Chapter 9. Sedimentary Rocks

Introduction

Learning Objectives

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

- Explain the differences between the four kinds of sedimentary rocks: clastic, chemical, biochemical, and organic
- Describe some of the specific kinds of rocks in each of the four categories, and the depositional environments in which they form
- Describe the various terrestrial and marine sedimentary depositional 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 what groups, formations, and members are in sedimentary rocks, and why they are used

Figure 9.1 Cretaceous sedimentary rocks exposed along a road near Drumheller, Alberta, Canada. Sedimentary rocks form in layers called beds. Each bed tells a story about the conditions in which it formed. In this picture the beds are telling about sea level rising and falling repeatedly. The black line about half way up the picture is a coal seam. It tells us that the environment was once swampy. [Karla Panchuk CC-BY 4.0]
Sedimentary Rocks Form From the Products of Weathering and Erosion

In Chapter 8 weathering and erosion were discussed. These are the first two steps in transforming existing rocks into sedimentary rocks. The remaining steps in the formation of sedimentary rocks are transportation, deposition, burial, and lithification. These steps are shown on the right-hand side of the rock cycle diagram in Figure 9.2.

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 when a change in conditions results in the transport medium no longer being able to carry some or all of the sediments. This could happen if the current slows down.

Burial occurs when more sediments are piled onto existing sediments, covering and compacting layers that formed earlier. Lithification is what happens when those compacted sediments become cemented together to form solid sedimentary rock. Lithification happens at depths of hundreds to thousands of metres within the Earth.

Four Types of Sedimentary Rocks

Sedimentary rocks can be divided into four main types: clastic, chemical, biochemical, and organic. Clastic sedimentary rocks are composed mainly of material that has been transported as solid fragments (clasts), and then cemented together by minerals that form from ions. Chemical sedimentary rocks are composed mainly of
material that has been transported as ions in solution. **Biochemical** sedimentary rocks also form from ions in solution, but organisms play an important role in turning those ions into calcium carbonate or silica body parts. **Organic** sedimentary rocks contain large amounts of organic matter, such as from plant leaves and tree bark.

## 9.1 Clastic Sedimentary Rocks

### How Clastic Sediments Become Sedimentary Rocks

**Lithification** is the process of turning sediments into solid rock. The steps in lithification are summarized in Figure 9.3.

![Lithification Diagram](image)

**Figure 9.3 Lithification turns sediments into solid rock. Lithification involves the compaction of sediments and then cementing the grains together with minerals from groundwater. [Karla Panchuk CC-BY 4.0]**

First, sediments that have been deposited are buried when more and more sediments accumulate above them. The weight of the overlying sediments pushes the clasts together, closing up some of the pore spaces between grains. The spaces often contain water, so the water is squeezed out. Forcing the grains together like this is called **compaction**.

**Cementation** is the next step. Groundwater flowing through the pore spaces contains ions, and these ions precipitate, leaving behind minerals on the surfaces of the grains. The minerals can fill in the spaces between the grains, and accumulate where two grains are touching. Over time the minerals (called **cement**)) bind the grains together. Quartz and calcite are common cement minerals, but depending on pressure, temperature, and chemical conditions, cement might also include other minerals such as hematite and clay.

Figure 9.4 shows sandstone viewed under a microscope. The grains are all quartz but they appear different shades of grey because they are being viewed through polarized light. It is difficult to tell the grains from the

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1 Pore spaces are the gaps between grains. They might contain air, water, or even hydrocarbons.
2 Polarized light interacts with the crystal structure in a mineral so that the light passing through the crystal will look different depending on how the crystal is oriented. If you were to rotate the slide in Figure 9.4 you would see the white grains turn black, and the black ones turn white. Different minerals respond in different ways, so this is a handy property for identifying minerals under the microscope.
cement in this case because both are made of quartz, but in the image on the right the more obvious grain boundaries are marked with dashed lines. Some of the cement is marked with blue shading. Using the image on the right, see if you can pick out the grain boundaries in the image in the left.

