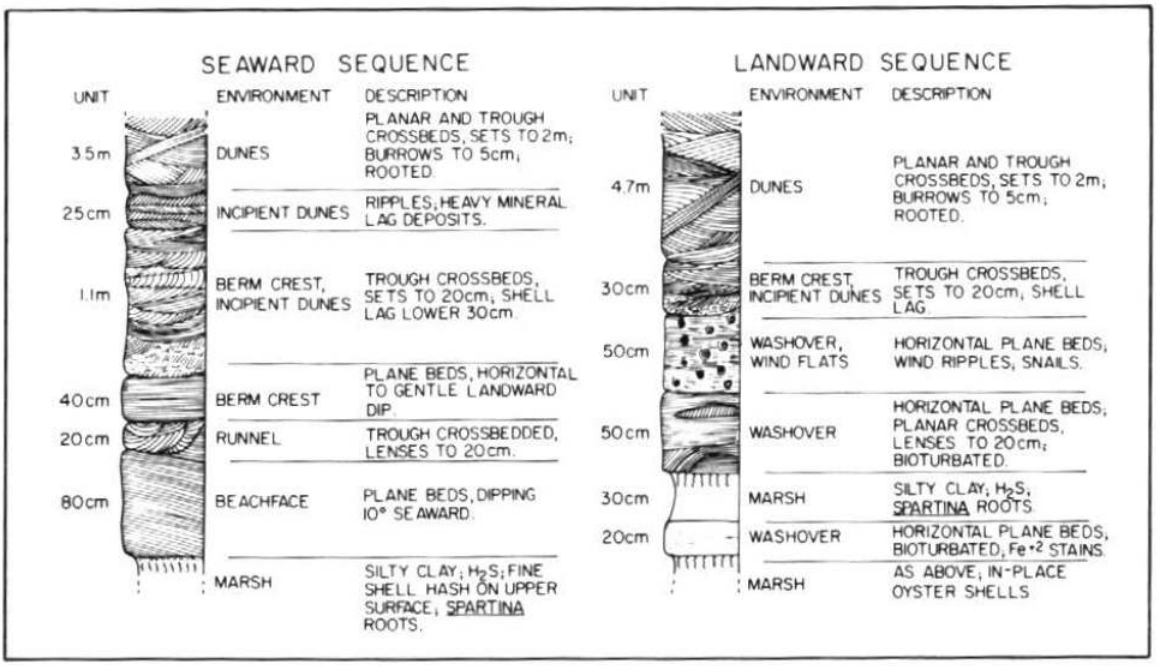


Figure #13: Barrier Island Stratigraphic Column

Stratigraphic Column of a Barrier Island Sequence from Reinson, G. E. (1979). In the figure, the top of the seaward sequence begins at the dune field and the bottom is the end of the barrier island near the ocean after the marsh one would expect a marine facies. The top of the landward sequence begins at the dune field and the bottom is at the end of the coastal side of the island, after the marsh, a lagoon facies, like the one in the next figure, would be expected. The marsh and washover portions of the right column are the back-barrier of the island. This particular column is from the Kiawah Island beach ridge.



Figure #14: Lagoon Stratigraphic Column

A lagoon stratigraphic column from Nichols, (1). In a barrier island sequence the top of this column would be followed by the barrier island facies, and below by coastline facies.

Walther's Law provides the fact that the lateral facies order will also be seen vertically in stratigraphic succession. Therefore, vertically one can expect in order the beach facies associated with the coastline, lagoon facies, barrier island facies, and then marine facies. The barrier island facies will have a vertical sequence within it: the back-barrier, dune field, and beach. The barrier island facies coarsens upwards as mud particles transition into the sands associated with the dunes and beach, (Nichols). The beach portion of the barrier island facies fines upward into the marine facies. Within the lagoon and back barrier facies, coarser grained sand with wave ripples may deposit in thin layers as overwash deposits as seen in both stratigraphic columns above. Keep in mind this is only a general vertical description, as seen in the above stratigraphic columns the vertical sequence can be more complicated. (1 and 2)

Lagoon and Lake facies are often very similar. However lagoons can be distinguished by the presence of marine fossils, and its close relation to the nearby facies of marine, barrier, and beach. (1)

Summary

A lagoon is a low energy environment with flow driven by the outlet of rivers or streams and tides. Barrier Islands have several sub-environments: back-barrier, dune field, and beach. Waves influence the beach, and tides shape the back-barrier. Wind transports sediment from the beach to the dunes, and sometimes into the back-barrier. High storm water carries sand from the beach and dunes into the back-barrier and lagoon, creating overwash deposits.

Facies and Sediment Characteristics, in Stratigraphic Order

Facies	Sedimentary Structures	Sediment Characteristics	Related Textbook Pages
Coastline (Beaches, Estuaries, Marshes, Tidal Flats)	See Related Pages	See Related Pages	Waves and Beaches Tides and Tidal Flats Siliclastic Shorelines and Estuaries Bogs and Marshes
Lagoon	Bioturbation, lamination, some wave ripples from overwash deposits	Mud, some sand from overwash deposits. Organic-rich	Siliclastic Shorelines and Estuaries
Back-Barrier (Barrier Island)	Mudcracks, bioturbation, cross-stratification dipping towards the coast	Mud, some sand from overwash deposits.	Tides and Tidal Flats Bogs and Marshes
Dune Field (Barrier Island)	Wind ripples, bioturbation, dunes, trough cross-bedding	Sand	Eolian Environments
Beach (Barrier Island)	Herringbone cross-stratification, wave ripples, cross-stratification dipping towards the sea	Sand	Waves and Beaches
Marine	See Related Pages	See Related Pages	Deep Marine Environments

Key Words

Barrier Islands, Islands, Lagoons, Depositional Environment, back-barrier, dipping cross-stratification, dunes, marsh, tidal flats, herringbone cross-stratification, atoll, coastal lagoon, atoll lagoon.

References

1. Nichols Sedimentology and Stratigraphy

2. https://www.tamiu.edu/cees/courses/fall2017/paleo%20labs/Lab04_Environments.pdf

3. https://en.wikipedia.org/wiki/Barrier_island

4. Bookshelves/Geology/Book:_An_Introduction_to_Geology_(Johnson,_Affolter,_Inkenbrandt,_and_Mosher)/05:_Weathering,_Erosion,_and_Sedimentary_Rocks/5.05:_Depositional_Environments

5. https://geo.libretexts.org/Bookshelves/Geology/Book:_Physical_Geology_(Earle)/06:_Sediments_and_Sedimentary_Rocks/6.03:_Depositional_Environments_and_Sedimentary_Basins

6. https://coastal.er.usgs.gov/hurricanes/impact-scale/overwash.php

7. https://geo.libretexts.org/Bookshelves/Ancillary_Materials/Laboratory/Book:_Laboratory_Manual_For_Introductory_Geology_(Deline,_Harris_and_Tefend)/10:_Sedimentary_Rocks/10.6:_Depositional_Environments

8. https://geo.libretexts.org/Bookshelves/Oceanography/Book%3A_Introduction_to_Oceanography_(Webb)/13%3A_Coastal_Oceanography/13.04%3A_Landforms_of_Coastal_Deposition

9. https://www.encyclopedia.com/earth-and-environment/geology-and-oceanography/geology-and-oceanography/barrier-islands

10. http://w3.salemstate.edu/~lhanson/gls214/gls214_barrier_isl.htm

11. https://oceanservice.noaa.gov/facts/lagoon.html

12. Reinson, G. E. (1979). Facies Models 14. Barrier Island Systems. *Geoscience Canada*, *6*(2). Retrieved from https://journals.lib.unb.ca/index.ph...icle/view/3154

13. https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/09%3A_Draft_Textbook/9.06%3A_Bedforms

14. https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/06%3A_Photos_of_Sediments_and_Strata/6.02%3A_Sedimentary_Structures/6.2.12%3A_Wind_Transported_Bedforms_and_Cross_Stratification

15. https://commons.wikimedia.org/wiki/File:Pink_Grotto_-_herringbone_cross-stratified_calcarenite_limestone_(San_Salvador_Island,_Bahamas)_4_(16204596080).jpg

16. https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/06%3A_Photos_of_Sediments_and_Strata/6.02%3A_Sedimentary_Structures/6.2.04%3A_Mud_Cracks

17. https://en.wikipedia.org/wiki/Cross-bedding

18. https://en.wikipedia.org/wiki/Padre_Island

19. https://en.wikipedia.org/wiki/Wake_Island

20. https://en.wikipedia.org/wiki/Venetian_Lagoon

21. Siliclastic Shorelines and Estuaries

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Biostratigraphy – Biozones and Zone Fossils

Colin Boisvert

Introduction

While specific minerals such as zircon or elements such as uranium, argon or strontium can provide a more precise geochronology value for a unit what if these elements/minerals are not detected in the rock? These minerals/elements are rare and often hard to find. Stratigraphy offers an alternative solution to radioactive minerals. Stratigraphy is the branch of geology concerned with the relative dating and sequence of rock units on the geologic timescale. This method is a relative dating method for rock units because while the Law of Superposition we can tell us undeformed layers further down are older than layers closer to the top, we don't how the exact age difference. Interpreting stratigraphy can be difficult due to geologic processes such as folding,faulting and unconformities which deform the stratigraphy in a region.Scientists use a variety of different branches of stratigraphy with different methods to date strata units.So what about fossils discovered in the stratigraphic layers? Finding fossils in Phanerozoic strata is relatively easy to do and scientists can use the relative age of fossils in the rock layers to build the geological time scale. **Biostratigraphy** is the branch of stratigraphy that uses widespread, quick evolving and well-studied fossils found in the rocks to date strata. It is a very helpful tool for scientists to build and modify the geological timescale!

So what is Biostratigraphy?

Biostratigraphy is the specific branch of stratigraphy that uses **index fossils** found in the strata to serve as biological markers and give a more precise estimate of the rock unit's age. **Index fossils** are fossils found in stratigraphic units that meet a set of criteria that allows us to date the stratigraphic unit rock to a range because of the animal's evolutionary and geologic record. Since an index fossil is unique and found only during a certain span of time, finding a specific index fossil in the strata provides a small span of time that we can date this unit to. When we find the same index fossil in stratigraphic units located far apart, we can use chronostratigraphy to correlate these units to the same age because they both contain the same index fossil. Chronostratigraphy studies the age of rock units relative to time so discovering the same index fossil pinpoints the age of two different rock units because of the same index fossil found in both.

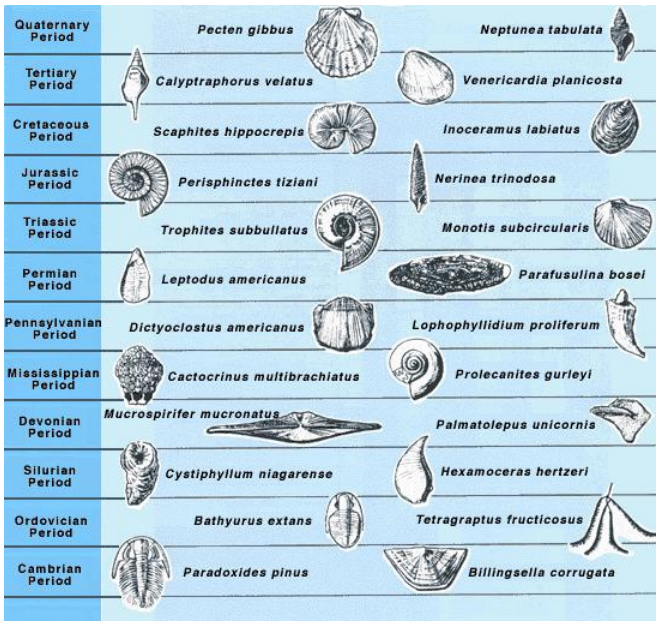


Figure 1: This figure gives the geologic timescale coupled with correlated species-specific index fossils for the different period of Earth's History (The USGS,2013).

Biostratigraphy is an extremely powerful tool for chronostratigraphic correlation. Life evolves through time, with new species emerging and other species going extinct. For time intervals and species that are well studied, the process of evolution provides a detailed temporal framework for correlating stratigraphic columns. The basic idea is for the geologist to identify a fossil's biozone. This is done by identifying the fossil species in the stratigraphic columns, compare them to the known age ranges of those species ,

and then constraining the age of the rocks from documented extinction and origination events of the identified species. This is an extremely powerful approach to correlating stratigraphic columns because each species is unique and changes through time. Magnetostratigraphy,another branch of stratigraphy that uses polarity switches recorded in the rock record to date strata units is often connected with biostratigraphy as seen in figure 3.

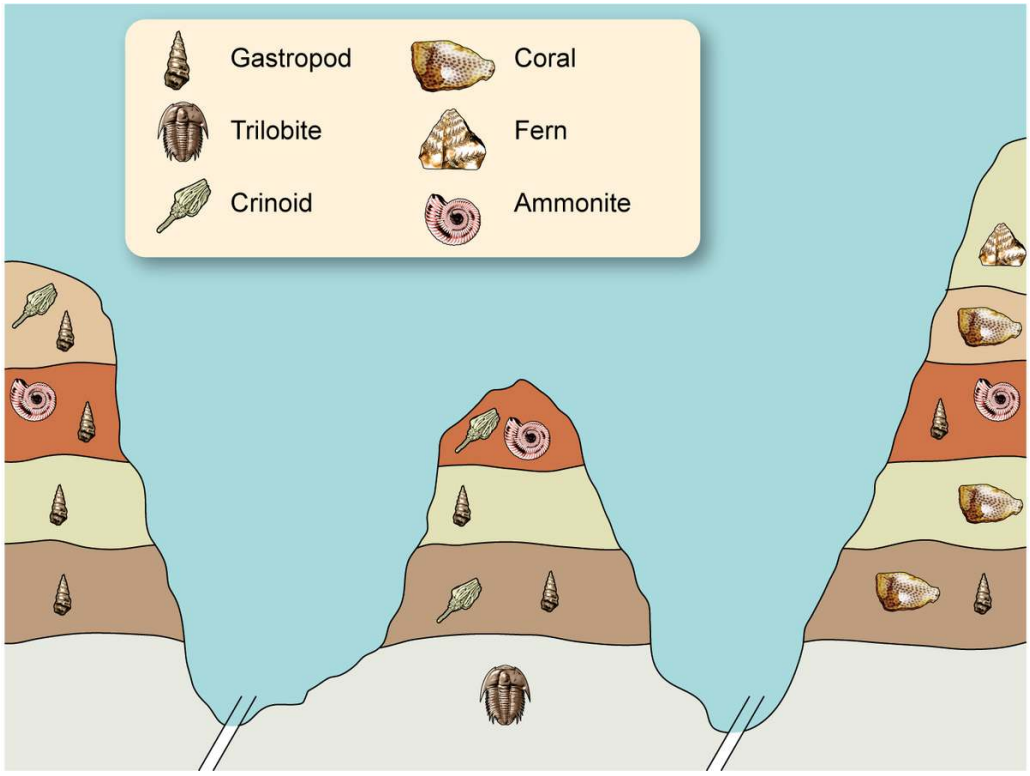


Figure 2: This figure illustrates how index fossils can help with chronostratigraphic correlation(Rosenkrantz, 2013). If we assume that the distance between the columns is hundred of miles, we can use the ammonite fossil to correlate the layer on the left with the one in the middle and the right. Then using the age range for that specific species we will have an idea how old the strata is with a range. This will tell us all strata below the ammonite are older than that age and the ones above are younger. If the gastropod species per rock layers are different we can do the same with them.

Biozones are zones of well-documented fossil species with distinct origination and extinction times. Specific biozones can be defined a number of ways:

- The total time of a fossil's existence.
- It could consist of the total time where two or more fossils coexist.
- It could be defined as the time between the origination of one fossil and the extinction of a different fossil, etc.

An example of a biozone chart, combined with magnetostratigraphic reversals can be found at: http://www-odp.tamu.edu/publications/189_IR/chap_02/c2_f6.htm

c2_f6.htm

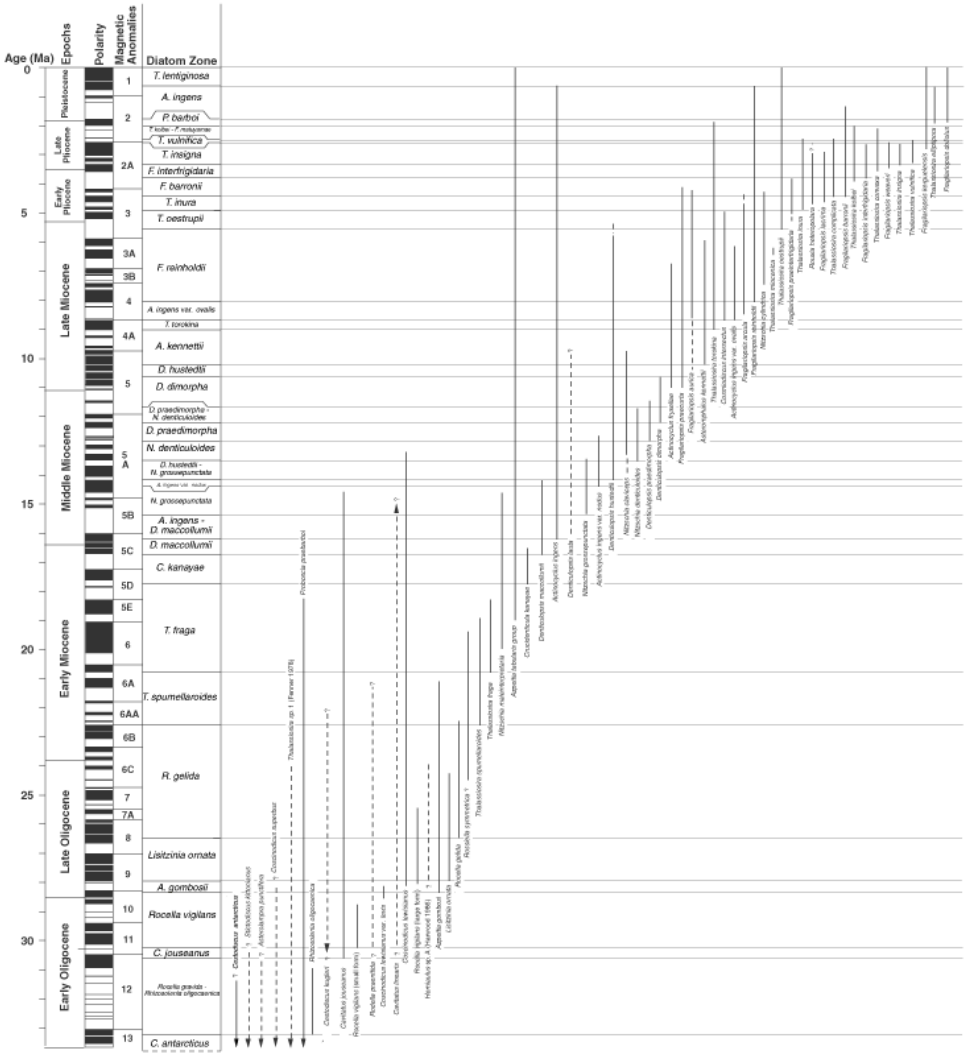


Figure shows some of the members of the Diatom family, a good index fossil and how they were used at one site in conjunction with magnetostratigraphy to date the rock units in the Paleogene-Neogene. (Gersonde et al., 1998, and Shipboard Scientific Party, 1999b).

Criteria for a good index fossil vs a bad one?

There are 4 main criteria that all have to be met for an organism to be considered a good index fossil.

1. **Have short geological ranges, e.g. they did not live for millions of years, and evolved quickly**; Quick evolution means scientists can track the morphological changes in a species. When a species evolves into a new species , scientists can use this information to build the timescale for that specific species as an index fossil. If we can track the evolution from species to species then we can easily pinpoint the beginning and end of one species and the transition to a new one . This combination allows us to identify an index fossil in the strata and have a more precise idea of what window of time we are looking at for the age of the rock unit.
2. **Distribution over a large region of the earth**; Since most of the Earth is covered in water it is easier for a marine fossil to be considered an index fossil vs land fossils which can be restricted to one continent usually.Oceans have risen and fallen with as much as 85% percent of the planet covered by the sea making it easier to find marine fossils. Since marine animals could more easily spread over a large portion of the globe, this helps with the potential for burial in marine strata millions of years later.On land an animal is more restricted in how far a species can spread so this makes it easier for marine animals to be classified as index fossils.

3. **Easily preserved and abundant;** Hard parts, such as bones, shells, or exoskeletons, are more easily preserved in sediment because they are not subject to erosion and decay in the way that soft tissues are. Because hard parts can still be eroded through weathering, some of those hard parts will have a better chance of preservation if a high number of them are buried.
4. **Sufficiently studied;** Fossils that aren't well-studied do not make good index fossils because we do not know enough about their evolutionary histories or over what time span they existed. With well-studied fossils, we do have this information and understand that the presence of a certain fossil signals a particular time range. For example, ammonites and trilobites are well-studied with specific age ranges so it is easy to use them as index fossils.

Reasons Why your favorite dinosaur Tyrannosaurus rex is not a good index fossil

Your Favorite Dinosaurian predator is not a good index fossil because while it is well-studied and its bones are easily preserved, it only lived in Western North America (Limited range over the Earth) and it lived for around 2-3 million years and it did not evolve quickly. Most dinosaurs in fact are not good index fossils because of their restricted geographical range , slow evolution and limited knowledge.

In fact, many tetrapod macrofossils that people know are not good index fossils because they do not fit one of the four criteria. If an organism is only found in one region, such as dire wolves in North America, or contains mostly soft parts like cartilage in most sharks fossils, then this makes them a poor candidate for an index fossil. Furthermore, if the organism has a long geological range or are rare fossils and not well studied this makes the species a poor candidate for being an index fossil as well. Fossils that contain a lot of soft parts, single species that lived for long periods of time,were endemic to a specific region or are rare in the field today are criteria for being a poor index fossil that should not be used. This would make using living fossils like the Coelacanth difficult to use as well as many living fossils have few fossils but ancient lineages making it seem like one species lived for a long time which is a criteria for being a poor index fossil. All together, if you see a shark tooth,Tyrannosaurus femur, and an ammonite shell in the strata unit you are studying, pick the ammonite for biostratigraphic purposes.

Index fossils of the Phanerozoic

Common examples of index fossils include:

Phanerozoic: Foraminfera (542-0 million years ago) Forams are an extant group of organisms withnumerous species that are well studied, have short temorpal ranges and are widespread. Since we find forams all over the place their evolution is well studied and their record of 18O means we can use them for stable isotpe studies with paleoclimates and as an index fossil.

Paleozoic:Trilobites (542-252 million years ago) Trilobites are a numerous group of marine arthropods with correlated species temporal ranges allowing for specific chronostratigraphic correlation based on specific index fossils of trilobites. Specific examples include *Paradoxides* as stated in Figure 1 which was a genus of Trilobite that contained 19 species that lived during the Mid-Late Cambrian Period. Species of this genus have been found up and down both sides of the Atlantic Coastline from Canada to Africa. All together these 19 species provide a temporal range from 514-497ma .Another genus example includes *Phacops*.

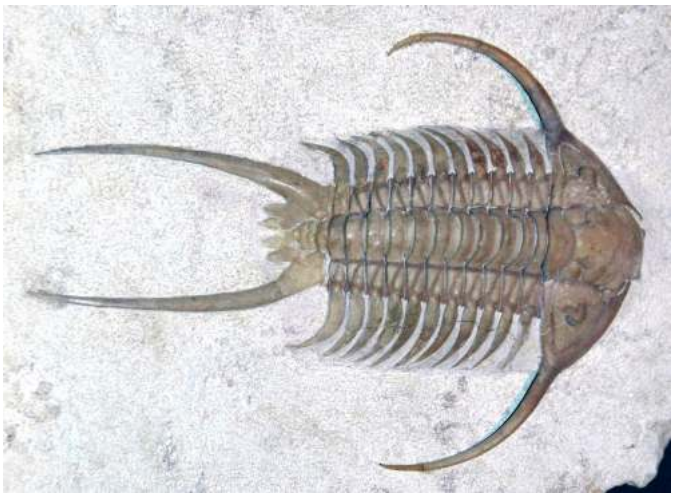


Figure 4: This figure illustrates a Trilobite fossil which were common in the Paleozoic and used as index fossils for this era as they are found all over the world for short periods of time with rapid evolution. Trilobites are arthropods related to insects arachnids and crustaceans (James St John,2010).

Mesozoic:Ammonites (252-66 million years ago) Once again this group of cephalopods was a prosperous marine group that thrived during the Mesozoic and this prosperity means we can follow the evolution of different species to help constrain certain species to different stages of the Mesozoic. This combined with their geographic range makes them a great index fossil. An example genera is *Perisphinctes* with 4 species covering the Middle-Late Jurassic epoch.



Figure 5: This picture illustrates an ammonite fossil which is a common index fossil for the Mesozoic as they are found all over the world for short periods of time with rapid evolution. In medieval times people believed ammonite fossils were serpents God had coiled up and turned to stone but now we know they are cephalopods related to the Nautilus and octopus.(Becks,2013).

Cenozoic: Diatoms (66-0 million years ago) This marine group also has a numerous amount of species that lived over short temporal ranges.

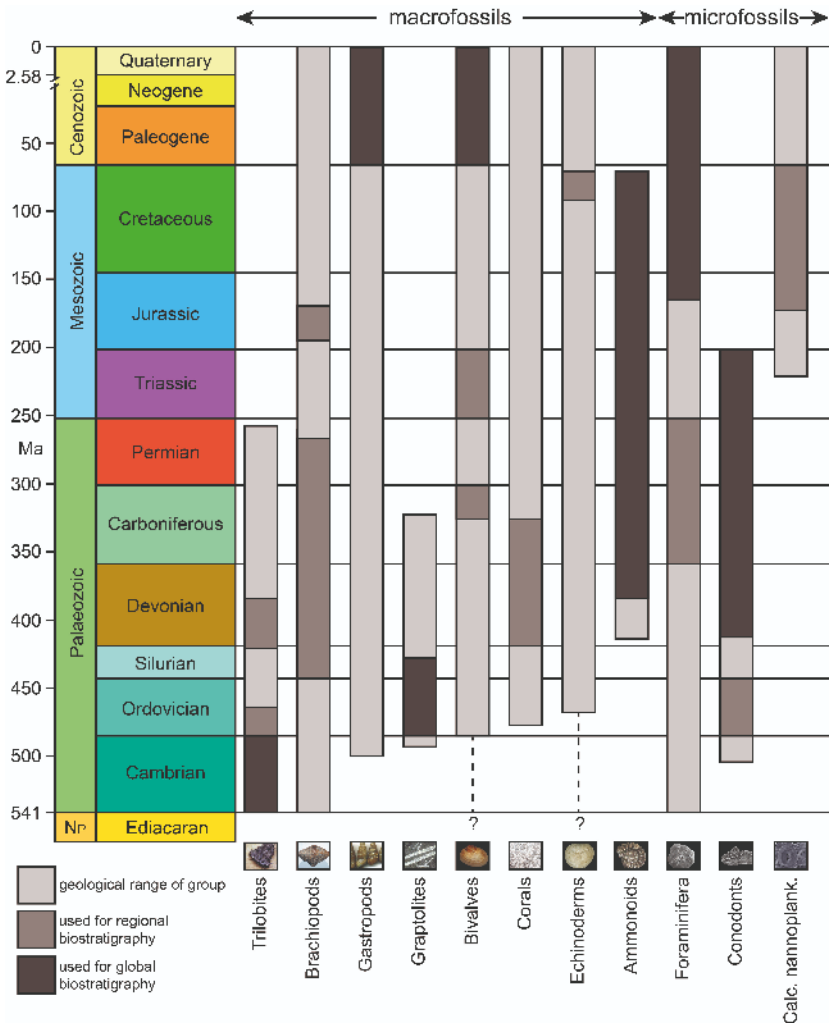


Figure 6: This figure illustrates a chart showing common index fossils as well as when and where they are appropriate to use across the Phanerozic and the world (Bond 2016).

Case study: Using index fossils to date rocks in India

In India, specifically the Triassic Spiti Basin, Jurassic Kachchh Basin, and Cretaceous Kachchh and Cauvery Basins, scientists used mainly Ammonoid Biostratigraphy coupled with biozones to help correlate and date the regions for a more precise chronostratigrpahic correlation of these basins in India during the Mesozoic (Krishna,2017). Scientists were unclear on how the basins formed and wished to accurately date the regions and start of the geologic events.

Ammonites are aquatic molluscs meaning wherever we find their fossils we can correlate this strata to an aquatic paleoenviornment. As for all the layers deposited in the sea, scientists examined these layers of rock to search for species of ammonites. When one was found it was identified by species and using the range of time for the known species, the scientists refined the strata into the relevant temporal stages of the respective periods(ex.the Barremanian stage of the Cretaceous). This built zones where certain species were connected to specific strata based on the age correlation. For the Triassic Spiti Basin , they were only able to build 35 ammonoid zones and mark the Early and Middle Triassic (Krishna 2017). For the Middle to late Jurassic in the Kachchh they created 35 ammonoid biozones and used ammonites found in other Jurassic basins to fill gaps in the earlier parts of the Jurassic (Krishna 2017). For the Cretaceous using mainly the Kachchh and Cauvery basins but exploring others such as the Cretaceous Spiti scientists were able to correlate roughly 18 informal zones to 9 or 10 of the stages of the Cretaceous (Krishna 2017). Correlating these strata, allowed scientists to build a picture of how these basins changed in regards to sea elevation and shifting geology of the moving subcontinent on its eventual path to Asia.

To summarize scientists identified different ammonite species in the strata to create a chronostratigraphic record of the Mesozoic. By identifying the ammonites present at the in the strata of specific basins, scientists could then use the known age

ranges of those fossils to more precisely date the rock units.They then correlated basins together based on lithostratigraphy to form a larger picture of the Mesozoic basins of India. Using successive species of ammonoids that evolved and died one after another the scientists were able to create ammonoid biozones that correlated stratigraphic units with a specific period of time plus or minus an error interval

Work Cited

Becks.2013.Ammonite fossil from Kilve beach in Somerset, England.https://commons.wikimedia.org/wiki/File:Ammonite_fossil_(8606998286).jpg

Dawn Sumner (Department of Earth and Planetary Sciences, UC Davis). Sedimentology and Stratigraphy Libretexts. https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/08%3A_Old_or_Lost_Pages/8.04%3A_Chronostratigraphy

David Bond.2016. Shows the most commonly used index fossils in biostratigraphy from the Cambrian onwards. I tentatively extended the range of bivalves and echinoderms into the Ediacaran (Neoproterozoic) based on some putative finds, although these groups are not used in biostratigraphy from that Period. https://commons.wikimedia.org/wiki/File:Biostratigraphic_index_fossils_02.jpg

Gersonde et al., and Shipboard Scientific Party.1998,1999. http://www-odp.tamu.edu/publications/189_IR/chap_02/c2_f6.htm

James St. John.2010.Paraceraurus exsul (Beyrich, 1846) fossil trilobite from the Ordovician of Russia (public display, FMNH PE 60828, Field Museum of Natural History, Chicago, Illinois, USA).Classification: Animalia, Arthropoda, Trilobita, Polymerida, CheiruridaeStratigraphy: apparently derived from the Asery Formation, Middle Ordovician,Locality: St. Petersburg area, Russia.https://commons.wikimedia.org/wiki/File:Paraceraurus_exsul_fossil_trilobite_(Asery_Formation,_Middle_Ordovician;_St._Petersburg_area,_Russia)_1_(15161039897).jpg

Krishna, J. 2017. Mesozoic Stratigraphic Framework in India with Focus on the Jurassic Geological Record in the Kachchh Basin. In *The Indian Mesozoic Chronicle* (pp. 27-143). Springer, Singapore.https://doi.org/10.1007/978-981-10-2477-1_2

Kurt Rosenkrantz.2010. Various fossils in layers.https://en.Wikipedia.org/wiki/File:Fossils.png

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Bogs and Marshes

Overall, I think this is a good start, but it is still an outline so you have quite a few questions to answer. I think pictures of each of the processes and structures would be helpful (Taryn Lausch 5/29/20).

Introduction

[insert photo here]

Intro to bogs and marshes

- what are they? why are they important? Functions of bog/marshes? What are the answers to these questions?

