Chapter 6 Sediments and Sedimentary Rocks

Learning Objectives

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Describe the differences between cobbles, pebbles, sand, silt, and clay and explain the relationship between clast size and the extent to which clasts can be transported by moving water or by wind.
- Describe the characteristics of the various types of clastic sedimentary rock, including the significance of differences in the composition of sandstones.
- Explain the differences in the characteristics and depositional environments of various types of chemical sedimentary rocks.
- Differentiate between various sedimentary depositional environments in both terrestrial and marine environments, and explain how the formation of sedimentary basins can be related to plate tectonic processes.
- Apply your understanding of the features of sedimentary rocks, including grain characteristics, sedimentary structures, and fossils, to the interpretation of past depositional environments and climates.
- Explain the importance of and differences between groups, formations, and members.

Figure 6.0.1 The Cretaceous Dinosaur Park Formation at Dinosaur Provincial Park, Alberta, one the world's most important sites for dinosaur fossils. The rocks in the foreground show cross-bedding, indicative of deposition in a fluvial (river) environment

In Chapter 5, we talked about weathering and erosion, which are the first two steps in the transformation of existing rocks into sedimentary rocks. The remaining steps in the formation of sedimentary rocks are transportation, deposition, burial, and lithification (Figure 6.0.2). Transportation is the movement of sediments or dissolved ions from the site of erosion to a site of deposition; this can be by wind, flowing water, glacial ice, or mass movement down a slope. Deposition takes place where the conditions change enough so that sediments being transported can no longer be transported (e.g., a current slows). Burial occurs when more sediments are piled onto existing sediments, and layers formed earlier are covered and compacted. Lithification is what happens—at depths of hundreds to thousands of metres—when those compacted sediments become cemented together to form solid sedimentary rock.

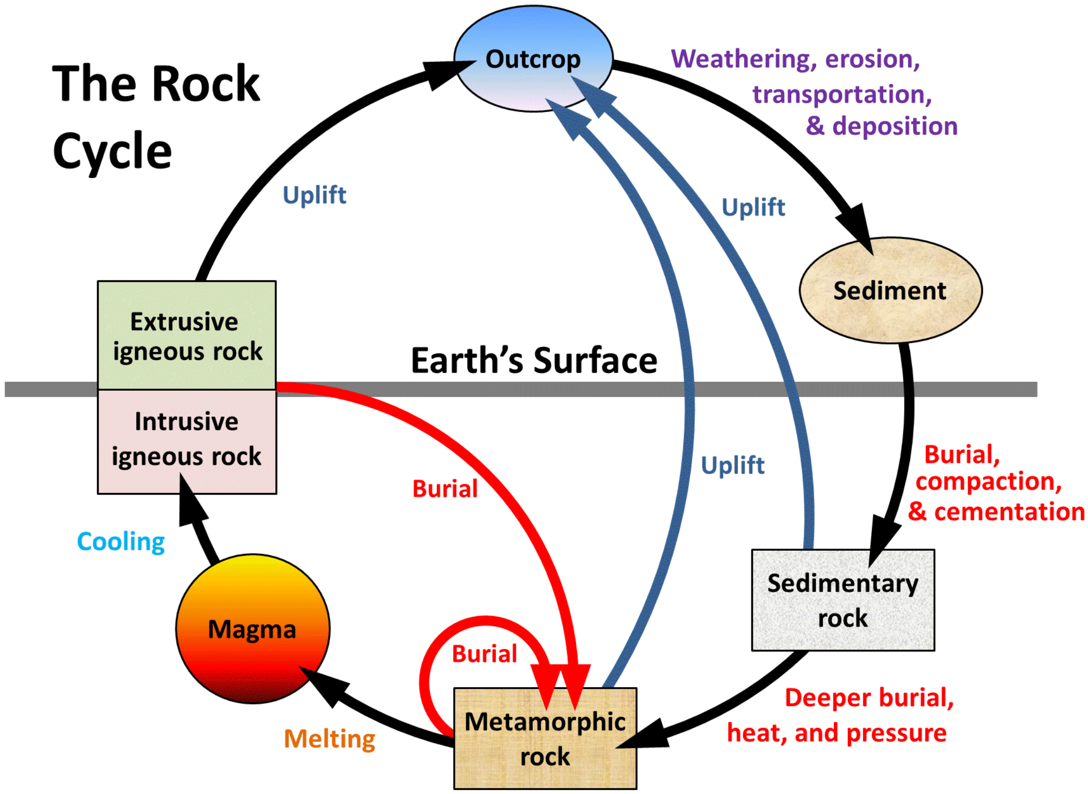

Figure 6.0.2 The rock cycle, showing the processes related to sedimentary rocks on the right-hand side.

In this textbook, we divide sedimentary rocks into two main types: **clastic** and **chemical**. Clastic sedimentary rocks are mainly composed of material that has been transported as solid fragments (clasts). Chemical sedimentary rocks are mainly composed of material that has been transported as ions in solution. It's important *not* to assume that mechanical weathering leads only to clastic sedimentary rocks, while chemical weathering leads only to chemical sedimentary rocks. In most cases, millions of years separate the weathering and depositional processes, and both types of sedimentary rocks tend to include at least some material derived from both types of weathering.

Media Attributions

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6.1 Clastic Sedimentary Rocks

A **clast** is a fragment of rock or mineral, ranging in size from less than a micron[1] (too small to see) to as big as an apartment block. Various types of clasts are shown in Figure 5.3.1 and in Exercise 5.3. The smaller ones tend to be composed of a single mineral crystal, and the larger ones are typically composed of pieces of rock. As we've seen in Chapter 5, most sand-sized clasts are made of quartz because quartz is more resistant to weathering than any other common mineral. Many of the clasts that are smaller than sand size (less than $^{1}/_{16}$th millimetre) are made of clay minerals. Most clasts larger than sand size (greater than 2 millimetres) are actual fragments of rock, and commonly these might be fine-grained rock like basalt or andesite, or if they are bigger, coarse-grained rock like granite or gneiss. Sedimentary rocks that are made up of "clasts" are called clastic sedimentary rocks. A comparable term is "detrital sedimentary rocks".

Grain-Size Classification

Geologists that study sediments and sedimentary rocks use the Udden-Wentworth grain-size scale for describing the sizes of the grains in these materials (Table 6.1).

1. A micron is a millionth of a metre. There are 1,000 microns in a millimetre.

Table 6.1 The Udden-Wentworth grain-size scale for classifying sediments and the grains that make up sedimentary rocks

[Skip Table]

Type	Description	Size range (millimetres)	Size range (microns)
Boulder	large	1024 and up	
	medium	512 to 1024	
	small	256 to 512	
Cobble	large	128 to 256	
	small	64 to 128	
Pebble (Granule)	very coarse	32 to 64	
	coarse	16 to 32	
	medium	8 to 16	
	fine	4 to 8	
	very fine	2 to 4	
Sand	very coarse	1 to 2	1000 to 2000
	coarse	0.5 to 1	500 to 1000
	medium	0.25 to 0.5 ($^1/_4$ to $^1/_2$ mm)	250 to 500
	fine	0.125 to 0.25 ($^1/_8$th to $^1/_4$ mm)	125 to 250
	very fine	0.063 to 0.125 (or $^1/_{16}$th to $^1/_8$th mm)	63 to 125
Silt	very course		32 to 63
	course		16 to 32
	medium		8 to 16
	fine		4 to 8
	very fine		2 to 4
Clay	clay		0 to 2

There are six main grain-size categories; five are broken down into subcategories, with **clay** being the exception. The diameter limits for each successive subcategory are twice as large as the one beneath it. In general, a **boulder** is bigger than a toaster and difficult to lift. There is no upper limit to the size of boulder.[2] A small **cobble** will fit in one hand, a large one in two hands. A **pebble** is something that you could throw quite easily. The smaller ones—known as **granules**—are gravel size, but still you could

2. The largest known free-standing rock (i.e., not part of bedrock) is Giant Rock in the Mojave Desert, California. It’s about as big as an apartment building—seven stories high!

throw one. You can't really throw a single grain of **sand**. Sand ranges from 2 millimetres down to 0.063 millimetres, and its key characteristic is that it feels "sandy" or gritty between your fingers—even the finest sand grains feel that way. **Silt** is essentially too small for individual grains to be visible, and while sand feels sandy to your fingers, silt feels smooth to your fingers but gritty in your mouth. Clay is so fine that it feels smooth even in your mouth.

Exercise 6.1 Describe the sediment on a beach

Providing that your landscape isn't covered in deep snow at present, visit a beach somewhere nearby—an ocean shore, a lake shore, or a river bank. Look carefully at the size and shape of the beach sediments. Are they sand, pebbles, or cobbles? If they are not too fine, you should be able to tell if they are well rounded or more angular.

The beach in Figure 6.1.1 is at Sechelt, B.C. Although there is a range of clast sizes, it's mostly made up of well-rounded cobbles interspersed with pebbles. This beach is subject to strong wave activity, especially when winds blow across the Strait of Georgia from the south. That explains why the clasts are relatively large and are well rounded.

Figure 6.1.1 Pebbles on an ocean beach at Sechelt, B.C.

See Appendix 3 for Exercise 6.1 answers.

If you drop a granule into a glass of water, it will sink quickly to the bottom (less than half a second). If you drop a grain of sand into the same glass, it will sink more slowly (a second or two depending on the size). A grain of silt will take several seconds to get to the bottom, and a particle of fine clay may never get there. The rate of settling is determined by the balance between gravity and friction, as shown in Figure 6.1.2. Large particles settle quickly because the gravitational force (which is proportional to the mass, and therefore to the volume of the particle) is much greater than the frictional resistance (which is proportional to the surface area of the particle). For smaller particles the difference between gravitational push and frictional resistance is less, so they settle slowly.

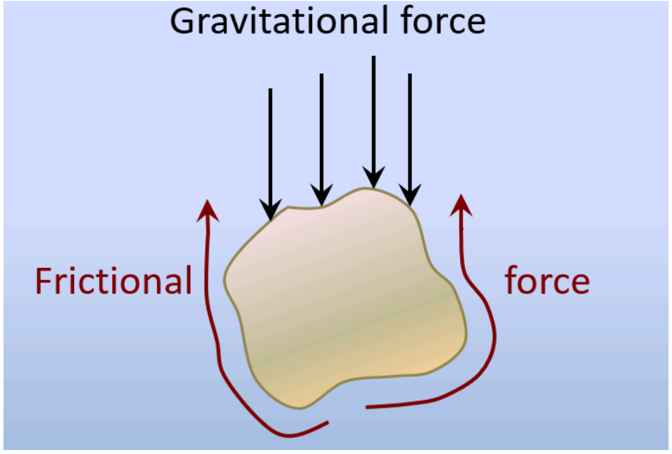


Figure 6.1.2 The two forces operating on a grain of sand in water. Gravity is pushing it down, and the friction between the grain and the water is resisting that downward force.