![Figure 9.4 View of sandstone under a microscope. Grains and cement are quartz. Left: Original image. Right: Visible grain boundaries are marked with dashed lines, and some of the cement is marked with blue shading. The red line shows where the cement has begun form following the crystal habit of quartz. [Karla Panchuk CC-BY 4.0 modified after Woudloper, Public Domain http://bit.ly/218II28]](https://physicalgeology.pressbooks.com)

An interesting feature of the sandstone in Figure 9.4 is marked by the red line in the image on the right. If you look closely you can see that the cement along the boundary marked in red has regular steps in it. This is because the quartz in the cement has “discovered” the crystal structure of the quartz grain that it is forming around, and has continued to build on it.

Types of Clastic Sedimentary Rocks

Clastic sedimentary rocks are named according to the characteristics of clasts (rock and mineral fragments) that make them up. Those characteristics include grain size, shape, and sorting. (To review grain sizes and the names for particles of different sizes, see Table 8.1. To review grain shape and sorting, see Figure 8.16.) The different types of clastic sedimentary rocks are summarized in Figure 9.5.

**Coarse-Grained Clastic Rocks Are Conglomerate or Breccia**

Clastic sedimentary rocks in which a significant proportion of the clasts are larger than 2 mm are known as **conglomerate** if the clasts are well rounded, and **breccia** if they are angular (top row of Figure 9.5). Conglomerates form in high-energy environments, such as fast-flowing rivers, where the particles can become rounded as they bump into each other while being carried along. Breccias typically form where the particles are not transported a significant distance in water, such as alluvial fans and talus slopes.
Figure 9.5 Types of clastic sedimentary rocks. [Karla Panchuk CC-BY-NC 4.0, photos by R. Weller/ Cochise College (permission for non-commercial educational use) unless otherwise indicated]
Medium-Grained Clastic Rocks Are Sandstone

Sandstone (middle row in Figure 9.5) is a very common sedimentary rock, and there are many different kinds of sandstone. It’s worth knowing something about the different types because they are organized according to characteristics that are useful for the detective work of figuring out what conditions led to the formation of a particular sandstone. Broadly, sandstones can be divided into two groups: arenite and wacke (rhymes with tacky).

Arenite is “clean” sandstone consisting mostly of sand-sized grains and cement, with less than 15% of fine-grained silt and clay in the matrix (the material between the sand-sized grains). Arenites are subdivided according to what the sand-sized grains are made of (Figure 9.6). If 90% or more of the grains are quartz, then the sandstone is a quartz arenite (also called a quartz sandstone). If more than 10% of the grains are feldspar and more of the grains are feldspar than fragments of other rocks (lithic3 fragments) then the rock suffers from a surplus of names. It can be called feldspathic arenite, arkosic arenite, or just arkose. If the rock has more than 10% rock fragments, and more rock fragments than feldspar, it is lithic arenite.

Wacke is a not-so-clean sandstone, with more than 15% fine-grained particles (clay, silt) in its matrix. A wacke can have more fine-grained particles than cement in its matrix, making for a crumbly rock. Wackes are subdivided in the same way that arenites are, giving quartz wacke, feldspathic wacke, and lithic wacke. Another name for a lithic wacke is greywacke.

Figure 9.7 shows thin sections4 (microscopic views) of quartz arenite, arkose, and lithic wacke. In the images, quartz grains are marked Q, feldspar grains are marked F, and lithic fragments are marked L. Notice the relative abundances of each component in the three types of rocks.

Fine-Grained Clastic Rocks Are Mudrocks

Rock composed of at least 75% silt- and clay-sized fragments is called mudrock. If a mudrock shows evidence of fine layers (laminations) it is called shale, otherwise it is siltstone, mudstone, or claystone, in order of increasing abundance of clay-sized particles. The fine-grained nature of mudrocks tells us that they form in very low energy environments, such as lakes, river backwaters, and the deep ocean.