- General location of bogs/marshes with relation to other environments

[insert satellite view/sketch here]

- Add in some example locations (I would choose famous bogs and marshes, or ones in California close to Davis)

Sediment Transport Processes

Flow characteristics within bogs and marshes What are the flow characteristics? Generally, they have very low flow and mostly accumulate organic matter, so you want to be sure to include the growth of plants even though that isn't specifically "sediment transport" - I now see that you have this in the characteristics of deposited sediment, which is good.

What kind of sediment carried through this environment?

- sed structures and examples There is a huge amount of bioturbation from roots, etc. However, the details vary depending on how much oxygen gets into the sediment.

Pictures of each of these structures would be great

Characteristics of Deposited Sediments

What grain sizes are typical of this environment?

Relatively low flow velocity here

- what does this mean about deposited seds

- organic material

- carbon sink

Sed structures

[insert examples of sed structures in this environment]

Vertical facies for environment

- changes through time?

[insert sketch/ strat column here]

Case Studies and Significance

Discuss some relevant studies

-maybe try to link in current environmental issues? e.g. loss of habitats, marsh rot

Studies that are closer to home/in California might be useful, as they give students an opportunity to go and visit them

Additional Reading

Some links for additional reading if reader is interested in topic

Links to marsh restoration projects in the Delta would be interesting

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Braided Rivers

Introduction

What is a braided river?

Braided rivers are a type of river that form a network of many branches within a channel. They often form when the bedload sediment is *high* compared to the suspended load, which then helps the development of bars, creating the braided character.

Fast flow and steep gradients characterize braided rivers. Much of the geometry of these rivers is shaped by the highest flows, when bars are covered in water. Many braided rivers have exposed bar tops for much of the year. These rivers are often found around mountainous regions with glaciers, or in areas with sparse vegetation.

We can distinguish braided rivers from other rivers, such as meandering rivers, by its steeper gradient, whereas meandering rivers have more gently dipping slopes. You can find more information on meandering rivers here. (insert link)



Figure 1. Photo of the Waimakariri River in South Island of New Zealand. In this photo you can see the many different branches of the braided river. By I, Gobeirne, CC BY 2.5, https://commons.wikimedia.org/w/inde...?curid=2437562

Sediment Transport Processes

Both the flow speeds and transport capacity vary dramatically within a braided river, which means the Reynolds number (Re) varies widely throughout the channel. (The Reynolds number is a measure of whether or not transport of a specific sediment grain size can occur due to the velocity of the water.) If the Reynolds number is low, then only smaller grain sizes are able to be transported. If the number is high, all grain sizes can be moved and transported downstream.

In braided rivers, the sediment is commonly coarse, especially in the middle of the stream. This requires fast flow and steep gradients for the sediment to be transported.

Friction with the riverbed tends to slow down the flow, especially where the flow is shallow. The Reynolds number in shallow areas is relatively low (but still high enough that the flow is turbulent) and the transport capacity is low. In the deeper middles of channels in the river, the Reynolds number is much higher. So, the coarsest sediment is transported in these ares, whereas the finer sediment gets deposited in shallow areas.

The formation of bars can occur in the middle of these rivers, due to the high amount of bedload sediment. Bars block the flow on the upstream side, and the upstream tends to erode. Areas of low flow and eddies form on the downstream sides of these bars, and tend to be sites of net deposition. Due to this process of erosion on one side, and deposition on the other, bars will migrate downstream through time. Secondary bedforms - such as planar beds, dunes, and ripples - will also form as a result of sediment transport on the bars and in the channels.

Characteristics of Deposited Sediment/Sedimentary Structures

Several sedimentary structures that are commonly found in braided rivers are trough cross-bedding, upper planar, and ripple laminations.

1. Trough cross-bedding in channels. This occurs due to the migration of irregular dunes.

2. The coarsest sediment can be lower flat laminated if flow speeds are not fast enough to form coarse grained dunes.

3. The sediment on the edges of bars fines upwards. This because the flow is shallower and slower (lower Re) as the bars increase. Sedimentary structures can include anything from upper planar to ripple laminations.

insert x-section of braided river

Vertical Sequence of Facies

As channels migrate back and forth, they leave a layer/sheet of sand containing abundant cross stratification. These sheets tend to fine upward because the channels migrating due to bar migration. Bar migration occurs due to more erosion upstream and more deposition on the opposite side, downstream. Sediment is finer grained higher up on the bars.

Braided river deposits generally include the following. A scoured surface and/or gravel lag at the base of a channel. This occurs due to amounts of material cleared out due to erosion of stream/channel bed, where the majority of sediment left is larger grains, such as gravel. Then, trough cross-bedded sands deposited just off the center of channels, and occasional tabular cross-stratification due to migrating bars. Next, sand deposited at slower speeds, causing ripple cross lamination. And overbank deposits from floods, mostly composed of sand, silt, and some mud. In the figure below, there is this pattern especially seen from the 5-10m height in the stratigraphic column.

The large scale geometry of the deposits include sheets of sand with various grain sizes, representing bar migration, with sand sheets separated by floodplain deposits.

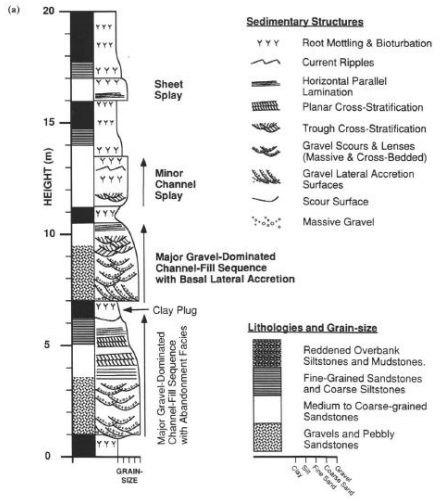


Figure 2. Example of stratigraphic column of braided river. Taken from Bentham et al., 1993 "Braided stream and flood-plain deposition in a rapidly aggrading basin: the Escanilla formation, Spanish Pyrenees". https://sp.lyellcollection.org/content/75/1/177

Braided rivers can be distinguished from meandering rivers. Braided rivers have coarser grain sizes, due to higher velocity flow in the channel. Meandering rivers will move/migrate towards the eroding bank, and therefore will have a more uniform shape, rather than braided rivers, which can migrate in many directions. Meandering rivers also contain abundant suspended sediment, leading to the formation of oxbow lakes, which are not found near braided rivers.

Summary

Braided rivers are characterized by their fast flow and steep gradients, forming when the bedload sediment is high compared to the suspended load. They form a network of many branches within a channel. These branches are separated by the formation of bars. These bars will migrate through time, causing the migration of the river channel.

The sediment in braided rivers is commonly coarse in the middle, and finer sediment is deposited in the shallow areas. Bars, which block the flow, will erode on the upstream side, and create areas of low flow on the downstream side, allowing for deposition to occur.

A braided river can be distinguished by a general fining upward sequence. The sheets of sand with various grain sizes represent bar migration. The river deposit will often have a scoured surface at the base of the channel. Then trough cross-bedding, tabular cross-stratification, and ripple cross-lamination. This is due to sand being deposited at slower speeds. As flooding occurs, there will be overbank deposits composed of finer sediments (sand,silt,mud).

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Carbonates-Reefs



https://en.Wikipedia.org/wiki/File:Coral_Outcrop_Flynn_Reef.jpg

Figure 0: The image above shows a healthy, colorful coral reef. The color is due to the symbiotic relationship with zooxanthellae algae, which produce color pigments. Corals need warm, clear water (without sediments).

Introduction:

Reefs consists of corals and other organisms made of calcium carbonate and are home to many colorful fishes. Coral reefs have a wide variety of calcareous corals that ultimately get broken up into fragments through physical weathering, which are then deposited helping to create the magnificent reefs you see. The most common type of coral today is the Scleractinia. Coral reefs are the rainforest of the sea with great diversity, but are highly threatened due to climate change and human impact. Corals have slow growth rates and can take thousands of years to grow and regrow if disturbed. Waves, or the water movement along fish such as Parrot Fish help break down carbonate shells and corals forming sand on bottom. Parrot fish help the coral reefs stay clean and eat up dead coral. Corals and calcium carbonate forms when carbonate (CaCo3) is absorbed from ions in the ocean when the water temperature are right, and there is movement which removes carbon dioxide. Biological conditions are the most dominant factor in making carbonates for reefs. Reefs form when free swimming coral larvae attach to rocks, and other submerged hard surfaces developing into polyps and maturely formed coral. Corals reproduce in a few ways either through internal or external fertilization through spawning in the water. Organisms produce carbonate skeletons from the ions in the water. There are calcareous snails and echinoderms. Calcareous organisms such as mollusks and brachiopods contribute to carbonate build up. Furthermore, when they get broken down they form the crushed coral sand which is habitat to other organisms. Aragonite is similar to carbonate and is also be found in reefs. Carbonate reefs usually form in shallow, warm, clear marine environments. Corals and biogenic carbonate production generally occurs in the photic one which is up to 100 meters in water depth. (Nichols, 2009). The top 10 meters is where most of the calcareous organisms are located due to the availability of sunlight and is known as the carbonate factory.

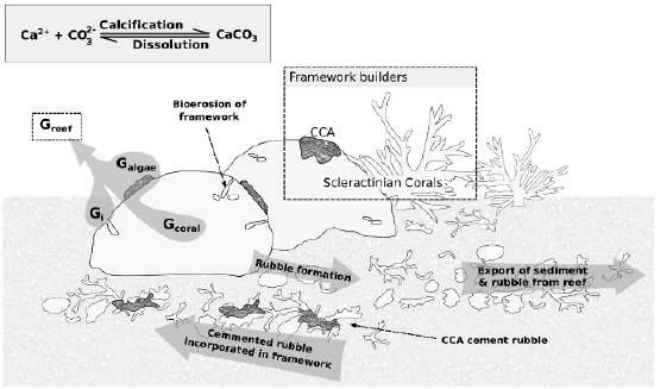


Figure 1: This image shows the process of forming Calcium Carbonate and some of the main reef building organisms.

https://www.researchgate.net/figure/Schematic-illustrating-the-coral-reef-carbonate-budget-and-the-modelled-parameters-G_fig1_273083843

Carbonate rocks do not require transportation of sediments and form from seawater ions. The specific chemical, biological, and temperature conditions that are present determine the amount of carbonate production. Carbonates are made by living organisms in which calcium carbonate makes up the organism's shell and skeleton. Calcite and aragonite are polymorphs that are the two main types of calcium carbonate made by organisms. The reaction is Ca^{2+}+ $Co3^{2-}$ to CaCo3 which can either go in the forward or backwards direction. Calcifying algae with its high abundance produce carbonate mud/sand grains which accumulate over time. When the algae die they get broken down and transported through the ocean currents. The Hjulstrom diagram is followed as other organisms and calcium carbonate sediments get transported. Coarser grains require higher flow speeds while smaller grains require lower flow speeds. Corals are another main calcium carbonate organism that form reefs. Corals are usually in well lit, clear water so that the zooxanthellae algae can undergo photosynthesis. The algae provides nutrients and the color to corals. Corals have robust skeletons and can withstand the moving waves. Wave motion increases the amount of calcium carbonate formation. Over times reefs grow upward creating steep, unstable slopes which can lead to turbidites.

Where are Coral reefs located?

Coral reefs are located next to the Tropics where there is warm, shallow, clear water. Reefs are found near the equator between 25 degrees North and South of the Equator. Reefs do not have much clastic material coming in, and if there was too many sediments floating in the water sunlight for the reef would be blocked. There are a few main coral reefs such as the Great Barrier Reef in Australia, in the Bahamas, Florida, and Hawaii.

Facies and Structure of Reefs:

Reefs are divided by many sub-environments including the fore reef and the back reef (Nichols, 2009). The fore reef is the seaward side of a reef and is the deepest. In the fore reef there is rudstone and grain stone facies. The Dunham carbonate classification will be discussed later on. The back reef is the sheltered area towards the lagoon and is the site of deposition. There is also the reef crest where robust corals are located in order to withstand waves. Going down the reef front towards the deeper ocean there are more delicate and branching corals since it is lower energy deep water. Behind the reef crest is the reef flat where robust forms are also present but as you go down towards the lagoon more globular forms are present (Nichols, 2009). In the reef front there is a mixture of bafflestone, bindstone and framestone corals.

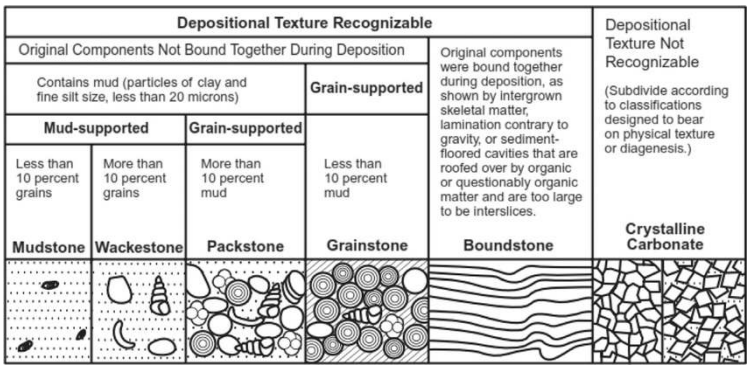
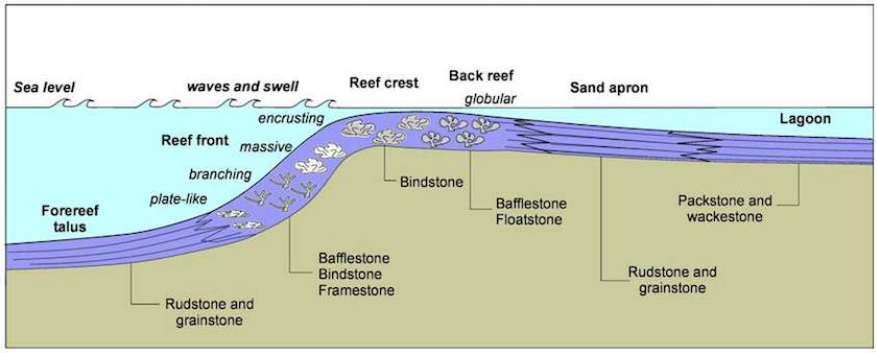


Figure 1.5 and 1.75: The Dunhams Classification Chart and the facies of coral reefs.

https://www.researchgate.net/figure/Dunhams-classification-of-carbonate-rocks_fig2_297736311



https://sites.google.com/site/wvugeol616advancedsed/home/carbonates-wpf?tmpl=%2Fsystem%2Fapp%2Ftemplates%2Fprint%2F&showPrintDialog=1

The main types of Reefs:

There are three main type of reefs including **fringing reefs, barrier reefs, and atolls**. (Nichols, 2009) These reefs are created by the movement of waves, submersion, and deposition over time. Barrier reefs include the Great Barrier Reef of Australia, Heron Island and Lady Elliot Island. Over time the reef type can change and a main distinguishing factor is the type of lagoon that forms around the reef. Other more specific and special reefs include apron, patch, ribbon and bank reefs.

Fringing Reefs: Fringing reefs are built right next to the shoreline and do not have a specific back reef lagoon area which distinguishes them from atolls and barrier reefs. Fringing reefs can form around volcanic islands. They can sometimes be hard to distinguish from a Barrier reef if it appears to have lagoon. The two main constituents of fringing and other types of reefs are the back reef and fore reef. The back reef is the shoreward and flat part of the reef. The reef slope is seaward of the beach and is steep and descending. The reef slope is where most of the corals grow due to less sediments and pollution accumulating. Specifically, corals grow the most profusely on the reef crest. Fringing reefs propagate from the shoreline, so the reef flat will go right to the beach and there will be no back reef in some fringing reefs. The Ningaloo Reef in Australia is one of many great examples of a Fringing Reef.

Barrier Reefs: Barrier reefs form parallel to the shoreline many kilometers away from the shore. Barrier reefs are separated by the land with the ocean. These reefs have a shallow, low energy back reef lagoon which is a site of deposition. The Great Barrier Reef in Australia is the largest Barrier reef which can even be seem from outer space made up of nearly 3,000 individual reefs. Coral polyps makes up a majority of this reef. This reef has human restrictions to protect it and is threatened by runoff from agriculture and sewage runoff.

Atolls: Atolls are ring shaped coral reefs that surround a lagoon. Atolls form from submerged volcanic islands/seamounts.(Atoll, 2012) As the underwater volcano erupts the lava is piled up on the seafloor. The elevation increases as the volcano continues to erupt and it surfaces to the water forming an oceanic island. Over time corals (Hermatypic corals) build a reef around the island. A

fringing reef is now created. The volcanic seamounts erode due to waves from the ocean, gets eroded and sinks. On the top there is a smooth flat seamount called a guyot due to the waves smoothing the top off. Atolls have a lagoon in the center due to erosion and over flooding of the eroded volcano. Over time a barrier reef forms which is further out to sea with a protected lagoon. A subsidence event occurs due to crashing waves which causes the ocean chemistry to change. Seaward the reef is healthy while towards the lagoon side the reef decays. The waves then break the weak material and sand and other crushed material build up forming Atolls. Atolls are fragile and can be eroded easily.

The image below shows the formation of an atoll. The first stage is a volcanic island, followed by a fringing reef, then a barrier reef and finally an atoll.

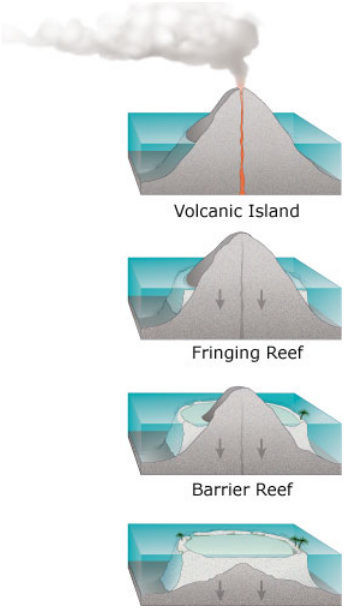


Figure 2: Shows Darwin's Subsidence Theory in forming an Atoll.

https://commons.wikimedia.org/wiki/File:Atoll_forming.jpg

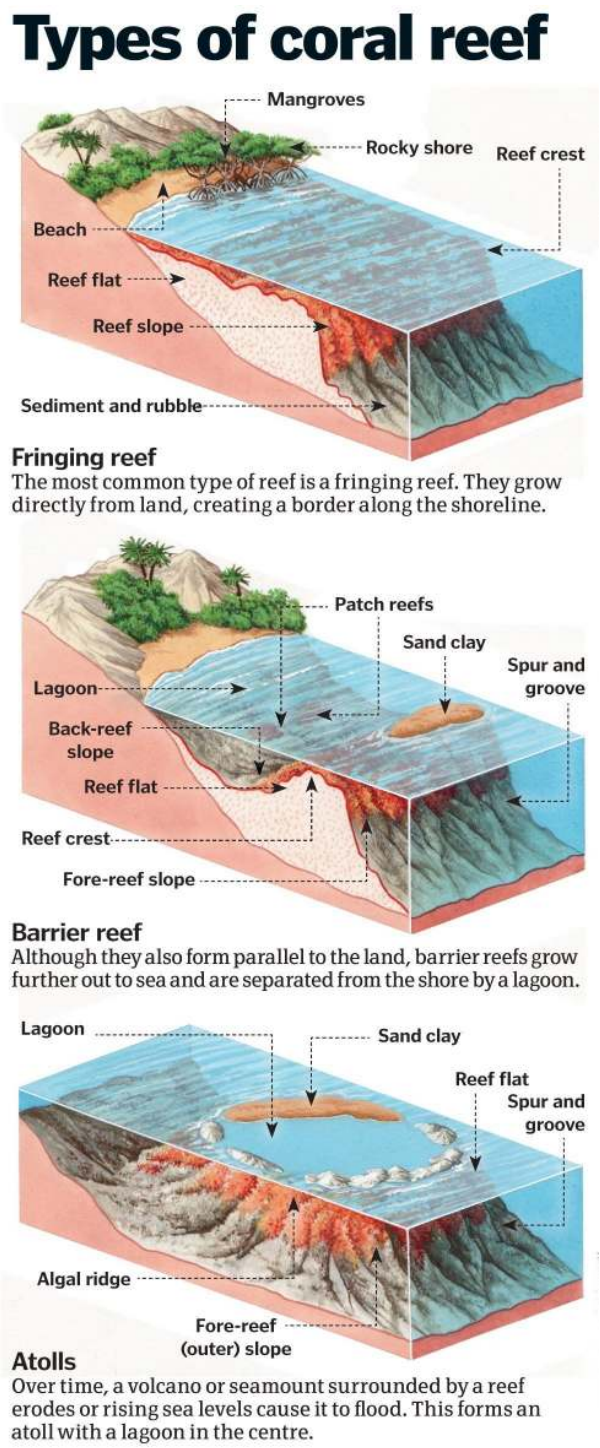
Darwin's Subsidence Theory: Darwin's Subsidence theory says how the different types of reefs are just the certain stages in reef development. Reefs can be converted into different types of reefs through time. Darwin proposed this theory when he was on his voyage of the Beagle. He proposed Fringing reefs get converted to Barrier reefs as a volcano subsides and vertical growth occurs. As the volcano subsides more and the corals grow up forming an atoll. There is still debate about this theory and if its 100% accurate. For instance, John Murray a scientists who did deep dives in his Challenger missions believes reefs form when dead corals dissolve and get washed out forming an atoll.(Woodroffe, 2011).

Lagoons: Lagoons are shallow bodies of water with limited connection to larger bodies of water(open ocean) usually through a barrier, or reef (Nichols, 2009). Lagoons are protected from open ocean waves. Ripples get formed in the shallow part of a lagoon from waves. Lagoons can either have a higher or lower salinity depending on the amount of rainfall. Lagoons form adjacent to reefs, specifically Barrier reefs. Atolls have a lagoon in the center as the volcanic island sinks and the corals grow up in a ring form. In barrier reefs the lagoon lies seaward between the shore and barrier reef. Lagoons are the main feature that determines the type of reef. Fringing reefs have no lagoons which distinguishes them from barrier reefs and Atolls.

Figure 3: The image below is of the Great Barrier reef in Australia.



Figure 4: The three main types of coral reefs and their features.



Source:

https://www.pinterest.co.uk/pin/452963675006130472/

The image above shows the main features of reefs such as a lagoon, reef flat, back reef and reef crest.

Carbonate Making and Sedimentation Processes:

Reef Growth conditions /Process:

Coral polyps require warm, clear, shallow and light sea water. Corals thrive where there is little sedimentation and mud getting transported from a river. Mud would block the sunlight and cause the coral polyps to die. Coral polyps excrete a calcareous substance and makes a hard skeleton of calcium carbonate. Over the years the corals grow upward, growing on top of existing dead polyps and also expand outward. Corals can even grow many meters down in darkness.

Biological, Physical (breaking up of shells), Chemical (ions)

Biological: Organisms

The majority of carbonate material is produced biogenically. Organisms produce hard skeletons/shells using carbonate ions in seawater. Carbonate producing organisms include mollusks, bivalves, gastropods, cephalopods, belemnites, brachiopods, barnacles, echinoderms, crinoids, and stromatorporoids (extinct sea sponges, that were important reef formers in the Paleozoic). The image below shows a Crinoid, or sea lily which forms several plates of calcium carbonate. These organisms are made of calcium carbonate and when they die they get broken down. If they end up below a certain depth they will dissolve and add ions to the water. The area where this occurs is below the lysocline which is about 750-4,300 meters for calcite (SEPM, 2013).

There are also plants and algae that produce carbonate. Biogenic carbonate is made from 3 main types of algae that settle and get broken down over time into calcium carbonate mud. The 3 main types of biogenic carbonate algae are Red algae (*Rhodophyta*), Green algae (*Chlorophyta*), and Yellow algae (*Chrysophyta/Coccoliths*) (Nichols,2009). There are also cyanobacteria including Stromatolites, oncoids that later form carbonate mud. Stromatolites, or layered calcareous mounds are produced by cyanobacteria. Sediment gets trapped and the cyanobacteria secrete lime. Finally, peloids and other bioclasts form carbonate mud.

Chemical: Ocean Chemistry and Carbonate Process

The chemical carbonate process as explained earlier is when chemical ions in seawater are used to make calcium carbonate. The reaction is $Ca^{2+} + Co3^{2-}$ to CaCo3 which can either go in the forward or backwards direction. Chemical processes usually involve bubbling and change of color and material. Carbon dioxide is used to help change carbonate ions in the ocean. The ocean chemistry, water depth, and biology affect the type of carbonate formed. An increase in surface area will increase the amount of chemical change and processes that occur.

Physical:

The physical process on reefs is accompanied with waves, bio-erosion and storms. In general physical weathering is the break down of material into smaller pieces without chemical change. However, as the material is broken down the surface area increases and it will be more susceptible to chemical weathering. Organisms break down broken up shells and turn them into sand. Storms break apart corals and bio-eroders, or the waves break up the pieces. In the physical process no new mineral is made and the original material is the same. The water depth and the waves determines the amount the carbonates will get broken down. Also, the thickness of the coral determines how quickly the coral can be broken down.

The image below is of a Crinoid, a calcium carbonate producing organism.



Figure 5: A Crinoid, or Sea Lily that forms calcium carbonate biologically.

https://upload.wikimedia.org/Wikipedia/commons/d/d2/Crinoid_on_the_reef_of_Batu_Moncho_Island.JPG



https://commons.wikimedia.org/wiki/File:Stromatolites_in_Sharkbay.jpg

Figure 6: The image above shows stromatolites in Shark Bay, West Australia which formed layers of carbonate produced by cyanobacteria.

Carbonates/Reefs in General:

In general when classifying carbonate and limestone rocks the Dunham Classification is used (Nichols, 2009). This classification classifies carbonate rocks based on the type of carbonate, texture, and what holds the grains together, or the support. The proportion of carbonate mud, and the framework of the rock are analyzed. (Nichols, 2009) First the rock is examined to determine if the rock has a matrix, or clasts framework. Second the nature of the grains and framework material makes up the second criteria for the classification. With this the carbonate is described as either a carbonate mudstone, wackestone, or boundstone (organic framework of coral colony) and many other specific names. Boundstone can be classified into bafflestone, bindstone and framestone (Nichols, 2009). These are all different types of carbonates.

Carbonate rocks are mostly form from the accumulation of calcareous organisms and are found in areas of high biological activity such as shallow ocean water. There is little siliclastic input in reefs and many carbonate rocks contain fossils/broken shell fragments. These carbonate rocks from reefs are used by sedimentologist to help construct the past geological events. Reef carbonates contain a good amount of hydrocarbons. Carbonates can form in many different types of depositional settings including basin and slope, reefs, and carbonate platforms. Carbonate platforms occur when there is a low input of detritus and clastic supply with shallow marine water. There are many types of carbonate platforms including ramp, rimmed and isolated platforms (Nichols, 2009). There are 3 main morphologies including carbonate banks and shelves. An example of a carbonate bank is a carbonate atoll. The types of grains present in the different platforms have changed over time due to the difference in abundances or calcareous organisms. For instance, in the Precambrian the main reef constituents were stromatolites, and in the Permian the large constituents were algae, sponges and corals. (Nichols figure 15.10, 2009)

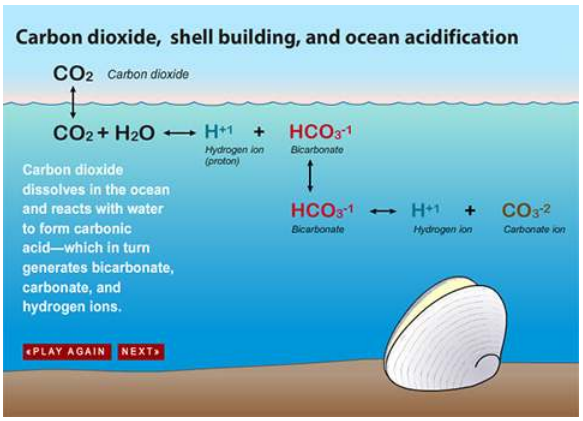
Coral reefs depositional environment usually can occur on platform margins. Platform margins are areas with strong waves and tidal current energy. Carbonates that form reefs where there is a break in slope on the sea floor. Barrier reefs have discontinuous thin beds of sediment. Major components of platform margins include reef frames, reef apron, back reefs, fore reefs, and barrier islands (Harris, 2009). The reef frame consists of in-situ calcareous organisms mixed with silt, mud and calcareous sand. The calcareous sand, silt and mud form from bioerosion and occasional storms. The next component the reef apron usually consists of silt and larger debris that came from the reef frame. The reef apron has cross bedding (Harris, 2009). The back reef is made of sheets of burrowed mud with laminated carbonates and skeletal pieces from the reef crest. The grain size is sand to mud. Sand shoals would form if reefs end up not forming in a platform margin.

Degradation of Coral reefs:

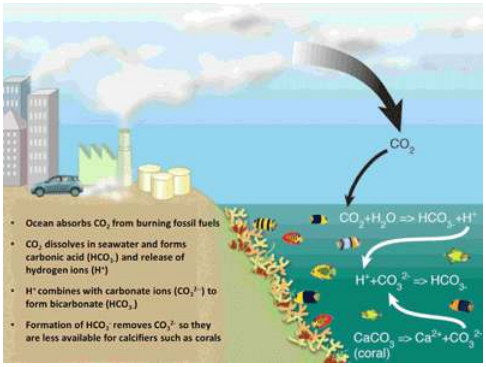
Ocean acidification and climate change is a major threat to coral reefs. Coral bleaching and global warming are becoming more prevalent in coral reefs (Poloczanska, 2017). Due to the increasing sea temperature and acidity the zooxanthellae algae are unable to thrive, dying causing the coral to lose its color. Warm water reefs are shifting to higher latitudes since the ocean temperature is increasing (Poloczanska, 2017). Without the algae the corals are prone to dissolving, have less nutrients, and later bleach adding

ions to ocean. Furthermore, corals and calcareous organisms must excrete enough calcium carbonate so they have strong skeletons to avoid bio-erosion and the waves. Fossil fuels and the increase in carbon dioxide is the main cause of coral bleaching due to the greenhouse effect. Carbon dioxide is absorbed by the ocean which is acidic while calcium carbonate is a base. Carbonic acid is formed and hydrogen ions are released. The hydroen ions combine with carbonate ions forming bicarbonate, removing carbonate that is needed for organisms to calcify. The two (carbon dioxide and calcium carbonate) react to neutralize each other and dissolving the coral. Other calcium carbonate organisms will not be able to form their shells since there will be less calcium ions and they will dissolve with the carbon dioxide. Coral reef fish will lose their habitat and have to move, or face dying. Another threat to coral reefs is tourism. Tourists break apart the corals to later sell, or keep them for their own interest. In addition fisherman are a threat. When fisherman trawl against the ocean floor they will break apart corals, destroying what took thousands of years to produce. Coral reefs could be eliminated between 2040-2050 (Poloczanska, 2017).

Figure 7&8: Show the processes of ocean acidification. These are different representations of ocean acidification.



https://education.ocean.org/oceanlitlib/assignments/1114405



https://reefresilience.org/stressors/ocean-acidification/ocean-carbon-chemistry/

Summary:

Overall, reefs are fragile ecosystems and are degrading due to climate change and ocean acidification. Coral reefs may be gone by 2050 if action is not done. Calcium carbonate is formed from CaCO3 and Ca. The three main types of reefs are fringe, barrier and atolls. There are other more special reefs within these including pinnacle reefs. Due to Darwin's Subsidence Theory the different types of reefs form from each other. Biological processes are the greatest constituent in reef building. Chemical and physical weathering are other processes that form, and create reefs. Dead calcareous organisms get broken down into sand and other particles. Ions in the water are used by organisms to secrete their carbonate. There are many different organisms and algae that secrete calcium carbonate. When the organisms die they get broken down and add to the reefs carbonate. The main structure of a reef includes a back and fore reef. Different facies make up the fore and back reef. The fore reef is the part that extends to the open ocean while the back reef extends to the lagoon and is where most of the deposition takes place.