Small particles that settle slowly spend longer suspended in the water, and therefore tend to get moved farther than large particles if the water is moving.

Transportation

One of the key principles of sedimentary geology is that the ability of a moving medium (air or water) to move sedimentary particles—and keep them moving—is dependent on the velocity of flow. The faster the medium flows, the larger the particles it can move. This is illustrated in Figure 6.1.3. Parts of the river are moving faster than other parts, especially where the slope is greatest and the channel is narrow. Not only does the velocity of a river change from place to place, but it changes from season to season. During peak **discharge**[3] at the location of Figure 6.1.3, the water is high enough to flow over the embankment on the right, and it flows fast enough to move the boulders that cannot be moved during low flows.

3. Discharge of a stream is the volume of flow passing a point per unit time. It's normally measured in cubic metres per second (m^3/s).

Figure 6.1.3 Variations in flow velocity on the Englishman River near Parksville, B.C. When the photo was taken the river was not flowing fast enough anywhere to move the boulders and cobbles visible here. During flood events the water flows right over the snow-covered bank on the right, and is fast enough to move boulders.

Clasts within streams are moved in several different ways, as illustrated in Figure 6.1.4. Large **bed load** clasts are pushed (by traction) or bounced along the bottom (by saltation), while smaller clasts are suspended in the water and kept there by the turbulence of the flow. As the flow velocity changes, different-sized clasts may be either incorporated into the flow or deposited on the bottom. At various places along a river, there are always some clasts being deposited, some staying where they are, and some being eroded and transported. This changes over time as the discharge of the river changes in response to changing weather conditions.

Other sediment transportation media, such as waves, ocean currents, and wind, operate under similar principles, with flow velocity as the key underlying factor that controls transportation and deposition.

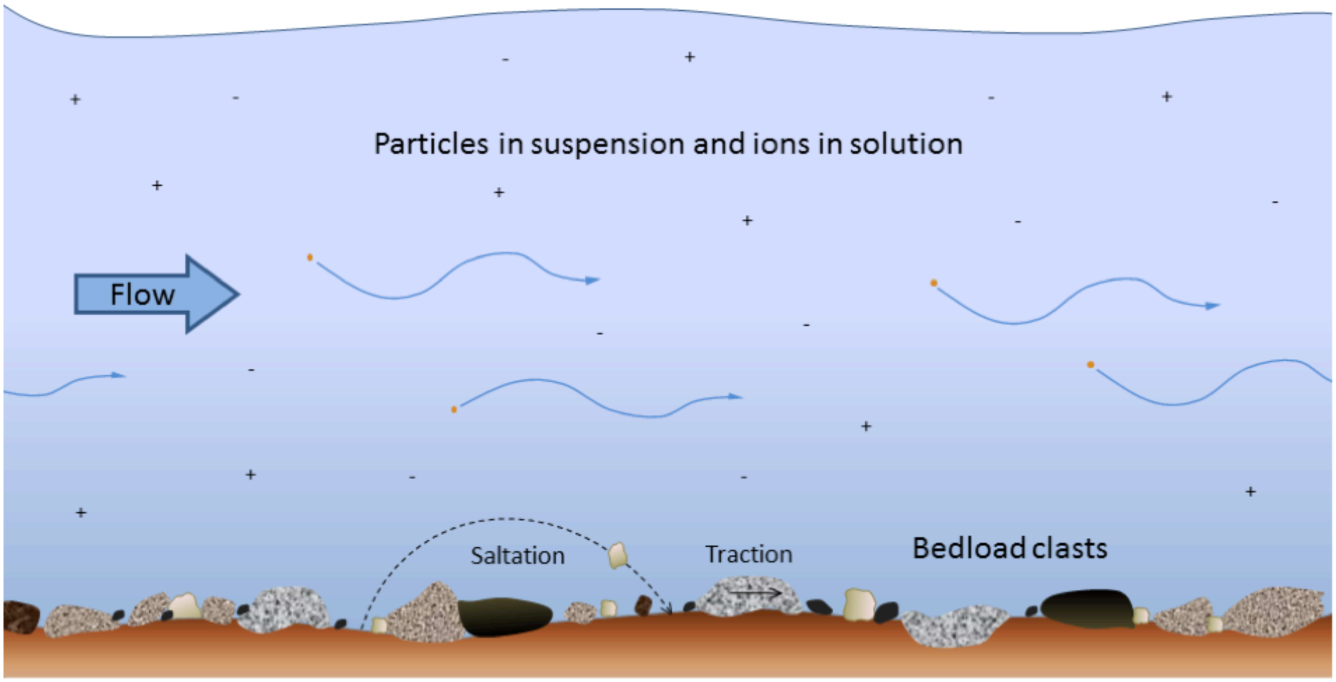


Figure 6.1.4 Transportation of sediment clasts by stream flow. The larger clasts, resting on the bottom (bedload), are moved by traction (sliding) or by saltation (bouncing). Smaller clasts are kept in suspension by turbulence in the flow. Ions (depicted as + and – in the image, but invisible in real life) are dissolved in the water.

Clastic sediments are deposited in a wide range of environments, including glaciers, slope failures, rivers—both fast and slow—lakes, deltas, and ocean environments—both shallow and deep. If the sedimentary deposits last long enough to get covered with other sediments they may eventually form into rocks ranging from fine mudstone to coarse breccia and conglomerate.

Lithification is the term used to describe a number of different processes that take place within a deposit of sediment to turn it into solid rock (Figure 6.1.5). One of these processes is burial by other sediments, which leads to compaction of the material and removal of some of the intervening water and air. After this stage, the individual clasts are touching one another. **Cementation** is the process of crystallization of minerals within the pores between the small clasts, and especially at the points of contact between clasts. Depending on the pressure, temperature, and chemical conditions, these crystals might include a range of minerals, the common ones being calcite, hematite, quartz and clay minerals.

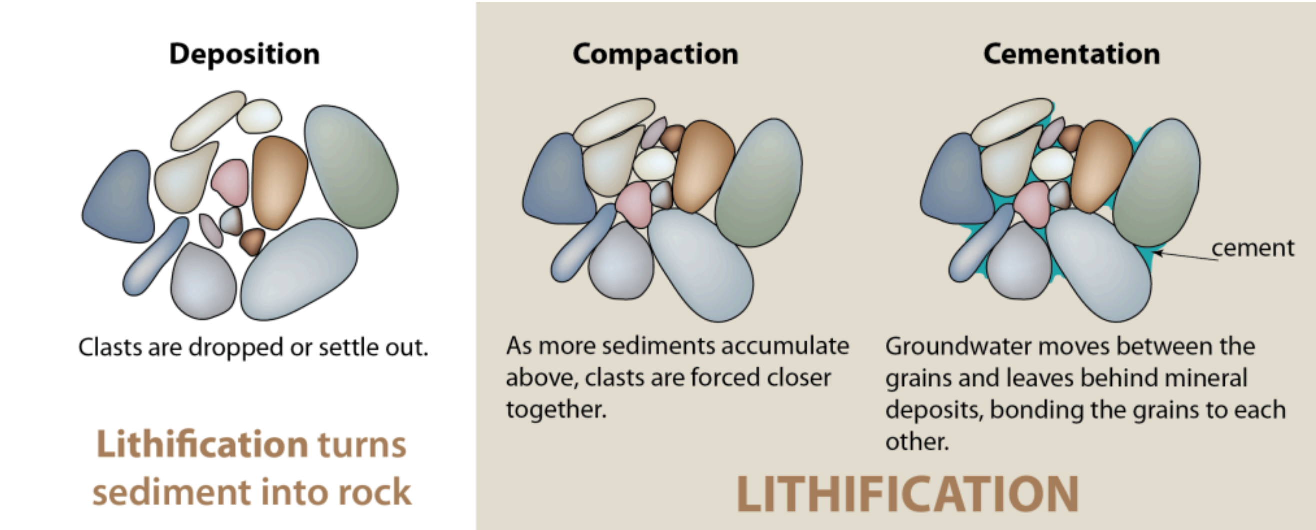


Figure 6.1.5 Lithification turns sediments into solid rock. Lithification involves the compaction of sediments and then the cementation of grains by minerals that precipitate from groundwater in the spaces between these grains. Source: Karla Panchuk (2016) CC BY 4.0

The characteristics and distinguishing features of clastic sedimentary rocks are summarized in Table 6.2. **Mudrock** is composed of at least 75% silt- and clay-sized fragments. If it is dominated by clay, it is called **claystone**. If it shows evidence of bedding or fine laminations, it is **shale**; otherwise, it is mudstone. Mudrocks form in very low energy environments, such as lakes, river backwaters, and the deep ocean.

Table 6.2 The main types of clastic sedimentary rocks and their characteristics.

[Skip Table]

Group	Examples	Characteristics
Mudrock	mudstone	Greater than 75% silt and clay, not bedded
	shale	Greater than 75% silt and clay, thinly bedded
Coal		Dominated by fragments of partially decayed plant matter often enclosed between beds of sandstone or mudrock.
Sandstone	quartz sandstone	Dominated by sand, greater than 90% quartz
	arkose	Dominated by sand, greater than 10% feldspar
	lithic wacke	dominated by sand, greater than 10% rock fragments, greater than 15% silt and clay
Conglomerate		Dominated by rounded clasts, granule size and larger
Breccia		Dominated by angular clasts, granule size and larger

Most coal forms in fluvial or delta environments where vegetation growth is vigorous and where decaying plant matter accumulates in long-lasting swamps with low oxygen levels. To avoid oxidation and breakdown, the organic matter must remain submerged for centuries or millennia, until it is covered with another layer of either muddy or sandy sediments. It is important to note that in some textbooks coal is described as an "organic sedimentary rock." In this book, coal is included with the clastic rocks for two reasons: first, because it is made up of fragments of organic matter; and second, because coal seams (sedimentary layers) are almost always interbedded with layers of clastic rocks, such as mudrock or sandstone. In other words, coal accumulates in environments where other clastic rocks accumulate.