3 “Lithic” means “rock.” Lithic clasts are rock fragments, as opposed to mineral fragments.
4 Thin sections are slivers of rock sliced thinly enough that light can pass through them, and they can be examined under a microscope.
Figure 9.7 Photos of thin sections of three types of sandstone. 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. [SE]

**Exercise 9.1 Classifying Sandstones**

The images below are magnified thin sections of sandstones. Using Figures 9.5 and 9.6, give the appropriate name for each rock.

| Sandstone 1. Rounded sand-sized grains are approximately 99% quartz and 1% feldspar. Silt and clay make up less than 2% of the rock. | Sandstone 2. Angular sand-sized grains are approximately 70% quartz, 20% lithic, and 10% feldspar. Silt and clay make up about 20% of the rock. |

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. Depending on the grain size in particular, they may eventually form into rocks ranging from fine mudstone to coarse breccia and conglomerate. By examining clastic sedimentary rocks for key features it is possible to translate the classification you’ve just learned into an interpretation of the environment in which the rocks were deposited.

**Sediment Maturity**

**Maturity** in sediments refers to the extent to which sediment characteristics reflect prolonged transport and weathering. Prolonged weathering and transport cause clasts to become smaller, rounder, and better sorted. It
removes minerals that are more susceptible to weathering, such as feldspar and clay, leaving a sediment consisting predominantly of quartz. On the spectrum of sediment maturity, quartz sandstone would be a mature sedimentary rock, and wacke would be an immature one.

9.2 Chemical and Biochemical Sedimentary Rocks

Clastic sedimentary rocks are dominated by components that have been transported as solid clasts (clay, silt, sand, etc.). In contrast, chemical and biochemical sedimentary rocks are dominated by components that have been transported as ions in solution (e.g., 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. The difference between chemical and biochemical sedimentary rocks is that in biochemical sedimentary rocks, organisms play a role in turning the ions into sediment. That means the presence and nature of biochemical sedimentary rocks are linked to the life requirements of the organisms that make them. In chemical sedimentary rocks, the process is inorganic, often resulting from a body of water evaporating and concentrating the ions. It is possible for one type of sedimentary rock to form from both chemical (inorganic) and biochemical (organically mediated) processes.

Chemical and biochemical sedimentary rocks are classified based on the minerals they contain, and they are frequently dominated by a single mineral. It’s true that some clastic sedimentary rocks, such as quartz sandstone, can also be dominated by a single mineral, but the reasons are different. A clastic sedimentary rock can have whatever minerals are in the parent rock. The minerals it ends up with will depend on how much “processing” the sediments undergo by physical and chemical weathering process, and transport before the rock was cemented. Chemical and biochemical sedimentary rocks are limited largely to those minerals that dissolve relatively easily in water. Because mineral content is a defining characteristic of chemical and biochemical sedimentary rocks, we will use it to organize out discussion of these rocks.

Carbonate Rocks

Carbonate rocks are those where the dominant mineral contains the carbonate anion (CO\(_3^{2-}\)). The main carbonate minerals are calcite and aragonite. Both minerals have the formula CaCO\(_3\) but they have different crystal structures. A less common carbonate mineral which is still important for forming carbonate rocks is dolomite, which has the formula CaMg(CO\(_3\))\(_2\). It is like calcite and aragonite, except that some of the calcium is replaced with magnesium.

Limestone

Limestone is made of calcite and aragonite. It can occur as a chemical sedimentary rock, forming inorganically due to precipitation, but most limestone is biochemical. In fact, limestone is by far the most common biochemical sedimentary rock.

Almost all limestone forms in marine\(^5\) environments, and most of that forms on the shallow continental shelves\(^6\), especially in tropical regions with coral reefs. Reefs are highly productive ecosystems populated by a

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\(^5\) We use the word marine when referring to salt water (i.e., oceanic) environments, and the word aquatic when referring to freshwater environments.

\(^6\) Today these are relatively narrow zones along the margins of continents, but for large parts of geologic history sealevel was much higher, and large parts of the interiors of continents were flooded.
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 as well as green and red algae, urchins, sponges, molluscs, and crustaceans. Some of the organisms use CaCO$_3$ to build tiny tests (shells), which accumulate on the ocean floor, but erosion also breaks them apart, scattering fragments in the surrounding region (Figure 9.8).

