7. Sedimentary rocks

Sediments and sedimentary rocks cover 90% of Earth's surface. They are essential to our understanding of the origin and evolution of life because they are the rocks containing fossils. They are also the rocks from which coal, oil, and natural gas can be extracted, and are often associated with reservoirs of groundwater.

7.1. What are sediments?

Examples of ***sediments*** include beach sand, the gravels of riverbeds, and the fine particles desert dunes are made of. These are sediments that have not yet been transformed into sedimentary rocks. They are still soft, unlithified. We will see in section 7.3 how soft sediments become a hard, lithified rock.
Sediments can be classified into two broad categories: solid matter and ions in solution.
Examples of solid sedimentary matter: (1) fragments of rocks and minerals, (2) the hard parts of organisms (biominerals, e.g. mollusk shells), and (3) organic matter (e.g. plant leaves).
Examples of ions in solution: Na^+, K^+, Cl^-, Ca^{2+}, CO_3^{2-}…

7.2. How do sediments form?

7.2.1. Weathering

Sediments form by destruction of preexisting rocks. The destruction process is called ***rock weathering***. Two types of weathering can be distinguished: (1) ***physical weathering*** and (2) ***chemical weathering***.

(1) *Physical weathering*

Major physical weathering agents are ***wind*** (eolian weathering), ***water***, and ***ice*** (glacial weathering). The dust carried by the wind abrades the surface of rocks. A good example of eolian weathering is the polished surface of stones in arid regions such as the Moroccan desert or Mars. Water is a powerful weathering agent. The destructive action of waves along shorelines is a good example. Receding shorelines due to wave action are common around the world. Given enough time, rivers can cut through hard rocks and form V-shaped valleys with steep flanks. One of the most remarkable examples is the Grand Canyon in the US. Ice is also a powerful agent of rock destruction. Glaciers are like rivers of ice which can carve large U-shaped valleys. During the last ice age, the northern polar ice cap was much more extensive than today. Regions of North America and northern Europe that are now ice-free still bear the marks of glacial weathering. Ice can also destroy rocks through ***frost wedging***. This weathering process results from the fact that the volume of water increases when it freezes. If liquid water fills the fractures in a rock and then freezes, ice expands and widens the fractures which can in turn break the rock. Plants may also participate in rock physical weathering through ***root wedging***. Plant roots in the fractures of a rock force them to open further as the plant grows which may lead to rock dislocation.

(2) *Chemical weathering*

Rainwater and CO_2 combine in soils to form the weak carbonic acid H_2CO_3. In contact with carbonate rocks, the carbonic acid dissolves $CaCO_3$. The products of this reaction, Ca^{2+}, HCO_3^- and CO_3^{2-}, are transported by rivers to the ocean. In the ocean, the ions Ca^{2+} and CO_3^{2-} can be used by marine organisms to build their calcareous hard parts (see related slide). Dissolution of $CaCO_3$ is responsible for the formation of caves and other dissolution features (***karst***).

The process of $CaCO_3$ dissolution does not require the action of living organisms. However, the active dissolution of $CaCO_3$ by organisms happens as well. For example, some bivalves are capable of dissolving $CaCO_3$ and bore holes in which they live.

Like carbonate rocks, silicate minerals can react with acidic groundwater. The products of this weathering reaction include dissolved ions (e.g. Ca^{2+}, Si^{4+}, Fe^{2+}, HCO_3^-, CO_3^{2-}, H^+) and clays. These ions are transported by rivers to the ocean and some can be used by marine organisms to build hard parts made of $CaCO_3$ and SiO_2. The weathering of silicate rocks results in a net removal of CO_2 from the atmosphere over millions of years. This slow removal of CO_2 must be balanced by an equally slow input of CO_2. This input of CO_2 is provided by volcanoes and hot springs.

7.2.2. Erosion and transport

The removal of sediments from their source area is called ***erosion***. Erosion is carried out by the same flowing agents causing rock physical weathering: ***wind***, ***water***, and ***ice***. Sediments are then transported by these same agents to the site of their deposition. If there is no active removal, sediments may simply move away from their source area by gravity. The downslope movement of sediments by gravity is called ***mass wasting***.

7.2.3. Sediment deposition

Solid sedimentary particles carried either by ***wind*** (eolian transport), ***water*** or ***ice*** (glacial transport) will at some point be deposited. Deposition of a sedimentary particle transported by wind or water occurs when the wind/water speed decreases and is no longer capable of carrying the particle in question.

In water, strong currents with a speed of >50 cm/s can carry all sizes of particles up to boulder-size (>25.6 cm). Moderately strong currents with a speed of 20-50 cm/s can carry sand (62.5 µm-2 mm) and smaller particles. Weak currents (<20 cm/s) can carry silts and clays (<2 mm). Note that we consider here only sediments consisting of fragments of rocks and minerals which generally have roughly the same density. We don’t consider material with a very low density like wood.