It's worth taking a closer look at the different types of sandstone because sandstone is a common and important sedimentary rock. Typical sandstone compositions are shown in Figure 6.1.6. Sandstones are mostly made up of sand grains of course, but they also include finer material—both silt and clay. The term **arenite** applies to a so-called clean sandstone, meaning one with less than 15% silt and clay. Considering the sand-sized grains only (the grains larger than $^{1}/_{16}$th mm), arenites with 90% or more quartz are called quartz arenites. If they have more than 10% feldspar and more feldspar than rock fragments, they are called feldspathic arenites or **arkosic arenites** (or just **arkose**). If they have more than 10% rock fragments, and more rock fragments than feldspar, they are **lithic arenites.**[4] A sandstone with more than 15% silt or clay is called a **wacke** (pronounced *wackie*). The terms *quartz wacke*, *lithic wacke*, and *feldspathic wacke* are used with limits similar to those on the arenite diagram. Another name for a lithic wacke is **greywacke**.

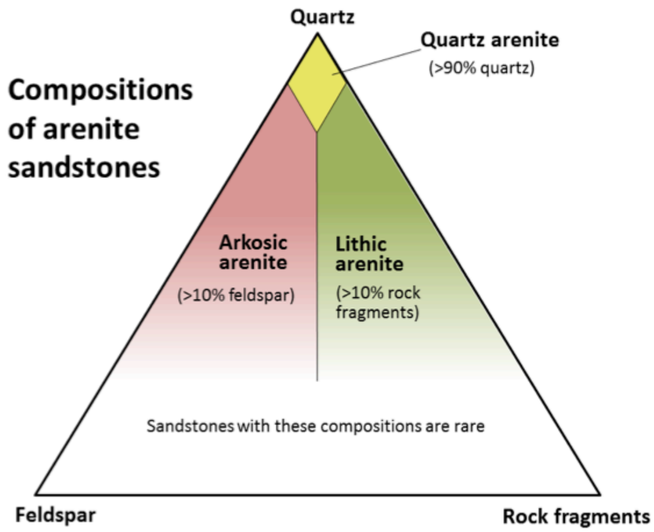


Figure 6.1.6 A compositional triangle for arenite sandstones, with the three most common components of sand-sized grains: quartz, feldspar, and rock fragments. Arenites have less than 15% silt or clay. Sandstones with more than 15% silt and clay are called wackes (e.g., quartz wacke, lithic wacke).

Some examples of sandstones, magnified in thin section are shown in Figure 6.1.7. (A thin section is rock sliced thin enough so that light can shine through.)

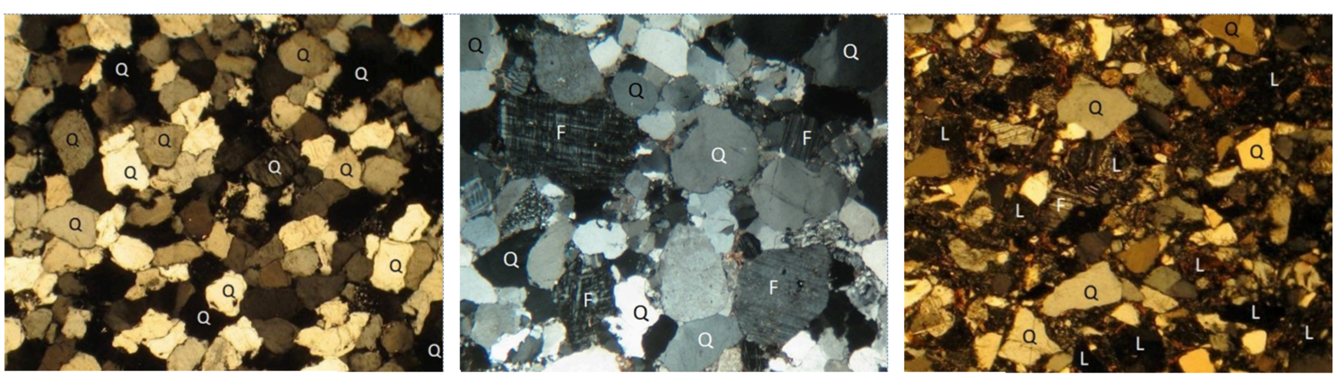


Figure 6.1.7 Microscope photos of three types of sandstone in thin-section. Some of the minerals are labelled: Q=quartz, F=feldspar and L= lithic (rock fragments). The quartz arenite and arkose have relatively little silt-clay matrix, while the lithic wacke has abundant matrix.

4. "Lithic" means "rock." Lithic clasts are rock fragments, as opposed to mineral fragments.

Clastic sedimentary rocks in which a significant proportion of the clasts are larger than 2 millimetres are known as **conglomerate** if the clasts are well rounded, and **breccia** if they are angular. Conglomerates form in high-energy environments such as fast-flowing rivers, where the particles can become rounded. Breccias typically form where the particles are not transported a significant distance in water, such as alluvial fans and talus slopes. Some examples of clastic sedimentary rocks are shown on Figure 6.1.8.

(a) Mudrock with bivalve impressions, Cretaceous Nanaimo Group, Browns River, Vancouver Island

(b) Coarse sandstone with cross-bedding, Cambrian Tapeats Formation Chino Valley, Arizona

(c) Conglomerate with imbricate (aligned, tilted down to the left) cobbles, Cretaceous Geoffrey Formation, Hornby Island, BC

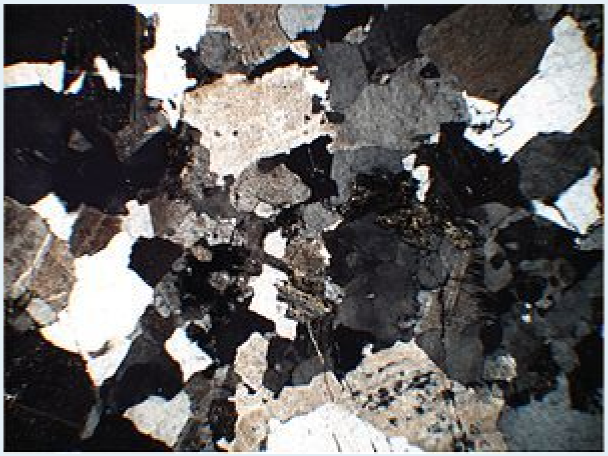
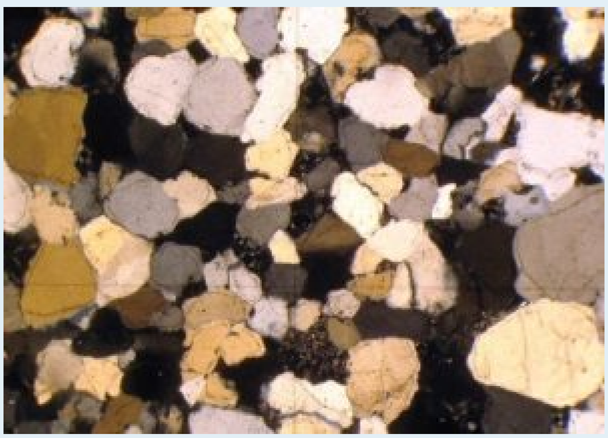
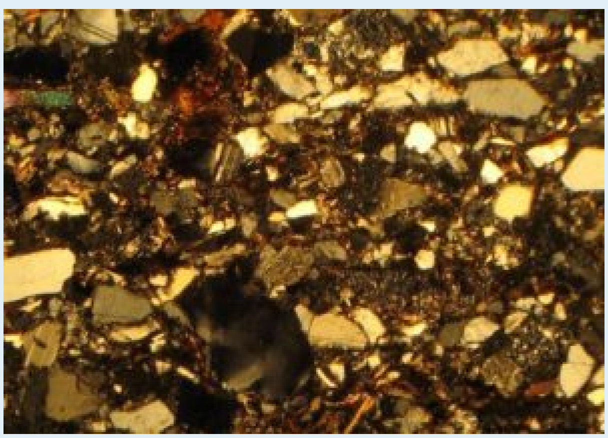
(d) Sedimentary breccia, the Pre-Cambrian Toby Formation, east of Castlegar, BC (image is approx. 1 m across)

Figure 6.1.8 Examples of various clastic sedimentary rocks. [Image Description]

Exercise 6.2 Classifying sandstones

Table 6.3 below shows magnified thin sections of three sandstones, along with descriptions of their compositions. Using Table 6.1 and Figure 6.1.6, find an appropriate name for each of these rocks.

Table 6.3 Classifying sandstones

Magnified Thin Section	**Description**
	Angular sand-sized grains are approximately 85% quartz and 15% feldspar. Silt and clay make up less than 5% of the rock.
	Rounded sand-sized grains are approximately 99% quartz and 1% feldspar. Silt and clay make up less than 2% of the rock.
	Angular sand-sized grains are approximately 70% quartz, 20% lithic, and 10% feldspar. Silt and clay make up about 20% of the rock.

See Appendix 3 for Exercise 6.2 answers.

Image Descriptions

Figure 6.1.8 image description: (A) Mudrock with bivalve impressions, Cretaceous Nanaimo group, Browns River, Vancouver Island. A very fine-grained rock with shell impressions. (B) Coarse sandstone with cross-bedding, Cambrian Tapeats Formation Chino Valley, Arizona. (C) Conglomerate with imbricate (aligned, tilted down to the left) cobbles, Cretaceous Geoffrey Formation, Hornby Island, BC. (D) Sedimentary breccia, the Pre-Cambrian Toby Formation, east of Castlegar, BC. [Return to Figure 6.1.8]

Media Attributions

- Figures 6.1.1, 6.1.2, 6.1.3, 6.1.4, 6.1.5, 6.1.6, 6.1.7, 6.1.8: © Steven Earle. CC BY.
- Exercise 6.2, first image: Aplite Red © Rudolf Pohl. CC BY-SA.

6.2 Chemical Sedimentary Rocks

Whereas clastic sedimentary rocks are dominated by components that have been transported as solid clasts (clay, silt, sand, etc.), chemical sedimentary rocks are dominated by components that have been transported as ions in solution (Na^{+}, Ca^{2+}, HCO_3^{-}, etc.). There is some overlap between the two because almost all clastic sedimentary rocks contain cement formed from dissolved ions, and many chemical sedimentary rocks include some clasts. Since ions can stay in solution for tens of thousands of years (some much longer), and can travel for tens of thousands of kilometres, it is virtually impossible to relate chemical sediments back to their source rocks.

Chemical weathering and chemical sedimentary rocks

Many students confuse chemical weathering with chemical sedimentary rocks, or mistakenly assume that when and where chemical weathering is taking place, chemical sedimentary rocks will accumulate. Most ions in solution in rivers, lakes and the ocean are produced during chemical weathering, but those ions can remain in solution for millions of years, and during that time they can travel hundreds of thousands of km (yes, literally around the world, several times). They might eventually come out of solution as a result of a biological process or a change in the chemical conditions and will then become a mineral crystal that can settle to form a chemical sediment.

So the calcium ions that are part of a calcite mud on the sea floor near Australia's Great Barrier Reef could literally have come from anywhere on Earth (and almost certainly came from many different places), and might have been in solution for as little as a few days or for as long as tens of millions of years.