Figure 9.9 shows a cross-section through a typical reef in a tropical environment (normally between 40°N and 40°S). Reefs tend to form 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. Reef-type carbonate fragments of all sizes, including mud, dominate these sediments.

In many such areas, carbonate-rich sediments also accumulate in quiet lagoons, where mud and mollusc-shell fragments predominate (Figure 9.10a) or in offshore areas with strong currents, where either foraminifera tests accumulate (Figure 9.10b) or calcite crystallizes inorganically to form **ooids** – spheres of calcite that form in shallow tropical ocean water with strong currents (Figure 9.10c).
Limestone also accumulates in deeper water, from the steady rain of the carbonate shells of tiny organisms that live near the ocean surface. Processes on the ocean floor cause the water in the deepest parts of the ocean to become more acidic. This puts a lower limit on how deep in the ocean calcite and aragonite can accumulate.

**Tufa and Travertine**

Calcite can form chemical sedimentary rocks on land in a number of environments. **Tufa** forms at springs. The tufa towers in Figure 9.11 formed where spring water encountered lake water.

**Travertine** (which is less porous) forms at hot springs. Similar material precipitates within limestone caves to form **speleothems** (mineral deposits in caves, Figure 9.12) such as **stalactites** and **stalagmites**.

![Figure 9.11 Tufa towers (made of calcium carbonate) in Mono Lake, California. Evaporation keeps the concentration of ions in the lake very high, allowing the calcium carbonate to precipitate. [Brocken Inaglory CC-BY-SA http://bit.ly/20JnS7A]](image1)

![Figure 9.12 Speleothems in Cave Nefza in Tunisia [Badreddine Besbes CC-BY-SA http://bit.ly/1TqMphg]](image2)
**Dolostone**

Dolostone (also referred to as dolomite) is the carbonate rock made of the mineral dolomite (CaMg(CO$_3$)$_2$). Dolostone is quite common (there’s a whole Italian mountain range named after it), which is surprising because 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 calcite such as that contained within limestone. This process is known as *dolomitization*, and it is thought to involve chemical reactions with magnesium-rich water percolating through rocks and sediments containing calcite.

**Chert**

Chert is made of silica (SiO$_2$). It has the same chemical formula as quartz, but is *cryptocrystalline*, meaning that quartz crystals are so small it is difficult to see them even under a microscope. Chert can be a chemical sedimentary rock, often forming as beds within limestone (Figure 9.13) or as irregular lenses or blobs (nodules). It can also be biochemical. Some tiny marine organisms (such as diatoms and radiolarians) make their tests (shells) from silica. When they die their tiny tests settle slowly to the bottom where they accumulate as chert. It is possible that some of the silica in chert nodules was derived by dissolving silica tests then reprecipitating the silica.

**Banded Iron Formations (BIFs)**

Some ancient chert beds — most dating to between 1800 and 2400 Ma — are also part of a rock known as a *banded iron formation (BIF)*. It is a deep sea-floor deposit of iron oxide that is a common ore of iron. These rocks are called banded because they consist of alternating layers of dark iron oxide minerals (magnetite and hematite) and chert stained red by hematite (Figure 9.14).

BIFs formed before Earth’s atmosphere was fully oxygenated. At that time, seawater contained abundant soluble ferrous iron (Fe$^{2+}$). However, once cyanobacteria began releasing oxygen into the atmosphere as a byproduct of photosynthesis, the iron in the seawater reacted with the oxygen, turning it into insoluble ferric iron (Fe$^{3+}$). The result was that iron oxide minerals precipitated and sank to the
ocean floor. The prevalence of BIFs in rocks dating from 2400 to 1800 Ma reflects a time when free oxygen was being added to the atmosphere, but removed just as quickly by chemical reactions. After 1800 Ma, little dissolved iron was left in the oceans so no more BIFs formed.

**Evaporites**

In arid regions, lakes and inland seas typically 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 9.15).