Sediments carried by ice deposit when the ice melts. The nature and morphology of these deposits is typical and can be recognized in the rock record. Glacial deposits are useful indicators of past climate.

In the case of mass wasting, the nature of sediments (e.g. size, shape) and slope steepness control deposition.

For ions in solution, deposition occurs either abiotically or biotically. An example of abiotic deposition is the precipitation of minerals in a saline lake by evaporation (see section 4.3). Biotic deposition of ions in solution is the process of biomineralization (see section 4.3). A good example is given by corals which use Ca^{2+} and CO_3^{2-} present in the ocean to produce their skeleton made of $CaCO_3$.

7.3. How do sedimentary rocks form?

How soft sediments (say beach sand) are transformed into hard sedimentary rocks (in this case, sandstone)?

As soft sediments accumulate, they are progressively buried under younger layers of sediments. The set of physical and chemical changes which happen to soft sediments after their burial is called ***diagenesis***. The result of diagenesis includes the transformation of soft sediments into hard rock. This transformation is called ***lithification***. Lithification results from two main diagenetic processes:

(1) ***Compaction***: as sediments are buried deeper and deeper under younger sedimentary layers, the pressure and temperature increase. Sediments are squeezed, compacted. The space between sediment grains gets smaller.

(2) ***Cementation***: dissolved ions in groundwater precipitate in the open space between individual sediment grains. Common mineral cements include calcite ($CaCO_3$), hematite (Fe_2O_3), and quartz (SiO_2).

Compaction and cementation contribute to reduce the rock ***porosity***. Porosity is a measure of the amount of open space (or ***pores***) in a rock.

7.4. Properties of sediments and sedimentary rocks

The characteristics of sediment grains can provide information about the environment in which they formed. Fundamental properties of sediments and sedimentary rocks include:

Grain size: since sedimentary particles have generally roughly the same density, grain size gives a good indication of the strength of the current. The occurrence of coarse sand in a sediment indicates a stronger water current than a sediment composed entirely of mud.

Sorting: sorting is a measure of the variation in grain size within a sediment. If all sediment grains have approximately the same size, the sediment is well sorted. If the sediment is made of a mixture of small grains and large grains, the sediment is poorly sorted. This also provides information about the type of current which transported the sediment. If the strength of the water current is unchanging, the size of sediment grains deposited tends to be uniform. If the strength of the water current is variable, the size of grains deposited varies accordingly.

Grain morphology: during transport sediment grains are abraded and become rounded. Therefore the roundness of sediment grains provides information on the distance of transport. The greater the distance of transport, the greater the roundness.

7.5. Sedimentary basins and depositional environments

Large amounts of sediments are deposited in depressions of the Earth's crust. Large depressions in which abundant sediments accumulate are called ***sedimentary basins***. The largest basins are the ocean basins. Their size and morphology is controlled by plate tectonics. An example of a large continental sedimentary basin is the East African Rift which corresponds to a divergent boundary where two plates are pulled apart. The rift contains many lakes in which sediments can accumulate. In the future, the plates will keep moving away from each other. The continental lithosphere will stretch and get thinner. The rift will grow larger and deeper leaving more space for sediments to accumulate. The downward movement of the lithosphere as it is stretched and thinned is called ***subsidence***. Subsidence is accentuated by the weight of sediments pushing down the lithospheric plate. Ultimately, seawater will flood the rift and seafloor spreading will begin, transforming the continental rift into an ocean basin. The two continental margins that are moving apart progressively cool as they are moving away from the source of heat. As it cools, the lithosphere gets denser and progressively sinks creating space for sediments to accumulate. This is a particular kind of subsidence called ***thermal subsidence***. It enables the accumulations of thick piles of sediments along continental margins (continental shelf).

There exist many different kinds of ***depositional environments*** (deserts, lakes, rivers, delta, beach, organic reef, continental shelf, deep sea…) which belong to either one of the three following categories: continental, shoreline, and marine environments. Each depositional environment is characterized by a unique combination of physical, chemical, and biological processes. The nature of sediments deposited in these environments is determined by these processes. For example, the deep sea is not affected by strong, sustained currents like shallow-water environments. The deep-sea is therefore generally characterized by a fine-grained sedimentation (mostly mud). Deep-sea organisms are also different from those living in shallow waters. Let's take another example: coral reefs. Coral reefs are associated to tropical and subtropical climate. They grow exclusively in shallow water and their rigid framework consists mainly of coral skeletons and crustose coralline algae. Although the organisms which compose them have evolved, organic reefs have been around for almost as long as the Earth has existed (e.g. stromatolites, see section 7.6.2).