The most common chemical sedimentary rock, by far, is **limestone**. Others include **chert**, **banded iron formation,** and **evaporites**. Biological processes are important in the formation of some chemical sedimentary rocks, especially limestone and chert. For example, limestone is made up almost entirely of fragments of marine[1] organisms that manufacture calcite for their shells and other hard parts, and most chert includes at least some of the silica tests (shells) of tiny marine organisms (such as diatoms and radiolarians).

Limestone

Almost all limestone forms in the oceans, and most of that forms on the shallow continental shelves, especially in tropical regions with coral reefs. Reefs are highly productive ecosystems populated by a wide range of organisms, many of which use calcium and bicarbonate ions in seawater to make carbonate minerals (especially calcite) for their shells and other structures. These include corals, of course, but also green and red algae, urchins, sponges, molluscs, and crustaceans. The hard parts of these organisms are

1. We use the word *marine* when referring to salt water (i.e., oceanic) environments, and the word *aquatic* when referring to freshwater environments.

eroded by waves and currents to produce carbonate fragments that accumulate in the surrounding region, as illustrated in Figure 6.2.1.

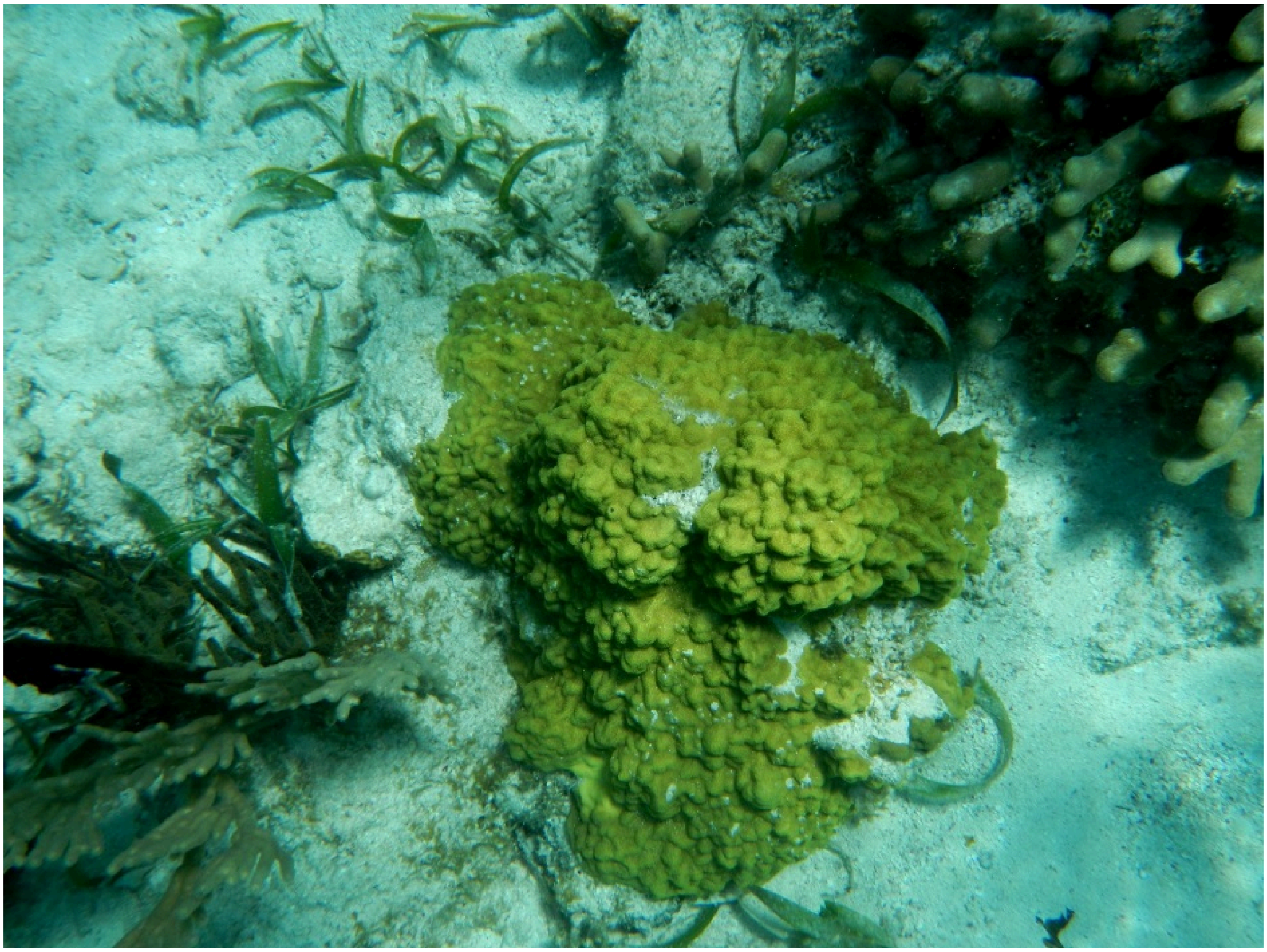


Figure 6.2.1 Various corals and green algae on a reef at Ambergris, Belize. The light-coloured sand consists of carbonate fragments eroded from the reef organisms, and this is the type of material that will eventually become limestone.

Figure 6.2.2 shows a cross-section through a typical reef in a tropical environment (normally between 40° N and 40° S). Reefs tend to form in areas with clear water (e.g., not close to the mouths of large rivers), and near the edges of steep drop-offs because the reef organisms thrive on nutrient-rich upwelling currents. As the reef builds up, it is eroded by waves and currents to produce carbonate sediments that are transported into the steep offshore **fore-reef** area and the shallower inshore **back-reef** area. These sediments are dominated by reef-type carbonate fragments of all sizes, including mud. In many such areas, carbonate-rich sediments also accumulate in quiet lagoons, where mud and mollusc-shell fragments predominate (Figure 6.2.3a) or in offshore areas with strong currents, where either foraminifera tests accumulate (Figure 6.2.3b) or calcite crystallizes inorganically to form **ooids**—spheres of calcite that form in shallow tropical ocean water with strong currents (Figure 6.2.3c).

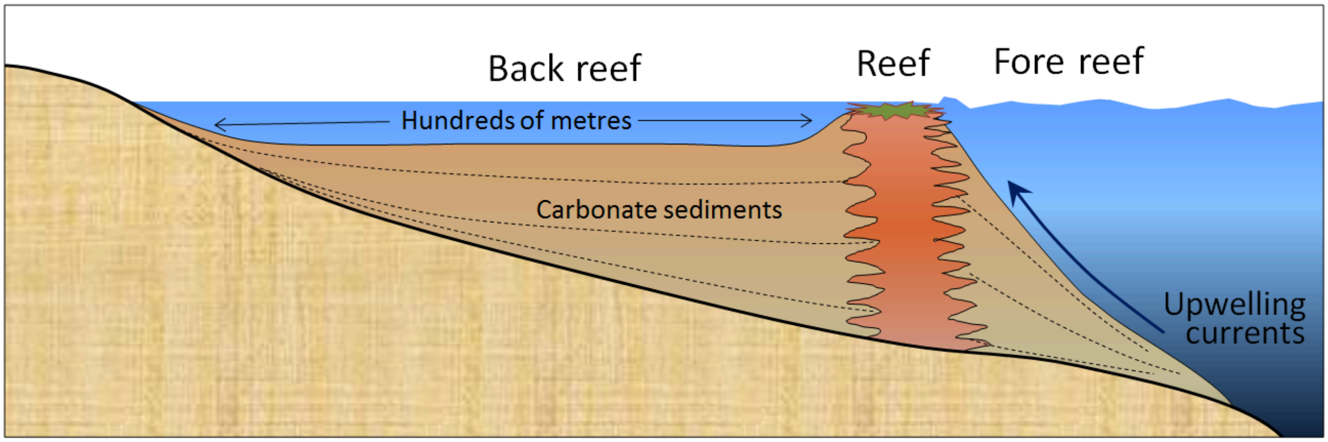


Figure 6.2.2 Schematic cross-section through a typical tropical reef.

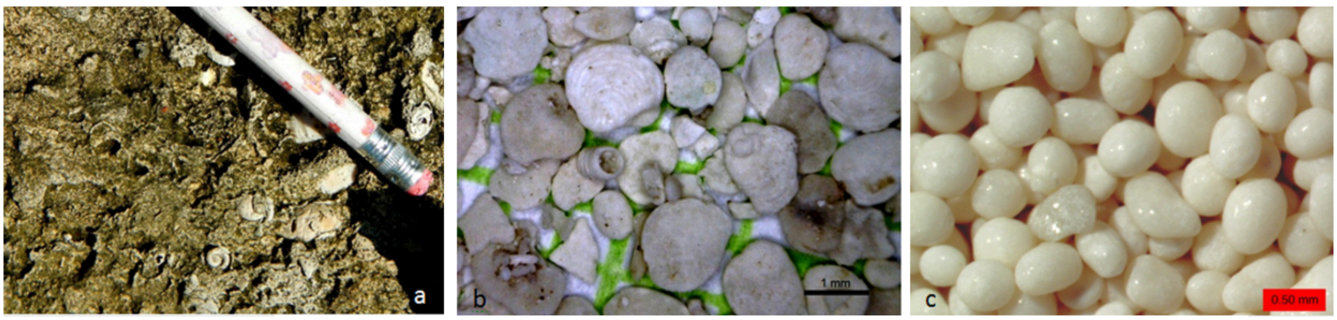


Figure 6.2.3 Carbonate rocks and sediments: (a) mollusc-rich limestone formed in a lagoon area at Ambergris, Belize, (b) foraminifera-rich sediment from a submerged carbonate sandbar in Belize (c) ooids from a beach at Joulters Cay, Bahamas.

Limestone also accumulates in deeper water, from the steady rain of the carbonate shells of tiny organisms that lived near the ocean surface. The lower limit for limestone accumulation is around 4,000 metres. Beneath that depth, calcite is soluble so limestone does not accumulate.

Calcite can also form on land in a number of environments. **Tufa** forms at springs (Figure 6.2.4) and **travertine** forms at hot springs. Similar material precipitates within limestone caves to form **stalactites**, **stalagmites,** and a wide range of other **speleothems**. Tufa, travertine and speleothems make up only a tiny proportion of all limestone.

Figure 6.2.4 Tufa formed at a spring at Johnston Creek, Alberta. The bedded grey rock to the left is limestone.