![Spotted Lake, near Osoyoos, B.C.](https://physicalgeology.pressbooks.com)

**Figure 9.15** Spotted Lake, near Osoyoos, B.C. 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.

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 (CaSO₄·H₂O) precipitates at about 20% of the original volume and halite (NaCl) precipitates at 10%. Other important evaporite minerals include sylvite (KCl) and borax (Na₂B₄O₇·10H₂O). Sylvite is mined as potash at numerous locations across Saskatchewan (Figure 9.16) from evaporites that formed during the Devonian (~385 Ma) when an inland sea occupied much of the region.

![Mining machine at the face of potash ore (sylvite) in the Lanigan Mine near Saskatoon, Saskatchewan. The mineable potash layer is about 3 m thick.](https://physicalgeology.pressbooks.com)

**Figure 9.16** A mining machine at the face of potash ore (sylvite) in the Lanigan Mine near Saskatoon, Saskatchewan. The mineable potash layer is about 3 m thick. [PotashCorp, used with permission]
Exercise 9.2 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. It may look a little like the photo here. These crystals are up to about 3 mm across.

9.3 Organic Sedimentary Rocks

Organic sedimentary rocks are those containing large quantities of organic molecules. Organic molecules contain carbon, but in this context we are referring specifically to molecules with carbon-hydrogen bonds, such as materials from the soft tissues of plants and animals. In other words, the carbon in calcite- CaCO₃ wouldn’t make calcite an organic mineral because it isn’t bonded to hydrogen.

An important organic sedimentary rock is coal. Most coal forms on swampy land adjacent to rivers and deltas, and where climates are humid and tropical to temperate. The vigorous growth of vegetation leads to an abundance of organic matter that accumulates within stagnant, acidic water. This limits decay and oxidation of the organic material. If this situation—where the dead organic matter is submerged in oxygen-poor water—is maintained for centuries to millennia, a thick layer of material can accumulate. Limited decay will transform this layer into peat (Figure 9.17a, 9.18 upper left).

At some point the swamp deposit is covered with more sediment — typically because a river changes its course or sea level rises (Figure 9.17b). As more sediments are added, the organic matter is compressed and heated. This has the effect of concentrating the carbon within the coal. The amount of heating will determine how far this process goes.
The further the process goes, the more the coal will go from having obvious pieces of plant material within it, to being a black, shiny mass. Low-grade lignite coal forms at depths between a few 100 m and 1,500 m and temperatures up to about 50°C (Figure 9.17c). This is still a relatively early stage in the coal formation process, so the lignite can resemble plant material very closely (Figure 9.18 upper right).

Figure 9.18 The formation of coal begins when plant matter is prevented from decaying by accumulating in low-oxygen, acidic water. A layer of peat forms. Heating and compression of peat form lignite, bituminous coal, and then anthracite, as pressures and temperatures increase. [Karla Panchuk CC-BY-NC; R. Weller photos by permission for non-commercial educational use.]

At between 1,000 m to 5,000 m depth and temperatures up to 150°C, bituminous coal forms (Figure 9.17d, 9.18 lower right). At depths beyond 5,000 m and temperatures over 150°C, anthracite coal forms (Figure 9.18 lower left). In fact, as temperatures rise, the lower-grade forms of coal are actually being transformed from sedimentary to metamorphic rocks. The transition from peat to anthracite results in a progressive increase in the carbon concentration, in hardness, and in the amount of energy available to be released upon combustion.
9.4 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 9.19.

![Depositional Environments Diagram](https://physicalgeology.pressbooks.com)

**Figure 9.19** Some of the important depositional environments for sediments and sedimentary rocks [SE after Mike Norton CC-BY-SA http://bit.ly/1QpPcIw]

Tables 9.1 and 9.2 provide a summary of the processes and sediment types that pertain to the various depositional environments illustrated in Figure 9.19. 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.