Figure 9: The image below is of a bleached coral due to the loss of its symbiotic algae.



https://en.m.Wikipedia.org/wiki/File:Bleached_coral,_Acoropora_sp.jpg

Key Words:

Carbonates (Calcium Carbonate)

Reef Types (Fringing, Barrier, Atoll)

Dunham's Carbonate Classification

Fore Reef

Back Reef

Stromatolites

zooxanthellae algae

Darwin's Subsidence Theory

Lagoon

Ocean Acidification

Works Cited

3 Types Of Coral Reefs You Should Know About | ReefCI. https://reefci.com/2019/02/14/four-types-of-coral-reefs-you-should-know-about/. 2019 Accessed 6 June 2020.

Atoll | National Geographic Society. https://www.nationalgeographic.org/encyclopedia/atoll/. 2012 Accessed 6 June 2020.

Carbonate Facies - SEPM Strata. http://www.sepmstrata.org/page.aspx?&pageid=90&6. May 2013 Accessed 6 June 2020.

Carbonates Rocks. http://www.geosci.usyd.edu.au/users/prey/FieldTrips/Yass04/Carbonates.html. Accessed 6 June 2020.

Nichols, Gary. (2009). Sedimentology and stratigraphy (2nd ed.). Chichester, UK ; Hoboken, NJ: Wiley-Blackwell.

Harris, Paul M. *Depositional Environments of Carbonate Platforms*. pages. 31.

James, Noel. *Reef Environment Carbonate Depositional Environments, GeoScienceWorld Books GeoScienceWorld*. https://pubs.geoscienceworld.org/books/book/1422/chapter/107173417/Reef-Environment. Accessed 6 June 2020.

Poloczanska, Elvira, et al. *Frontiers | Coral Reef Ecosystems under Climate Change and Ocean Acidification | Marine Science*. May 2017, https://www.frontiersin.org/articles/10.3389/fmars.2017.00158/full.

Sumner, Dawn. “1.13: 14. Carbonates.” *Geosciences LibreTexts*, Libretexts, 3 June 2019, geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/01%3A_Lecture_Notes/1.13%3A_14._Carbonates.

Woodroffe, Colin. *Subsidence Hypothesis of Reef Development | SpringerLink*. Book 2011 Accessed 6 June 2020.

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Chemical Weathering

What is Chemical Weathering?

Chemical Weathering is an erosional process in which rocks and other materials are broken down by chemical reactions (predominantly by water and chemicals dissolved within it).

A. Types of Chemical Weathering

1. dissolution

This process occurs when water comes into contact with rocks and dissolves the minerals that make up that rock into individual elements. The dissolution of calcite is a good example of this process, when water comes into contact with rocks that have abundant amounts of calcite such as limestone the calcite dissolves into the solution. The calcite will stay in the solution until the water either evaporates, reacts with other minerals, or is precipitated by another organism to make its shell. This process is extremely important on Earth, it allows many organisms such as mollusks, echinoderms, foraminifera, and coccolithophores to produce their shells which protect them. These organisms are very important to our ecological system especially foraminifera and coccolithophores because they play a vital role in the silicate geochemical weathering cycle which helps control Earths climate system.

2. Alteration

Alteration occurs when minerals come in contact with water and are converted into different minerals with a different chemical structure, different chemical composition, or both. This alteration process is important in the formation of clay minerals in sediments. Rocks such as granite and basalt can come into contact with water and have their feldspars altered into clay minerals through this chemical reaction: $KAlSi_3O_8 + 4H^+ + 2H_2O \Rightarrow 4K^+ + Al_4Si_4O_{10}(OH)_8 + 8SiO_2$.

3. Oxidation

Oxidation occurs when oxygen reacts with other elements and electrons are transferred between the two elements, an example of oxidation is when oxygen reacts with iron to form iron oxide. Iron oxide formation is a process that is similar to alteration and forms what we know in everyday life as rust. This iron oxide is much weaker than the original iron in the rock and therefore makes the rock more likely to deform brittlely.

B. Mineralogy of Weathered Rocks

Rocks that have been chemically weathered do not have the same mineral composition as the parent rock. Overall, the composition of sediment depends on the mineralogy of the original rock, how it is transported, and the weathering environment. Different minerals weather at different rates according to the Goldich stability series, minerals like quartz and muscovite weather much less easily than minerals like olivine and pyroxene (Goldich 1938). Some minerals like olivine and pyroxene weather easier because they have more cations and more ionic bonds (Goldich 1938). Many igneous minerals that are high in magnesium and iron weather quickly to form clays, whereas the more felsic minerals tend experience physical weathering because they are more resistant to chemical weathering. The hardness of minerals also plays a role in how the rocks are weathered, when hard quartz grains hit softer plagioclase grains the plagioclase will break into smaller grains. Clay minerals stick together well and are very soft but due to their small grain size they cannot be broken down further into smaller grains by the collision with larger harder grains.



Figure 1: Example of Goldich's dissolution series from his 1938 paper where he studied soil profiles in order to understand the weathering rates of different minerals (taken from http://www.columbia.edu/~vjd1/weathering.htm)

C. Controls on weathering

Climate plays a major role in chemical weathering, warmer temperatures makes chemical reactions happen faster and as a result minerals weather faster in warmer more humid climates. Water is a huge part of chemical weathering as well because the water causes the dissolution of minerals in the rocks. The more water that is present the faster the dissolution and weathering occur. Vegetation also has a strong affect on the rate at which rocks weather, vegetation produces weak acids that increase the rate of both dissolution and alteration which in turn increases the rate at which weathering occurs.

D. Erosion

When rocks break down into smaller grains they produce sediment that is available for transport. Fluid flow and gravity are the two main driving forces that transport sediment from its source region to dispositional areas such as sedimentary basins. transport by water is by far the most common type of transport and occurs in rivers, streams, lakes, and other large bodies of water. Another form of fluid flow is glacial flow where glaciers that are moving break up sediment at the leading edge of the glacier where the sediment moves with the glacier as it flows. The other form of fluid flow is wind blown transport of sediment, this happens mostly in deserts and airid environments where small sand grains can be picked up by the wind and transported to different areas. Wind transports primarily sand size grains and smaller because larger grains are to heavy for wind to transport under normal conditions.

E. Transport Capacity

Transport capacity is “the maximum amount of sediment this flow can carry in suspension under equilibrium conditions for a particular sediment material” [*Celik and Rodi*, 1991, p. 192]. As minerals begin to weather they tend to break down into smaller clasts and undergo alteration into clays along with other types of minerals. These alterations can lead to a change in transport capacity of the weathered minerals compared to the original parent rock. Weathering tends to decrease grain size and allows more sediment to be suspended and transported in a flow that is in equilibrium. The opposite can also be true for example, when minerals weather into clays that have a sticky texture it may lead to less transport of sediment than would have otherwise happened with sand grains or pebble sized grains.

F. Why is Chemical Weathering Important?

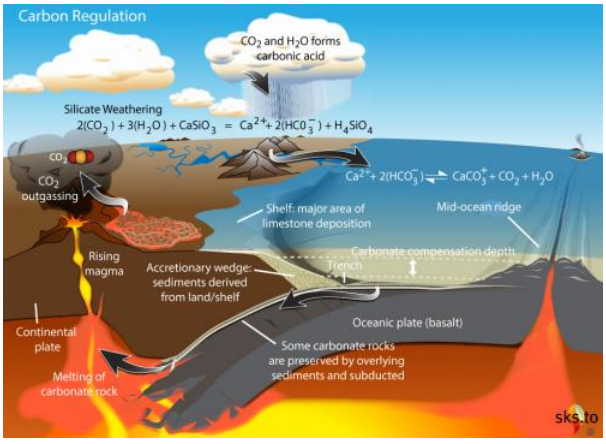


Figure 2. Graphic depicting the carbonate-silicate geochemical cycle. (taken from https://canvas.ucdavis.edu/courses/424715/files/folder/Lecture%20pdfs?preview=7639033)

Chemical weathering is the main process that drives the carbonate-silicate geochemical cycle. Figure 2 shows how this cycle controls the long term transformation of silicate rocks into carbonate rocks over geologic time. This process is also the Earth's main way of controlling its climate through the break down of silicate rocks and the burial of carbon.

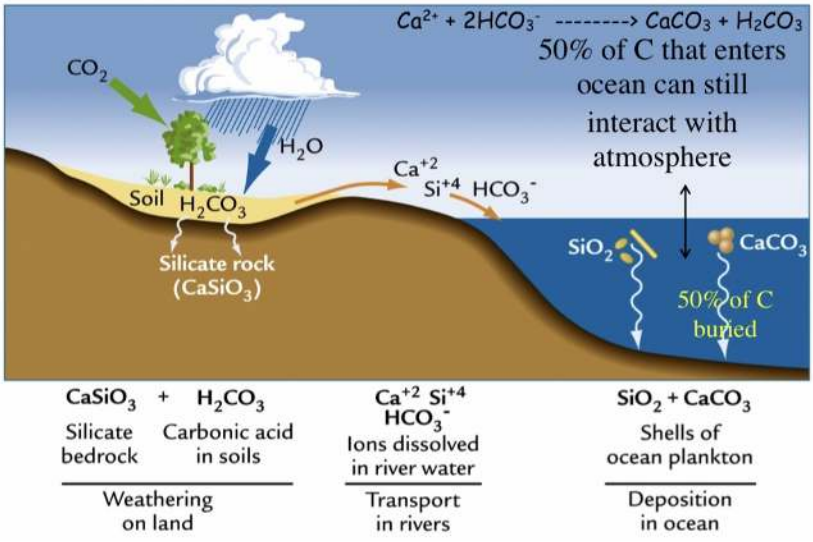


Figure 3. Graphic depicting how the Earth chemically weathers silicate rocks into bicarbonate, silicon, and calcium and buries the carbon on the ocean floor. (taken from https://canvas.ucdavis.edu/courses/424715/files/folder/Lect2HCoure%20pdfs?preview=7639033)

G. How does the carbonate-silicate geochemical cycle regulate climate

The first step in the cycle is the production of carbonic acid in the atmosphere from the combination of water and carbon dioxide. Figure 3 shows that over long geologic time scales dissolution takes places and silicate rock dissolve into calcium, silicon, and bicarbonate ions which are then transported by a fresh water system such as a river to the ocean. In the ocean shell producing organisms precipitate their calcium carbonate shells by the reaction Ca^{2+}+2HCO3$^-$ ⇒ $CaCO_3$+CO_2+H_2O. One of the carbon dioxides in the reaction is released back to the atmosphere while the other is trapped in the calcium carbonate shell of an organism. When the organism dies their shell will deposit on the sea floor and stay there as a carbon sink until the ocean floor is subducted and the shells are melted in the Earth. The cycle restarts after the carbon dioxide is outgassed, by volcanism, back into the atmosphere. Fundamentally this entire process is based on chemical weathering specifically dissolution of silicate rocks by carbonic acid. When carbon is sequestered on the ocean floor by the carbonate-silicate geochemical cycle it allows the planet to cool down because there is less carbon in the atmosphere to form carbon dioxide which means the planet will experience less of a greenhouse effect. Without chemical weathering on this planet there would be no inorganic process to remove carbon from the atmosphere which means the planet would likely be much hotter than it is today and may not be habitable for life. This is why the process of chemical weathering is so important for the planet and we should all thank this process for keeping our planet habitable for all of the life that inhabits it including humans.

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Chemostratigraphy-Strontium isotopes and others

Adelicia Johnson

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Chronostratigraphy

Loosely based on Chronostratigraphy

What is **Chronostratigraphy**?

Chronostratigraphy is the branch of geology that studies the age of rock strata in relation to time. The basic idea is to correlate which rocks around the world formed at the same time in an effort to reconstruct past events and determine depositional environments in Earth history. Another useful thing about chronostratigraphy is that can help us find valuable resources. For example, most of the oil deposits found today were deposited in the Mesozoic, so with this knowledge scientists can look for rock units of similar age to locate the oil deposits.

While not an all-inclusive list, some of the different techniques used in chronostratigraphy are: **event stratigraphy**, **magnetostratigraphy**, **sequence stratigraphy**, and **biostratigraphy**. Below are explanations of each of these techniques.

What is **Event Stratigraphy**?

Event stratigraphy involves identifying the sedimentary effects of an unusual event in multiple stratigraphic columns. If one can demonstrate the the effects were all produced by the same event, one can reasonably interpret the effects to have happened at the same time in the different columns. This is done via **marker beds** and **event horizons**.

A **marker bed** is a bed/thin subdivision of a layer with distinctly different characteristics from the host sediment above or below it. For a marker bed to be useful, it must be easily traced over long distances. An **event horizon** is a discontinuity surface within the stratigraphic sequence where the normal progression of the stratigraphy is altered. Events can be an erosional,depositional, or biological episode where the evidence of the event can be clearly seen in stratigraphic sequence.



Figure 1: Fairport Chalk bentonite marker bed beneath a shallow ledge of limestone Photo: Libretexts https://upload.wikimedia.org/wikipedia/commons/a/ab/Fairport_Chalk_bentonite_marker_bed_F-1_20171230.jpg

The usefulness of event stratigraphy is that one can prove that the sedimentary effects of an event happened at the same time in different stratigraphic columns. For example, volcanoes often spread ash out over wide areas and this ash is preserved in stratigraphic section. If geologists can prove the ash in different stratigraphic sections came from the same volcanic event, a chronostratigraphic correlation can be made between the sections. The issue with event stratigraphy is that the event has to impact multiple depositional environments. Since each depositional environment is governed by different processes, an individual event may not be universally impactful enough to distinguish it from normal depositional processes across each affected environment. Another issue is that the event has to be specific to the area of study in interest (ash deposits may not help you when

looking for evidence of a tsunami event) and often there are multiple events within a stratigraphic sequence which can complicate chronological correlations with other sequences.

What is **Magnetostratigraphy**?

Magnetostratigraphy is a geophysical technique concerned with the correlation/dating of sedimentary and volcanic sequences. In rocks, magnetic minerals can become magnetized and align with the Earth's magnetic field. When these minerals become lithified, the magnetization is preserved and the direction of magnetization can be measured. This is useful because over Earth's history there has been several reversals of the magnetic poles and this occurred globally so paleomagnetists have been able to use this data to map out the times in Earth's history where the magnetic field was normal and reversed. In sedimentary rocks, clay-sized minerals align like magnets to the Earth's poles and when an igneous rock cools it acquires a thermoremanent magnetization from the Earth's magnetic field. Any stratigraphic section that preserved remanent magnetism containing a series of reversals ought to be matchable to the global magnetic polarity time scale.

Some of the strengths of this method are:

- the unique patterns of geomagnetic reversals are isochronous (occurring at the same time) global marker beds
- the reversals are present as long as minerals containing remanent magnetism are present (this is totally independent of facies). This is why geologists are able to correlate marine to continental units with magnetostratigraphy
- radiometric dating is always subject to margins of error, whereas a rock's paleomagnetic polarity is absolute. Knowing the paleomagnetic polarity of a sample can give a means of constraining its age independent of radiometric methods.

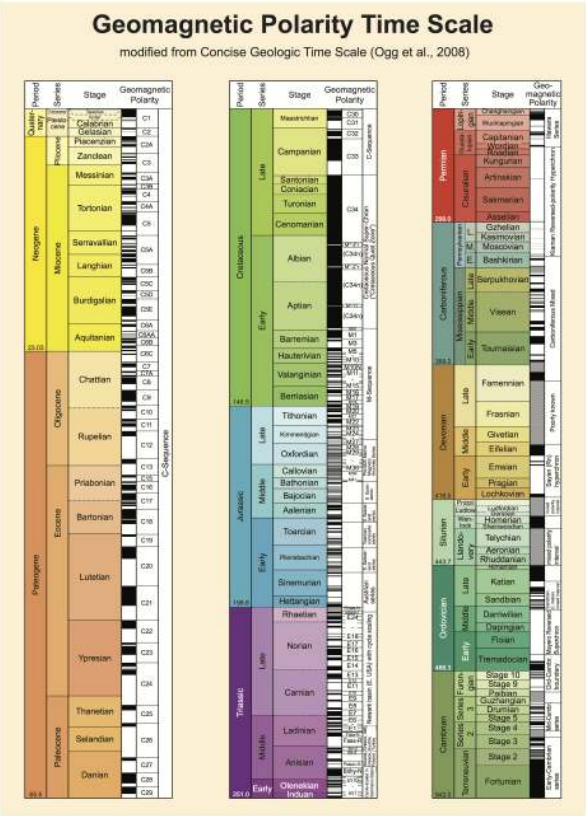


Figure 2: This is the Magnetic Polarity Time Scale correlated to the Geologic time scale. Black periods are "normal" (North points to today's true north) and white periods are "reversed". Figure: from Libretexts

The drawbacks of magnetostratigraphy are:

- Magnetostratigraphy requires a stratigraphic section in which a pattern of reversals is visible! Whereas a lithostratigraphic marker bed, biozone, or chemostratigraphic anomaly might be recognized from a single outcrop.
- Changes in depositional rate or disconformities can obscure/alter the magnetostratigraphic pattern within a stratigraphic section
- Some intervals of geologic time are not useful because they contain few reversals so it is hard to correlate it to the Magnetic Polarity Time Scale

What is **Sequence Stratigraphy**?

This section based on this webpage

Sequence stratigraphy is the branch of sedimentary stratigraphy that deals with the order/sequence in which depositionally related strata (rock units) were laid down in the available spaces at the time of deposition. Basically, it is the analysis of sedimentary deposits in a time-stratigraphic context and involves subdividing sedimentary basin fill into individual sequences of deposition which can then be linked to changes in the two parameters of sediment supply and accommodation. The main purpose of this technique is to reconstruct how sediments filled a basin and how the stratigraphy was formed through space and time. Sequence stratigraphy can help geologists figure out how sea level has changed by looking for where coarse and fine grained sediments were deposited within a basin. Below are some terms used in sequence stratigraphy:

- Eustasy - sea level at a given time (influenced by tectonic movement)
- Transgression - periods of sea level rise which leave retrogradational stacking patterns of strata
- Regression - periods of sea level fall which leave progradational stacking patterns of strata

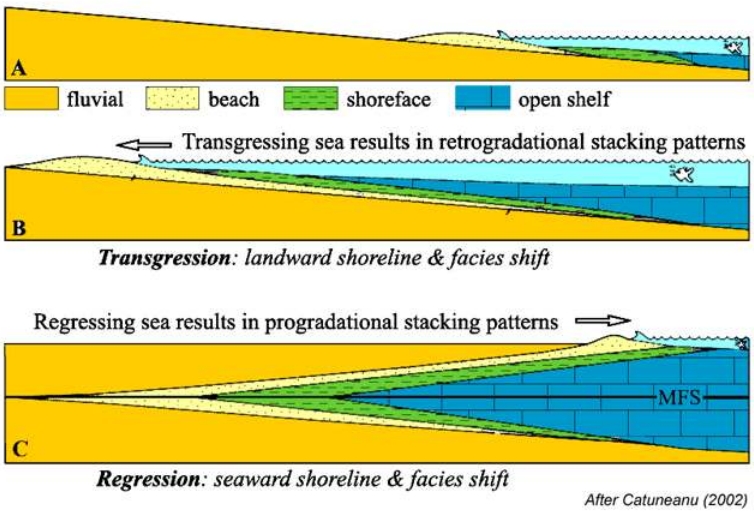


Figure 3: The depositional effects of sea rise and fall on stratigraphy. Note the different stratigraphic layers and how transgression and regression have distinct patterns. Photo: SEPM Strata

In the figure above, the effects of transgression and regression are shown. Sea level rise results in a retrogradational stacking pattern while sea level fall results in a progradational stacking pattern. In B, the beach layer is spread out and moved up the beach as the sea level rises. In C, the beach layer is spread out and pulled back in to the ocean as the sea level falls.

In sequence stratigraphic models, sediment supply is often assumed to be constant while accommodation (the space available for potential sediment accumulation) changes through time as a result of fluctuations in sea level. The different sedimentary sequences refer to the amount of stratigraphy that was deposited during an episode of sea level fall and subsequent rise. Sequence stratigraphic models are a simplification of of what actually happened and are often complicated and full of difficult terminology, but it is still a very useful tool for economic geologists because it allows them to better understand the stratigraphy of sedimentary basins of value.

What is **Biostratigraphy**?

A more in depth explanation can be found here: Biostratigraphy

The basic idea is for the geologist to identify fossils in the stratigraphic columns, compare them to the ranges of those organisms know from previous studies, and then interpret the age of the rocks from documented extinction and species origination events. Finding the same index fossil in two spatially distanced stratigraphic units allows us to constrain their time of deposition to the same time. This is done with **index fossils** which are fossils that have the following characteristics:

- have short geological ranges (they did not live for millions of years, and evolved quickly)
- were distributed over a large region of the earth
- were easily preserved
- were abundant and are well studied.

This method is particularly useful because it does not depend on isotope dating for an accurate estimate of the age of stratigraphic units. The issues though are that fossil species need to have the characteristics of a good index fossil and it needs to be relevant to whatever you are studying.

Works Cited:

All notes from Dawn Sumner, UC Davis GEL 109:

https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/08%3A_Old_or_Lost_Pages/8.04%3A_Chronostratigraphy

Figures from libretexts and SEPM Strata http://sepmstrata.org/page.aspx?&pageid=229&3

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Deep Marine Environments

Introduction

The deep ocean is the world's largest depositional environment, encompassing all of the ocean floor below the continental shelf and slope environments.

The majority of deposition away from continental margins takes place where there is little to no flow to transport sediments in from elsewhere. Deposition consists primarily of the slow accumulation of suspended material on the sea floor.

Sediment Transport

For the most part, deep marine environments are very still and experience little to no flow. Turbidity currents may reach deep ocean, depending on the size and density of the load, but generally do not extend more than a few thousand kilometers away from continental margins. Because of this, sedimentary structures are rare and are usually restricted to the planar lamination associated with the uppermost portions of turbidite deposits.

The majority of sediments are deposited through settling of suspended material, which consists primarily of bioclasts from microscopic planktic organisms and relatively small amounts of clay- and silt-sized dust. Deposition by settling occurs very, very slowly and is usually measured in mm/ka.

Characteristics of Deposited Sediment

Sediments deposited here are generally silt-size or smaller, with the exception of Radiolarian bioclasts, which may reach up to 0.5mm in diameter. The characteristics of the deposited sediment tend to depend on the ratio of calcareous to siliceous material, as well as the ratio of bioclasts to dust.

The relative amounts of these materials are determined by the water's ability to dissolve the bioclasts. Dissolution occurs more readily at depth, but the actual depth at which a given chemical will dissolve in seawater, known as its "compensation depth," varies both spatially and temporally according to pressure, temperature, and the existing dissolved load. Higher pressure and lower temperature enable dissolution of chemicals like carbonates, and if a large amount of material is already dissolved, it will require higher pressures to dissolve more. This would move the compensation depth down.

The tests of planktic organisms are made of either calcium carbonate, in the case of *foraminifera* and coccoliths, or hydrous silica, in the case of diatoms and *Radiolaria*. Calcium carbonate dissolves more readily than silica, so the **carbonate compensation depth (CCD)** is always above the **silica compensation depth (SCD)**.

Above the CCD, **calcareous ooze** accumulates the fastest of the three, so it makes up the majority of deposition there. Calcareous ooze lithifies as lime mudstone, sometimes referred to as pelagic limestone.

Below the CCD, only dust and silica can deposit, as the calcareous organisms dissolve before reaching the sea floor, and **siliceous ooze** accumulates more quickly than red clays. As a result, the majority of deep marine deposits are of siliceous ooze, which lithifies as **chert**. Chert is an amorphous hydrous silica that is characteristic of deep marine depositional environments. If *Radiolaria* are visible as white dots in the chert, it is known as **Radiolarian chert**. Small layers of carbonates are sometimes found in deep marine chert as a result of turbidites from carbonate platforms.

Below the SCD, only dust can deposit, which lithifies as mudstone. Since the majority of the dust blown across the ocean comes from aeolian environments where it has been heavily oxidized, deep sea dust deposits form red clays which lithify as red or red-brown mudstones.

Chemogenic Deposits

In some places chemicals may precipitate directly out of the water and onto the sea floor. One relatively common precipitate is Mn-oxide, which enters the water in solution either through hydrothermal activity or continental weathering. Over time, Mn is concentrated into hard, round, black blobs known as Mn-nodules.

Fossils

Planktic organisms make up a significant proportion of deposits in deep marine environments, though few are large enough to fossilize. *Radiolaria* up to 0.5mm may be seen in any sediments above the SCD, and macroscopic *foraminifera* are common above

the CCD. Body fossils of larger open-water organisms such as cephalopods or whales are significantly less common, but pelagic organisms with hard shells or bones will sink to the ocean floor after death and potentially fossilize.

Trace fossils are almost exclusively of the *Nereites* ichnofacies, consisting of regular, surficial feeding traces. Benthic organisms in the deep ocean are rare because nutrients are rare, and the regularity of these feeding traces is thought to be a strategy to increase efficiency.

Facies

Due to the basin-like shape of the ocean floor, the mud, chert, and mud limestone facies tend to create something resembling concentric rings, with mud limestone closest to continental margins and the mud facies farthest away. Turbidite deposits become more common closer to continental margins.

Vertical facies changes are influenced by tectonic processes as well as changes the carbonate and silica compensation depths. As a deep marine basin is uplifted (or the CCD and SCD over it lowered), it will transition from mud to chert, then to mud limestone.

Summary

Because there is very little flow to transport sediment, sedimentary processes in deep marine environments are largely based around settling and chemical processes.

There are three primary facies associated with deep marine sedimentary deposition: mud limestone, which is primarily composed of calcareous ooze from calcareous planktic organisms; chert, which is primarily siliceous ooze from siliceous planktic organisms; and red mud, which is composed of dust, soot, and ash blown over the ocean. Their locations relative to one another are governed by the CCD and SCD, which determine how deep calcareous and siliceous material can go before dissolving.

Anything floating in the open ocean may make its way down to the sea floor and be incorporated into sediments, provided it does not dissolve. Because of this, pelagic fossils are relatively common in deep marine sediments.

Reference

Nichols, Gary, 2009, Sedimentology and Stratigraphy, 2nd ed.: Chichester, UK, Wiley- Blackwell.

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Eolian Environments

Introduction

Aeolian or **eolian** environments are those in which sediment deposition is primarily governed by wind. They are typically associated with **arid** environments (areas that recieve <250 mm/yr precipitation), for two main reasons. First, water is a much more powerful transport agent than air due to its fluid properties, so a lack of water is prerequisite for air to be the dominant sedimentary force. Second, lack of water leads to scarce vegetation, which further facilitates wind-driven erosion because vegetation can stabilize sediment and prevent it from being easily moved around.

Thus the most common eolian environments are rocky deserts and **ergs** (the technical term for sandy deserts). Another, less common, eolian environment includes areas with glacial outwash, where melting ice has released loose sediment, and plants have not yet had time to stabilize it.

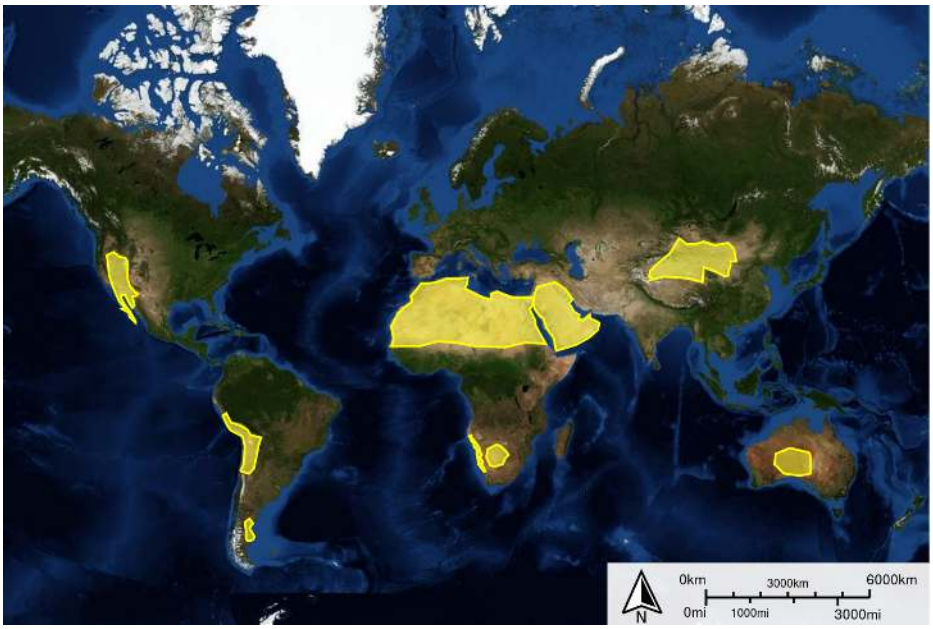


Figure 1: Distribution of the world's largest deserts. Source

Sediment Transport Processes

Air has very different fluid properties compared to water, a fact which plays an important role in the eolian deposition of sediment. Air is orders of magnitude less dense than water, making grain transport much less efficient - in fact, it takes winds in excess of 60 mph just to move a grain 0.5 mm in diameter. Most sand grains are transported by rolling or saltation, though clay- and silt-sized particles can be carried in suspension by strong enough winds, sometimes in quantities great enough to cause dust storms. In areas where winds weaken, they may deposit their silt-sized suspended load in sequences known as **loess**. Air also has much lower viscosity than water, so air flows are generally turbulent.



Figure 2: Ripples in an ice-age era loess deposit, where the grains have been compacted together. Loess deposits can preserve important information about climate change over the last few million years. Source

Eolian Sedimentary Deposits

Composition and Grain Size

As mentioned above, air is much less dense than water, making it less capable of transporting large grains. Thus one characteristic of eolian deposits is that they are unlikely to contain sediment grains larger than coarse sand. Air's low viscosity also means that it has much less of a 'dampening' effect on impacts between grains, so the processes of abrasion that lead to a compositionally mature deposit are accelerated relative to water-driven processes. As a result, most aeolian deposits will have primarily well-rounded grains of quartz and perhaps chert, with little to no micas and weaker minerals. These grain impacts will also characterize their environment. In rocky deserts, rocks subjected to frequent, heavy wind conditions often have smooth, polished faces due to this sand-blasting effect.

Structures/Bedforms

Like aqueous processes, eolian processes generate familiar structures like ripples and dunes. They also create **draas**, which are like massive dunes hundreds of meters in wavelength and amplitude (draas are to dunes as dunes are to ripples, essentially).

Eolian structures do differ slightly from their aqueous counterparts, however. Because air flow is very turbulent, there is no laminar flow sublayer like in water ripples. Instead, saltating grains push coarser grains up the back sides of the ripples to the crests where they eventually avalanche off the lee slope. The smaller grains at the crests, where wind speeds are highest, are transported away, and may accumulate in troughs between the larger grains. Thus large grains become more concentrated at the tops of ripples while smaller grains are more concentrated at the bases. Thin, reversely graded layers are therefore indicative of aeolian transport.

Eolian ripples and dunes migrate in the same way that aqueous ripples and dunes do, by continuous erosion on the windward side and deposition on the leeward side of these structures. Migrating dunes commonly create large-scale cross-stratification in the rock record, however migrating ripples rarely leave clear cross-lamination because the sand in these deposits is so well-sorted.



Figure 3: Ripples on dunes in Death Valley National Park. Source

Facies

Arid environnments typically only have a few types of deposits in them. Aside from the aeolian sand dunes discussed above, these environments may contain poorly-sorted alluvial fan and river deposits, as strong but temporary flash floods are not uncommon in desert settings and can generate debris flows. These might manifest in the rock record as matrix -supported conglomerates, perhaps separated by thin beds of sandstone deposited between storm events. Arid environments may also support ephemeral lakes, which leave behind thin beds of mudstone and evaporite deposits when they dry up.

Summary

Thanks to the fluid properties of air, and to the arid environments with which they are most closely associated, eolian deposits can be identified by a number of different criteria. They are very well-sorted and well-rounded, with grain sizes rarely if ever exceeding that of coarse sand. On a fine scale, they may show reverse grading in thin laminae, but rarely cross-lamination. On a larger scale, cross-stratification is common. Finally, their association with arid environments like deserts means they can be found alongside evaporite deposits from ephemeral lakes, or poorly sorted alluvial fan and river deposits associated with flash flooding events.