Dolomite ($CaMg(CO_3)_2$) is another carbonate mineral, but *dolomite* is also the name for a rock composed of the mineral dolomite (although some geologists use the term **dolostone** to avoid confusion). Dolomite rock is quite common (there's a whole Italian mountain range named after it), which is surprising since marine organisms don't make dolomite. All of the dolomite found in ancient rocks has been formed through magnesium replacing some of the calcium in the calcite in carbonate muds and sands. This process is known as **dolomitization**, and it is thought to take place where magnesium-rich water percolates through the sediments in carbonate tidal flat environments.

Chert

As we've seen, not all marine organisms make their hard parts out of calcite; some, like radiolarians and diatoms, use silica, and when they die their tiny shells (or tests) settle slowly to the bottom where they accumulate as chert. In some cases, chert is deposited along with limestone in the moderately deep ocean, but the two tend to remain separate, so chert beds within limestone are quite common (Figure 6.2.5), as are nodules, like the flint nodules of the Cretaceous chalk of southeastern England. In other situations, and especially in very deep water, chert accumulates on its own, commonly in thin beds.

Figure 6.2.5 Chert (brown layers) interbedded with Triassic Quatsino Fm. limestone on Quadra Island, B.C. All of the layers have been folded, and the chert, being insoluble and harder than limestone, stands out.

Banded iron formation

Banded iron formation (BIF) is a deep sea-floor deposit of iron oxide that is a common ore of iron (Figure 6.2.6). BIF forms when iron dissolved in seawater is oxidized, becomes insoluble, and sinks to the bottom in the same way that silica tests do to form chert. BIF is prevalent in rocks dating from 2400 to 1800 Ma, a result off changes in the atmosphere and oceans that took place over that time period. Photosynthetic bacteria (i.e., **cyanobacteria**, a.k.a. blue-green algae) consume carbon dioxide from the atmosphere and use solar energy to convert it to oxygen. These bacteria first evolved around 3500 Ma, and for the next billion years, almost all of that free oxygen was used up by chemical and biological processes, but by 2400 Ma free oxygen levels started to increase in the atmosphere and the oceans. Over a period of 600 million years, that oxygen gradually converted soluble ferrous iron (Fe^{2+}) to insoluble ferric iron (Fe^{3+}), which combined with oxygen to form the mineral hematite (Fe_2O_3), leading to the accumulation of BIFs on the sea floor. After 1800 Ma, little dissolved iron was left in the oceans and the formation of BIF essentially stopped.

Figure 6.2.6 An example of a banded iron formation with dark iron oxide layers interspersed with chert stained red by hematite. This rock is 2.1 billion years old.

Evaporites

In arid regions many lakes and inland seas have no stream outlet and the water that flows into them is removed only by evaporation. Under these conditions, the water becomes increasingly concentrated with dissolved salts, and eventually some of these salts reach saturation levels and start to crystallize (Figure 6.2.7). Although all evaporite deposits are unique because of differences in the chemistry of the water, in most cases minor amounts of carbonates start to precipitate when the solution is reduced to about 50% of its original volume. Gypsum ($CaSO_4·H_2O$) precipitates at about 20% of the original volume and halite (NaCl) precipitates at 10%. Other important evaporite minerals include sylvite (KCl) and borax ($Na_2B_4O_7·10H_2O$). Sylvite is mined at numerous locations across Saskatchewan (Figure 6.2.8) from evaporites that were deposited during the Devonian (~385 Ma) when an inland sea occupied much of the region.

Figure 6.2.7 Spotted Lake, near Osoyoos, B.C. The patterns on the surface are salt. This photo was taken in May when the water was relatively fresh because of winter rains. By the end of the summer the surface of this lake is typically fully encrusted with salt deposits.

Figure 6.2.8 A mining machine at the face of potash ore (sylvite) in the Lanigan Mine near Saskatoon, Saskatchewan. The mineable potash layer (on the right) is about 3 metres thick.

Exercise 6.3 Making evaporite

This is an easy experiment that you can do at home. Pour about 50 mL (just less than 1/4 cup) of very hot water into a cup and add 2 teaspoons (10 mL) of salt. Stir until all or almost all of the salt has dissolved, then pour the salty water (leaving any undissolved salt behind) into a shallow wide dish or a small plate. Leave it to evaporate for a few days and observe the result. What is the size range and shape of the crystals you grew?

It may look a little like Figure 6.2.9. These crystals are up to about 3 millimetres across.

See Appendix 3 for Exercise 6.3 answers.

Figure 6.2.9

Media Attributions

- Figures 6.2.1, 6.2.2, 6.2.3ab 6.2.4, 6.2.5, 6.2.7, 6.2.9: © Steven Earle. CC BY.
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6.3 Depositional Environments and Sedimentary Basins

Sediments accumulate in a wide variety of environments, both on the continents and in the oceans. Some of the more important of these environments are illustrated in Figure 6.3.1.

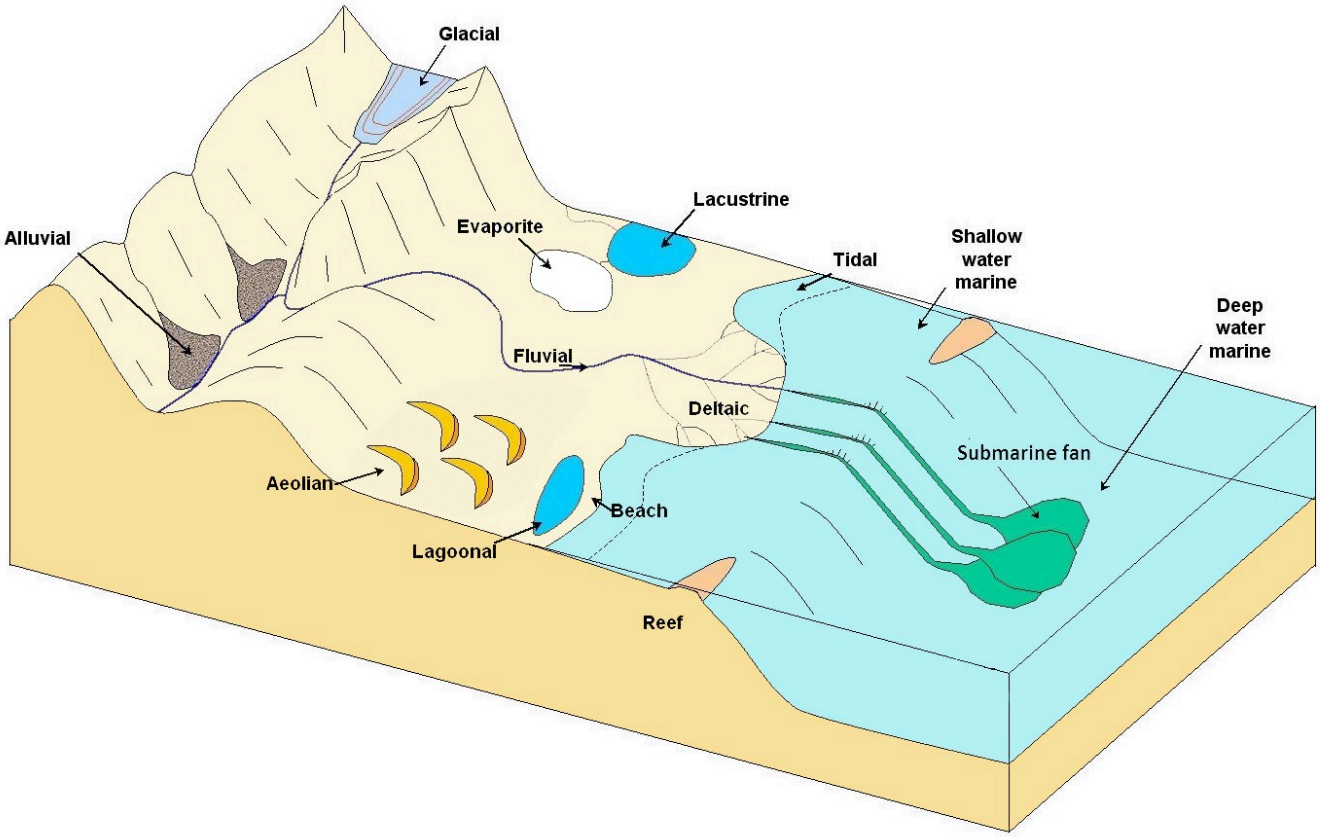

Figure 6.3.1 Some of the important depositional environments for sediments and sedimentary rocks.

Table 6.4 provides a summary of the processes and sediment types that pertain to the various depositional environments illustrated in Figure 6.3.1. We'll look more closely at the types of sediments that accumulate in these environments in the last section of this chapter. The characteristics of these various environments, and the processes that take place within them, are also discussed in later chapters on glaciation, mass wasting, streams, coasts, and the sea floor.

Table 6.4 The important terrestrial depositional environments and their characteristics

Environment	Important transport processes	Depositional environments	Typical sediment types
Glacial	gravity, moving ice, moving water	valleys, plains, streams, lakes	glacial till, gravel, sand, silt, and clay
Alluvial	gravity	steep-sided valleys	coarse angular fragments
Fluvial	moving water	streams	gravel, sand, silt, and organic matter (in swampy parts only)
Aeolian	wind	deserts and coastal regions	sand, silt
Lacustrine	moving water (flowing into a lake)	lakes	sand (near the edges only), silt, clay, and organic matter
Evaporite	moving water (flowing into a lake)	lakes in arid regions	salts, clay

Table 6.5 The important marine depositional environments and their characteristics

Environment	Important Transport Processes	Depositional Environments	Typical Sediment Types
Deltaic	moving water	deltas	sand, silt, clay, and organic matter (in swampy parts only)
Beach	waves, longshore currents	beaches, spits, sand bars	gravel, sand
Tidal	tidal currents	tidal flats	silt, clay
Reefs	waves and tidal currents	reefs and adjacent basins	carbonates
Shallow water marine	waves and tidal currents	shelves and slopes, lagoons	carbonates in tropical climates, sand/silt/clay elsewhere
Lagoonal	little transportation	lagoon bottom	carbonates in tropical climates
Submarine fan	underwater gravity flows	continental slopes and abyssal plains	gravel, sand, mud
Deep water marine	ocean currents	deep-ocean abyssal plains	clay, carbonate mud, silica mud

Most of the sediments that you might see around you, including talus on steep slopes, sand bars in streams, or gravel in road cuts, will never become sedimentary rocks because they have only been deposited relatively recently—perhaps a few centuries or millennia ago—and are likely to be re-eroded before they are buried deep enough beneath other sediments to be lithified. In order for sediments to be preserved long enough to be turned into rock—a process that takes millions or tens of millions of years—they need to have been deposited in a basin that will last that long. Most such basins are formed by plate tectonic processes, and some of the more important examples are shown in Figure 6.3.2.