Useful indicators of past depositional environments are ***sedimentary structures***. Although many sedimentary structures exist, only the most common are described herein. When one looks at an outcrop of sedimentary rocks, the most conspicuous sedimentary structure is often the ***bedding*** or ***stratification plane*** (see related slide for illustration). Sedimentary beds can be a few cm thick to several m thick. Bedding results from changes in sedimentation affecting grain size and/or sediment composition. The equivalent of bedding at the mm scale is called ***lamination***. Bedding is useful to study tectonic deformation (folds and faults) because sediment layers are usually deposited flat and horizontal. Other remarkable sedimentary structures are ***ripple marks*** (see related slide for illustration). Ripple marks are a common feature of sandy beaches. The geometry of ripple marks preserved in sedimentary rocks provides information on the transport agent (wave vs. wind, unidirectional vs. bidirectional, current direction). ***Burrows*** are also sedimentary structures. They represent one example of sedimentary structures resulting from the activity of living organisms. Other biological sedimentary structures include traces left at the surface of sediments by benthic organisms (benthic means living on the seafloor).

In conclusion, geologists are able to reconstruct past sedimentary environments based on the characteristics of sedimentary rocks. When you have a succession of sedimentary rocks of different ages at an outcrop or in a drill core, it becomes possible to study environmental changes over geological time scales. The fossil content of the rock can also be used to understand the evolution of life.

7.6. Types of sedimentary rocks

7.6.1. Siliciclastic sedimentary rocks

Siliciclastic sedimentary rocks are composed of fragments of rocks (lithic fragments) and minerals. The name “siliciclastic” comes from the fact that the composition of these rocks is dominated by silicate minerals (e.g. quartz).

Siliciclastic rocks are classified according to grain size (coarse = ***conglomerate***, medium = ***sandstone***, fine = ***shale***) or grain composition (e.g. arkose = sandstone containing at least 25% of a mineral called feldspar).

7.6.2. Biochemical sedimentary rocks

Biochemical sedimentary rocks are usually formed by accumulation of the hard parts of marine organisms (e.g. bivalve shells, coral skeletons…). A beach deposit consisting of fragments of bivalve shells (***bioclasts***) is an example. Coral reef framework is another example. Bivalve shells and coral skeletons are made of $CaCO_3$. Another major biomineral is silica (SiO_2). Marine microorganisms such as diatoms and radiolarians secrete a tiny shell made of silica that can accumulate on the deep seafloor.

The constituents of biochemical sedimentary rocks are generally formed by the direct biological precipitation of $CaCO_3$. But biological activity can also induce precipitation of $CaCO_3$ indirectly. Photosynthetic microbial mats called stromatolites are a good example. The equilibrium between dissolved calcium and carbonate ions in the sea and the mineral calcium carbonate can be written as follows: $Ca^{2+} + 2HCO^{3-} \leftrightarrow CaCO_3 + CO_2 + H_2O$. The reaction of photosynthesis is $6H_2O +$

$6CO_2$ + sunlight → $C_6H_{12}O_6$ + $6O_2$. Photosynthesis consumes CO_2 whereas calcification releases CO_2 in the environment. Consequently, the photosynthetic activity of stromatolites tends to promote calcification by shifting the equilibrium state of the carbonate system to the right (Ca^{2+} + $2HCO^{3-}$ → $CaCO_3$ + CO_2 + H_2O). Stromatolites can form rigid pinnacle-like structures and these structures owe their rigidity to the early cementation induced by photosynthesis (see related slide for illustration).

7.6.3. Chemical sedimentary rocks

Chemical sedimentary rocks are formed by precipitation of minerals which does not involve biological activity. For example, minerals precipitating at the bottom of a saline lake subject to intense evaporation. The accumulation of minerals in this kind of setting produces a rock called ***evaporite***. One of the most common constituent of evaporites is NaCl (halite or table salt).

7.6.4. Organic sedimentary rocks

Organic sedimentary rocks are formed by accumulation of organic matter (e.g. plants). Usually, organic matter is quickly decomposed by bacterial activity. However, in particular settings which are characterized by a high rate of accumulation of organic matter and low levels of oxygen, organic matter can be preserved and accumulate.

An example of such accumulation is ***peat***. Peat forms in wetlands by accumulation of plants. Low oxygen concentrations prevent the complete decomposition of organic matter. As peat is buried under younger sediments, the increase in pressure transforms peat into ***lignite*** (compressed peat). At greater depth, pressure and temperature increases further and lignite is converted into ***coal***. Coal is a complex mixture of mineral matter and organic carbon compounds. Increasing further the pressure and temperature transforms coal into ***anthracite***. Anthracite has a higher carbon content than coal. Coal and anthracite have a different chemical composition than peat and lignite. Heat and pressure have modified their composition and texture. They are not strictly speaking sedimentary rocks anymore but metamorphic rocks (see next chapter).