Figure 4: Migrating and static sand ripples on Mars. Despite extremely low atmospheric pressure, wind is currently the dominant transport agent on the surface of Mars due to the lack of surface water and vegetation. Source

Key Words

- Aeolian/eolian
- Arid environments
- Ergs
- Loess
- Draas

References

https://geo.libretexts.org/Courses/U...lian_Processes

https://geo.libretexts.org/Courses/U...d_Environments

Ruddiman, William F. *Earth's Climate: Past and Future*. W. H. Freeman and Company, 2008.

Nichols, Gary. *Sedimentology and Stratigraphy*. Wiley-Blackwell, 2009.

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Extra Credit 21

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Figure Example

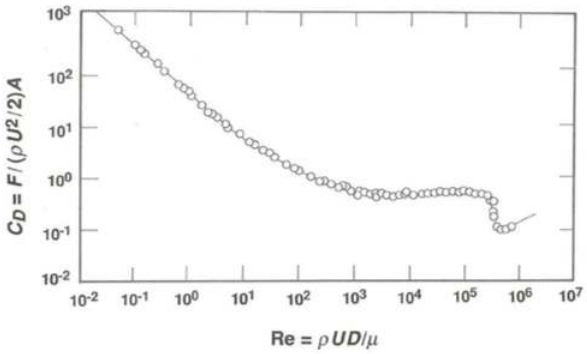


Figure 1: Plot of dimensionless drag force vs. Reynolds number for flow of a viscous fluid past a sphere. The dimensionless drag force is expressed in the form of a conventionally defined drag coefficient rather than as the dimensionless drag force F_D; see further in the text. Experimental points are from several sources, and are somewhat generalized. Some of the data points are from settling of a sphere through a still fluid, and others are from flow past a sphere held at rest. For a more detailed plot, see, for example, Schiller (1932).

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Floodplains and Oxbow Lakes

What is a Floodplain?

Floodplains are large expanses of alluvium deposited by the decrease in river flow speed when rivers flood. Grain sizes of floodplain deposits vary from clay to gravel.

Floodplain Formation

As rivers meander through a relatively flat area, they erode sediment at the outer edge of any curves. This lateral erosion caused by snaking meanders creates a flat valley over time.

When a river floods, the area the water is flowing through increases exponentially. As the water breaches its bank, it escapes into the rest of the valley. The water is unable to maintain the speed it was going before, and it slows down. As water slows down it can no longer keep sediment grains in transport, and it deposits them. Every time a river floods, it deposits the sediment it was carrying outside its boundaries. Over time, the flooding river replenishes a significant amount of sediment into its valley, building up the sediment. Eventually, the deposits from the flooding river may form a levee tall enough to keep the river from overflowing in that area.

Meandering Rivers

https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/Textbook_Construction/Meandering_Rivers

Some rivers in flat areas flow in windy patterns, called "meanders" that form flood-plains and oxbow lakes. There is an entire page about them if you click on the link above.

What is an Oxbow Lake?

A "C"-shaped lake that was once part of a meander that got cut off. The still-standing water of the small lake is eventually filled with mud, leaving behind fine-grained mud overlying channel deposits.

Oxbow Lake Formation

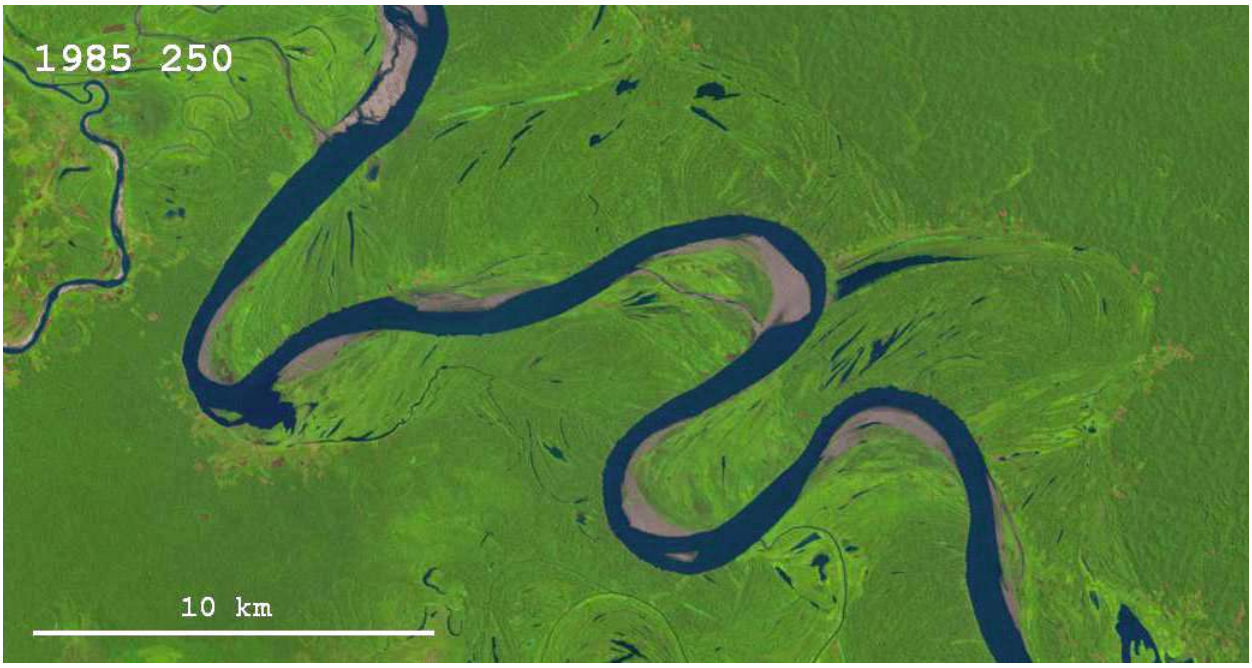
As rivers erode on the outside of a curved section of river, two meanders (the curved part) can erode and move the outside of the river until two loops connect with each other. The river uses the shortcut and the loop that got cut out stays as an oxbow lake until it eventually fills with mud and dries up or the river meanders back to it again.

Below is a .gif of Landsat imagery that shows the evolution of a river in a floodplain and the formation of an oxbow lake as the river meanders.

Images from NASA/USGS Landsat; Compiled by Zoltan Sylvester, Geologist.

Link to Original Site:

https://hinderedsettling.com/2014/03/16/rivers-through-time-as-seen-in-landsat-images/?unapproved=10656&moderation-hash=3d3b56b001dfce60e3552784fd52dfff#comment-10656



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Freshwater Lakes

Introduction

Freshwater lakes are inland bodies of water, typically formed from depressions in the earth's surface. These basins usually form from continental extension, strike slip faulting, or as sag basins. They are bounded by sills, and usually fed by streams and rivers from the surrounding environment. If there are channels that output water and sediment, the lake is hydrologically open. Hydrologically closed lakes (only water and sediment input) may also be freshwater if their dissolved ion concentrations are low enough. Freshwater has a solute concentration below approximately 5 grams per liter.

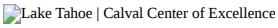


Figure 1: Lake Tahoe. https://calval.cr.usgs.gov/apps/lake-tahoe

Water is the primary media of sediment transport into and out of lakes, but wind may also deposit or erode sediment. Liquid water flow from channels is turbulent and depends on channel width, depth, and flow speed. Flow is largely constrained to above 10 to 20 meters lake depth; this upper oxygenated portion is called the epilimnion. Wind driven surface currents may be up to 30 centimeters per second in speed. They produce waves which may transport sediment around the lake, but wind usually only erodes sediment above the water level. Waves also mix the water and facilitate diffusion of oxygen in the upper layers of the lake.

Sediment Transport Processes

Sediment is usually carried to and from lakes by water from channels, but wind may also transport fine sediment. Flows from channels that move sediment are turbulent, with coarser grains under upper planar flow and fine grains being carried in suspension. Slower flow speeds produce dunes and current ripples, which are asymmetrical. Waves are also responsible for shaping lake shorelines, by both eroding and depositing sediment to make beaches. Waves may form from both air and water flows over the lake. They tend to produce wave ripples, which are symmetrical.

Grains move via in several ways within channels and lakes, depending upon the lift force produced by the transporting fluid:

- **Rolling** occurs when a grain rolls across the bed's surface (yes, really). They roll due to friction between the substrate and the fluid flow.
- **Saltation** occurs when a grain is lifted off the bed surface and falls back down in a series of jumps. The lift force isn't sufficient to carry the grain indefinitely.
- **Suspension** is when a grain is lifted into a flow and carried continuously. This is common for clay sized grains, but larger grains may be suspended in more turbulent flows.



Figure 2: Colorado River Draining into Lake Mead. https://www.nps.gov/lake/learn/understanding-the-lakes.htm

add a description of what the reader should pay attention to, e.g. why is part of it red, what is the light band above the water level

Figure 2 shows the Colorado River draining into Lake Mead. Note the plumes of fine rust colored sediment being transported in suspension. The lighter bands of rock above the shoreline are previous shorelines. Fine to coarse grained sediment may be carried into a lake. Fine sediment is carried in the epilimnion for away from the lake margins, while coarse sediment immediately drops out of suspension into the hypolimnion and forms turbidites. Grading of beds is typically fining upwards, especially near the mouths of rivers transporting sediment.

Lake levels are determined by inputs of water and sediment. Many freshwater lakes rely on sediment and fluid input from rivers, so I suggest visiting the chapter on them here for more information.

Waves are also really important, helping make beaches and erode shorelines. I recommend adding something about them, especially since you mention wave ripples as one of the most common structures in lake deposits.

Characteristics of Deposited Sediment

Sand and mud sized grains are most common, but carbonates, evaporites, and organic material may also be present. Sand is most common on the shoreline, but may also form parts of the lake floor in shallower areas. Mud may be in deep lake or overbank floodplain deposits. Cobbles and gravel occur in turbidites, mostly at their bases.

Structures in lake deposits resemble those in other low energy environments, but with their own unique features. Wave ripples and parallel laminations are the most common structures. Wave ripples only appear in shallow or nearshore lake deposits. This is because they form from wind currents, which produce elliptical motion at the lake's surface. This is gradually translated vertically into standing waves at the bed surface, leading to symmetrical ripples.

Other structures include root casts, mud cracks, and signs of bioturbation. Root casts and mud cracks form when the lake's shoreline recedes, exposing finer silt and clay to air. Plants colonize this exposed sediment and leave root casts. Mud cracks form due to the desiccation of the sediment, but because clay is cohesive, the bed doesn't fall apart. Bioturbation is when organisms dig into and churn sediment to make living burrows, escape from predators, or forage for food.



Figure 3: Feeding traces from an unknown animal; Death Valley, CA. http://www.pitt.edu/~cejones/GeoImages/5SedimentaryRocks/SedStructures/Bioturbation1.html

Be sure to describe where the root cases and mud cracks form relative to the lake shoreline. They require changes in lake level to form, typically, so adding something about what determines lake level would be helpful (especially given your image of Lake Mead above)

The most common organisms found in lake sediments are gastropods, bivalves, and ostracods. Shells and calcareous algae also form the source of much calcareous mudstone called , which may be deposited at the margins or deeper depths of lakes. Vertebrates are also known. Charophytes, a type of green algae, are also indicative of freshwater lake environments due to their intolerance of saline water.



Figure 4: Devonian charophytes from Rockford, IL. https://www.eeob.iastate.edu/faculty/DrewesC/htdocs/fossil-buttons.htm

Typical Vertical Sequence of Freshwater Lake Facies

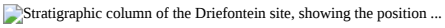


Figure 5: A stratigraphic column showing fluviolacustrine deposits. https://www.researchgate.net/publication/221818423_The_Earliest_Post-Paleozoic_Freshwater_Bivalves_Preserved_in_Coprolites_from_the_Karoo_Basin_South_Africa/figures?lo=1

It would be very helpful to connect the movement of the shoreline and fining/coarsening upward cycles to lake level changes

Flow typically transitions from more to less energetic over time. This is reflected in bedding layers as fining upward, where gravel transitions to sand, then silt and mud. Figure 5 above shows fluviolacustrine deposits from a Triassic locality in South Africa, specifically those in the Burgersdorp formation. You can see both abrupt and continuous changes in grain size and sedimentary structures. The sinuous lines represent erosional surfaces, while the linear ones represent gradual change. The coarsening upward beds, changing from mudstone to fine sand, show an increase in flow speed and turbulence, suggesting a regression of the shoreline. Conversely, the fining upward beds suggest a transgression due to the lack of turbulent flow allowing mud and silt to settle from suspension. Lake shorelines fluctuate frequently over time, which we can see through the presence of erosional surfaces, changes in grain size, and sedimentary structures. These differences in grain size and structures reflect lake margin and deep lake facies. Lake margin facies are typically coarse grained with sand or gravel, and their most common structures are wave ripples and current ripples. Deep lake facies typically consist of fine mud and frequently have planar laminations.

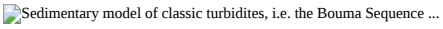


Figure 6: The Bouma Sequence. https://www.researchgate.net/publication/335685532_Verification_of_gravity-flow_models_case_study_from_the_Lower_Eocene_sediments_Tylmanowa_site_SE_Poland

Deep lake facies consist of clay and silt sized sediments, with their main structures being parallel laminations. The Bouma sequence above depicts a turbidite deposit, with gravel and coarse sand transitioning to very fine sand and then mud. These deposits form when debris flows drop sediments down a sloping surface, frequently near the mouths of rivers depositing sediment. The gravel and coarse sand drops from suspension first, then the fine sand, with the mud eventually settling from suspension when the flow loses enough energy. Turbidites are explained in more detail here. Variations in this sequence also appear in alluvial deposits, explained in more detail here. Overbank deposits in lakes may also form fine laminated mud, but unlike deep lake facies, the mud frequently has root casts.

Case Study: The Yixian Formation

This is where things get interesting!

For more than the past 30 years, many exceptional fossils have been found in China. One of their most famous and productive formations is the Yixian Formation located in the Liaoning province of northeastern China. It's early Cretaceous in age, between approximately 139-122 Ma. It is divided into at least three members: the lowermost Lujiatun Member, composed of fluvial and volcaniclastic rocks, the Xiatulaigou Member, composed of basaltic lava flows and associated breccias, and the Jianshangou Member (Wang et al, 2016).

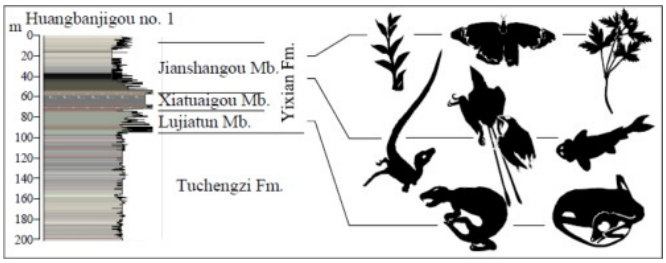
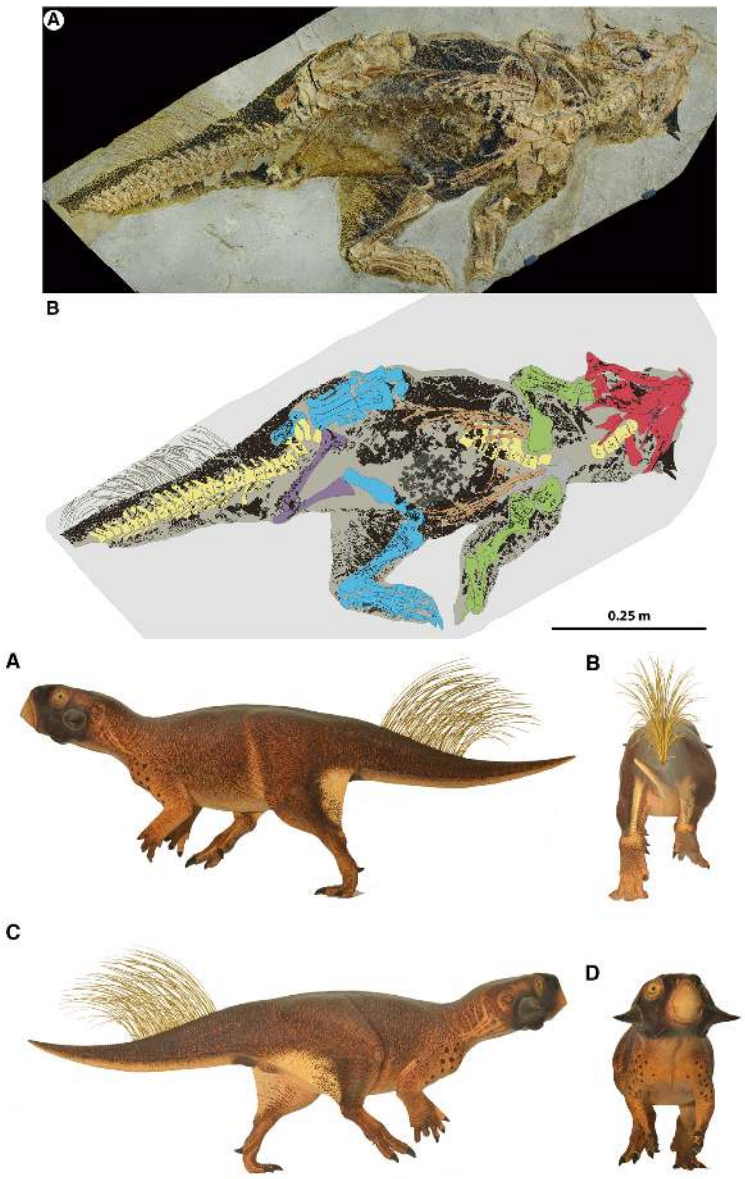


Figure 7: Diagram showing the Yixian and underlying Tuchengzi formations in a stratigraphic column. Taken from Wang et al. 2016.

The **Jianshangou Member** is a lacustrine component of the Yixian formation, and is highly fossiliferous. It has 4 subunits, or beds, with distinctive characteristics (Wang et al, 2016). The basal most is the Dajianshanzi bed, which is largely composed of volcaniclastic sediments and has freshwater bivalves. Then there is the Anjiagou Bed, composed of fine laminated mud interbedded with fine volcanic ash, which produced the first known feathered dinosaur *Sinosauropteryx* and birds such as *Confuciusornis*. Further up section is the Hengdaozi Bed, consisting of light mudstones and sandstones interbedded with ash. It preserves large amounts of insect and angiosperm fossils. Finally, the Huangbanjigou Bed consists of mudstones with varying degrees of lamination along with ash. The Jianshangou Member generally preserves a remarkably complete fossil record of the ecosystem, including gymnosperms, angiosperms, insects, molluscs, non-avian dinosaurs, birds, and mammals. Collectively, they're referred to as the **Jehol Biota**. It is the dinosaurs from this and similar beds that revealed the prevalence of feathers among non-avian dinosaurs, and they contain some of the earliest known flowering plants as well, such as *Archaefructus*.

One of the dinosaurs preserved in the Yixian beds is *Psittacosaurus*, a small dinosaur related to *Triceratops*. Several species are known. The exceptional preservation occurs due to the very fine mud and volcanic sediments, along with a very low energy depositional environment. This individual likely died and stayed in place, and was buried by successive layers of mud and ash settling from suspension. This allowed not only the bones, but imprints of the scaly skin and other soft tissues to be fossilized. The skin is preserved as residues of calcium phosphate, which the scales contained in life (Vinther et al, 2016). The preservation is so fine that impressions of the melanosomes, the tiny organelles that produce pigment, are visible under an electron microscope (Vinther et al, 2016)! Additionally, the scales show conspicuously different textures on different areas of the body.



Figures 8 and 9: *Psittacosaurus sp*. SMF R 4970 under cross polarized light and a model reconstruction. The darker portions of the specimen in Figure 7 are melanin residues, showing pigmentation variations on different areas of the body. The dinosaur was buried on its back, and the body was slightly crushed by the overburden. Both figures taken from Vinther et al. 2016.

Summary

Freshwater lakes consist of inland bodies of water supplied by rivers and streams. Waves are common physical phenomena that shape the deposition and sedimentary structures of beds. If we're incredibly lucky, as we are with the Yixian formation, lakes can provide us with a magnificent view of prehistoric life almost literally in the flesh.

References

Bohacs, K. M. (1999). Lake-basin type, source potential, and hydrocarbon character; an integrated sequence-stratigraphic-geochemical framework. *AAPG Bulletin*, *83*(11), 1878. doi:10.1306/E4FD42AB-1732-11D7-8645000102C1865D

Li, Q., Gao, K.-Q., Meng, Q., Clarke, J. A., Shawkey, M. D., D'Alba, L., . . . Vinther, J. (2012a). Reconstruction of Microraptor and the evolution of iridescent plumage. *Science (New York, N.Y.)*, *335*(6073), 1215. doi:10.1126/science.1213780

Li, Q., Gao, K.-Q., Meng, Q., Clarke, J. A., Shawkey, M. D., D'Alba, L., . . . Vinther, J. (2012b). Reconstruction of Microraptor and the evolution of iridescent plumage. *Science (New York, N.Y.), 335*(6073), 1215. doi:10.1126/science.1213780

Nichols, G. (2009). Sedimentology and stratigraphy. In (2nd ed. ed.). Chichester, UK ; Hoboken, NJ: Wiley-Blackwell.

Pan, Y., Sha, J., Zhou, Z., & Fürsich, F. T. (2013). The Jehol Biota: Definition and distribution of exceptionally preserved relicts of a continental Early Cretaceous ecosystem. *Cretaceous Research, 44*(C), 30-38. doi:10.1016/j.cretres.2013.03.007

Vinther, J., Nicholls, R., Lautenschlager, S., Pittman, M., Kaye, Thomas g., Rayfield, E., . . . Cuthill, Innes c. (2016). 3D Camouflage in an Ornithischian Dinosaur. *Current Biology, 26*(18), 2456-2462. doi:10.1016/j.cub.2016.06.065

Wang, Y., Olsen, P. E., Sha, J., Yao, X., Liao, H., Pan, Y., . . . Rao, X. (2016). Stratigraphy, correlation, depositional environments, and cyclicity of the Early Cretaceous Yixian and ?Jurassic-Cretaceous Tuchengzi formations in the Sihetun area (NE China) based on three continuous cores. *Palaeogeography, Palaeoclimatology, Palaeoecology, 464*, 110-133. doi:10.1016/j.palaeo.2016.06.043

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Sediment Transport Processes

Sediment Characteristics

Sediment Transport Processes



Colorado River Flowing into Lake Mead. https://www.nps.gov/lake/learn/understanding-the-lakes.htm

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Sediment Characteristics

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Glacial Erosion

What is glacial erosion?

In glacial environments, the primary form of erosion is physical. Physical erosion is caused by the breaking up of rocks without changing their chemical composition. There is very little to no chemical weathering occurring in glacial environments due to the low temperatures. Glacial erosion can physically change rocks in many ways, such as the following major ways:

1. Ice can freeze in the cracks of rocks after rain, causing the ice to expand the cracks and lead to pieces of rock breaking off
2. Flow of glaciers “plucking” rocks up from the base of the flow
3. As the ice flows through glacial valleys they grind against the floor, along with other rocks

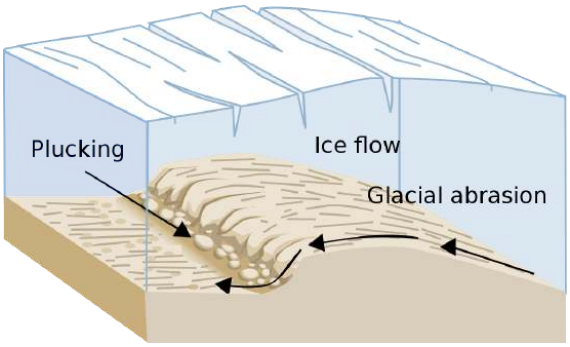


Fig 1. (https://commons.wikimedia.org/wiki/F...glaciar-en.svg)

What do the effects of glacial erosion look like?

The above listed examples can contribute to the way glacial erosion influences landscapes by carrying many small pebbles to large boulder sized rocks and clasts. Their most prominent effects are listed as follows:

1. Rocks with smoothed off faces from dragging against other rocks, also known as faceted clasts.
2. Striations and grooves within rocks due to the dragging or scraping across of rocks being carried by glaciers.
3. Glacial pavements that cause valleys to be smoothed off and flat due to glacial flow.
4. Rock flour, which formed from the bits of rock that are abraded off as facets, striations, grooves, and glacial pavements.
5. Glacial polish, which is caused when rocks or pebbles in glaciers slide across bedrock leaving it smooth.



Fig 2: Glacial striations left on bedrock in a glacial valley (https://commons.wikimedia.org/wiki/F...tion_21145.JPG)

Geomorphic Glacial Structures caused by Erosion

While glacial erosion can cause striations and other effects to bedrock, it can also form geomorphic structures. These structures are seen very frequently where there were once glaciers and are very common in glacial valleys.

1. Cirques are caused when glaciers erode into mountains, causing bowl-shaped and amphitheater-like depressions.

2. U-shaped valleys, or troughs, are caused as glaciers flow through v-shaped valleys previously carved by rivers. These sharp, narrow v-shaped valleys are then widened and steeper from the glaciers flowing through eroding the sides and bottom.
3. Fjords are narrow inlets to the ocean that become steeper and wider due to glacial flow and erosion. Their walls are similar to that of U-shaped valleys, however they have floors below sea level and are thus full of water.
4. Hanging valleys, shown in figure 3, are formed when a smaller glacier joins a larger valley glacier. These two glaciers have different depths (with the smaller glacier being shallower than the larger glacier) which when the glaciers have melted or retreated, causes the floor of the smaller glacier to be up higher above the valley floor. Waterfalls are common when rivers flow through hanging valleys.
5. Moraines are the leftover material from glaciers. This consists of soil and rock that is deposited as glaciers move and melt. There are four different kinds of moraines classified depending on where they formed in or on the glacier: lateral moraines (at the top of the glacier's edge), medial moraines (on top of and inside glaciers), superglacial moraines (on top of glacier), and terminal morianes (at the end of a glacier).



Fig 3: Hanging valley in Yosemite NP.



Fig 4: Fjord in Norway. (https://commons.wikimedia.org/wiki/F...gian_Fjord.jpg)

Where can effects of this phenomenon be seen in the world?

A particularly relevant area to Californians and hikers alike dominated by glacial erosion is that of Yosemite National Park. Tuolumne Meadows, located inside Yosemite NP, is a popular spot for rock climbers due to its large vertical rock faces. Tuolumne River runs through the park and cut the area into a V-shaped valley before a global cooling trend caused it to freeze over. Yosemite was then carved by a glacier, leaving a large U-shaped valley between the Sierra Nevada Mountains. Since it is dominated by glacial activity, most of the exposed bedrock is polished granite and there are a number of glacial lakes, rivers, and waterfalls. These are all the left over effects of glacial erosion and then melting, filling in those carved out areas. The steep walls of Tuolomne Meadows and many other popular climbing locations are due to the way the glaciers flowed through the previously glacially dominated area, leaving the high steep rock formations behind long after the glaciers had already retreated. Glacier National Park, in Montana, is dominated by sedimentary rocks overlain by magma instead of granites, but two million years ago was similarly dominated by these "rivers of ice". Glacier NP is characterized by multiple U-shaped valleys, cirques, and moraines. The park also currently has upwards of 20 alpine glaciers that have formed within the past 6,000 years.



Fig 5: Half Dome in Yosemite National Park, CA. (https://commons.wikimedia.org/wiki/F...P_-_Diliff.jpg)



Fig 6: Iceberg Cirque in Glacier National Park, MT. (https://commons.wikimedia.org/wiki/F...erg_Cirque.jpg)

Sources:

https://commons.wikimedia.org/wiki/F...tion_21145.JPG

https://commons.wikimedia.org/wiki/F...osemite_NP.JPG

https://www.nps.gov/articles/cirques.htm

https://www.nationalgeographic.org/encyclopedia/moraine/

Becker, Richard A.; Tikoff, Basil; Riley, Paul R.; and Iverson, Neal R., "Preexisting fractures and the formation of an iconic American landscape: Tuolumne Meadows, Yosemite National Park, USA" (2014). *Geological and Atmospheric Sciences Publications*. 151.
https://lib.dr.iastate.edu/ge_at_pubs/151

https://commons.wikimedia.org/wiki/F...P_-_Diliff.jpg

https://www.nps.gov/glac/learn/education/geology.htm

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Glacier Deposits

Overview

Glaciers erode and transport rock as they flow down slope. Then, when the glaciers start to melt or recede, the sediment is deposited as unsorted glacial till, often in characteristic landforms such as moraines and their associated sedimentary facies.

Glacial Erosion and Transport

Erosion

Because glacial environments are so cold, glacial erosion tends to be physical rather than chemical. Erosional processes include:

- Rocks breaking due to water freezing and expanding in fractures
- Rocks picked up off the valley floor by the base of a flowing glacier
- Rocks grinding against each other or the floor of the glacial valley as they are transported by flowing ice.

These processes produce certain distinctive sedimentary features:

- Clasts with smooth facets where they were dragged against other rocks
- Rocks with striations and grooves where they were dragged against other rocks
- Valley floors that have been eroded flat
- "Rock flour" made of clay-sized lithic grains.

Glacial erosion is also associated with erosional landforms such as U-shaped valleys, cirques, and aretes.



Figure 1: Yosemite Valley is a U-shaped glacial valley. (CC BY-SA 2.0; Daniel Mayer via Wikipedia)

Laminar Flow

Because ice is much more viscous than water or wind, sediment in a glacier is transported by laminar flow instead of turbulent flow. In laminar flow, the fluid particles (in this case, ice serves as a highly viscous fluid) flow in straight layers parallel to the direction of current, with minimal mixing. In a glacier, this means that any sediment and debris that gets incorporated into the body of ice will be carried alongside other grains as the glacier flows without becoming sorted by grain size as they would in water. The grains will not mix into the rest of the glacier, and as a result they tend to form sediment-rich bands in zones of heavy erosion such as the outer edges of a glacier.



Figure 2: Two converging glaciers carrying sediment as they flow towards the upper left corner of the image. Notice the bands of sediment, and the way these bands converge where the two glaciers meet.



Figure 3: A video demonstrating laminar flow (bottom) vs turbulent flow (top) of dye in water.

Glacial Deposition

Till

As the glacier melts or sublimates, all of the sediment carried in the glacier is freed from the ice as it recedes. Grains transported by ice, unlike those transported by water, are not sorted by size (though streams of meltwater may sort and transport the sediment after deposition). Once this pile of sediment is cemented into a rock, the result is a **diamictite**, a sedimentary rock made up of unsorted grains. A more specific name for an unsorted sedimentary rock with grains *deposited by ice* is a **tillite**. The loose sediment is called **till** in its unlithified form.



Figure 4: Glacial till. Notice the range of grain sizes mixed together with no sorting.

Moraines

A **moraine** is a ridge-shaped mound of till that forms as a glacier recedes. There are different types of moraines that are named depending on which part of the glacier the sediment comes from.

- A **terminal moraine** is a moraine that forms at the edge of a glacier's farthest extent. As the glacier melts and recedes, **recessional moraines** will form upslope from the terminal moraine, on land that was once covered by the glacier.
- Moraines also form along the sides of a retreating glacier; these are known as lateral moraines. Sediment tends to gather on the sides of glaciers from erosion or mass wasting of glacial valley walls. If there was a sediment-rich band in the center of the glacier, this will form a **medial moraine**. Such bands form when two tributary glaciers join together.
- In the space the receding glacier once occupied within the moraines, the bedrock is covered by a thinner layer of till called a **till sheet** or **ground moraine**.

Figure 5: Lateral moraines protrude from both sides of a glacial valley, and a terminal moraine dams a proglacial lake.

Glacial Erratics and Dropstones

Ice is capable of carrying very large, heavy pieces of rock. When the glacier melts, it may leave behind rocks that have been transported a great distance and seem out of place in their new environment. A **glacial erratic** is a large rock that is left behind by a retreating glacier. Because they were transported by the ice, the erratics are usually made of a different rock type than the local bedrock in the place they are deposited.

A **dropstone** is deposited in a similar manner, but in a marine or lacustrine environment as an iceberg (a fragment of a glacier floating in water) melts and drops any sediment that was trapped in the ice. Dropstones tend to be much larger than the fine-grained sediment found in marine environments.

Meltwater Structures

After the sediment is deposited by a receding glacier, it is often rearranged by the meltwater flowing from the glacier. This secondary process of transport and deposition creates additional glacial landforms. Unlike till, these structures are generally sorted by grain size because the main agent of transport is flowing water.