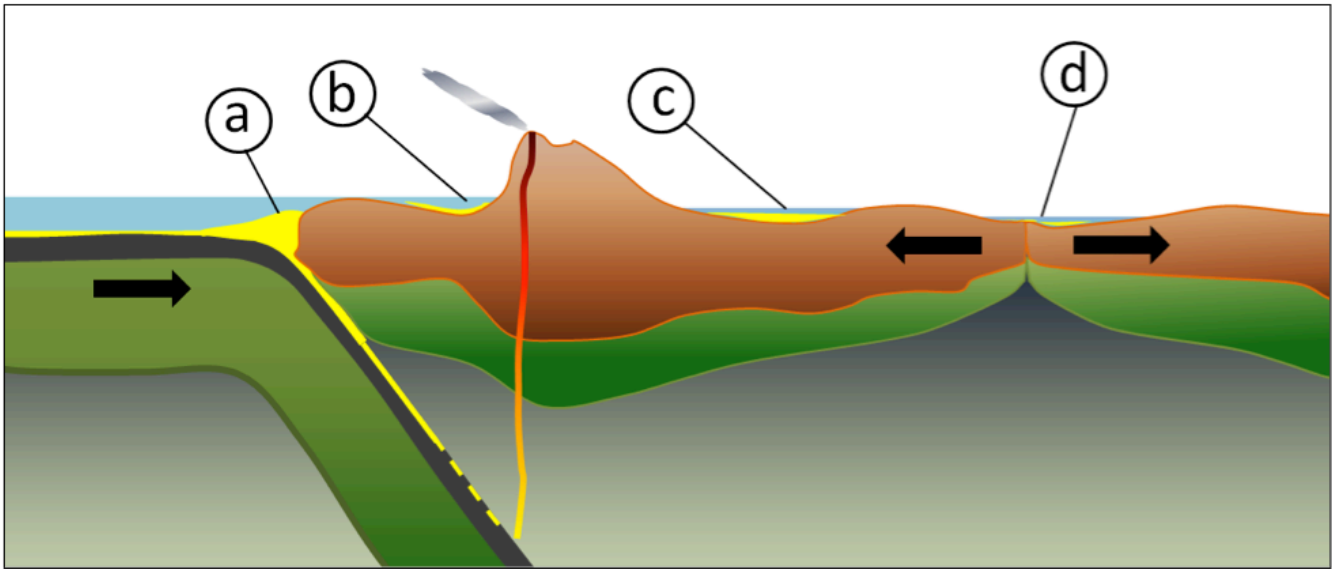

Figure 6.3.2 Some of the more important types of tectonically produced basins: (a) trench basin, (b) forearc basin, (c) foreland basin, and (d) rift basin.

Trench basins form where a subducting oceanic plate dips beneath the overriding continental or oceanic crust. They can be several kilometres deep, and in many cases, host thick sequences of sediments from eroding coastal mountains. There is a well-developed trench basin off the west coast of Vancouver Island. A forearc basin lies between the subduction zone and the volcanic arc, and may be formed in part by friction between the subducting plate and the overriding plate, which pulls part of the overriding plate down. The Strait of Georgia is a forearc basin. A foreland basin is caused by the mass of the volcanic range depressing the crust on either side. Foreland basins are not only related to volcanic ranges, but can form adjacent to fold belt mountains like the Canadian Rockies. A rift basin forms where continental crust is being pulled apart, and the crust on both sides of the rift subsides. As rifting continues this eventually becomes a narrow sea, and then an ocean basin. The East African rift basin represents an early stage in this process.

Media Attributions

- Figure 6.3.1: Schematic diagram showing types of depositional environment © Mike Norton. Adapted by Steven Earle. CC BY-SA.
- Figure 6.3.2: © Steven Earle. CC BY.

6.4 Sedimentary Structures and Fossils

Through careful observation over the past few centuries, geologists have discovered that the accumulation of sediments and sedimentary rocks takes place according to some important geological principles, as follows:

- The **principle of original horizontality** is that sediments accumulate in essentially horizontal layers. The implication is that tilted sedimentary layers observed to day must have been subjected to tectonic forces.
- The **principle of superposition** is that sedimentary layers are deposited in sequence, and that unless the entire sequence has been turned over by tectonic processes, the layers at the bottom are older than those at the top.
- The **principle of inclusions** is that any rock fragments in a sedimentary layer must be older than the layer. For example, the cobbles in a conglomerate must have been formed before the conglomerate was formed.
- The **principle of faunal succession** is that there is a well-defined order in which organisms have evolved through geological time, and therefore the identification of specific fossils in a rock can be used to determine its age.

In addition to these principles, that apply to all sedimentary rocks (as well as volcanic rocks), a number of other important characteristics of sedimentary processes result in the development of distinctive sedimentary features in specific sedimentary environments. By understanding the origins of these features, we can make some very useful inferences about the processes that led to deposition the rocks that we are studying.

Bedding, for example, is the separation of sediments into layers that either differ from one another in textures, composition, colour, or weathering characteristics, or are separated by **partings**—narrow gaps between adjacent beds (Figure 6.4.1). Bedding is an indication of changes in depositional processes that may be related to seasonal differences, changes in climate, changes in locations of rivers or deltas, or tectonic changes. Partings may represent periods of non-deposition that could range from a few decades to a few millennia. Bedding can form in almost any sedimentary depositional environment.

Figure 6.4.1 The Triassic Sulphur Mt. Formation near Exshaw, Alberta. Bedding is defined by differences in colour and texture, and also by partings (gaps) between beds that may otherwise appear to be similar.

Cross-bedding is bedding that contains angled layers within otherwise horizontal beds, and it forms when sediments are deposited by flowing water or wind. Some examples are shown in Figures 6.0.11, 6.1.7b, and 6.4.2. Cross-beds formed in streams tend to be on the scale of centimetres to tens of centimetres, while those in **aeolian** (wind deposited) sediments can be on the scale of metres to several metres.

Figure 6.4.2 Cross-bedded Jurassic Navajo Formation aeolian sandstone at Zion National Park, Utah. In most of the layers the cross-beds dip down toward the right, implying a consistent wind direction from right to left during deposition.

Cross-beds form as sediments are deposited on the leading edge of an advancing ripple or dune under steady state conditions (similar flow rate and same flow direction). Each layer is related to a different ripple that advances in the direction of flow, and is partially eroded by the following ripple (Figure 6.4.3). Cross-bedding is a very important sedimentary structure to be able to recognize because it can provide information on the process of deposition, the direction of current flows and, when analyzed in detail, on other features like the rate of flow and the amount of sediment available.

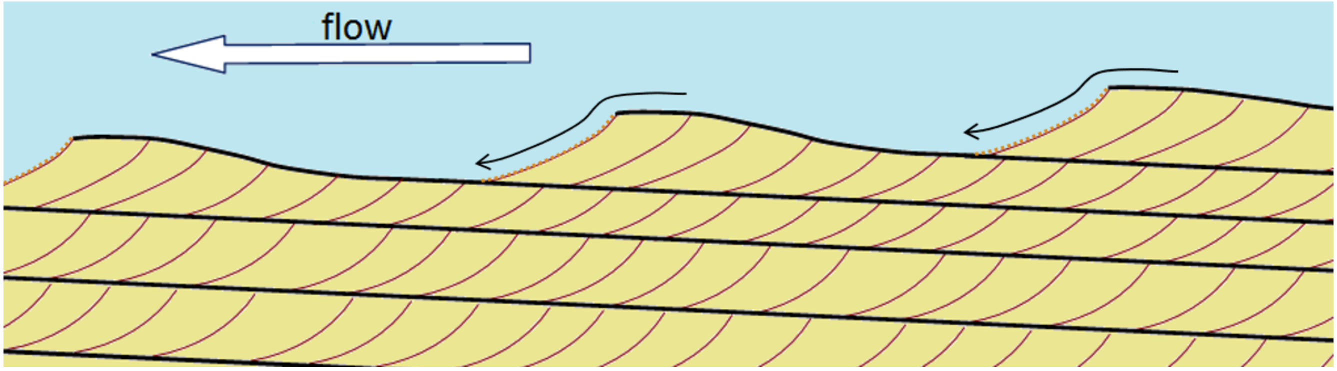

Figure 6.4.3 Formation of cross-beds as a series of ripples or dunes migrates with the flow. Each ripple advances forward (right to left in this view) as more sediment is deposited on its leading face (small arrows). (On each ripple the last deposited layer is represented by small dots.)

Graded bedding is characterized by a gradation in grain size from bottom to top within a single bed. "Normal" graded beds are coarse at the bottom and become finer toward the top. They are a product of deposition from a slowing current (Figure 6.4.4). Most graded beds form in a submarine-fan environment (see Figure 6.4.1), where sediment-rich flows descend periodically from a shallow marine shelf down a slope and onto the deeper sea floor. Some graded beds are reversed (coarser at the top), and this normally results from deposition by a fast-moving debris flow (see Chapter 15).