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 will 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 9.20.
### Table 9.1 Terrestrial Environments

<table>
<thead>
<tr>
<th>Environment</th>
<th>Key transport processes</th>
<th>Depositional settings</th>
<th>Typical sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacial</td>
<td>gravity, moving ice, moving water</td>
<td>valleys, plains, streams, lakes</td>
<td>glacial till, gravel, sand, silt, and clay</td>
</tr>
<tr>
<td>Alluvial</td>
<td>gravity</td>
<td>steep-sided valleys</td>
<td>coarse angular fragments</td>
</tr>
<tr>
<td>Fluvial</td>
<td>moving water</td>
<td>streams</td>
<td>gravel, sand, silt, and OM*</td>
</tr>
<tr>
<td>Aeolian</td>
<td>wind</td>
<td>deserts and coastal regions</td>
<td>sand, silt</td>
</tr>
<tr>
<td>Lacustrine</td>
<td>moving water</td>
<td>lakes</td>
<td>sand, silt, clay, and OM*</td>
</tr>
<tr>
<td>Evaporite</td>
<td>moving water</td>
<td>lakes in arid regions</td>
<td>salts, clay</td>
</tr>
</tbody>
</table>

*OM means organic matter

### Table 9.2 Marine Environments

<table>
<thead>
<tr>
<th>Environment</th>
<th>Key transport processes</th>
<th>Depositional settings</th>
<th>Typical sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deltaic</td>
<td>moving water</td>
<td>deltas</td>
<td>sand, silt, clay, OM*</td>
</tr>
<tr>
<td>Beach</td>
<td>waves, long-shore currents</td>
<td>beaches, spits, sand bars</td>
<td>gravel, sand</td>
</tr>
<tr>
<td>Tidal</td>
<td>tidal currents</td>
<td>tidal flats</td>
<td>silt, clay</td>
</tr>
<tr>
<td>Reefs</td>
<td>wind</td>
<td>deserts and coastal regions</td>
<td>sand, silt</td>
</tr>
<tr>
<td>Shallow water marine</td>
<td>waves and tidal currents</td>
<td>shelves and slopes, lagoons</td>
<td>carbonates (tropical climates); sand/silt/clay (elsewhere)</td>
</tr>
<tr>
<td>Lagoonal</td>
<td>little transportation</td>
<td>lagoon bottom</td>
<td>carbonates (tropical climates)</td>
</tr>
<tr>
<td>Submarine fan</td>
<td>underwater gravity flows</td>
<td>continental slopes and abyssal plains</td>
<td>gravel, sand, mud</td>
</tr>
<tr>
<td>Deep water marine</td>
<td>ocean currents</td>
<td>deep-ocean abyssal plains</td>
<td>clay, carbonate mud, silica mud</td>
</tr>
</tbody>
</table>

*OM means organic matter
Figure 9.20 Some of the more important types of tectonically produced basins: (a) trench basin, (b) forearc basin, (c) foreland basin, and (d) rift basin [SE]

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 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.

9.5 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** states that sediments accumulate in essentially horizontal layers. The implication is that tilted sedimentary layers observed today must have been subjected to tectonic forces.
- The **principle of superposition** states 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** states 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.
- The **principle of faunal succession** states 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, a number of other important characteristics of sedimentary processes lead to 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 9.21). 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 centuries. Bedding can form in almost any depositional environment.

![Figure 9.21 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.](https://physicalgeology.pressbooks.com)

**Cross-bedding** is bedding that contains angled layers and forms when sediments are deposited by flowing water or wind. An example is shown in Figure 9.22. Cross-beds 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.

Cross-beds form as sediments are deposited on the leading edge of an advancing ripple or dune. Each layer is related to a different ripple that advances in the flow direction, and is partially eroded by the following ripple (Figure 9.23). Cross-bedding is a very important sedimentary structure to recognize because it can provide information on the direction of current flows and, when analyzed in detail, on other features like the rate of flow and the amount of sediment available.
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 down flow.

Graded bedding is characterized by a change 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, a product of deposition from a slowing current (Figure 9.24). Some graded beds are reversed (coarser at the top), and this normally results from deposition by a fast-moving debris flow. Most graded beds form in a submarine-fan environment (see Figure 9.19), where sediment-rich flows descend periodically from a shallow marine shelf down a slope and onto the deeper sea floor.
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 9.25).

Mud cracks form when a shallow body of water (e.g., a tidal flat or pond), into which muddy sediments have been deposited, dries up and cracks (Figure 9.26). 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.
The various structures described above are critical to understanding and interpreting 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.