- Water flowing along the base of the glacier carries and deposits sediment in a manner similar to a river. An **esker** is a sinuous ridge made of sediment, formed by the flow of a meltwater stream below the ice. As the glacier melts and recedes, the esker is exposed.
- When water flows on top of or through the ice it may deposit sediment that gradually accumulates into a mound. As the glacier recedes, the mound is left behind forming a hill called a **kame**.
- A **drumlin** is another type of glacial hill, characterized by their asymmetrical shape with one steep side facing opposite the direction of glacial flow, and one elongate, gently sloped side pointing in the flow direction. The method of their formation is still debated.

Glacial Facies Assemblages

Moraine Facies

This facies consists of mounds (morraines) of diamictite. The clasts are mostly lithic fragments, including silt and clay-sized rock flour. The clasts tend to be angular, and some may have facets and striations.

Till Sheet Facies

This facies is composed of planar sheets of diamictite. Shale and sandstone interbeds are rare, and structurally resemble turbidites. The clasts are similar to those in the moraine facies: angular lithic fragments with some facets and/or striations and silt and clay-sized rock flour.

Distal Glacial Lacustrine/Marine Facies

Consisting of sediments deposited in proglacial lakes and similar marine environments, the distal glacial facies is characterized by interbedded shale and sandstone with structures resembling turbidites. Large isolated clasts (mostly angular lithic fragments) are found in the shale and decrease in frequency as distance from the glacier increases.

Related Libretexts pages:

- 9.10: Glacial Environments
- 14.5: Glacial Landforms
- 6.1.6: Glacial Environments (Chapter 7)
- 1.2: 2. Fluid Flow 1
- https://www.sciencedirect.com/scienc...12825287900614

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Effects of Sediment Composition & Compaction on Groundwater Pumping in the San Joaquin Valley

by Veronica Guerra

I. History of Groundwater Use in California's Central Valley

The original demand for groundwater in the Central Valley dates back to the California Gold Rush (Ref. 1). In the mid-1800s, settlers from the Gold Rush began farming in the Delta and Central Valley (Ref. 1). The rise of agriculture necessitated new water sources and transport methods, especially in the San Joaquin Valley (Ref. 1). This was remedied in part by groundwater development, which began in California around 1880 (Ref. 1). By 1913, pumping wells had become an effective groundwater retrieval method in the Central Valley (Ref. 1). Groundwater pumping persisted for years, but with adverse effects (Ref. 1). From 1926 to 1970, pumping caused widespread compaction of fine-grained sediments and "significant land subsidence" (subsidence exceeding 1 ft.) in about half of the San Joaquin Valley, even exceeding 26 ft. in certain localities (Refs. 1, 2, 3).

In the early 1970s, groundwater pumping finally began to decline (Ref. 2). With the increasing reliance on surface water imports, land compaction slowed down and groundwater levels began to steadily recover (Ref. 2). However, drought conditions from 1976-77, 1986-92, 2007-09, and 2012-2015 reduced surface water availability and thus drove increases in groundwater pumping, causing sediment to compact again and water levels to decline to near-historic lows (Refs. 2, 3).

II. About the San Joaquin Valley

A. Basins

The San Joaquin Valley is made up of two basins: the San Joaquin Basin and the Tulare Basin (Ref. 1).

The San Joaquin Basin is comprised of the San Joaquin River, part of the San Francisco Bay/Sacramento—San Joaquin River Delta (hereafter called "Delta"), and populous cities including Merced, Modesto, Stockton, and Turlock (Ref. 1). Most of the land in this basin is used for agriculture, creating a strong reliance on groundwater (Ref. 1). Groundwater makes up as much as 30% of the region's annual water supply that is used for agricultural and urban purposes (Ref. 1).

The Tulare Basin is the drainage site for the Kings, Kaweah, Kern, and Tule Rivers (Ref. 1). Many of these rivers formed lakes that have long since dried out and whose feedwaters have been diverted for irrigation (Ref. 1). Today, much of Tulare Basin is used for agriculture and petroleum extraction (Ref. 1). It is also home to major cities including Bakersfield, Fresno, and Visalia (Ref. 1). As such, groundwater has been a major source of water for agricultural and urban uses (Ref. 1). Up until the early 2000s, groundwater made up an overwhelming majority of Tulare Basin's total water supply (≥ 69% from 1998-2001) and the entirety of Fresno and Visalia's water supplies (Ref. 1). Since then, groundwater recharge programs have been implemented by water districts to undo some of the damage (Ref. 1).

B. Groundwater Issues

Declines in groundwater storage have been prominent in the San Joaquin Valley (Ref. 1). As a result of groundwater pumping, water levels in the 1960s declined "to historic lows in the western San Joaquin Valley" and major land subsidence occurred (Ref. 1). Later that decade, the issue was somewhat remediated with the onset of a surface water

delivery system, which delivered water from the Sacramento Valley and the Delta to the “heavily pumped San Joaquin Valley” (Ref. 1). By the early 1970s, the system “was fully functional” and helped groundwater levels recover “in the northern and western parts of the San Joaquin Valley” (Ref. 1). As of 2009, however, groundwater levels and storage were still declining (Ref. 1).

III. Effects of Groundwater Pumping on Water Quality

While certain minerals and trace elements are usually naturally found in groundwater, human activities can influence their concentration (Ref. 4). Among these materials whose concentrations have been affected by groundwater pumping in the San Joaquin Valley are chloride, nitrate, and arsenic (Refs. 5, 6, 7).

A. Chloride and Nitrate

According to chloride spatial distribution maps of the San Joaquin Basin, groundwater concentrations of chloride increase towards the Delta (see Fig. 1) (Refs. 5, 6). Concentrations from well water locally exceed 100 mg/L or 250 mg/L, while wells further east have concentrations of less than 50 mg/L (Refs. 5, 6). The extra chloride may be entering groundwater from any of three potential sources: irrigation return, delta sediments, and deeper deposits as a result of groundwater pumping (Ref. 5).

Water from these three sources can be distinguished by their chloride concentrations. Water from irrigation return has a relatively low chloride concentration but high nitrate concentration (Ref. 5). In contrast, water from delta sediments and deeper deposits both have high concentrations of chloride (Ref. 5). Izbicki et al. and Metzger suggest that these two sources are the biggest contributors of chloride to groundwater (Refs. 5, 6).

Evidently, sediment composition can have a profound effect on water quality. When water is pumped in areas that are in contact with delta or deep sediments, harmful minerals and elements can be pulled into the water, making the water unfit to drink.

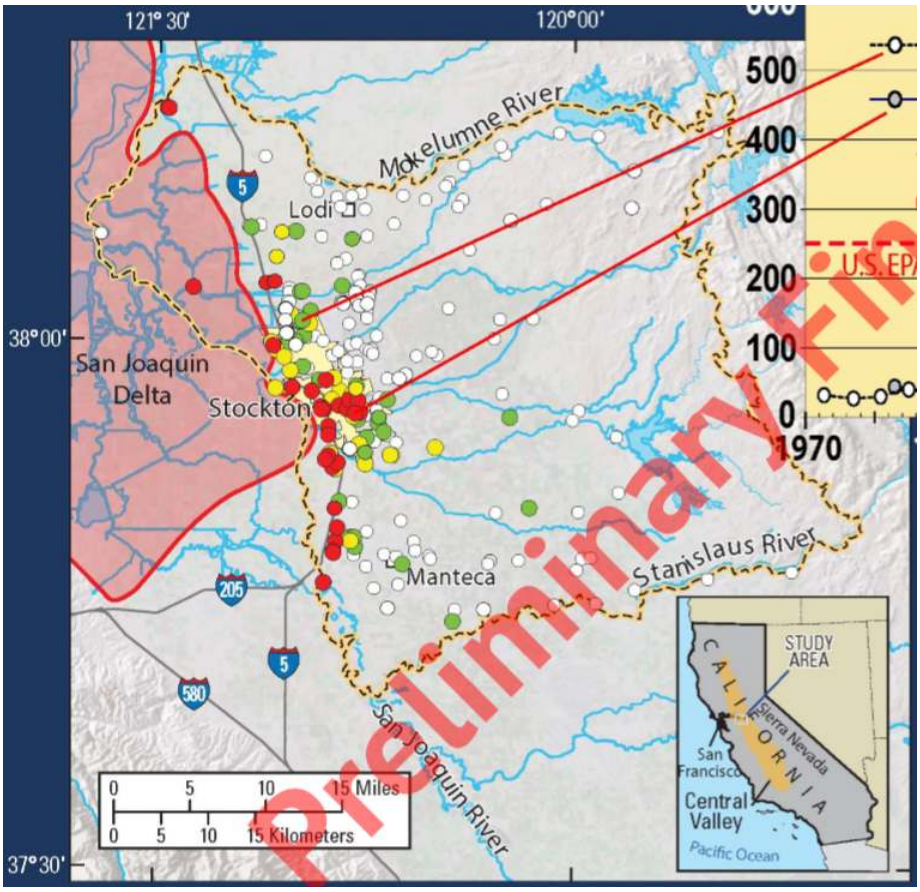


Figure 1. Map of chloride concentrations in the San Joaquin Basin. Legend: white = less than 50 mg/L; green = 50-100 mg/L; yellow = 100-250 mg/L; red = over 250 mg/L. From Metzger (Ref. 6).

B. Arsenic

Two toxic forms of arsenic have appeared in well water in the Eastern San Joaquin Groundwater Subbasin: arsenite (As III) and arsenate (As V) (Ref. 4). From 1974 to 2001, arsenic concentrations in up to one-third of wells in this area exceeded the Maximum Contaminant Level (MCL) of 10 µg/L and locally exceeded 60 µg/L (see Fig. 2) (Ref. 8). Concentrations typically increase towards the Delta, much like chloride concentrations, and increase with depth (Ref. 8). This is concerning because pumping may influence arsenic levels (Ref. 8). Izbicki et al. simulated the response to groundwater pumping in the San Joaquin Groundwater Subbasin using MODFLOW (Ref. 8). They found that when pumping persisted for 1,000 days, deeper deposits “contributed increasingly to the yield of the well”; arsenic levels increased accordingly (Ref. 8).

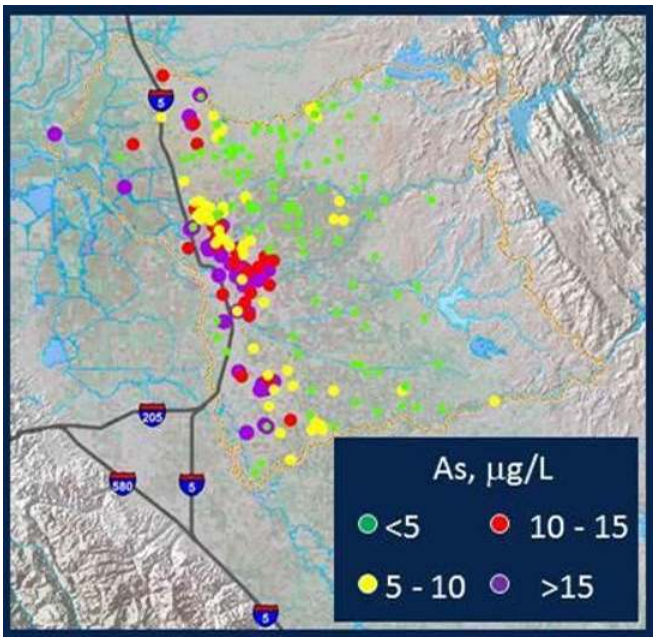


Figure 2. Map of arsenic concentrations in the San Joaquin Basin. From Izbicki et al., 2014 (Ref. 5).

Arsenic in this area can come from a variety of sources. The primary source is weathering of arsenic-bearing minerals from volcanic deposits or alluvium from the Sierra Nevada (Ref. 8). This includes iron-sulfide minerals like pyrite, which often contain arsenic in their crystal structures (Refs. 5, 8). However, the amount of arsenic can vary depending on whether the pyrite is a primary or secondary mineral (Refs. 5, 8). In the San Joaquin Basin, octahedral pyrite crystals, a primary mineral, were found to contain up to 4% arsenic by weight (Refs. 5, 8). In contrast, twinned pyritohedron crystals, a secondary mineral, did not contain any (Refs. 5, 8).

Arsenic concentrations also increase with pH and under anoxic conditions (Ref. 8). When mineral grains are coated in iron and manganese oxide, arsenic can desorb when the pH is greater than 7.6 or be released through reductive dissolution under anoxic conditions (Ref. 8).

Somewhat like chloride and nitrate, arsenic concentrations in groundwater are dependent on the composition of the individual mineral grains making up deep deposits; however, pH and oxygen levels also play a role. It is therefore important that the composition of deep deposits is considered prior to pumping. Otherwise, as the results from Izbicki et al. suggest, the contribution of arsenic from these deposits may be heightened (Ref. 8).

IV. Effects of Groundwater Pumping on Water Levels and Land Subsidence

A. How Groundwater Pumping Causes Land Subsidence

The process of groundwater pumping in the Central Valley has irreversible effects on water levels and land subsidence (see Fig. 3). Persistent pumping since the 1960s has caused water levels to significantly decline (Ref. 9). When water levels decline, fine-grain deposits irreversibly compact because they drain so slowly, causing “extensive land subsidence” in the San Joaquin Valley (Refs. 1, 9). By 1970, about half of the San Joaquin Valley (roughly 5200 mi^2) had subsided by at least 1 ft. (Ref. 1).

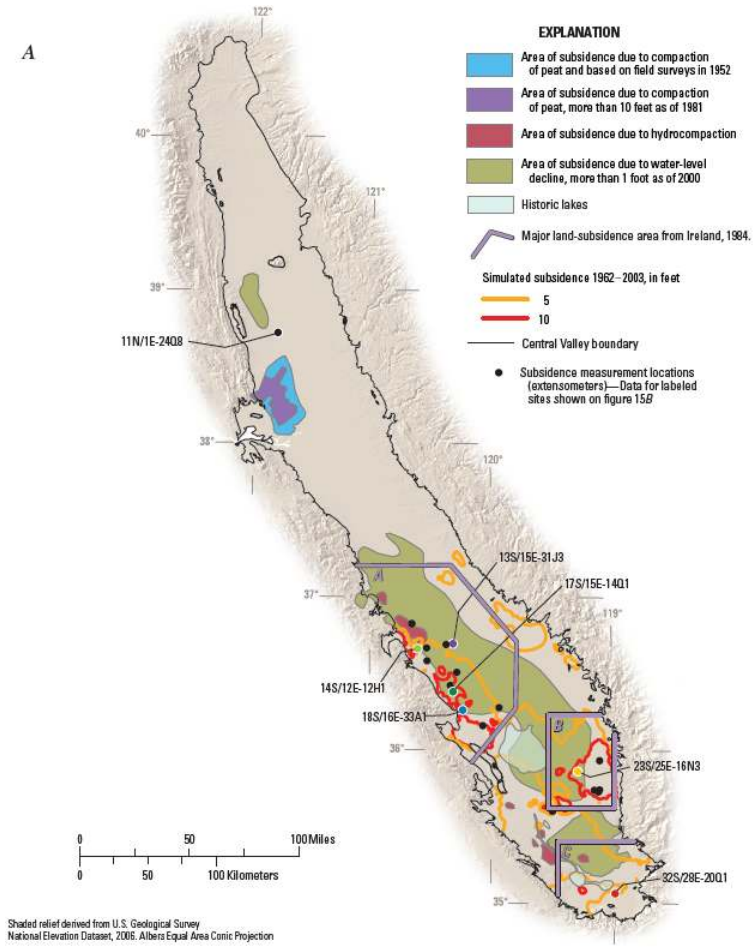


Figure 3. Map of land subsidence in the Central Valley. From Faunt, ed., 2009 (Ref. 1).

B. Areas Affected by Land Subsidence

Three areas in the San Joaquin Valley have been significantly affected by land subsidence as a result of groundwater pumping: "(1) 1500 mi^2 in the Los Banos-Kettleman City area, (2) 800 mi^2 in the Tulare-Wasco area, and (3) 400 mi^2 in the Arvin-Maricopa area" (Ref. 1). The Los Banos-Kettleman City area experienced head declines of up to 500 ft "in the confined part of the aquifer" due to groundwater pumping (Ref. 1). This caused inelastic compaction of clay deposits, resulting in land subsidence of up to 28 ft (Ref. 1).

Other affected areas outside of the San Joaquin Valley include the Sacramento Valley and Yolo County (Ref. 1). Studies from the early to mid-1990s showed that the Sacramento Valley experienced up to 4 ft of subsidence since 1954 while Yolo County was just beginning to experience subsidence of several feet (Ref. 1).

C. Recent Land Subsidence

From 2008-2010, which overlapped with the 2007-09 drought, 1200 mi^2 of the northern San Joaquin Valley subsided at a rate of 0.5-11 in/yr (Ref. 10). Surveys showed that those rates continued at least through 2013, even though much of this period was not a drought period (Ref. 10). This suggests that subsidence is highly dependent on surface water imports (Ref. 10). When surface water imports are low, more groundwater is extracted, driving land subsidence (Ref. 10). A reliable surface water supply may be critical for recovering water levels and slowing down subsidence in the future (Ref. 10).

V. Current Endeavors

Models are currently being used to simulate and understand the effects of groundwater pumping in the Central Valley and its future hydrologic conditions, including the Central Valley Hydrologic Model (CVHM), Global Climate Models (GCM), and MODFLOW (Refs. 1, 8, 9). The results of these studies can help guide future decisions made to help monitor and manage groundwater levels and subsidence.

References

Faunt, C.C., ed., 2009, Groundwater Availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 225 p., https://pubs.usgs.gov/pp/1766/

Delta-Mendota Canal: Evaluation of Groundwater Conditions & Land Subsidence: United States Geological Survey, https://ca.water.usgs.gov/projects/c...ota-canal.html.

Land Subsidence in the San Joaquin Valley: United States Geological Survey, https://www.usgs.gov/centers/ca-wate...center_objects

Fram, M.S., 2017, Groundwater quality in the Western San Joaquin Valley study unit, 2010: California GAMA Priority Basin Project: U.S. Geological Survey Scientific Investigations Report 2017–5032, 130 p., https://doi.org/10.3133/sir20175032.

Izbicki, J.A., Metzger, L.F., O'Leary, D.R., 2014, Overview of USGS study results in Northeastern San Joaquin Groundwater subbasin: Implications for water quality and groundwater recharge: U.S. Geological Survey, https://ca.water.usgs.gov/projects/c...y_recharge.pdf.

Metzger, L., 2014, Chloride Mapping on the Basis of Electromagnetic Log Data: U.S. Geological Survey, https://ca.water.usgs.gov/projects/c...de_mapping.pdf.

O'Leary, D., Izbicki, J., 2014, Movement of recharge water from land surface to wells: U.S. Geological Survey, https://ca.water.usgs.gov/projects/c...rge_water_.pdf.

Izbicki, J.A., Stamos, C.L., Metzger, L.F., Halford, K.J., Kulp, T.R., Bennett, G.L., 2008, Source, Distribution, and Management of Arsenic in Water from Wells, Eastern San Joaquin Ground-Water Subbasin, California: U.S. Geological Survey Open File 2008-1272, 8 p, https://pubs.usgs.gov/fs/2009/3057/.

Central Valley Hydrologic Model (CVHM): U.S. Geological Survey, https://ca.water.usgs.gov/projects/c...ogic_Model.pdf.

. Sneed, M., 2014, Land Subsidence along the Delta-Mendota Canal in the Northern Part of the San Joaquin Valley, California: U.S. Geological Survey, https://ca.water.usgs.gov/projects/c...dota-Canal.pdf.

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Meandering Rivers

Introduction

Meandering Rivers are located on flat terrain that reduces the flow speed of water, allowing the river to curve or "meander". The bends in the river will migrate back and forth within the river valley. There is a differentiation in flow speeds within a meandering river channel that produces areas of erosion and deposition. There are distinct sedimentary structures that result from this process.

Sediment Erosion/Deposition



Figure 1: Aerial photograph of a meandering river. The point bar, where sediment is deposited, can be seen in the inner bend of the river. There is a build up of gray colored sediment. The bank of the channel is where erosion occurs, and is located on the outer bend of the river. http://www.public-domain-image.com/full-image/nature-landscapes-public-domain-images-pictures/river-public-domain-images-pictures/meandering-river-aerial-photography.jpg.html

When the water moves around a curve, the velocity of the water is highest along the outer part of the channel. This area is referred to as the **bank** of the channel, and it is where erosion of sediment occurs. Erosion is caused by the increase in flow velocity, which has the force to erode and transport sediment from the bank. On the inside bend of the river, known as the **point bar**, water velocity is slower because it doesn't have to travel as far as the water on the outside of the bend. This allows sediment to settle out and be deposited. As this cycle of erosion and deposition continues, the river will migrate in it's river valley. This migration can lead to the creation of an **oxbow lake**, which is described further here: https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner)/Textbook_Construction/Floodplains_and_Oxbow_Lakes.

Sedimentary Deposits/Structures

Due to the higher velocity in the middle and outside bend of the river channel, coarser sediment will be deposited in those areas. The coarser grains will be transported to these parts of the river channel because the higher velocity is able to transport the heaver grains. This is related to the concept of **Reynolds Number**, which measures whether sediment transport of a specific grain size will be able to occur based on the velocity of the water.

There are two distinct areas within the river channel that are characterized by different flow speeds and grain size, the outer edge and the inner bend of the channel. The different flow speeds will carry different sized sediment grains, which will produce a cross section that is asymmetrical. The coarser grains will be present in the outer edges of the channel, while finer sediment will be along the inside of the channel. The different flow speeds within the channel, along with the different grain sizes, will produce unique sedimentary structures. The coarser grained areas that result from a faster flow speed will have upper planar lamination or dune cross stratification. The point bar of the river will produce current ripple lamination, due to the finer sediment and slower flow speeds. As the river migrates towards the direction of the eroding bank, the current ripples of the point bar will end up being deposited on top of planar lamination/dune cross stratification of the bank.

Facies/Stratigraphic Column

The typical facies that occur within a meandering river environment include a scoured base of flow, which is caused by the high flow velocity in the middle of the channel that is able to pick up and transport large sediment particles. There would also be a lag deposit of mud rip-up clasts and the coarsest sediment within the facies. A **lag deposit** is where physical processes remove the finer sediment, leaving behind the course grains. As we move upward in the stratigraphic column, the grain size will become more fine. The structures you should find are trough cross stratification, rippled sands, and finally sigmoidal cross stratification resulting from the point bar migration.

Periodically, the river will flood, causing its floodplain to fill with fine-grained sediment. This is due to the water flow velocity decreasing as it flows away from the river channel. More information on floodplains can be found on the previously linked page on Oxbow Lakes and Floodplains. The floodplain facies will be incorporated into the typical meandering river facies.

Figure 2: A typical stratigraphic column for a meandering river system with the lag deposits on the bottom, followed by trough cross stratification and ripple cross lamination. This is overlain by a typical floodplain facies that is composed of mud cracks and root traces in a fine grained sediment. https://www.geol.umd.edu/~jmerck/geol342/images/10pointbarfloodplain.jpg

There are also key differences in the facies for a meandering river channel and a braided river channel. Braided river channels will have coarser grain sizes due to their faster flow speeds. Meandering rivers carry lots of sediment within suspension that will be deposited in the structures associated with this environment, including point bars and oxbow lakes. Lastly, the migration of meandering rivers is more uniform in direction than a braided river because it will always migrate towards the eroding bank. A braided channel will migrate in many directions at the same time.

Key Words

Meandering

River Channels

Point Bar

Eroding Bank

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Oxygen Isotopes and Chemostratigraphy

What is Chemostratigraphy?

Edited by Colin Boisvert, notes in blue

Chemostratigraphy Shouldn't this be in bold? is the study of the trace element and isotopic variability of sedimentary layers and is often used in conjunction with other types of stratigraphic analysis such as biostratigraphy, lithostratigraphy, or chronostratigraphy. It concerns itself with correlating geochemical changes with a geological event or age, a process known as fingerprinting Bolden. When we observe that a particular trace element or isotope responds to a certain process, we can use those observed changes to interpret a geologic event. When interpreted this way, we call that chemical a proxy for a given process. For example, oxygen isotopes respond to changes in temperature and are a common proxy for climate change in the past. By observing how oxygen isotopes vary in a stratigraphic sequence over time, one can infer what the climate in that region may have been like over that time period (1).

In geochemistry, many proxies are not measured by themselves as a total quantity but instead in relation to another relevant trace element or isotope as a ratio. For example, oxygen isotopes are measured as the abundance of one isotope to another: 18O/16O. This means that in order to interpret geologic events, we look at relative changes in one element or isotope when compared to another across a stratigraphic sequence (1, 2).

I would add an initial figure and table here to illustrate what you mean by oxygen demonstrates a proxy for paleoclimates. citing a paper and using a figure from it to show the change in temp over a period of time should do the trick like this paper Bohaty and Zachos 2003 Significant Southern Ocean warming event in the late middle Eocene. The 2 column table will demonstrate a list of 4-5 chemical proxies you can find and their relative use. ex. oxygen for paleoclimates,carbon for photosynthesis, etc... just for comparision can other proxies be used for paleoclimates?

Oxygen Isotopes

Why would we want to study oxygen isotopes specifically as a chemostratigraphic tool? Fundamentally, oxygen stable isotopes as a proxy respond to temperature variations brought about by climate change. Meaning that if we study oxygen isotopes, we can gain some insight into climatic controls over time. They are usually studied in some hydrologic context and can be observed in most naturally-occurring substances that contain oxygen. These substances include, but are not limited to: carbonate shells from marine and terrestrial sediments, calcite deposits, ice sheets(specifically Ice cores from these sheets), and liquid water.

We trace oxygen isotopes by looking at the ratio of 18O to 16O. Over 99% of the oxygen on Earth is 16O, with most of the remainder being 18O (1,2). Since there is significantly less 18O on Earth, we can compare subtle fluctuations in 18O relative to 16O to get a sense of what climatic processes were happening at some point or region over a certain amount of time. Give a short sentence on why there is less 18O compared to 16O and which does evaporation prefer when sucking water out of the ocean.

It is worth noting that oxygen isotopes are not the only proxy with which we can study climate change. Other proxies, such as strontium isotopes, carbon isotopes, or trace elements, also describe different processes and have different drivers. Since oxygen isotopes tend to respond to temperature variability, they can give us a picture of basic environmental and/or climatic changes over time. Coupling oxygen isotope records with other proxies gives that picture more detail.

As stated above add the table to illustrate this last paragraph.

Measuring Oxygen Isotopes

18O/16O values are reported relative to international standards usually VSMOW. By using a standard, this provides a reference point for the observed values and gives context to the observer. Values for aqueous oxygen isotopes, sourced from solid, liquid, and gaseous phases, are reported against Vienna Standard Mean Ocean Water (VSMOW). Values for carbonaceous oxygen isotopes, such as those from seashells or calcite deposits, are reported against Vienna Pee Dee Belemite (VPDB). When reporting relative to a standard, these proxies use the following delta notation (1):

 *(Equation from ref. 2)

Where,

(18O/16O)sample = the value of your sample
(18O/16O)standard = the reference value of your standard (either VSMOW or VPDB)
d18O = the notation used to represent the value of your sample relative to the standard (called "delta 18 O")

It is important to note that d18O is reported in ‰, or “per mil”, hence the multiple of 1000 included in the calculation. ‰ simply means “parts per thousand”, much like how % means “parts per hundred” or “per cent”.

The Water Cycle and Oxygen Isotopes

To understand how we can trace oxygen isotopes and interpret their variability in these proxies, we must review the water cycle. In general, water evaporates out of the oceans, condenses into clouds, precipitates over land as rain and snow, forms river runoff, and is deposited back into the ocean where the cycle restarts (Fig. 1). At each of these stages, oxygen isotopes in water molecules respond, or sort themselves, in a way that we can measure. As mentioned before, oxygen isotopes respond to temperature, and they do so in a way sorting themselves, with respect to their relative masses.



Figure 1. A simplified water cycle, emphasizing evaporation, precipitation, and runoff (3).

We will start with water evaporating from the ocean. Since 16O is more lightweight than 18O, it will have a greater tendency to evaporate out of the ocean than 18O will. This means that 18O/16O in the ocean goes up (because more 18O stays in the ocean than leaves it) and 18O/16O of the water vapor goes down (because 18O generally stays in the ocean).

Once a cloud forms and moves over land, 18O has a tendency to become more mobile. Since it is heavier, it will tend to condense, form raindrops, and fall to the ground relatively more frequently than 16O will. This means that rain will tend to have a higher 18O/16O than the cloud that it came from. In this sense, 18O falls out of clouds more frequently than 16O does because it is literally heavier. This is more pronounced with proximity to the ocean, meaning that places near coastlines will have higher d18O when compared to places further inland.

Once a cloud reaches a cold enough area to produce snow, that snow has a much lower d18O value when compared to the original, evaporated ocean water because so much of the source 18O has already fallen out. This usually means that snow, and therefore ice sheets, contain a disproportionately large amount of 16O (the lighter isotope) when compared to 18O (the heavier isotope) (2).

River runoff usually has an “in-between” value, since it can be a combination of snow melt from upstream, rainwater, and input water from other sources.

Consequently, this all means that in order to move more 18O out of the ocean and onto any location on land, you must put more energy into the ocean by increasing the temperature. This means that, for example, proxies in marine sediments showing decreased d18O is a sign of a warm, possibly ice-free period (2). This implies that at the time those sediments formed, there was more 18O throughout the hydrologic cycle in general and that much of the 16O-rich ice had melted and re-integrated with the oceans. If those same proxies showed higher d18O, then that would be a sign of a cold period, possibly an ice age, and would have the opposite implications (2). This is all also true for many terrestrial proxies, but with reversed d18O values corresponding to warm and cold events (1). For reference, Figure 2 shows the typical d18O values for different ice and water reservoirs (2). Careful with these last 3 paragraphs the way the 18O/16O ratio operates between the evaporation condensation cycle and glaciers is different while the ideas are somewhat connected and should be stated as such. These paragraphs give me the idea they are more linked. Since 16O is light it gets sucked into glaciers more leaving a heavier ocean during cold times and then when melt occurs the ratio goes back down but this is slightly different from the evaporation cycle ratios as learned in Gel 108. this may help

https://www.seas.harvard.edu/climate/eli/research/equable/isotope.html



Figure 2. Typical d18O values at different regions on Earth. Polar ice caps tend to have very negative d18O values, reflecting a higher concentration of 16O relative to 18O (2). In contrast, the deep ocean waters have slightly positive values, reflecting opposite concentrations. Both the negative values seen in ice and the positive values seen in the ocean are consistent with the idea that 18O tends to stay in the ocean unless enough energy is applied to move it out of the ocean.

Oxygen Isotopes as a Chemostratigraphic Tool

Given the natural range of d18O values shown in Figure 2, it is important to note that different types of proxies will produce different d18O values. For example, very positive values in marine sediments potentially describe the same geologic event as very negative values in polar ice cores. This section uses benthic foraminifera fossils (Fig. 3) from marine sediments as an example for how we construct d18O chemostratigraphic records for paleoclimates.



Figure 3. Examples of benthic foraminifera fossils (4).

Foraminifera (or “forams”, for short) are microscopic, single-celled organisms. There are planktonic varieties, which live within the uppermost water column, and benthic varieties, which live along the seafloor. Both kinds of forams take dissolved calcium and bicarbonate ions directly from the water column to build their calcium carbonate (CaCO3) shells. In doing so, they preserve the d18O signature of the surrounding water within their shells. When they die, their shells are buried and preserved in the sediment. By examining the d18O variability from layer to layer and cross-referencing with chronostratigraphy and/or age-dating, forams can be used to create a natural record of ocean d18O variability through time. Sure forams can record the delta18O record but why can they create a natural record of ocean variabity through time. (its because they are considered index fossils and species change rapidly over well studied short temporal ranges combined with the oxygen isotope record they provide to create a bigger picture of the paleoclimate of the ocean through time.

As previously discussed, d18O fundamentally responds to temperature variability. Likewise, the d18O preserved in foram shells also depends on surrounding temperatures and will show enrichment in 18O (more positive values) when the surrounding water is colder and depletion in 18O (less positive values) when the surrounding water is warmer. In other words, the shells reflect the composition of the water at the time the shells were formed and that composition gives us insight to how both the ocean environment and global climate dynamics may have changed over time (1).