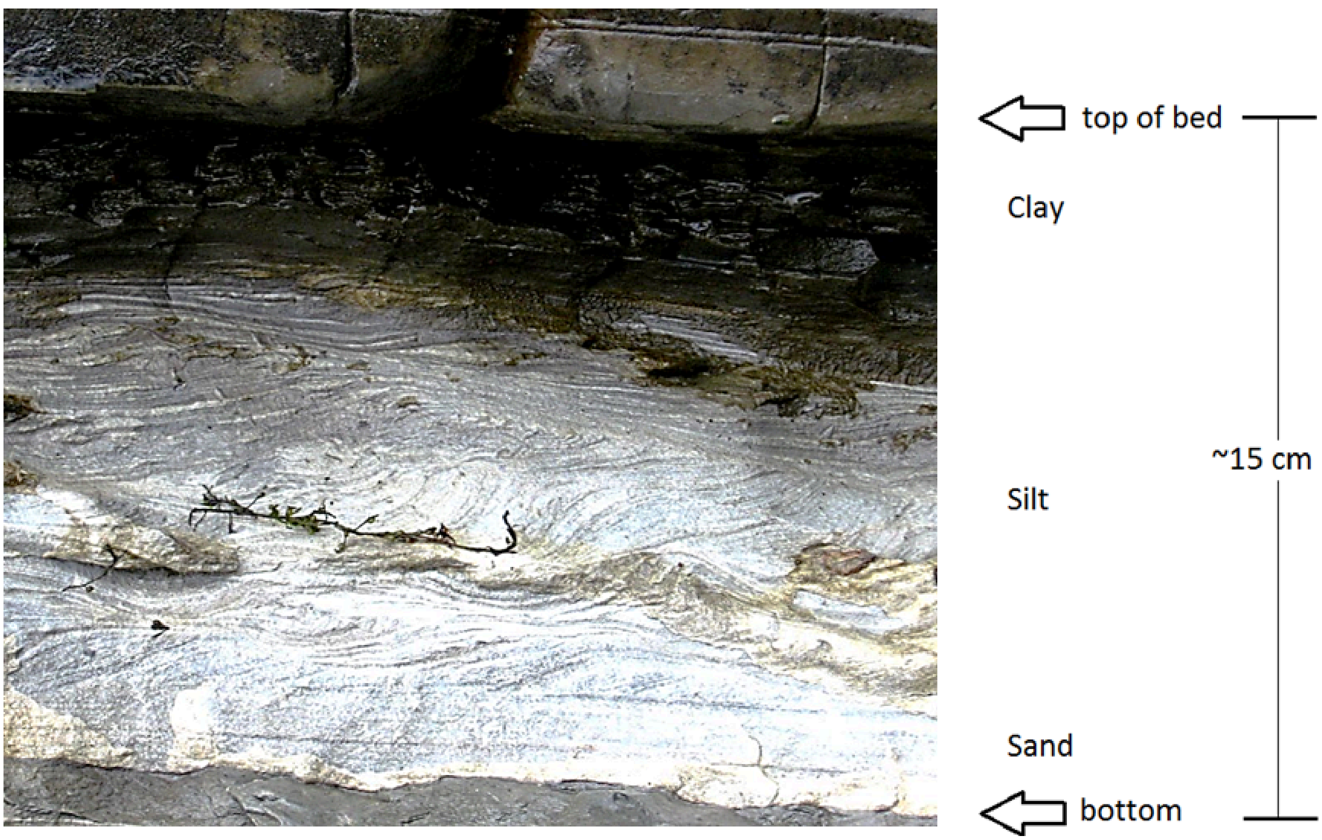

Figure 6.4.4 A graded turbidite bed in Cretaceous Spray Formation rocks on Gabriola Island, B.C. The lower several centimetres of sand and silt probably formed over the duration of less than an hour. The upper few centimetres of fine clay may have accumulated over several hundred years.

Ripples, which are associated with the formation of cross-bedding, may be preserved on the surfaces of sedimentary beds. Ripples can also help to determine flow direction as they tend to have their steepest surface facing in the direction of the flow (see Figure 6.4.3).

In a stream environment, boulders, cobbles, and pebbles can become **imbricated**, meaning that they are generally tilted in the same direction. Clasts in streams tend to tilt with their upper ends pointing downstream because this is the most stable position with respect to the stream flow (Figure 6.4.5 and Figure 6.1.7c).

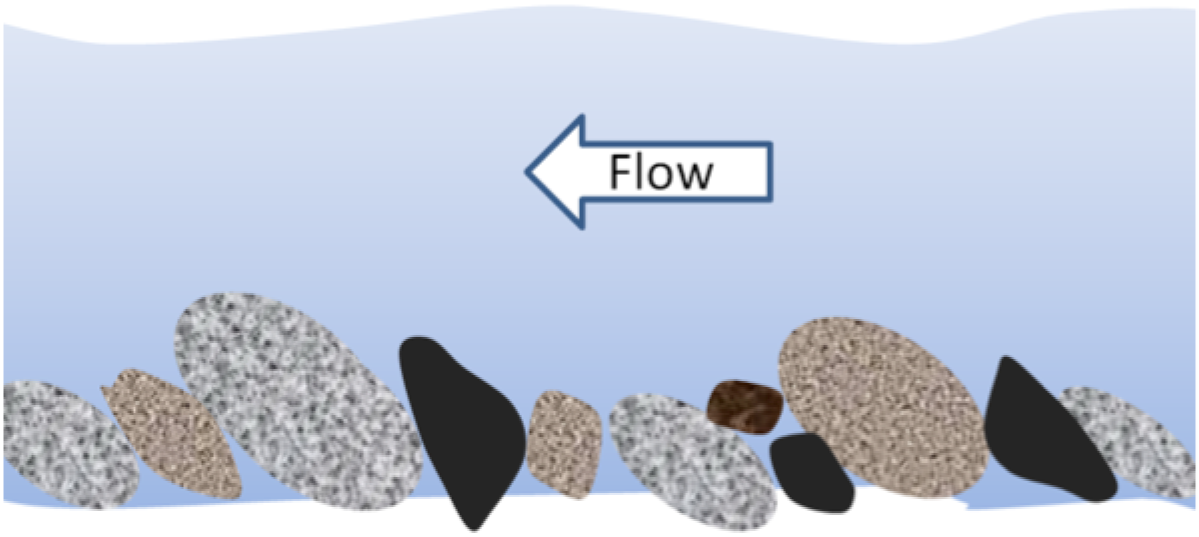

Figure 6.4.5 An illustration of imbrication of clasts in a fluvial environment.

Mud cracks 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 (Figure 6.4.6). 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.

Figure 6.4.6 Mudcracks in volcanic mud at a hot-spring area near Myvatn, Iceland.

The various structures described above are critical to understanding and interpreting the conditions that existed during the formation of sedimentary rocks. In addition to these, geologists also look very closely at sedimentary grains to determine their mineralogy or lithology (in order to make inferences about the type of source rock and the weathering processes), their degree of rounding, their sizes, and the extent to which they have been sorted by transportation and depositional processes. Some of the types of differences that we might want to look for are illustrated in Figure 6.4.7.

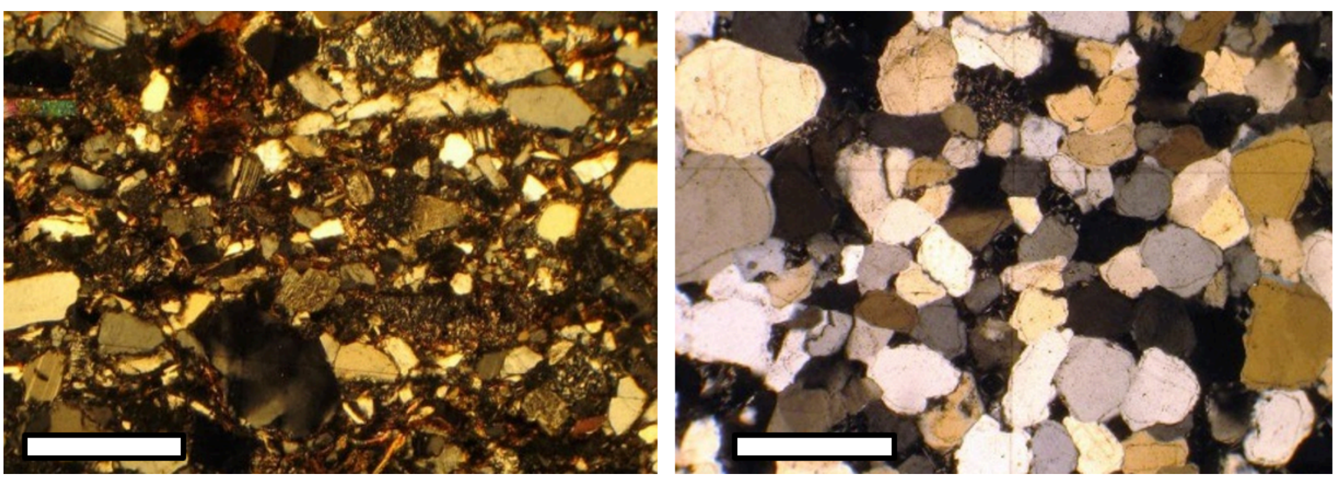

Figure 6.4.7 Thin section photos of two sandstones with very different grain characteristics. The one on the left has angular grains with a wide range of different types (quartz, feldspar, biotite, rock fragments), and is poorly sorted (grains range from less than 0.05 mm to ~1 mm). The one on the right has relatively well-rounded grains of quartz only, and the size range is much less (approx. 0.25 to 1 mm). (Scale bars are 1 mm.)

We won't be covering fossils in any detail in this book, but they are extremely important for understanding sedimentary rocks. Of course, fossils can be used to date sedimentary rocks, but equally importantly, they tell us a great deal about the depositional environment of the sediments and the climate at the time. For example, they can help to differentiate marine versus terrestrial environments; estimate the depth of the water; detect the existence of currents; and estimate average temperature and precipitation. For example, the tests of tiny marine organisms (mostly foraminifera) have been recovered from deep-ocean sediment cores from all over the world, and their isotopic signatures have been measured. As we'll see in Chapter 19, this has provided us with information about the changes in average global temperatures over the past 65 million years.

Exercise 6.4 Interpretation of past environments

Sedimentary rocks can tell us a great deal about the environmental conditions that existed during the time of their formation. Make some inferences about the source rock, weathering environment, type and distance of sediment transportation, and deposition conditions that existed during the formation of the following rocks:

1. **Quartz sandstone:** no feldspar, well-sorted and well-rounded quartz grains, cross-bedding
2. **Feldspathic sandstone and mudstone:** feldspar, volcanic fragments, angular grains, repetitive graded bedding from sandstone upwards to mudstone
3. **Conglomerate:** well-rounded pebbles and cobbles of granite and basalt; imbrication
4. **Breccia:** poorly sorted, angular limestone fragments; orange-red matrix

See Appendix 3 for Exercise 6.4 answers.

Media Attributions

6.5 Groups, Formations, and Members

Geologists who study sedimentary rocks need ways to divide them into manageable units, and they also need to give those units names so that they can easily be referred to and compared with other rocks deposited in other places. The International Commission on Stratigraphy (ICS) has established a set of conventions for grouping, describing, and naming sedimentary rock units.

The main stratigraphic unit is a **formation**, which according to the ICS, should be established with the following principles in mind:

> *The contrast in lithology between formations required to justify their establishment varies with the complexity of the geology of a region and the detail needed for geologic mapping and to work out its geologic history. No formation is considered justifiable and useful that cannot be delineated at the scale of geologic mapping practiced in the region. The thickness of formations may range from less than a meter to several thousand meters.*

In other words, a formation is a series of beds that is distinct from other beds above and below, and is thick enough to be shown on the geological maps that are widely used within the area in question. In most parts of the world, geological mapping is done at a relatively coarse scale, and so most formations are in the order of a few hundred metres thick. At that thickness, a typical formation would appear on a typical geological map as an area that is at least a few millimetres thick.

A series of formations can be classified together to define a **group**, which could be as much as a few thousand metres thick, and represents a series of rocks that were deposited within a single basin (or a series of related and adjacent basins) over a few million to a few tens of millions of years.