A Note About Fossils

Fossils are not covered in detail in this book, but they are extremely important for understanding sedimentary rocks. Fossils can be used to date sedimentary rocks, but just as 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, aquatic, and terrestrial environments; estimate the depth of the water; detect the existence of currents; and estimate average temperature and precipitation.

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 later, this provides us with information about the changes in average global temperatures.

Exercise 9.3 Interpretation of Past Environments

Sedimentary rocks can tell us a great deal about the environmental conditions that existed during the time of their formation. For each of the following rocks, make some inferences about the following:

• source rock
• weathering
• sediment transportation (how, how far)
• depositional conditions

Quartz sandstone: no feldspar, well-sorted and well-rounded quartz grains, cross-bedding

Feldspathic sandstone and mudstone: feldspar, volcanic fragments, angular grains, repetitive graded bedding from sandstone upwards to mudstone

Conglomerate: well-rounded pebbles and cobbles of granite and basalt; imbrication

Breccia: poorly sorted, angular limestone fragments; orange-red matrix
9.6 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) (http://www.stratigraphy.org/) 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 (rock type). 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 9.27). The Nanaimo Group strata comprise a 5000 m 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 is still being mined in the Campbell River area.

The Nanaimo Group is divided into 11 formations as described in Figure 9.28. In general, the boundaries between formations are based on major lithological differences. As can be seen in the far-right column of Figure 9.28, 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. The differences in the depositional environments are probably a product of variations in tectonic-related uplift over time.
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.

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 9.30.

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Formation</th>
<th>Lithologies</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>~56-66</td>
<td>Gabriola</td>
<td>sandstone with minor mudstone</td>
<td>submarine fan, high energy</td>
</tr>
<tr>
<td>~66-67</td>
<td>Spray</td>
<td>mudstone/sandstone turbidites</td>
<td>submarine fan, low energy</td>
</tr>
<tr>
<td>~67-68</td>
<td>Geoffrey</td>
<td>sandstone and conglomerate</td>
<td>submarine fan, high energy</td>
</tr>
<tr>
<td>~68-70</td>
<td>Northumberland</td>
<td>mudstone turbidites</td>
<td>submarine fan, low energy</td>
</tr>
<tr>
<td>~70</td>
<td>De Courcy</td>
<td>sandstone</td>
<td>submarine fan, high energy</td>
</tr>
<tr>
<td>~70-72</td>
<td>Cedar District</td>
<td>mudstone turbidites</td>
<td>submarine fan, low energy</td>
</tr>
<tr>
<td>~72-75</td>
<td>Protection</td>
<td>sandstone and minor coal</td>
<td>nearshore marine and onshore deltaic and fluvial</td>
</tr>
<tr>
<td>~75-80</td>
<td>Pender</td>
<td>sandstone and minor coal</td>
<td>nearshore marine and onshore deltaic and fluvial</td>
</tr>
<tr>
<td>~80</td>
<td>Extension</td>
<td>conglomerate, with minor sandstone and some coal</td>
<td>nearshore marine and onshore deltaic and fluvial</td>
</tr>
<tr>
<td>~80-85</td>
<td>Haslam</td>
<td>mudstone and siltstone</td>
<td>shallow marine</td>
</tr>
<tr>
<td>~85-90</td>
<td>Comox</td>
<td>conglomerate, sandstone, mudstone (coal in the Campbell River area)</td>
<td>nearshore fluvial and marine</td>
</tr>
</tbody>
</table>
Chapter Summary

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

9.1 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.

9.2 Chemical and Biochemical Sedimentary Rocks

Chemical and biochemical sedimentary rocks form from ions that were transported in solution, and then converted into minerals by chemical and/or biological processes. The most common chemical rock, limestone, typically forms in shallow tropical marine 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.
9.3 Organic Sedimentary Rocks

Organic sedimentary rocks contain abundant organic carbon molecules (molecules with carbon-hydrogen bonds). An example is coal, which forms when dead plant material is preserved in stagnant swamp water, and later compressed and heated.

9.4 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.

9.5 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 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.

9.6 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

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