Benthic forams are most often studied in d18O stratigraphy because they are easier to interpret d18O variability through time (Fig. 4). Since they live on the bottom sediment and have more limited mobility, their d18O signal theoretically responds only to temporal environmental changes. Planktonic forams are more likely to move around, causing their d18O signals to reflect more spatial variability. These forams may have been transported across some horizontal distance, giving a d18O signal that represents an unknown location. Additionally, since planktonic forams live at various depths within the water column, and temperature of the water can vary with depth, their d18O signal may actually reflect vertical spatial variability rather than environmental change over time. Studying benthic forams allows for location to be controlled so changes in d18O can reflect changes over time (2). Again, great paragraph but don't forget to mention why over time unless you have a consecutive series of species living that have constricted time windows to study the variation to build the bigger picture.

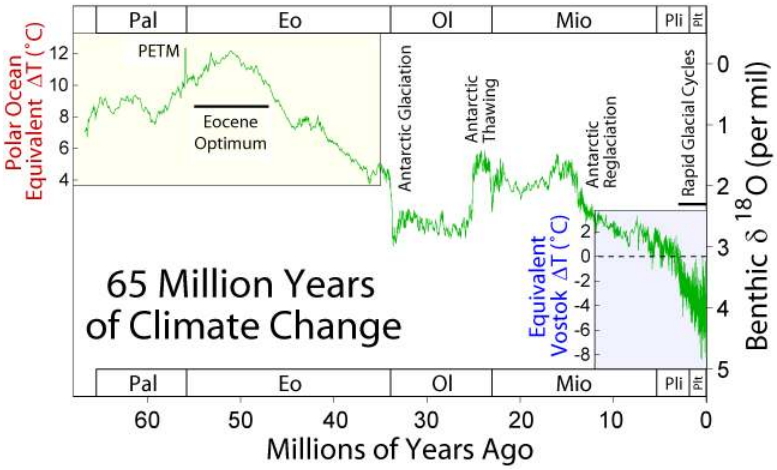


Figure 4. Climatic record of the Cenozoic as documented by d18O from benthic foraminifera. More negative values (toward the top of the chart) represent warmer periods. More positive values (toward the bottom of the chart) represent colder periods. Several dramatic shifts in d18O have been noted. The PETM (Paleocene-Eocene Thermal Maximum) represents a temporary(use rapid instead of temporary as this event lasted 170ka and temporary isn't a clear geologic term)*, intense warming period. The Antarctic Glaciation is marked by a permanent, positive shift at the end of the Eocene that cooled the Earth and caused the Antarctic ice sheet to form. At the end of the Oligocene, there was a negative shift that caused melting of the ice sheet. After about 10 million years of stability, a continuous positive shift occurred. The Antarctic ice sheet reformed and the Earth went through several glacial cycles (*Ice ages)*up to the present (5).* I wouldn't italicize the figure caption hard to read. good figure though something like this for the top of the page.

Great start. Can you provide more information on why one would want to use d18O as a chemostratigraphic tool (noted, working on that)? Also, they reflect water d18O in addition to temperature. And in fact, temperatures vary significantly laterally, so the temperature dependence of d18O isn't the part that makes it a *stratigraphic* tool. It's the changes in seawater d18O due to ice volume that change ocean chemistry globally, making d18O useful as a stratigraphic tool. The temperature dependence is very useful for reconstructing ancient environments, though, when the water d18O changes can be accounted for as well (Great points. Temperature dependence is the driving factor, so that's important to include. This is partially addressed in the newly-added water cycle section. The next step is talking about how forams record isotopes in the water column and that will address how d18O is useful as a stratigraphic tool.). Section 3.3.1.3 of this chapter will be helpful: https://www.sciencedirect.com/scienc...24199682000030

good work cited, very clear

The page is very well done and thorugh, once the few extra explanations/ misunderstandings are worked out this page is ready to rock and relevant figures in appropriate places.

References:

(1) Ramkumar, Mu. *Chemostratigraphy: Concepts, Techniques, and Applications*. Elsevier publishing, 2015.

(2) Ruddiman, William F. *Earth's Climate: Past and Future*. W. H. Freeman and Company, 2008.

(3) [I'm not really sure how to cite this one] https://encounteredu.com/multimedia/images/why-is-the-water-cycle-important-to-us

(4) [I'm not really sure how to cite this one] https://commons.wikimedia.org/wiki/File:Benthic_foraminifera.jpg

(5) [I'm not really sure how to cite this one] https://commons.wikimedia.org/wiki/File:65_Myr_Climate_Change.png

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Physical Weathering

Physical Weathering

Sediment comes from the break down of rocks into smaller, transportable components. This occurs via two processes: **physical weathering** and **chemical weathering**. Physical weathering consists of breaking apart rocks and crystals through different processes without changing their chemical composition. The results of physical weathering are smaller components of the same material that is being weathered. There is no change in chemical composition. Physical weathering tends to produce mostly sand-sized sediment and larger grains because most of the fracturing occurs along mineral boundaries. Physical weathering of fine grained or finely crystalline rock can produce abundant very fine grains, but most of the sediment from these rock types consists of rock fragments called **lithic clasts**. Lithic clasts produced from physical weathering range in size from very fine silts and clays to large boulders and gravel.



Figure 1: Mountain regions undergo rapid physical weathering due to wind, ice, and temperature changes. Photo: Greg Bulla - Eastern Sierras.

Physical weathering, also known as mechanical weathering, works along with chemical weathering to efficiently wear down rocks. Breaking a rock through physical weathering increases the effective surface area in which chemical weathering can occur, and through changing the composition of rocks in chemical weathering, the durability of a rocks surface can decrease allowing for it to be more easily removed by physical processes. From this, we can see that both chemical and physical weathering work together to increase rock erodibilty.

Physical Weathering Processes

There are 6 common ways in which physical weathering happens.

Abrasion:

Abrasion is the process by which clasts are broken through direct collisions with other clasts. Gravity causes abrasion as rocks tumble down a mountainside or cliff. Abrasion also commonly occurs in river beds where clasts tumble along the bottom with the current or on sand dunes where wind causes grains of sand and silt to collide with exposed rock. Rocks can also undergo abrasion within glaciers too, where clasts embedded in ice grind along the rock below. Clasts that undergo abrasion tend to be come more round and smooth. This process is called **rounding.**



Figure 2: *Abraded rocks along river stream bed. Note the rounded and flattened shape. Photo: Yannis Papanastasopoulos - Greece.*

Frost Wedging:

Frost wedging occurs in places that have the right temperatures to freeze water and then melt water. This commonly happens in polar regions and mid latitude mountains where sunlight can melt water during the day and refreeze overnight when temperatures drop. Frost wedging is directly related to the fact that as water freezes its volume increases by roughly 9%. Liquid water percolates into existing cracks within a rock. The pressure of expanding ice causes cracks to widen and extend. This processes then repeates as melted water further fills newly formed cracks and freezes. Frost wedging works quickly and results of which can be seen at the bottom of hill-slopes as piles of fragmented rocks.

Biological Activity/Root Wedging:

Weathering processes can happen due to the activity of living organisms. Burrowing animals can break rocks and stir sediments causing physical weathering. Animals that burrow can also bring fresh material to the surface where physical and chemical weathering can work more efficiently. Plant roots in search of nutrients in water grow into fractures. As the roots grow they wedge the rock apart similar to the frost wedging process. This is called root wedging. During root growth, organic acids can form contributing to chemical weathering.

Salt Crystal Growth:

Another expansive force that can break rocks is created by the growth of salt crystals. This process frequently happens near shorelines and in arid regions ie: beaches and deserts. The process begins when water that has dissolved salt in it penetrates cracks in rocks. As the water evaporates, salt crystal begin to form. These crystals expand pushing against existing grains in the rock, this eventually breaks it.

Sheeting:

Sheeting, also known as exfoliation, happens in regions with large masses of igneous rocks. It is caused by the pressure release as overburden rock is eroded away. The process of removing overlying rock is called **unloading**. As the pressure is released, expansion of the rock causes concentric layers of cracks to form within the igneous body. These layered "sheets" are then broken off by continued weathering.



Figure 3: *Half Dome is commonly used as an example of exfoliation. Note the large fractured sheets. Photo: Stephen Leonardi.*

Thermal Expansion:

When minerals are subjected to different temperature ranges they expand and contract. Rapid temperature fluctuations such as day night cycles can cause individual grains in rocks to expand and contract at different rates. Individual grains can be squeezed from the rock surface or fractures can form to relieve stress. The efficiency of this method is debated by geologist, but no less contributes to physical weathering processes. Climates that experience rapid temperature changes such as deserts display this weathering.

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Proglacial Lakes and Marine Environments

Work to do on this page:

1. Hyperlink phrases with other pages in the textbook
2. Add to Influences
3. Add to Facies

Welcome to Proglacial Lakes and Associated Marine Environments!

Outline of this page:

1. Introduction (why you should care), fig 1, 2
2. Sediment Transport Processes, fig 3, 4
3. Vertical Sequence, fig 5
4. Summery

Note: Subheadings will be in *italics*, keywords will be in **bold** when they are introduced, and a scavenger hunt for the remainder of the article (mostly for esthetic). Words (besides headings) outlined in blue are hyperlinks to pages where you can learn more about the keyword or phrase.

Topics will be introduced, and the figures will be below them, so if you are stuck, look ahead! If you are still stuck, look to the related material and links for more information. Additionally, don't hesitate to contact your professor, they like the conversations :)!

Keywords: Proglacial Lake, glacier, Ice, Moraine, Debris Flow, Turbidities, Outburst Flood (Jokulhaups)

Related Pages:

Introduction:

Why study Proglacial Lakes and associated Marine Environments?

Proglacial lakes are formed as melt water from a glacier pools. Depending on the type of dam that holds the melt water, proglacial lakes can either be stable long after the glacier melts, or can fail catastrophically to produce **jokulhaups, outburst floods**. Given their nature, these lakes have important hazard implications in the past and present. In the past, the Younger Dryas, a major shifts in global climate, has been attributed to the outburst flood of a large proglacial lake. At present, with a warming planet, proglacial lakes are increasing in volume and abundance, as seen in figure 1. This increase puts communities at risk of outburst floods that may have not been at risk before.

From a scientific standpoint, proglacial lakes are important in studying climate because they preserve data with high temporal resolution. They are on par with speleothems in preservation, which allows us as scientists to make interesting observations into the past.

Again, studying proglacial lakes are important because:

- They preserves pristine records of paleoenvironments
- Have caused important changes in paleoclimates, such as the Younger Dryas
- becoming increasingly more common with the disappearance of glaciers



Fig1: The enlargement of Proglacial lakes off of the Llewellyn Glacier (British Colombia) in the Juneau Ice Field, Alaska (courtesy of Mauri Pelto, Professor of Environmental studies and head of the North Cascades Glacier Climate Project). The left image depicts lake levels in 1984, and the right shows the expansion of these lakes in 2016. Markings A-D in both satellite images represent approximate end of proglacial lakes (red denotes 1984 and yellow denotes 2016).

What makes up a proglacial lake?

Proglacial lakes come in several varieties. We will discuss ice, moraine, debris flow, and bedrock dammed proglacial lakes.

Ice dammed lakes are associated with the ice margin of a glacier. The rate of lake formation is heavily linked to glacier movement and ice accumulation. Ice accumulation is slow, and linked to glacier mass balance and the surrounding climate. Because of their ice dependence, ice dammed lakes only exist as long as the ice exists.

Moraine dammed lakes are associated with glacial retreat, often when the front of a glacier detaches from the remainder of the glacier. Moraine dominated lakes will fill places of low topography that was previously occupied by ice or melt water, and can continue to evolve. Consequently, these lakes can live longer than the glacier

Debris flow dammed lakes are associated with slope failure of the surrounding bedrock from removal of bedrock material by the glacier. These lakes are short lived, and often either fail or are filled in by new debris flows.

Bedrock dammed lakes are *associated* with depressions in regions a glacier sat before. They are initially filled with melt water below the glacier, and can last long after the glacier.

Summery of the three common types of proglacial lakes and what they mean for structural integrity of the lake

- Ice dammed -> can be short lived, only as ice maintains integrity
- Moraine dammed -> long lived, can outlast glacier
- Debris flow dammed -> short lived, only as loose debris maintains integrity
- bedrock dammed -> long lived

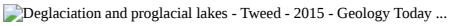


Fig2: Schematic on different types of proglacier lakes. (Tweed, Fiona S., and Jonathan L. Carrivick. "Deglaciation and proglacial lakes." *Geology Today* 31.3 (2015): 96-102.) Ice dammed lakes are bordered by ice, bedrock dammed lakes fill in a bowl in the bedrock created by the glacier, "landslide" or debris lakes are bordered by debris flows, and moraine dammed lakes are bordered by moraine at the toe of the glacier.

What influences a proglacial lake? (To be continued)

Proglacial lakes are heavily influenced by glacier dynamics and the surrounding environment.

Some Important Interactions Between Proglacial Lakes and Glaciers:

- Water Depth
- Bathymetry
- Hydrology/Limnology
- Sedimentation

Sediment Transport Processes:

What Sedimentary structures are common in proglacial lakes and Marine Environments (Fig3)

Sedimentation in proglacial lakes is tied to glacial dynamics, and often dependent on the distance between the glacier and the deposition area. Close to the glacier, channels that run underneath the glacier deposit sediments in subaqueous fans and submerged ramps. These slopes are occasionally altered by turbidity currents. Additionally, the type of sediment and distance it travels is dependent on the speed of the water from the glacial channel. Ultimately, most sediment in proglacial lakes settles due to suspension settling. These fine grained sediment layers can be disturbed by ice rafted debris, larger clasts that were carried by ice

that had chipped off the glacier and transported across the lake. Organic material in proglacial lakes provide high temporal geochronology resolution, and are useful in reconstructing climate.

Summery of Sediment Structures

- fine sediment, with layers of turbidity currents
- drop stones/ ice rafted debris (IRD)
- subaqueous fans/ submerged ramps

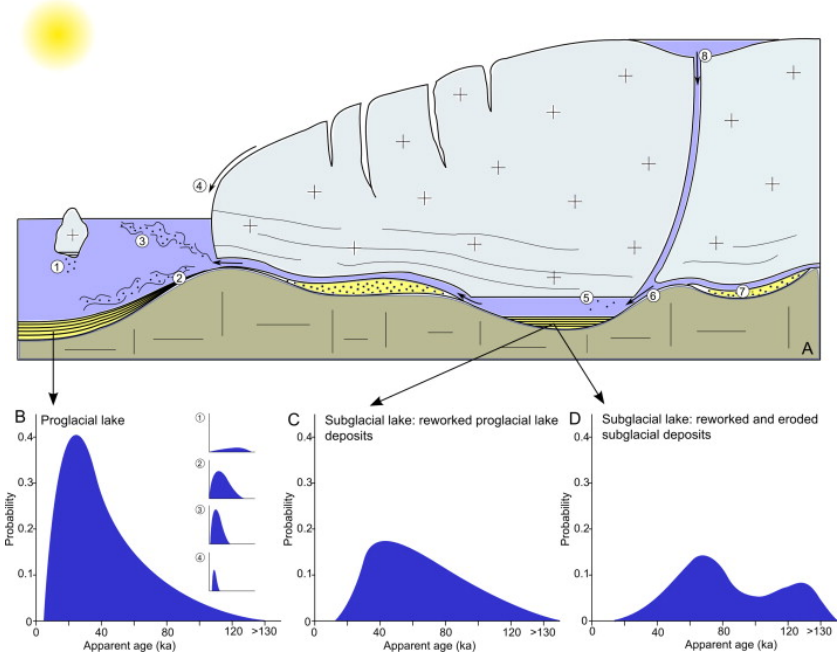


Fig3: Sediment types from Proglacial Lakes. 1: drop stones from icebergs, 2: Sediment deposited from Turbidity currents, 3: buoyant plumes, 4: drainage below the glacier, 5: debris melting from ice, 6: bedrock erosion, 7: reworking inherited sediments, 8: drainage (Livingstone, Stephen J., et al. "Discriminating between subglacial and proglacial lake sediments: an example from the Dänischer Wohld Peninsula, northern Germany." *Quaternary Science Reviews* 112 (2015): 86-108.)

Outburst floods:

Another dispositional feature of proglacial lakes are outburst floods. These floods occur when the proglacial lake's dam is broken, or if the flow overtops the lake's dam. Material deposited in these features are a mix of sediment sizes, from silt to boulder size (fig_).

More information about outburst floods can be seen here:

Animation of outburst flood: https://www.youtube.com/watch?v=awLGxl5JmjY

Buton outburst flood 1994: https://www.youtube.com/watch?v=3hMM5NiLIRw

Buton outburst flood 1994:https://www.youtube.com/watch?v=jpmtflUnwc4: Little corny, but good information!

Outburst floods have historically altered climate systems. The Younger Dryas was a period of intense cold on our planet caused by the failure of Lake Agazzi, a proglacial lake that had held melt water from the Laurentide Ice Sheet. As water rushed to the Northern Atlantic, the increase in cool freshwater shut down the gulf stream. By doing so, heated water from the equator did not reach as far north, causing further cooling.

More information on the Younger Dryas:

Scientific article: https://pubs.geoscienceworld.org/gsa/geology/article/38/4/383/130267/What-Caused-the-Younger-Dryas-Cold-Event

Younger Dryas Animation: https://www.youtube.com/watch?v=kqWIwp1beIw (no sound)

Younger Dryas Information: https://www.youtube.com/watch?v=8RpG49hSkjw (watch the first video first to see the animation, this one is just talking)

Summery of Outburst Floods:

- A dam may fail from overfill or breaking of ice and cause an outburst flood
- Outburst floods in the sedimentary record display clasts of mixed sizes
- Historical significance:
  - Lake Agazzi and the Younger Dryas cold event
- implications in mountain communities in a changing world



Fig 4: Kehew and Lord; Glacial Lake Outbursts; Figs. 5 Mixture of sediment sizes from a outburst flood

Typical Vertical Sequence of Facies Representing the environment:

- rhythmites: layers of sediment lain down periodically
- turbidity currents: density currents that rapidly move a large amount of material down slope
- suspension settling: resultant of a calm environment, suspension settling describes the process of depositing finer material out of the medium (water here) by way of gravity.

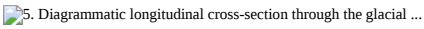


Fig 5: This figure represents the type of facies that can be seen within a proglacial lake facies. In such a dynamic environment, there are many processes to observe like turbidites, rhythamlets in the shallow segment, and braided river deposits leading up to the lake. Kehew, Alan & Lord, M.L. & Kozlowski, Andrew & Fisher, Timothy. (2009). Proglacial megaflooding along the margins of the laurentide ice sheet. Megaflooding on Earth and Mars. 104-127. 10.1017/CBO9780511635632.007.

Summery:

Proglacial lakes are important features of glacial environments and can aid in reconstructing paleoclimates. The longevity of these lakes is dictated by the type of dam that holds in the water. Sedimentation in these lakes is heavily dictated by the current glaciation, and ranges from deposition by suspension to turbidity currents on the lakes sides. Ice rafted debris can carry glacial sediments far across the lake, and potentially across the ocean. Proglacial lakes have the potential to create outburst floods when dams break or the lakes are overfilled. These outburst floods have the potential to cause a catastrophic hazard in mountainous regions like Nepal. Further, extreme outburst floods can alter climate by interfering with ocean currents, as was the case in the Younger Dyas. Proglacial lakes are relevent in the geosciences because of their fine scale temporal resolution of material useful in chronostratigraphy.

For more information on this exciting topic, visit these resources!

References/More Material

Proglacial lakes:

1. Proglacial Lakes:character, behavior, and geological importance by Jonathan L. Carrivick and Fiona S. Tweed

Failure of proglacial lakes associated with the Laurentide Ice Sheet:

1. Catastrophic glacial-lake outburst spillways: form and process relationships by Alan E. Kehew, Western Michigan University and Mark L. Lord, Western Carolina University

Anything else remotely glacier related:

1. Antarctica Glaciers: look around the site! They have great information on many glacier related topics
2. Glacial Types-Retreat

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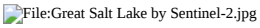
River Dominated Deltas

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Saline Lakes

Introduction

Saline lakes occur in the hydrographically lowest areas of arid environments within closed-drainage basins (Hardie et al, 1978). They can be categorized into several categories: ephemeral, perennial, acidic, and alkaline (Hardie et al, 1978). Moreover, they have several depositional sub-environments: alluvial fans, sandflats, dry mudflats, dune fields, perennial and ephemeral stream floodplains, perennial and ephemeral lakes, springs – travertine and tufa flats and mounds, and shoreline features (Hardie et al, 1978).


File:Great Salt Lake by Sentinel-2.jpg

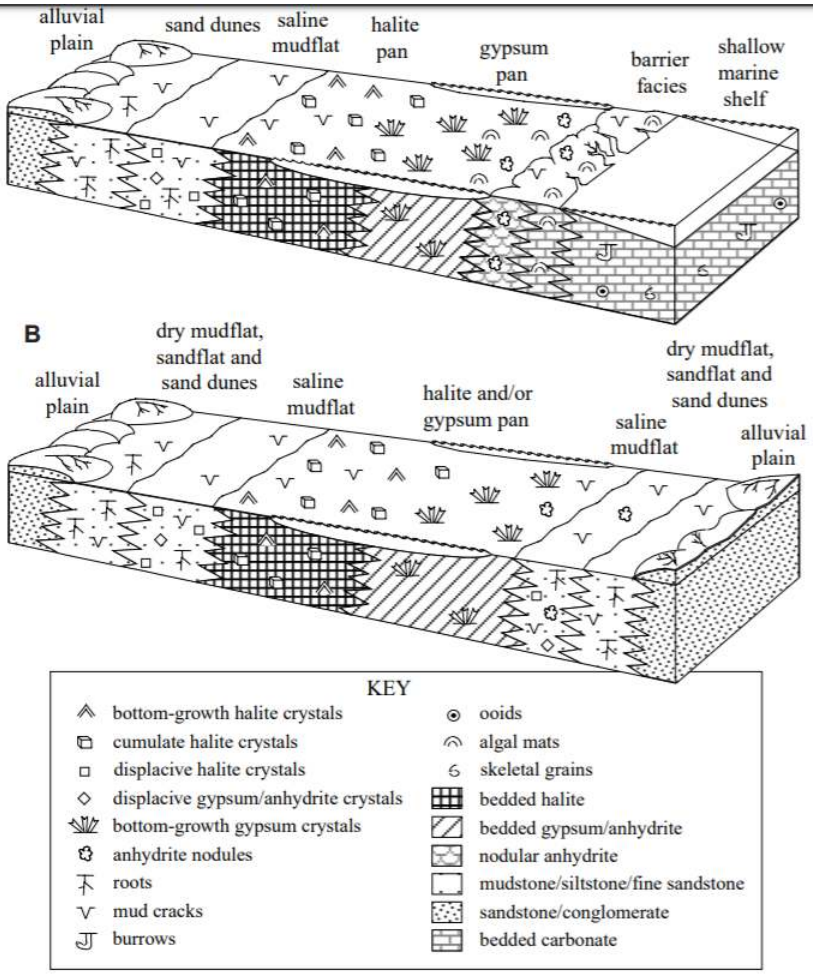
(Above, there is a picture of the Great Salt Lake in Utah, USA. It is one of the largest lakes in the United States aside from the Great Lakes and is largely considered a saline lake. Various portions of the lake are too salty for anything other than a few highly-specialized species.)

Fluids

A lake is called a saline lake if the water in it is made up of more than 5000 ppm of dissolved solute (Hardie et al, 1978). The amount of precipitation/influx of water into saline lakes is less than the amount that is evaporating and water flow into and out of the saline lake is non-existent or at least restricted (Hardie et al, 1978). Considering these circumstances, saline lakes are very low energy depositional environments. Also, the influx into this environment may come from perennial or ephemeral streams, springs, groundwater, or un-channeled sheet flow from storms (Hardie et al, 1978).

Sediment Transport Processes

Sediment transport into saline lakes is typically driven by fluid flow from storm flooding (Hardie et al, 1978). And so fluid flow is high in the alluvial fan sub-environment and slows as it passes through sandflats, then mudflats, and then into the saline lakes. Once storm floodwaters reach the mudflat environment, they have moderate velocities, are shallow, and un-channeled (Hardie et al, 1978). Evaporative pumping is another major way sediment (in the form of salts) is transported within saline lakes, particularly in the mudflat facies/sub-environment where this process creates surface efflorescence (Hardie et al, 1978). The dune field facies is associated with the bottom of the alluvial fan, sandflat, and both of the inflow stream floodplain sub-environments of saline lakes in that when any of these areas lack efflorescent salt crusts, they can be eroded and have sediment deposited on them by wind (Hardie et al, 1978).



(Above, is a figure from Benison and Goldstein 2001. It illustrates a cross-section of a salt lake depositional environment [this is the bottom cross-section] and a cross-section of a coastal marina [the cross-section on top]. Notice that the pan above occupies the area where the lake would normally be after it is recharged with water.)

Blue-green algae are associated with the precipitation of tufas and travertines in both spring orifices and inflow streams; however, the cause of this association may be due to the metabolisms of the algae or inorganic precipitation of carbonates that trap the algae (Hardie et al, 1978).

Characteristics of Deposited Sediment

Saline lakes are subdivided into several sub-environments that can be used as facies: alluvial fans, sandflats, dry mudflats, dune fields, perennial and ephemeral stream floodplains, perennial and ephemeral lakes, springs – travertine and tufa flats and mounds, and shoreline features (Hardie et al, 1978).

Alluvial Fans and Sandflats

Saline lakes are surrounded by alluvial fans that are typically created by stream point flows and have gravelly wedges that then fan out with very coarse sediments (Hardie et al, 1978). Alluvial fans are typically the products of storm-flooding and so this type of flow creates four kinds of deposits: shallow braid channel deposits, fills inside deeper incised channels, sieve deposits, and debris flow deposits (Hardie et al, 1978). On the surface of the alluvial fan, the braid channel deposits appear as coarse gravel bars that are isolated by braided shallow stream channels (Hardie et al, 1978). In vertical sections, the braid stream deposits in alluvial fans appear as cross-cutting lenses that are made up of framework-supported boulders and pebbles that may be imbricated and may have gaps in the framework filled in by sand (Hardie et al, 1978). Incised channel fill deposits can be several meters thick and have sediment that fines upward in grain size (Hardie et al, 1978). Evaporative pumping of groundwater beneath an alluvial fan's surface

can also create calcite pore cement, caliche crusts, coatings, root moulds, and nodules within the fan's sediment (Hardie et al, 1978). Within ephemeral and perennial saline lakes, the water has very little velocity (Hardie et al, 1978).

The deposits of the alluvial fans then lead into sandy aprons, which are referred to as the sandflats facies. The sediment in sandflats are finer than those in the alluvial fans and have pore and vug fillings that are likely to be gypsum, which can dehydrate into anhydrite, or high-Mg calcite (Hardie et al, 1978). The sandflats can also have wind ripples and longitudinal trains (Hardie et al, 1978).

Dry Mudflats

The dry mudflat facies is commonly associated with ephemeral saline lakes and are in general differentiated from the ephemeral saline lake facies in that they preserve depositional structures. At the surface, the mudflats will usually have polygonal mudcracks which are desiccation cracks and a thin layer of saline crusts which are surface efflorescences (Hardie et al 1978). Two types of saline crusts can form: thin, brittle, and dense crust made up of micritic alkaline earth carbonates; and puffy, porous, and crystalline crusts that are made up of soluble minerals like halite, trona, thermonatrite, or thenardite (Hardie et al, 1978). In addition, the soluble minerals in the second type of saline crust are usually dissolved by storm flooding and so their presence is recorded via the disruption and destruction of the top part of each depositional unit (Hardie et al, 1978). However, the sedimentary features of dry mudflats are not well known, but it is hypothesized that they could have small, millimeter-scale laminae and crystals of gypsum, glauberite, etc. (Hardie et al, 1978). The flow velocity, shallowing storm flood water, and traction deposition in dry mudflats could also produce sedimentary structures that are fine grained but also upper flow regime bedforms (Hardie et al, 1978).

Ephemeral Lakes

Ephemeral lakes are a type of saline lake that is shallow and every few years dries up leaving behind a layer of salt(s) precipitated by the evaporating brine (Hardie et al, 1978). These lakes are cyclically recharged via storm water runoff and then gradually recede as the water evaporates, which leads to the formation of two sub-facies – a salt pan facies and a saline mudflat facies (Hardie et al, 1978). The salt pan facies occurs in the lowest part of the lake bed and it is characterized by layered salts, while the saline mudflat facies occurs around the salt pan and is characterized by muddy clastic sediment that contains salt mineral crystals (Hardie et al, 1978). Also, the saline mudflat sub-facies may have the following features: root casts, When the turbulence from the storm flooding ceases, silt and clay-sized grains settle from suspension they create a thin lamina that extends across the recharged saline lake (Hardie et al, 1978). Wind-induced waves may then cause the formation of wave ripples on the mud lamina or rework the mud lamina into a silt clay lenticular lamination (Hardie et al, 1978). In the salt pan facies, this thin mud lamina can become the site of bacterial reduction of sulfate and creates iron sulfides and sulfuric acid, which give the sediment a black coloring (Hardie et al, 1978). Additionally, the salt pan facies is characterized by couplets of layers following a storm flooding of the lake – the thin mud lamina that is black in color and has intergrown salt crystals and an overlying, thick layer of crystalized salts (Hardie et al, 1978).

Perennial Lakes

Perennial saline lakes are a type of saline lake that remains deeply water-filled to some extent for most years. The strata of perennial lakes reflect the fact that they are constantly depositing saline material onto the lake bottom and so a major structure within these strata are crystalized salt laminae (Hardie et al, 1978). Clastic mud laminae can also be deposited at irregular points throughout the strata of a perennial lake as a result of different storm flood events (Hardie et al, 1978). The salt crystal laminae can also be altered diagenetically as a result of bacterial reduction into a different material, such as sulfide, or through recrystallization which would erase the original depositional structure (Hardie et al, 1978).

Dune Fields

Erosion from wind action on the bottom of the alluvial fan, sandflat, and both of the inflow stream floodplains sub-environments creates the dune fields, deflation flats, and hollows that are characteristic of the dune fields facies (Hardie et al, 1978). In some cases where the sediments of a dry saline lake bed are eroded, the sand making up the dunes in this facies can be made up of salt mineral grains like gypsum (Hardie et al, 1978).

Shoreline

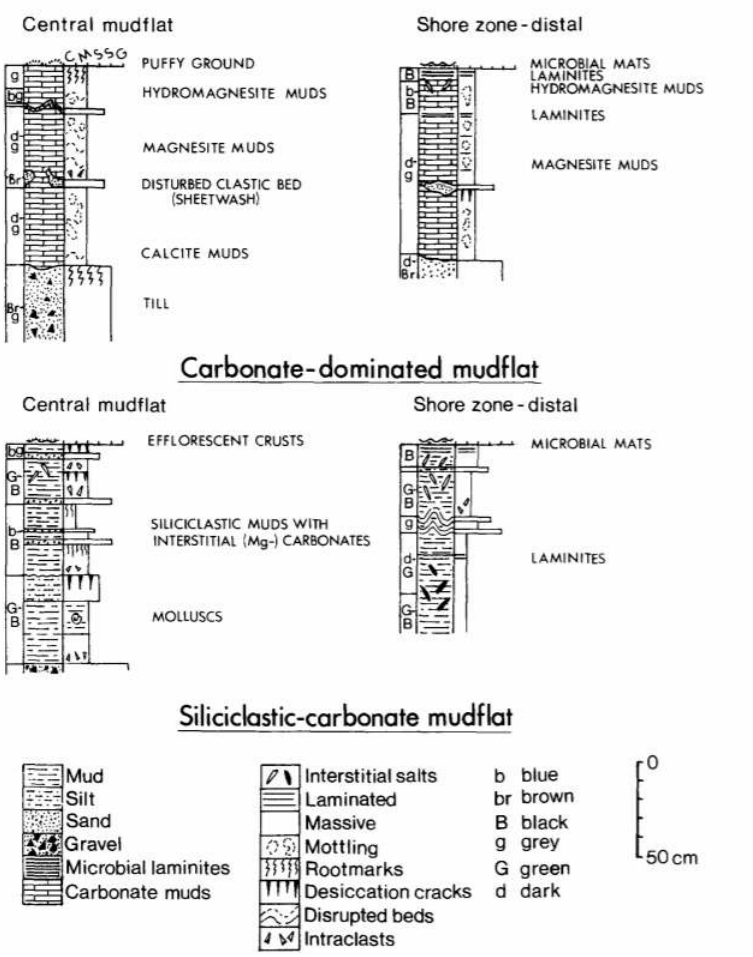
The shoreline facies is partly influenced by groundwater discharge from springs that may be located in them (Renaut and Long 1989). As a result, travertine deposits may be found on the shoreline along with spring mounds (Renaut and Long 1989). Typically,

shoreline deposits vary based on the saline lake's water level and this leads to the deposition of sparingly-soluble salts during high stands and deposition of more readily soluble salts during low stands (Renaut and Long 1989). In some parts of the shoreline, wind-action can cause certain areas of the lakeshore to have more salts deposited on them - resulting in a thicker salt layer. Deposits on the shoreline may consist of carbonate muds and their deposits are typically laminated and/or display mottling (Renaut and Long 1989).