In areas where detailed geological information is needed (for example, within a mining or petroleum district) a formation might be divided into **members**, where each member has a specific and distinctive lithology. For example, a formation that includes both shale and sandstone might be divided into members, each of which is either shale or sandstone. In some areas, where particular detail is needed, members may be divided into beds, but this is only applicable to beds that have a special geological significance. Groups, formations, and members are typically named for the area where they are found.

The sedimentary rocks of the Nanaimo Group provide a useful example for understanding groups, formations, and members. During the latter part of the Cretaceous Period, from about 90 Ma to 65 Ma, a thick sequence of clastic rocks was deposited in a foreland basin between what is now Vancouver Island and the B.C. mainland (Figure 6.5.1). The Nanaimo Group strata comprise a 5000-metre-thick sequence of conglomerate, sandstone, and mudstone layers. Coal was mined from Nanaimo Group rocks from around 1850 to 1950 in the Nanaimo region, and even more recently in the Campbell River area. The Nanaimo Group is divided into 11 formations as described in Table 6.6. In general, the boundaries between formations are based on major lithological differences. As can be seen in the far-right column of Table 6.6, a wide range of depositional environments existed during the accumulation of the Nanaimo Group rocks, from nearshore marine for the Comox and Haslam Formation, to fluvial and deltaic with backwater swampy environments for the coal-bearing Extension, Pender, and Protection Formations, to a deep-water submarine fan environment for the upper six formations.

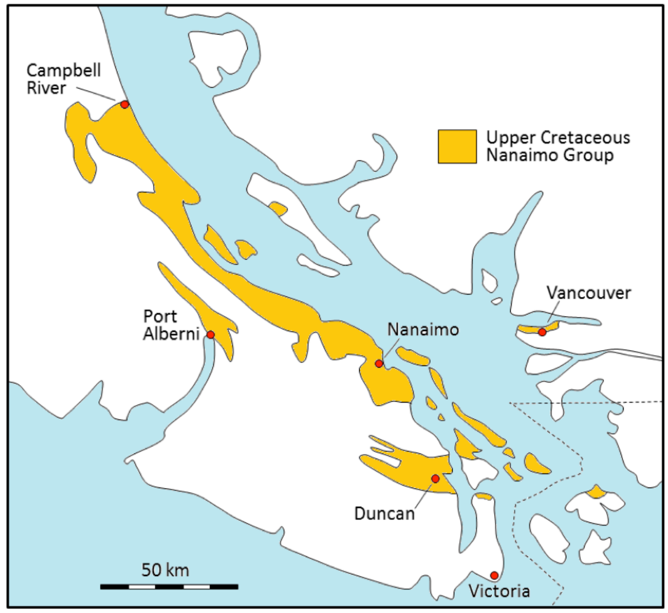

Figure 6.5.1 The distribution of the Upper Cretaceous Nanaimo Group rocks on Vancouver Island, the Gulf Islands, and in the Vancouver area. [Image Description]

Table 6.6 The formations of the Nanaimo Group[1]

[Skip Table 6.6]

Approximate Age (Ma)	Formation name	Lithologies	Depositional Environment
65 to 66	Gabriola	Sandstone with minor mudstone	Submarine fan, high energy
66 to 67	Spray (Fine grained)	Mudstone/sandstone turbidites	Submarine fan, low energy
67 to 68	Geoffrey	Sandstone and conglomerate	Submarine fan, high energy
68 to 70	Northumberland (Fine grained)	Mudstone turbidites	Submarine fan, low energy
70	De Courcy	Sandstone	Submarine fan, high energy
70 to 72	Cedar District (Fine grained)	Mudstone turbidites	Submarine fan, low energy
72 to 75	Protection	Sandstone and minor coal	Nearshore marine and onshore deltaic and fluvial
75 to 80	Pender	Sandstone and minor coal	Nearshore marine and onshore deltaic and fluvial
80	Extension	Conglomerate, with minor sandstone and some coal	Nearshore marine and onshore deltaic and fluvial
80 to 85	Haslam (Fine grained)	Mudstone and siltstone	Shallow marine
85 to 90	Comox	Conglomerate, sandstone, mudstone (coal in the Campbell River area)	Nearshore fluvial and marine

In tables like this one, the layers are always listed in order, with the oldest at the bottom and the youngest at the top.

The five lower formations of the Nanaimo Group are all exposed in the Nanaimo area, and were well studied during the coal mining era between 1850 and 1950. All of these formations (except Haslam) have been divided into members, as that was useful for understanding the rocks in the areas where coal mining was taking place. Within some of those members even some individual beds have been named if they were of specific importance to the mining industry.

Although there is a great deal of variety in the Nanaimo Group rocks, and it would take hundreds of photographs to illustrate all of the different types of rocks, a few representative examples are provided in Figure 6.5.2.

1. **[Based on data in Mustard, P., 1994, The Upper Cretaceous Nanaimo Group, Georgia Basin, in J. Monger (ed) Geology and Geological Hazards of the Vancouver Region, Geol. Survey of Canada, Bull. 481, p. 27-95.]**

Figure 6.5.2a Representative photos of Nanaimo Group rocks. Turbidite layers in the Spray Formation on Gabriola Island. Each turbidite set consists of a lower sandstone layer (light colour) that grades upward into siltstone, and then into mudstone. (See Figure 6.4.2 for detail.)

Figure 6.5.2b Two separate layers of fluvial sandstone with a thin (approx. 75 centimetres) coal seam in between. Pender Formation in Nanaimo.

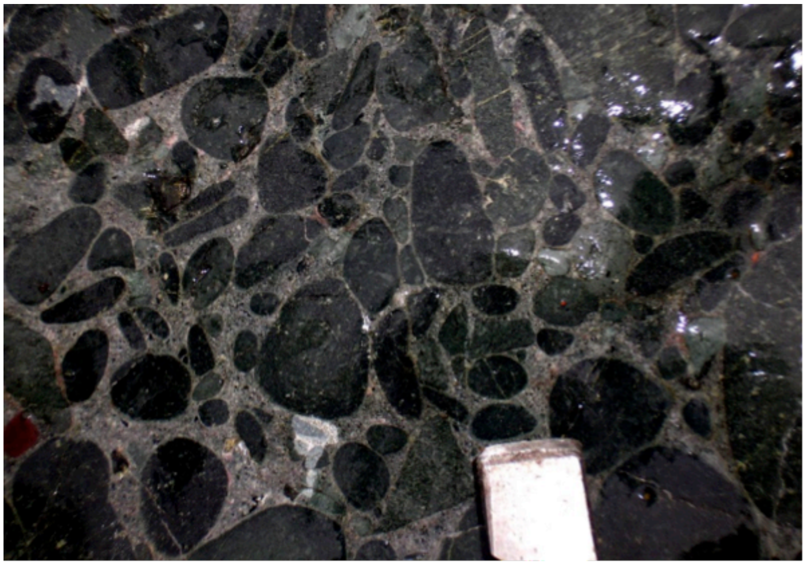

Figure 6.5.2c Comox Formation conglomerate at the very base of the Nanaimo Group in Nanaimo. The metal object is the end of a rock hammer that is 3 centimetres wide. Almost all of the clasts in this view are well-rounded basalt pebbles cobbles eroded from the Triassic Karmutsen Formation which makes up a major part of Vancouver Island.

Image Descriptions

Figure 6.5.1 image description: A map showing that Nanaimo Group rocks are present along the east coast of Vancouver Island from Nanaimo to Campbell River, farther inland in areas around Port Alberni and Duncan, on much of the Gulf Islands and a bit in the Vancouver area. [Return to Figure 6.5.1]

Media Attributions

- Figure 6.5.1: Redrawn based on Mustard, P., 1994, The Upper Cretaceous Nanaimo Group, Georgia Basin, in J. Monger (ed) Geology and Geological Hazards of the Vancouver Region, Geol. Survey of Canada, Bull. 481, pp. 27-95. © Steven Earle. CC BY.
- Figure 6.5.2abc: © Steven Earle. CC BY.

Summary

The topics covered in this chapter can be summarized as follows:

Section	Summary
6.1 Clastic Sedimentary Rocks	Sedimentary clasts are classified based on their size, and variations in clast size have important implications for transportation and deposition. Clastic sedimentary rocks range from conglomerate to mudstone. Clast size, sorting, composition, and shape are important features that allow us to differentiate clastic rocks and understand the processes that took place during their deposition.
6.2 Chemical Sedimentary Rocks	Chemical sedimentary rocks form from ions that were transported in solution, and then converted into minerals by biological and/or chemical processes. The most common chemical rock, limestone, typically forms in shallow tropical environments, where biological activity is a very important factor. Chert and banded iron formation are deep-ocean sedimentary rocks. Evaporites form where the water of lakes and inland seas becomes supersaturated due to evaporation.
6.3 Depositional Environments and Sedimentary Basins	There is a wide range of depositional environments, both on land (glaciers, lakes, rivers, etc.) and in the ocean (deltas, reefs, shelves, and the deep-ocean floor). In order to be preserved, sediments must accumulate in long-lasting sedimentary basins, most of which form through plate-tectonic processes.
6.4 Sedimentary Structures and Fossils	The deposition of sedimentary rocks takes place according to a series of important principles, including original horizontality, superposition, and faunal succession. Sedimentary rocks can also have distinctive structures, such as cross bedding, graded bedding and mud cracks, that are important in determining their depositional environments. Fossils are useful for determining the age of a rock, the depositional environment, and the climate at the time of deposition.
6.5 Groups, Formations, and Members	Sedimentary sequences are classified into groups, formations, and members so that they can be referred to easily and without confusion.

Questions for Review

Answers to Review Questions at the end of each chapter can be found in Appendix 2.

1. What are the minimum and maximum sizes of sand grains?
2. How can you easily distinguish between a silty deposit and one that has only clay-sized material?
3. What factors control the rate at which a clast settles in water?

4. The material that makes up a rock such as conglomerate cannot be deposited by a slow-flowing river. Why not?
5. Describe the two main processes of lithification.
6. What is the difference between a lithic arenite and a lithic wacke?
7. How does a feldspathic arenite differ from a quartz arenite?
8. What can we say about the source area lithology and the weathering and transportation history of a sandstone that is primarily composed of rounded quartz grains?
9. What is the original source of the carbon that is present within carbonate deposits such as limestone?
10. What long-term environmental change on Earth led to the deposition of banded iron formations?
11. Name two important terrestrial depositional environments and two important marine ones.
12. What is the origin of a foreland basin, and how does it differ from a forearc basin?
13. Explain the origin of (a) bedding, (b) cross-bedding, (c) graded bedding, and (d) mud cracks.
14. Under what conditions is reverse graded bedding likely to form?
15. What are the criteria for the application of a formation name to a series of sedimentary rocks?
16. Explain why some of the Nanaimo Group formations have been divided into members, while others have not.