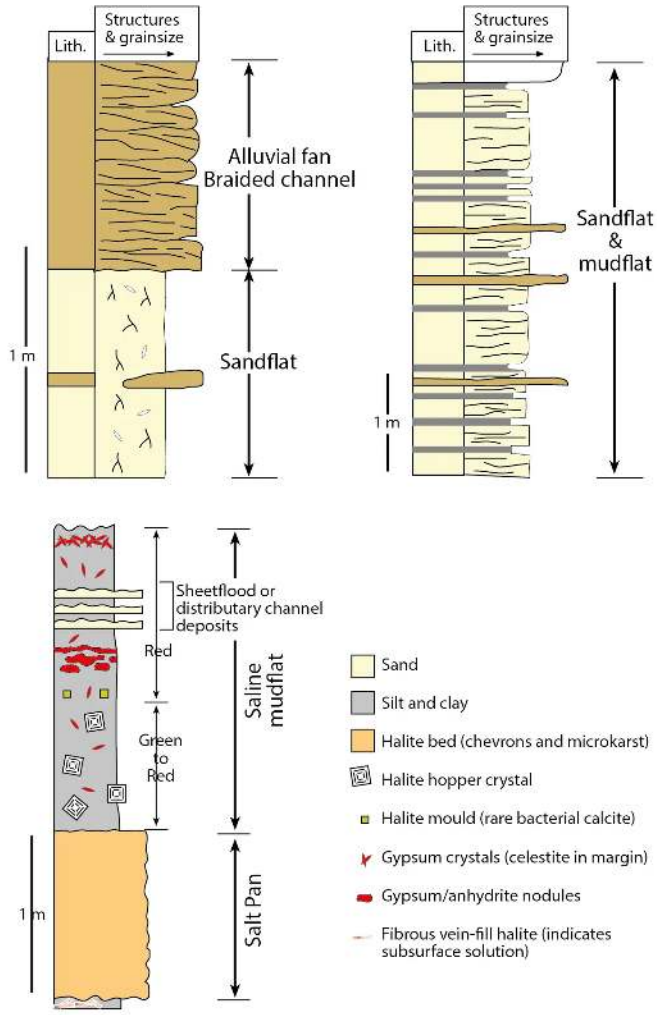
Biological Deposition

In the saline lake sub-environments, bioturbation may come in the form of halophyte plant roots, invertebrate burrows, bird feeding pits, or terrestrial animal burrows (Hardie et al, 1978). The alluvial fan, sandflats, dunes, and mudflats facies tend to have these features, which interrupt or destroy depositional layers (Hardie et al, 1978). Blue-green algal mats can accumulate on the bottom of saline lakes and it is diagenetically possible for them to be converted into kerogen, which has been associated with oil shales (Hardie et al, 1978). Additionally, the shoreline facies is commonly occupied by small cyanobacterial mats (Renaut and Long 1989).

Vertical Sequence of Facies



(The above was taken from Renaut and Long 1989. It depicts stratigraphic columns of Carbonate-dominated and Siliclastic-carbonate mudflat facies within the saline lakes of the Cariboo Plateau in British Columbia, Canada. The mudflat facies and shoreline facies are interlinked in that depending on the water level of the saline lake the shoreline can move further up a mudflat or down to its lowest extent.)



(Source. The above illustrates a stratigraphic section of Bristol Dry Lake, USA. Notice that alluvial fan facies starts off with the coarsest grains and that the sediments closer to the saline lake have finer sediment. Also, note that the bottom saline mudflat section illustrates a periodic increase in grain size due to faster water flow from storm flooding.)

Saline lake deposits can be differentiated from marine deposits in that they are halite dominated, have many soil features, lack marine fossils, and the scarcity of carbonates (Benison and Goldstein, 2001). Additionally, the strata associated with saline lake deposits have a combination of aeolian, flood, desiccation, and evaporation -related features (Benison and Goldstein, 2001).

Summary

Saline lakes are a unique depositional environment whose deposits are influenced by largely periodic water flow from storm flooding, but they are also shaped by aeolian processes and the surfacing of groundwater through springs. Along the cross-section of this environment towards the lake-itself, water flow is expected to decrease into a near or complete standstill. The deposits as a result decrease in grain size towards the lake - largely forming mud layers at the perimeter of and within the saline lake. As the lake level changes, the type of salts deposited change and the level change defines the saline mudflat subfacies and dry mudflat facies as the border between these is the shoreline. Sedimentary structures are highly deformed within the saline lake due to disturbance from salt crystal growth and many of the facies along the shoreline and within the lake are deposited upon by microorganisms including cyanobacteria. Lastly, the habitat surround saline lakes is in danger of disappearing putting a variety of organisms that rely on it in danger (Further Reading).

References

Benison, K.C., and Goldstein R.H. “Evaporites and Siliciclastics of the Permian Nippewalla Group of Kansas, USA: a Case for Non-Marine Deposition in Saline Lakes and Saline Pans.” *Sedimentology*, vol. 48, no. 1, 2001, pp. 165–188., doi:10.1046/j.1365-3091.2001.00362.x.

Hardie, L.A., Smoot, J.P., Eugster, H.P. “Evaporites and Siliciclastics of the Permian Nippewalla Group of Kansas, USA: a Case for Non-Marine Deposition in Saline Lakes and Saline Pans.” *Modern and Ancient Lake Sediments*. Special Publications of the International Association of Sedimentologists, no. 2, 1978, pp. 7-41.

Renaut, R.W., and Long, P.R. "Sedimentology of the saline lakes of the Cariboo Plateau, Interior British Columbia, Canada." *Sedimentary Geology*, vol. 64, 1989, pp. 239-264.

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Storms and Shallow Marine Deposits

Marine Deposition

Most sediments eventually get transported into the oceans. In the sedimentary record, shallow marine deposits are the most abundant due to their large volume and the low erosion rates in those environments. Marine deposits above sea level are often uplifted by tectonics which exposes them to significant erosion. Shallow marine sedimentary deposits include storms, waves, and tides.



Figure 1: Depositional environments. (https://link.springer.com/chapter/10...642-38800-2_13)

Storms

Storms produce both large waves as well as strong and irregular currents. The combination of waves with currents produces unique deposits that can be used to recognize ancient storms in a marine sequence.

Storms generally begin far from the shore and become stronger at the shoreline over time, then either die out or move on. Therefore, near shorelines storms tend to start with low energy flows and increase in speed until the first part of the storm is eroded away, then decrease back to lower energy flows. As the storm wanes, the coarsest sediment is deposited, then finer sand is deposited by waves and currents, and then wave ripples, and so on. The reverse of the sedimentary structures is seen as the storm approaches. There is typically a small amount of sediment deposited at the start of a storm due to some sediment having been eroded yet, and flow speeds increase over time. Consequently, there is typically no recorded of the first half of a storm sequence in the rock record. It is only the second half that is preserved. Storm deposits usually consist of an erosion surface with sediment of decreasing grain sizes upwards.

Hummocky Cross Stratification (HCS)

Hummocky and swaley cross stratification are deposited as a combination of strong currents as well as large waves unique to storms, and is only found in medium to fine sands. When currents wash eroded sand into an area with strong oscillatory flow from waves, rounded hummocks of sand accumulate on the sea floor separated by lows (swales). These rises are a few to 10 cm high and tens of cm across. Variations in current strength cause local erosion, and the locations of hummocks and swales changes over time. This produces erosional surfaces that truncate older laminae. HCS is characterized by low angle laminae truncated by low angle surfaces. There are many concave and convex up laminae and fewer flat laminae.

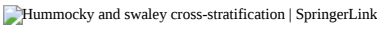


Figure 2: HCS (https://link.springer.com/referencew...020-3609-5_112)

- Storm Sequence

Figure 3: A diagram of a typical storm deposit.

(https://archive.usgs.gov/archive/sit.../11/index.html)

Waves

It is important to know that waves have bi-directional flow every few seconds. The oscillating current in both directions is the same in deep water, however this is not always the case near the shore.

Wave Ripples

- Wave ripples experience transport in both directions every few seconds, unlike current ripples. In rocks, they have a distinctive symmetric shape when the flow in each direction is the same speed. Additionally, cross-laminations that dip in two directions are also present, regardless of the ripples being symmetric.
  - At low flow ripple crests are sharp. This is because the boundary layer does not have enough speed or momentum to get rid of the crest of the ripple and the grains that are moved are deposited on the upper part of the slope.
  - High flow ripples have rounded crests. This is due to the crests eroding and deposition occurring further down the slope.
- In shallow water, currents from waves can be strong enough to flatten ripples. Since the flow switches directions too frequently, dunes are unable to build up. Therefore, where flow speeds are too fast to form ripples, the sedimentary surface tends to be

planar or broadly scalloped as the waves are focused into certain areas. This produces flat lamination (different from upper planar lamination), where waves are in very shallow water relative to their height.



Figure 4: Wave ripples, with a pen for scale.

(https://www.geol.umd.edu/~jmerck/geo...ctures/05.html)

Tides

Two key characteristics that are unique to tides are that flow changes direction once or twice per day, and the speed of flow is cyclical. The flow goes onshore, stops at high tide, then flows offshore and stops at low tide. There is a great deal of variability in tides depending on geography. Flow speeds vary, consequently producing different sedimentary structures. The main characteristic to look for is the variations in flow speed and direction. Another important point about tidal processes is that bi-directional flow can have varying speeds over hours.

- Tidal sedimentary structures
  - herringbone cross stratification

Reactivation Surfaces

Reactivation surfaces form when flow in one direction is stronger than the other, but the other flow is still strong enough to modify the bedform shape. Reactivation surfaces are erosion surfaces within the sets of cross stratification. They looks like irregular surfaces that are oriented similarly to the foresets, but usually have a shallower dip. Additionally, the foresets above and below the reactivation surface typically have slightly different orientations. As is common in tidal environments, reactivation surfaces indicate varying flow directions.



Figure 5: Diagram showing how reactivation surfaces are formed.

(https://pubs.geoscienceworld.org/boo...-sedimentology)

Mud Drapes

Mud drapes are one type of sedimentary structure that can form from cyclical flow speeds. During slack tides (low or especially high), fine grained sediment can fall out of suspension draping tidal bedforms with mud. Since mud is cohesive, it does not always erode during the following tidal flow, particularly in the separation zone where there is a slow flow. Therefore, sand foresets coated with mud are very common in tidal environments.

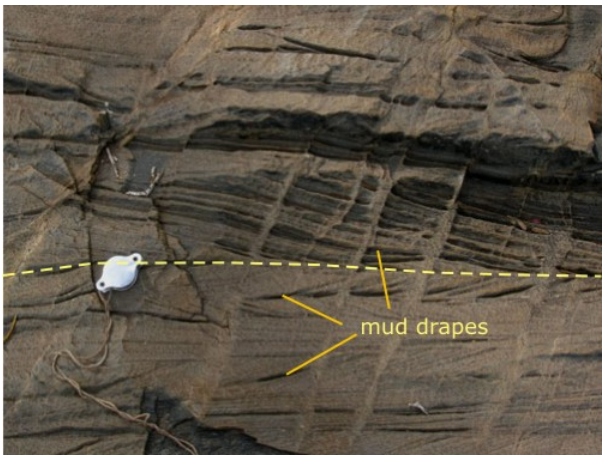


Figure 6: Mud drapes outcrop. (http://all-geo.org/highlyallochthono...ion-years-ago/)

Summary: Waves, storms, and tides are processes that are unique to shallow marine deposition (including some large lakes).

Associated Depositional Environments:

- Tides and Shallow Subtidal Environments
- Waves and Beaches

Sources:

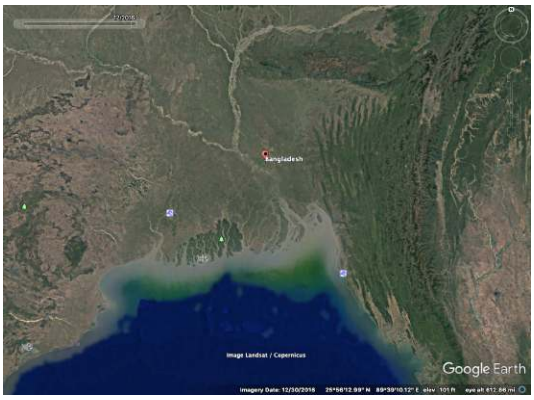
https://geo.libretexts.org/Courses/U...ocesses_Part_1

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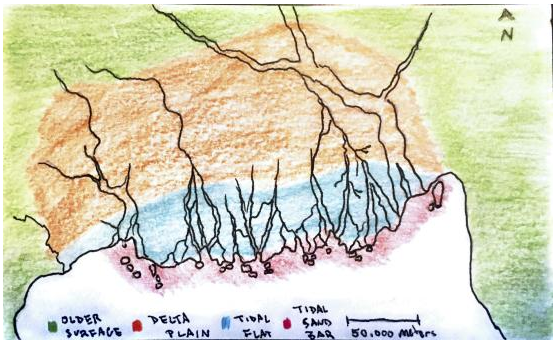
Tide-influenced Deltas

Introduction

- Rivers drain toward large bodies of water such as the ocean. Sediment carried by the river will accumulate at the mouth of the river to form a delta. Tidal currents from the ocean create a redistribution of sediment as well as a change in geometry.
- Fresh water from snow packs and other inland drainage flows towards the mouth of the delta while sea water is mixed from the ocean tide.
- Tide-influenced deltas are one of three examples of types of deltas that commonly exist around the world. Other two include river-dominated and wave-dominated
- There is an oscillation between flow direction within the environment due to the influence of both tidal currents and river flow.



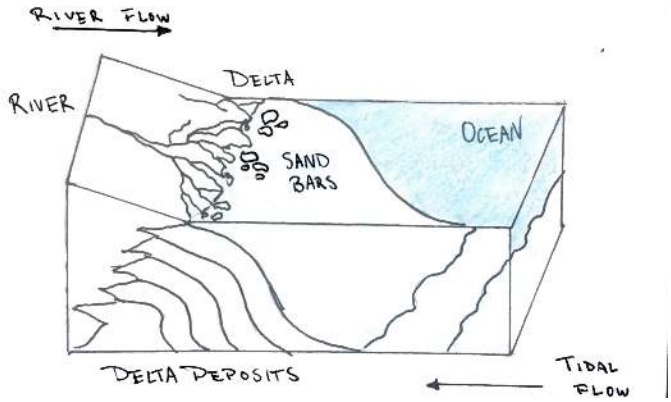
- [Figure 1] (Left) Satellite Imagery from of Google Earth of Ganges Delta located within the Indian states Bangladesh and West Bengal.

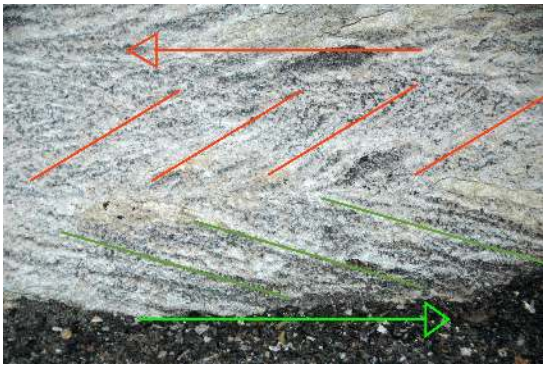


- [Figure 2] (Right) Sketch of Ganges Delta with estimated facies. Facies include; older surface facies, delta plain facies, tidal plain facies, and tidal sand bar facies.

Sediment Transport Process

- Sediment is transported by the flow of water in rivers towards the sea, as sediment approaches the delta, there is a large influence by tidal currents. The delta is not to be confused with tide-dominated, there is an exchange of flow direction between the river and tidal currents within these locations when the tide retreats. This is also not to be confused with wave dominated deltas whereas oscillation is more frequent.
- The ocean's tide oscillates at a given location (our tide-influenced delta) which directly affects the flow direction within the delta. When a tide moves towards the coast, the flow direction is dominated to flow towards inland. As the tide retreats back into the ocean, the flow direction changes ~180 degrees to flow away from the river, allowing the river output to dominate the flow direction for the moment. This oscillation pattern is continuous over time in tide-influenced deltas, creating unique sedimentary structures, such as herringbone cross stratification and reactivation surfaces.





[Figure 3] (Left) Cross section view of tide-influenced delta with influences of oscillation of direction of flow.

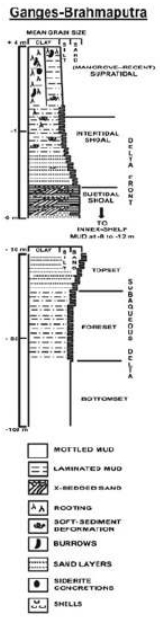
[Figure 4]: (Right) Example of Herringbone Cross Stratification bedding of aragonitic-calcernite limestone in San Salvador Island, Bahamas. Recognition of limestone rock and original image referenced at end.

- The flow speed within this environment depends on the size of the river, size of the delta, and intensity of tidal influence. Sediment is carried from rivers towards the delta; the amount of sediment and grain size range depends on the flow speed of the river. The grain size range of sediment found in tide-influenced deltas include silt to medium-sand size grains.
- Sedimentary structures in these environments include parallel laminations to the flow direction, herringbone cross stratification, reactivation surfaces, mud drapes and also include signs of bioturbation within delta plains where the activity of water is minimal. Many of these structures represent the ongoing direction of flow and change in speed of overall flow.

Characteristics of Deposited Sediment

- The grain size ranges between mud size grains up to medium-sand sized grains. It is uncommon to find sediment grains larger than sand-size grains but is still possible when large natural influences interfere the steady flow of a tide-influenced delta. This could include a high tide, large river flow from inland flooding, or storm.
- Within the sedimentary structures found in these environments, there is a range of grain sizes that associate with specific settings. Mud drapes as an example is mostly consistent of mud-sized grains. Herringbone cross stratification can host grains larger than sand size grains, depending on the flow speed that influenced the shape of stratification. Weak flows will provide smaller grains like mud-size grains while faster flows may carry sand, gravel, and even pebble sized grains.
- In fine sediments like mud, there is often times bioturbation within areas like the delta plains. Bioturbation can include burrowing of small animals or traces of roots scattered within the area. Much of the conserved bioturbation is located on land within the delta plains where activity does not disturb the development of these traces.
- In reference to Walther's Law, our lateral depositional environment is also represented within a vertical sequence of the tide-influenced delta. Under the surface, there is a vertical progression of the depositional layers stacked. These facies include the delta plain facies, tidal flat facies, and tidal sand bar facies.

Typical Vertical Sequence of Facies Representing Tide-Influenced Delta



- It is complicated to capture all of the different types of vertical stratigraphy columns due to the high variability of conditions that can alter the depositional settings of the environment.
- The vertical sequence provided is an example of the Ganges-Brahmaputra tide-influenced delta mentioned from above.
- Within the stratigraphy column, there is noted sequence between mud-size grains and sand-size grains, there is no signs of larger grain sizes present within the environment. The amount of sediment and sediment size range depends mostly on the rivers output from seasons of normal flows, deficient flows, and flooded flows.
- Within the finer sediments such as the laminated mud and mottled mud there are signs of bioturbation such as burrowing, roots, and shells.

[Figure 5] Example Stratigraphy Column of Ganges Delta by Steven Goodbred and Yoshiki Saito

Summary

- Tide-influenced deltas are one three different types of common deltas that exist around the world.
- Sediment transportation relies heavily on the strength and size of river, tide level influences the direction of sediment flow.
- Grain sizes range between mud-sized grains up to medium-sized grains, larger grain sizes are uncommon.
- Herringbone cross stratification, reactivation surfaces, mud drapes, and bioturbation are examples of sedimentary structures found within the depositional environments.

Key Words

-Tide -Herringbone Cross Stratification -Reactivation Surfaces -Mud Drapes -Bioturbation -Walther's Law

References

- [Figure 1] Map showing location of Ganges Delta located within the Indian states Bangladesh and West Bengal. *Google Earth*, https://earth.google.com/web/search/ganges+delta/@23.37273386,89.70764721,6.94387251a,820268.90000285d,35y,0.651h,2.43012009t,0r/data=ClMSKRIgZDdhZGE3OWMxYTM4MTFlNzgwODMwM2Y1NDdlZTE2YTYiBWlscF83IiYKJAmrWfp026s1QBGqWfp026s1wBmB2jdetRpAwCHzK5QEKwFhwA
- [Figure 4] St. John, James. “Herringbone Cross-Stratified Calcarenite Limestone.” *Flickr*, 26 Mar. 2007, https://www.flickr.com/photos/jsjgeo...n/photostream/.
- [Figure 5] Goodbred, Steven & Saito, Yoshiki. (2011). Tide-Dominated Deltas. 10.1007/978-94-007-0123-6_7. https://www.researchgate.net/figure/Stratigraphic-succession-models-for-three-major-tide-dominated-delta-systems-a-the_fig6_229151208
- *Tide Dominated Deltas - SEPM Strata*, 3 Apr. 2013, www.sepmstrata.org/page.aspx?pageid=313.

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Tides and Shallow Subtidal Environments

Tides, Waves, and Ocean Currents

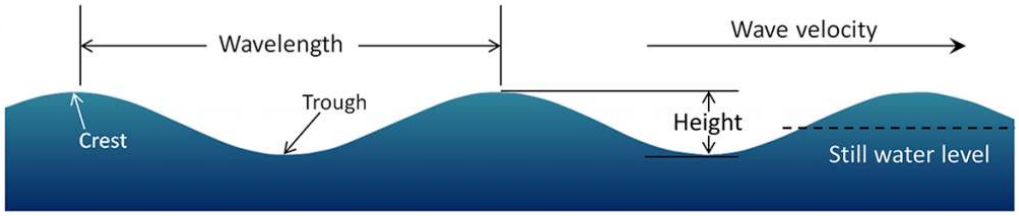


Figure 1: Components of a Wave (Modified by PW from Steven Earle "Physical Geology".)

Tides, waves and currents play an important role in shaping and influencing the creation of subtidal environments of our modern coastal beaches, estuaries and lagoons. Interactive factors that influence subtidal environments are tides, waves, and ocean currents.

Waves are a form of energy that is being transmitted. Water move as a reaction to this energy in orbital motions creating the physical components of a wave as seen in Figure 1 (1). As the wave moves, water moves forward and up over wave crests and down into the troughs (1). Shallow water waves occur when the depth is less than 1/20 of a wavelength(1). In shallow waves, the wave base connects with the sea floor changing their motion from orbital to horizontal (1).

The alternating advance and retreat of seawater along the coast, rivers and lakes are called **tides**. Tides are driven by a combination of gravity fields of the sun and moon in addition to the Coriolis effect. High tide is when water advances to its furthest extent and low tides is when it recedes to its furthest extent. Tides are susceptible to change in sea levels.

Tidal flats or mudflats form where tides alternately flood and expose low areas along the coast (4). Typically tidal flats are broken into three different sections, which may be abundant or absent in each individual tidal flat: Supratidal, Intertidal, and **subtidal** (4). Subtidal environments have a wide distribution of facies associated with water depth and tidal and wave energy. Subtidal environments are important in understanding depositional environments as they are areas where facies are more likely to be preserved.

Sediment Transport and Deposition in Subtidal Environments

In subtidal environments, processes of sediment transport are widely influenced by three factors: initiation of motion (erosion), transport, and deposition. These shallow marine environments are regulated by water-level fluctuation. Grain sizes in subtidal environments range from medium sand to clay. Because of these dominant grain sizes, sediment transport in suspension is an important mode of transportation (2). Larger, coarser sediments are transported as bedload (2).

As flow intensity increases, more sediment is suspended within the water column. However, the frequent and rapid reversing of flow or tides results in the most commonly observed sedimentary structure, herringbone cross-stratification (2). Additionally, a fluctuating bed shear stress for erosion and deposition caused by the increasing and decreasing flow of tides, also causes scouring and settling lags. These tidal and erosional forces creates various types of depositional subtidal environments such as sand bars, spits, tidal flats, and dunes (2).

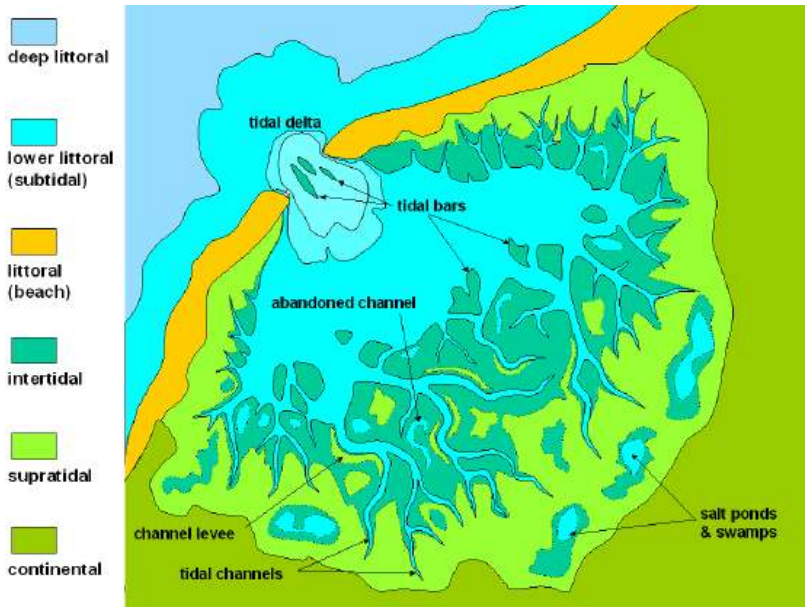


Figure 2: General diagram of a tidal flat and associated features.

Subtidal environments that are formed along the coast, between land and sea or at river mouths, show various characteristics that define a constantly changing current and rely on a high sediment supply. Tidal magnitude can vary depending on the size and area of its channel, such as a tide entering through a funnel-shaped estuary. These tides and waves influence estuaries and deltas, creating various depositional environments (2). Estuaries are coastal bodies of water where freshwater and seawater mix (3). Estuaries are typically connected to the sea and are strongly influenced by tides (3).They can be composed of fine grain sediments transported by rivers or deltas (2). Furthermore, long term alternations in wave direction can further erode and deposit sediments in these subtidal environments. These alternating waves driven by high and low tides, can cause variations in bed and lamina thickness (2).

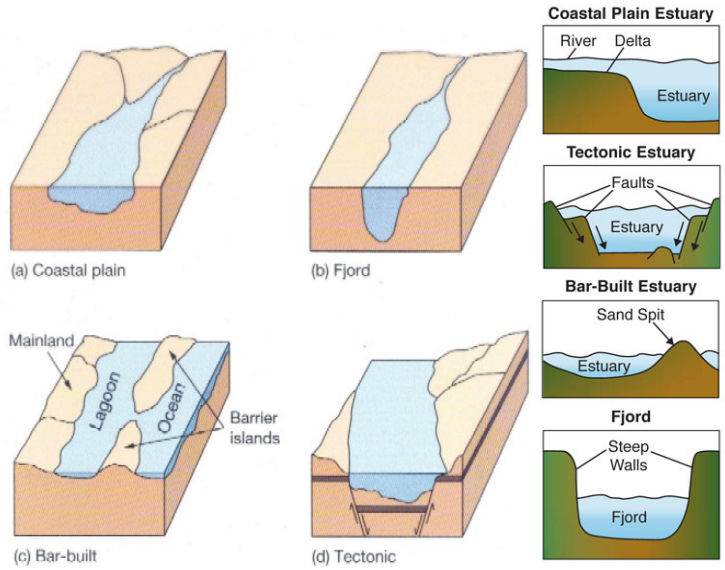


Figure 3: Types of Estuaries (5)

Subtidal Facies

During storms or other events that alter sea level, these subtidal environments are exposed to high energy tides, waves and storm impacts. They become lower and sediment grains begin to show **upwards fining**, as larger grains are brought in by waves (2). Fining upwards of sediments consists of coarse sediments at the base and progressively finger sediments at the top in an uninterrupted vertical sequence (2). Typically, a fining-upward succession reflects a decrease in energy as the environment changes from subtidal to intertidal. Other sedimentary structures that can be observed within these subtidal environments are **hummocky cross stratification** (2). These hummocky cross stratifications are good indicators of a wave-dominated tidal flats produced by alternating tide directions over a single tidal cycle (2).

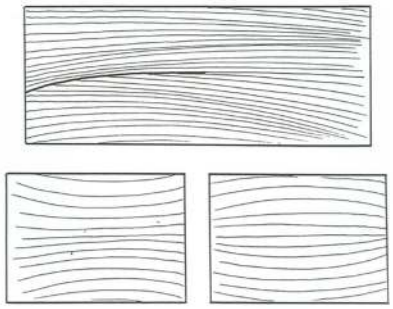


Figure 4: Hummocky cross stratification (6)

Sources:

1. https://geo.libretexts.org/Bookshelves/Oceanography/Book%3A_Introduction_to_Oceanography_(Webb)/10%3A_Waves/10.01%3A_Wave_Basics

2. Davis, R.A., Dalrymple, R.W., Principles of Tidal Sedimentology, 2012. Springer Science Journal. https://books.google.com/books?hl=en&lr=&id=hyuIYTTjFL4C&oi=fnd&pg=PR3&dq=tidal+influences+in+subtidal+environments&ots=FTbUZaDBpL&sig=B5spLd6IBiT2YHyuc6vBgCVjNSE#v=onepage&q&f=true

3. https://geo.libretexts.org/Bookshelves/Oceanography/Book%3A_Oceanography_(Hill)/09%3A_Coastal_Processes/9.1%3A_Estuaries

4. https://geo.libretexts.org/Bookshelves/Geology/Book%3A_An_Introduction_to_Geology_(Johnson%2C_Affolter%2C_Inkenbrandt%2C_and_Mosher)/12%3A__Coastlines/12.02%3A_Shoreline_Features

5. http://www.jht.com/icuf/202/YTMS-08B-135.htm

6. https://geo.libretexts.org/Bookshelves/Sedimentology/Book%3A_Introduction_to_Fluid_Motions_and_Sediment_Transport_(Southard)/16%3A_Cross_Stratification/16.04%3A_Important_Kinds_of_Climbing-Bed-Form_Cross_Stratification

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Tides and Tidal Flats

Introduction

The vertical rise and fall of the tides, created by the gravitational force of the Moon and Sun acting on the oceans water, also creates a horizontal motion of the water in the bays, harbors and estuaries. These are **tidal currents**. The tidal range of a particular location is dependent less on it position north/south of the equator than on other physical factors in the area; topography, water depth, shoreline configuration, size of the ocean basin, and others [1]. For more information on Tides and Shallow Subtidal Environments, see this page.

Shorelines that are influenced by strong daily tidal currents are called **tidal mudflat depositional environments**. Tides are currents that are the result of the gravitational forces exerted by the moon and the rotation of the earth. Shorelines that have strong tidal currents as well as seafloors with low gradients can have large areas that are submerged during high tide and exposed to air during low tide. These areas often have smaller particles than a normal shoreline since the tidal currents can pull marine sediments into the area. In addition, the strong bidirectional currents, daily drying out, exposure to the elements, and abundant life create abundant indicators of these environments [4].

Mudflats (tidal flats) are areas in which coastline shores are separated from the destructive forces of the ocean's waves. [2]. **Tidal flats**, also known as mudflats, are flooded at high tide and exposed at low tide [3].

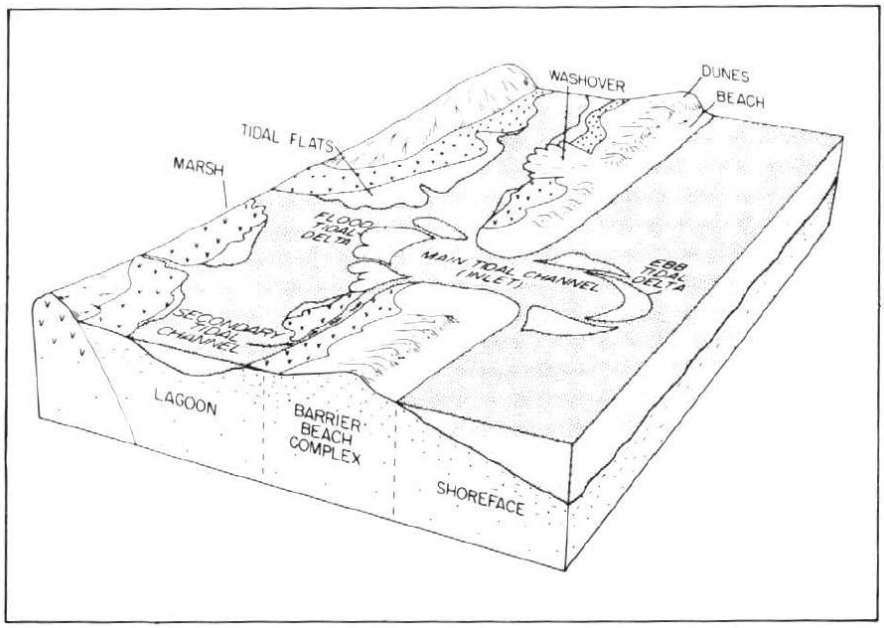


Figure 1: Location of tidal flats compared to other coastal depositional environments. This figure diagram locations across the barrier island topography from Reinson, G. E. (1979) [source]

Characteristics of Transport and Deposition

Figure 2 shows a cross section of the tidal flat environment and the lateral relationship of grain size. As shown in the figure, large sized grains are found seaward and there is a fining in grain size as you move inland. The King Sound area shows a change from sand to sand/mud to mud.

Figure T22

Figure 2: Cross sections of example tidal flat environments

Lateral environments

Part of the coast emergent during low tide and submerged during high tide is the *intertidal* zone. That part of the coast permanently submerged below the low-water line is the *subtidal* zone. That occurring above the zone of high-tide inundation is the *supratidal* zone [8]

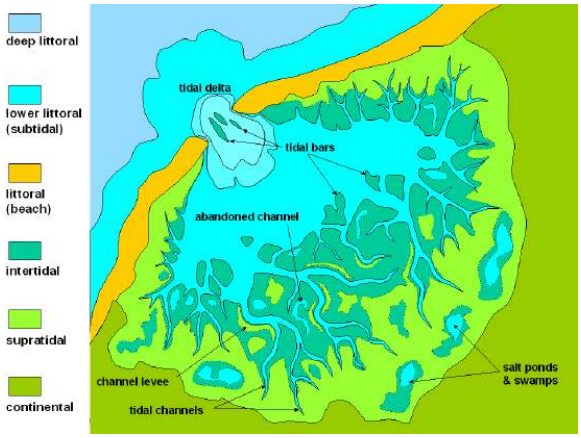


Figure 3: The lateral relationship of depositional environments from the ocean (top left) to inland salt ponds and swamps (bottom right)

Grain Size

Fine sediment is brought in during high tide and deposited as the tide turns. Tidal flats also have high deposition rates [3].

Common grain size of sediment in tidal flats is silt and clay [6]. Tidal flats may be muddy, sandy, gravelly, or covered in shell pavements, and compositionally they may be underlain by siliciclastic or carbonate sediments. The sediments commonly contain both siliciclastic *and* carbonate particles [8].

If there is sand and mud on the tidal flat, tidal and wave processes result in a partitioning of particle sizes: generally, sand dominates the low tidal flats, mixed sand and mud occur on mid-tidal flats, and mud on the high tidal flats. [8]

Sedimentary structures

Mudflats form when silt and mud are brought in by seas, oceans, and tributaries. The mud and the silt are deposited into bays and lagoons when the tide comes in. The water mixes with the mud and silt, creating the muddy quicksand that occurs in **mudflats**. Once the tide lowers, the mudflats are exposed along with what inhabits them [7].

During the event of a high tide, sea water level rises to engulf the entire area bringing in nutrients from the oceans. As the sea water extracts during the low tide, a vast amount of nutrient is left behind making the mudflat a rich feeding ground for a plethora of organisms that it hosts. The abundance of nutrients make mudflats one of the world's most productive ecosystems, and as such, produces one of the most diversified range of living organisms. [2] The rich ecosystem provided by the tidal flats makes the area very active and will commonly contain evidence of **bioturbation** [3].



Figure 4: An example of bioturbation in a rock (the lighter tube-like features)

Root structures can also be present in tidal flats [8].

Herringbone cross stratification can be present because, due to changing flow directions, two sediment transport directions are common; one for onshore flow and one for offshore flow. This gives rise to current ripples showing transport in two directions and dune migration in two directions [source].

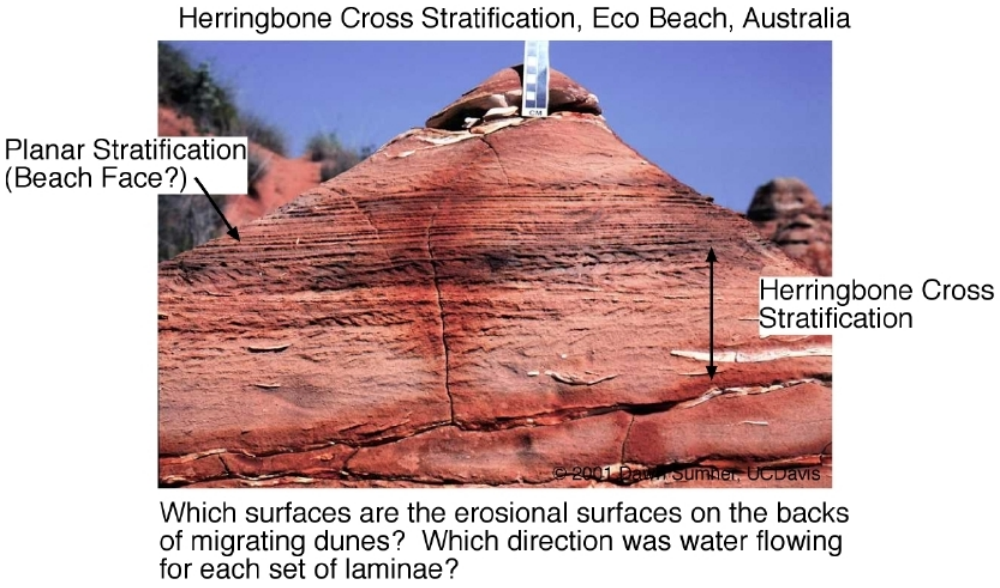


Figure 5: An example of herringbone cross stratification

Mudcracks form when a shallow body of water (e.g., a tidal flat or pond or even a puddle), into which muddy sediments have been deposited, dries up and cracks. This happens because the clay in the upper mud layer tends to shrink on drying, and so it cracks because it occupies less space when it is dry. [source]



Figure 6: An example of mudcracks

Muddrapes: During slack tides (low or especially high), fine grained sediment can fall out of suspension draping tidal bedforms with mud. Because mud is cohesive, it does not necessarily erode during the next tidal flow, particularly in the separation zone where flow is slow, e.g. at the bases of ripples and dunes. [source]

As the land slopes down on the side of the island facing the mainland, the low-lying areas transition into a salt marsh or mud flat habitat, which is protected from wave action, but is influenced by tidal changes. The mud flats are colonized by grasses, which slow down the movement of water and lead to increased sediment deposition, building up the land in the marsh. Different species of grasses eventually dominate the different elevations of the salt marsh, depending on their tolerance for submersion in seawater. These salt marshes are very important habitats for many invertebrates, birds, and juvenile fish. [5]



Figure 7: Tidal flat shown here on the left.

Vertical Facies

Figure T23

Figure 8: Geomorphology of tidal flats.

For stratigraphers and students of sedimentary rocks, identifying tidal flats in the geologic record is often an important step in the reconstruction of paleoenvironments, the location of facies associated with coastlines, and

the recognition of such markers in stratigraphic sequences in basin analyses [8].

- Strat column and describe expected sequence vertically



Figure 9: An example of stratigraphic columns in tidal flat environments.

Summary

Common grain size includes multiple different grain sizes, including sand, silt, and clay particles. The main common sedimentary structures are bioturbation, herringbone cross stratification, and mudcracks. Sediment accumulates during high tide and is deposited as the tide recedes.

Key Words

- Tidal flats
- Mud flats
- Bioturbation

References

https://link.springer.com/referenceworkentry/10.1007/1-4020-3880-1_19

Bookshelves/Geology/Book:_An_Introduction_to_Geology_(Johnson,_Affolter,_Inkenbrandt,_and_Mosher)/05:_Weathering,_Erosion,_and_Sedimentary_Rocks/5.05:_Depositional_Environments

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Turbidites

Introduction

You're likely familiar with the process of landslides. In bodies of water, a similar process occurs and produces **turbidites**. Turbidites are deposited from slurries of sediment and water in any standing body of water (lakes, oceans). They can occur in any layer of a water body (near surface, benthic) as long as there is an oversteepened slope. The fluid involved is water, which mixes with sediment. The new sediment and water mixture is denser than the surrounding water. Turbidites are commonly seen with other sedimentary structures such as ripple lamination, sole marks, and flame structures.



Figure 1: Turbidites deposited on a submarine fan in the Cretaceous Pigeon Point Formation (Pebble Beach near Pescadero, CA). An erosional surface (black arrow) is overlain by a normally graded bed. Ripple lamination is visible in a lower bed (green arrow). (© 2003 Dawn Y. Sumner)

Sediment Transport Processes

Now that we have a better grasp of what a turbidite is, let's look at a step by step outline of how they occur.

1. Turbidity flows start with slope failure in soft sediment. Slopes become oversteepened where sedimentation rates are very high, such at the mouths of rivers. Because flow speeds are very low in standing water, the sediment does not get washed down slope. Rather, it builds up until there is subaqueous slope failure. Earthquakes are common triggers for these slides.
2. Sediment and water mix creating a “fluid” that is denser than the surrounding water because of the entrained sediment. Thus, it flows downhill even if the slope is very low (1°).
3. The base of the flow is commonly erosional on steep slopes, so even more sediment is entrained in the flow.
4. Enough sediment is entrained that erosion stops. Deposition begins as the slope gets shallower or the flow starts to slow down. Initially, the coarsest grains are deposited (remember the Hjulstrom diagram) and then finer grains, so the sediment is “graded”. However, the sediment is usually poorly sorted because the flow is a slurry of water and sediment so hydraulic sorting is reduced. (**Facies = Bouma a**)
5. Sediment concentration decreases with deposition, so one gets more hydraulic sorting. The flow is very fast so the sediment has upper planar lamination. (**Facies = Bouma b**)
6. As the flow slows more, grain size decreases and ripples start to form. Dunes do not usually form for two reasons: a) often only fine sand and finer grains are left in the flow by this point; and b) dunes do not have time to develop. (**Facies = Bouma c**)
7. Eventually, the flow slows to the point that bedload transport stops and deposition is mostly settling of silt and then clay. The progressive settling of coarser and then finer grains produces a faint lamination, but it is not as strong as the planar laminations

in Bouma b. (**Facies = Bouma d**)

8. Mud settles out producing shale. This can look identical to background settling of clays brought into the lake/ocean as suspended sediment. (**Facies = Bouma e**)

Bouma divisions a-d can take hours or a day or so to be deposited. However, division e, which is usually the thinnest, commonly accumulates over months or longer (e.g. hundreds of years) depending on how frequent turbidites are in the area.

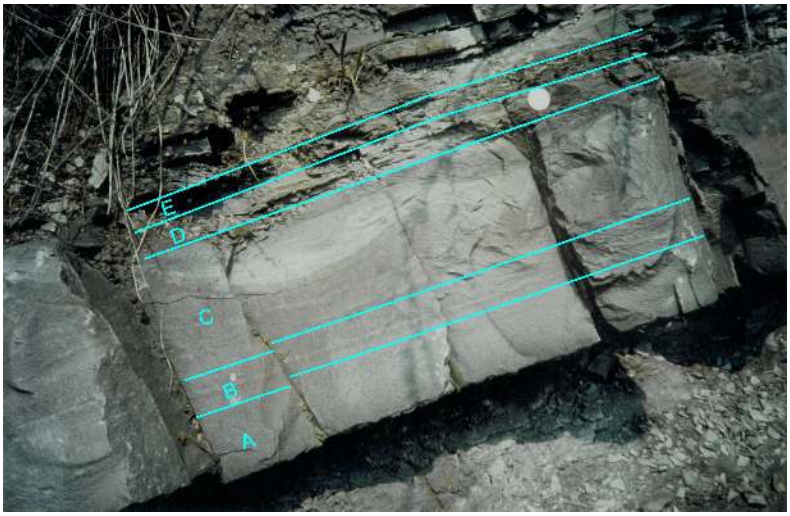


Figure 2: Complete Bouma sequence (a-e) in Devonian Sandstone in Becke-Oese Quarry, Germany (CC BY-SA 3.0; Jo Weber via Wikimedia)

So how do turbidites look in action? For obvious reasons, it is difficult to record a turbidite on camera, but the below video was fortuitously filmed by underwater equipment in Mendocino Canyon off the coast of California (see Sumner and Paull, 2014, for a full description).



It is important to note that the parts of turbidites that are deposited change down slope and usually only a few of the subdivisions are preserved. In the most proximal (up slope) environments, divisions a and b are most common. In the more distal areas, all of the coarser sediment has already been deposited upstream, so divisions d and e are most common. Generally, there are also channels which fan out producing variations in rock types that change in space and through time.

Characteristics of Deposited Sediment

The most common sedimentary structures associated with turbidites are current ripple cross laminations, flame structures, sole marks, planar laminations, and contorted ripple laminae. The below pictures should give you a better idea of what these structures look like in the field.



Figure 3: Flame structures formed where turbidites were deposited over shaley layers in the Cretaceous Pigeon Point Formation. (© 2003 Dawn Y. Sumner)

For a quick refresh, flame structures are deformation in soft sediments that form in unconsolidated sediments that are usually saturated with water. When an overlying bed becomes too heavy, it forces the bed below it to push up though the overlying bed, creating a rounded wavy pattern that resembles flames.

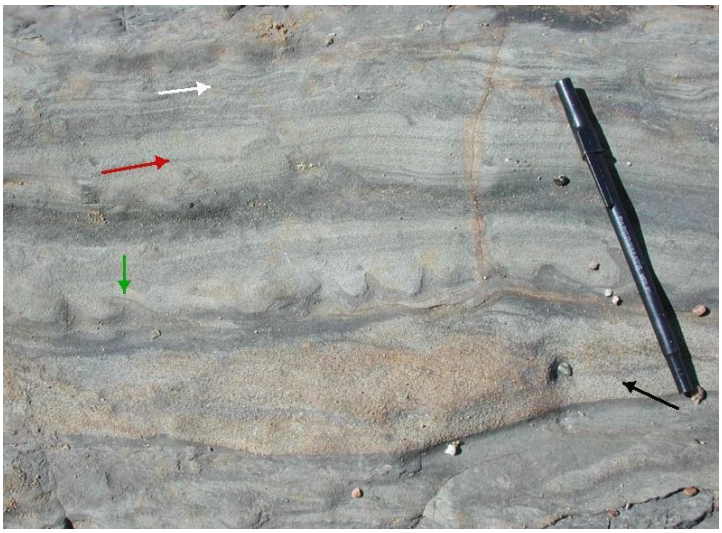


Figure 4: These turbidites show faint current ripple cross laminations (black arrow), flame structures (green arrow), planar laminations (red arrow), and possible contorted ripple laminae (white arrow). Photo taken in the Cretaceous Pigeon Point Formation (© 2003 Dawn Y. Sumner)



Figure 5: Cretaceous Sole Marks in Cache Creek, CA. Black arrow indicates direction of paleocurrent (© 2001 Dawn Y. Sumner)



Figure 6: Coarse sand to pebble cross stratification filling a submarine channel fan in the Cretaceous Pigeon Point Formation. The pitted weathering (black arrow) is due to differential cementation and reflects diagenetic processes rather than depositional processes.

As the turbidite facies is a very high energy environment, there is usually few fossils or biotubation activity. However, there is generally some degree of bioturbation in Bouma e, though this is not a defining characteristic of turbidite facies.

Typical Vertical Sequence of Facies Representing This Environment

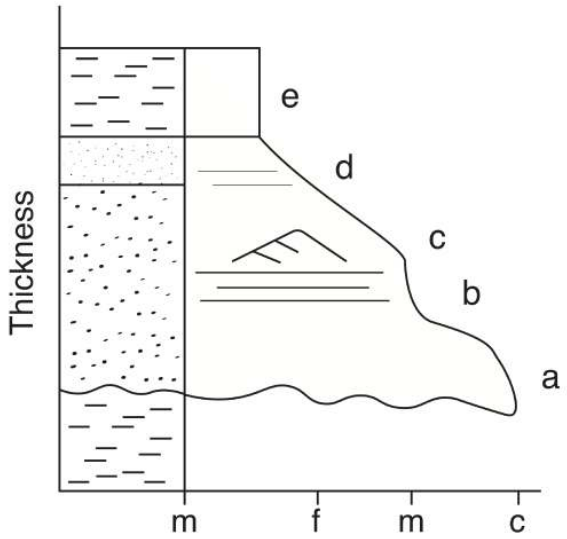


Figure 7: A model of the Bouma sequence (Created by Taryn Lausch)

As we can see from the figure, the expected succession of rocks we would see from this environment are mudstone, coarser grained sandstone, finer grained sandstone, siltstone, and finally mudstone again. The rocks fine upward as the flow slows, resulting in the bouma sequence.

The wavy line at the base of Bouma a in Figure 7 indicates an erosional surface, and flute casts or scour marks are sometimes present. As the flow slows down, it is no longer erosional, and larger sediments (coarse sand) begin to be deposited in Bouma a. As the flow is still moving rather quickly at the point, the sandstone deposited in Bouma a is usually massive. Moving to Bouma b, the flow continues to slow down, there is less turbulence, and grain size continues to fine, allowing for the formation of upper planar lamination. The flow slows down more in Bouma c, depositing even finer grained sandstone, and you begin to see current ripples.

In Bouma d, the flow is very slow moving, and silt settles out of suspension as opposed to being part of the bed load. Faint planar lamination can be seen in Bouma d, and can be confused for the planar lamination on Bouma b, however the lamination in Bouma d are usually not as well defined. Eventually, the flow stops and the water is still again, allowing for the accumulation of mud and the preparation for the next turbidite flow.

The difficulty in recognizing turbidite stratigraphy is that not all of the parts of the Bouma sequence will be clearly distinguishable, particularly the faint planar lamination of Bouma d. Not all parts of the sequence will be preserved, perhaps just the ripple marks and some flame structures. It is helpful to use the key parts of the sequence such as the upward fining trend, planar laminations and sole marks or flame stuctures to distinguish a turbidite. It is also important to note that the vertical sequence is an accumulation of multiple turbidite events. A single turbidite flow will leave behind the Bouma sequence with Bouma a closer to the failure point and Bouma e furthest
away.

A small sidenote about the history of turbidite discovery: Turbidite flows were initially controversial because a process that resulted in the bouma sequence had not been observed in modern depositional environments. Many geologists did not believe that you could generate strong enough currents underwater to get those flow characteristics. Eventually in 1964, two geologists Bruce Heezen and Avery Drake realized that an event in 1929 provided strong evidence for turbidity currents. In 1929, which is long before there were satellites, under water telegraph cables were strung from Newfoundland to Europe. In November, about 30 cables broke in order from farthest north and shallowest to farther south and deeper water. At the time, people did not know why they broke, but Heezen and Drake suggested that a turbidity current was triggered by an earthquake and the cables broke as the turbidity current passed over them (they are strong flows!). Because they were continuously used for communication, the time each cable broke was precisely known. Heezen and Drake calculated that the front of the flow traveled at 250 km/h (36,000 cm/s) when the turbidite first formed and then slowed to around 20 km/h (7000 cm/s) by the time the last cables broke 500 km from the source. This was a fast, strong flow and may be typical of turbidites. These flow speeds are very erosive. It is only after the turbidite slows down even more that you get deposition. The characteristics of the flow seen by the breaking cables fit the flow characteristics proposed by the sedimentologists, and now turbidity currents and the facies model developed for turbidites are widely accepted and often treated as a good example of rocks that closely reflect flow characteristics.

Summary

Turbidites are subaqueous flows that begin with a slope failure. As sediment builds up and the slope gets steeper and steeper, and earthquake or simply oversteepening of the slope can cause a submarine debris flow, ie a turbidity current. This flow extends down the slope with a dense mixture of sediment and water. As the slope decreases, the flow slows down and sediments begin to be deposited. Turbidites all have the same flow characteristics consisting of a very strong erosive flow, deposition of a normally graded bed that is massive, followed by upper plane bedding, rippled finer sands, coarsely laminated silts, then shales.

Keywords:

- bouma sequence
- sole marks
- flame structures
- upward fining
- planar lamination
- current ripple cross laminations

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Waves and Beaches

Introduction:

Beaches are a type of landform that typically occur along coastlines and are present alongside bodies of water. They usually experience waves or current flow behavior that deposits and reworks sedimentary grains as well as their geologic structure over time. The fluids at work in shaping this environment include water and air (laminar, turbulent, and transitional flow types).

Sediment transport processes:

The key transport processes that dominate in shaping this type of environment include waves and turbulent flows via storms, lower to higher energy, respectively. Flow speeds present in this environment are almost always too fast (experiencing higher Reynolds' Number) to allow for mud-sized grains to accumulate. Rather, small, medium, and larger sedimentary grains tend to be transported with a very poorly sorted accumulation at the depositional site (1).



There are many different flow speed and turbulence variations present in waves. The ebb and flow nature of the tides at varying depths modulate the maximal and minimal flow speeds experienced among the waves (Reynolds' Number). These factors all lead to a multitude of sedimentary variations along beaches.

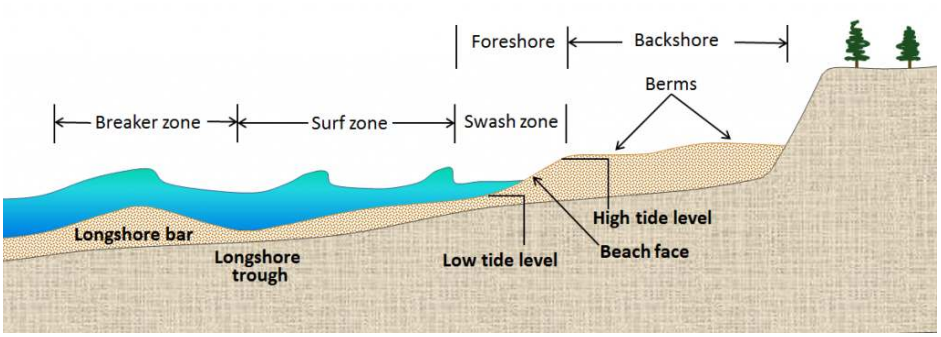
At the breaker zone, wave turbulence of varying flow speeds is experienced. As the waves move in from offshore (greater depth) carrying sedimentary grains of varying sizes and shapes closer to the swash zone (shallower depths), the flow speed, and therefore turbulence, increases rapidly. The suspended grains transported by these waves promptly deposit medium-to-larger/coarser sized sedimentary grains at a varying gradient along the breaker zone (2). The accumulation of sedimentary grains at this site tends to be poorly sorted and sub-rounded to angular, forming planar laminae dipping towards the ocean at the contact site. As the waves move back offshore from the breaker zone (high turbulence and flow speeds) they tend to carry and transport some medium-to-heavy grains back as the tide recedes from the swash zone, others are left deposited at the base.

In contrast to the breaker zone, turbulence and flow speeds of waves located in the offshore zone tend to be lower in energy and more consistent. Flow energy (Reynolds' Number) and turbulence decreases with increasing depths, which is due to the difference in aeolian influence present on the surface of the water versus the lack thereof at greater depths. Larger and coarser grains tend to be carried and transported closer to the surface in this zone with smaller grains experiencing transportation and deposition closer at the base (1).

During periods of high tides, such as storms, the behavior and location of grain transportation and deposition shift greatly. As the ebb and flow of high tides act along the shoreline, the tides will usually reach up and over the berm (maximum distance the waves can reach under normal non-stormy conditions) and deposit sedimentary grains further in along the shoreline. The presence of high winds under these conditions create aeolian dunes along the drier portions of the beach face.

Characteristics of deposited sediment:

The common sedimentary structures that are characteristic of this environment are produced by the processes of wave ripples, planar lamination, cross-bedding, and bioturbation (3). Sedimentary grains of all varying sizes and shapes are deposited along the coastline - depending on the turbulence experienced by the waves' ebb and flow (Reynolds' number at the time of sediment deposition). The principle of original horizontality, as is the case with sediment and stratigraphic units, is very much at play in this environment.



Grains deposited along and past the berm zone of the beach tend to be smoother in texture and less dense due to ease of transportation. Under non-stormy conditions, this zone experiences aeolian behavior and produces wind ripples, cross-bedding, and dunes as sedimentary structures. Grains tend to be well sorted with varying grain shapes present (1).

Grains deposited at the breaker zone tend to be poorly sorted, medium to coarser/larger in size and range from sub-rounded to angular in shape. This is due to the gradual decrease in depth as the wave approaches the breaker zone and thus increasing in turbulence. The sedimentary structures present at this zone tend to be wave ripples and planar laminae with a dip towards the ocean (6).

In the offshore zone, the transportation and deposition of sedimentary grains vary in size, sorting, and shape depending on the depths of the current. This is due to the circular motion of waves caused by the behavior of wind blowing across the surface. This aeolian influence across the ocean surface decreases gradually with increasing depths until being eliminated entirely just prior to reaching the ocean floor. The sedimentary structures present within this zone include cross-bedding lamination, planar lamination, and bioturbation via marine organism behavior.

Typical vertical sequence of facies:

Walther's Law of Facies states that the vertical depositional succession of stratigraphic facies reflects the lateral changes in sedimentary layers witnessed within the environment. It also states that when a depositional environment shifts laterally, stratigraphic layers will be deposited on top of one another (6). Walther's Law is very much at play in a beach environment. As the overall sea level rises and falls, the present stratigraphic layers will be altered in accordance with Walther's Law. Going from the beach, to the breaker zone where shallow marine rocks reside, to the offshore zone where deep marine rocks reside, all these layers will shift laterally reflecting the behavior experienced by the tide. Parts of the aforementioned lateral layers will also be deposited on top of another in accordance with the ebb and flow of the waves.

*Quick note regarding Walther's Law. If erosion, non-deposition, or a break in deposition have taken place in the stratigraphy - Walther's Law will not work in these cases (4).

Walther's Law - before/after

Stratigraphic Column (7)

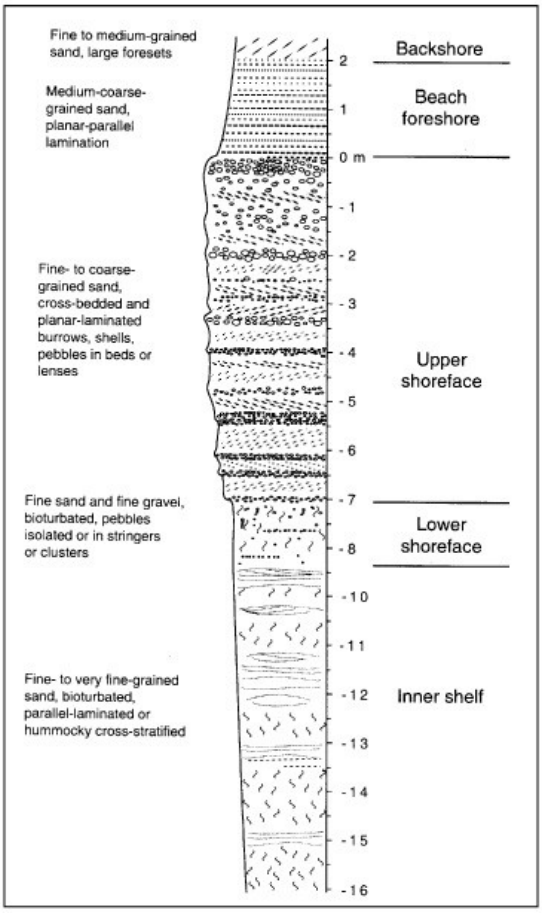
Summary:

Beaches are a type of landform that typically occur along coastlines and are present alongside bodies of water. They usually experience waves or current flow behavior that deposits and reworks sedimentary grains as well as their geologic structure over time. The vertical depositional succession of stratigraphic facies reflects the lateral changes in sedimentary layers witnessed within this environment. Common sedimentary structures that are characteristic of this environment are produced by the processes of wave ripples, planar lamination, cross-bedding, and bioturbation. The key transport processes that dominate in shaping this type of environment include waves and turbulent flows via storms, lower to higher energy (Reynolds' Number), respectively.

Keywords:

Laminar flow, Turbulent flow, Depositional environments, Grain sizes, Beaches, Paleo-beach, Principle of Original Horizontality, Grain transport, Coastline, bioturbation, Wave ripples, Current ripples, Dunes, Planar lamination, Stratigraphic columns, Trace/body fossils, Tides, Translational flow.

References:



1) https://geo.libretexts.org/Courses/University_of_California_Davis/UCD_GEL_109%3A_Sediments_and_Strata_(Sumner), Dawn Sumner UCD

2) https://www.youtube.com/watch?v=U9wtyfwlhCc&feature=youtu.be, "*Underwater in the breaker zone - small waves in the Bahamas*", Dawn Sumner UCD

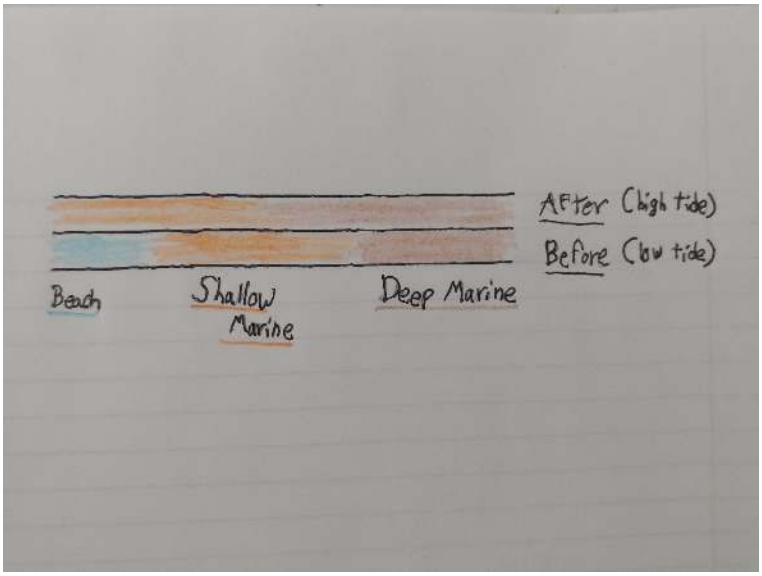
3) https://www.youtube.com/watch?v=CHZtSPZcdz0, "*Beaches and Waves*", Dawn Sumner UCD

4) https://www.youtube.com/watch?v=UG1WuSUoCcw, "*Walther's Law*", Dawn Sumner UCD

5) https://journals.lib.unb.ca/index.ph...icle/view/3154

6) Nichols Sedimentology and Stratigraphy

7) Clifton H.E. (2005) Coastal Sedimentary Facies. In: Schwartz M.L. (eds) Encyclopedia of Coastal Science. Encyclopedia of Earth Science Series. Springer, Dordrecht



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