

Sediments and Sedimentary Rocks

Sedimentary rocks accumulate from the operation of surface properties over time. The crust comprises only the outer 0.3% of the radius of the earth, and sedimentary rocks make up a relatively minor proportion of the crust. Nevertheless, sediments cover more than 80% of the Earth's *surface* and they record important information on surface conditions and processes over Earth history. Information about climate, sea level rise and fall, chemistry of the oceans, tectonics, meteorite impacts, etc. are preserved in sediments.

Sedimentary processes are also responsible for the redistribution of chemical elements over the Earth's surface, and the chemical differentiation associated with weathering and sedimentation provides a basis for sedimentary rock classification.

Principle Sedimentary Rock Types

Sedimentary rocks can be grouped very broadly into two categories: **siliciclastic** rocks and **carbonates + evaporates** (chemical precipitates). Siliciclastic rocks are *residues* of the weathering process (just like peridotites are residues of mantle melting processes) and carbonates + evaporates are precipitates from aqueous solution (you can think of the ocean as a huge aqueous lava lake undergoing fractional crystallization...).

Siliciclastics

Siliciclastic rocks are classified based on the sizes of their constituent particles (clasts):

Conglomerate	>5 mm
Sandstone	1/16-2mm
Shale	<1/16 mm

Conglomerates are composed of large rock fragments and make up a minor fraction of the total sedimentary rock mass (<1% by weight).

Sandstones are composed primarily of quartz, feldspar, and rock fragments. They can be subclassified in terms of "sorting" (basically, the width of the clast size distribution; narrow size distribution = well-sorted) and the intensity of the chemical weathering to which they have been subjected.

Graywackes are the least altered by chemical weathering and have bulk compositions similar to their source rocks. They are not well sorted and contain abundant clay minerals. Graywackes are usually deposited relatively near their source—they are characteristic of foreland basin deposits.

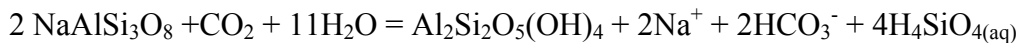
Lithic sandstones are composed primarily of lithic fragments (rock fragments) along with quartz and feldspars. They are better sorted than graywackes and hence have less clay. Clay minerals are enriched in aluminum, and the chief

compositional difference between lithic sandstones and their source rocks is depletion in Al.

Arkoses are composed primarily of quartz and feldspars. They have been subjected to more intense weathering than lithic sandstones or graywackes, and most of the mafic minerals are gone. Arkoses are enriched in K-feldspar relative to plagioclase because K-spar dissolves more slowly than plagioclase in water. From the pink K-spar and hematite left by the dissolved mafic minerals, arkosic sandstones are often known as “red beds.”

Quartzites, also known as *quartz arenites*, are composed primarily of quartz, which is the most resistant to weathering of the major rock forming minerals. They are products of intense weathering and are well sorted, which usually implies that they have been transported far from their source.

Shales are composed primarily of clay minerals, along with some fine-grained quartz and feldspar. Clay minerals are products of the incongruent dissolution of rock-forming minerals by aqueous solutions. For example, albite dissolves incongruently in water to form kaolinite $[Al_2Si_2O_5(OH)_4]$ —an important clay mineral + solutes:



Other important clay minerals are montmorillonite $[(Al,Mg)_8(Si_4O_{10})_4(OH)_8 \cdot 12H_2O]$ and illite, a mica that has significant Ca and Mg substitution for K. Shales are enriched in Al, Mg and K relative to their source rocks. They are the most abundant sedimentary rocks, composing ~70% of the entire sedimentary rock mass.

Carbonates

Carbonates (e.g. limestones) are composed primarily of the carbonate minerals calcite, aragonite, and dolomite. Most calcite and aragonite (polymorphs, both with composition $CaCO_3$) is precipitated from seawater by organisms. Dolomite $(Ca,Mg)CO_3$ is a secondary mineral that forms during *diagenesis*—after burial, calcite and aragonite react with fluids and dolomite precipitates. The dolomite content of carbonate rocks increases steadily with the age of the rock, and the oldest carbonate rocks have very little primary calcite remaining.

The particles that compose carbonate sediments can be grouped into several categories:

Carbonate mud – microcrystalline carbonate, usually less than $5\mu m$ in diameter. Some carbonate mud is formed by the mechanical or biological abrasion of larger particles, but most is precipitated directly, either as aragonite crystals precipitated inorganically from seawater (whether this happens in nature is controversial) or as aragonite needles produced within the tissues of calcareous algae.

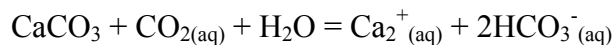
Skeletal particles – the whole and broken skeletons of invertebrates and calcareous algae.

Ooids – subspherical sand-size carbonate particles that have concentric rings of calcium carbonate surrounding a nucleus of another particle. They usually form in a tidal setting—the surfaces of rolling grains on the bottom provide heterogeneous nucleation sites for the inorganic precipitation of aragonite.

Peloids – small (30 to 100 μm in diameter) rounded aggregates of carbonate mud. Most of these are fecal pellets that have passed through the digestive systems of bottom-feeding marine organisms like polychaete worms, gastropods, and crustaceans.

Carbonates are deposited both in *carbonate reefs*, which are shallow-water, usually warm environments and in the deep seas as *calcareous oozes*, which are composed of the tests (shells) of planktonic microorganisms like *foraminifera* and *coccoliths* (coccolith tests are the constituents of blackboard chalk).

Carbonate accumulates on the ocean floor only above a certain depth, called the **carbonate compensation depth (CCD)**. The solubility of calcite and aragonite increase with depth, and below the CCD all carbonate minerals are dissolved. We can rationalize the increasing solubility of carbonate minerals with depth by examining the calcite dissolution reaction:



The solubility of CO₂ in water increases with pressure and increasing concentration of CO_{2(aq)} causes the reaction to proceed to the right. In modern oceans the CCD varies between 4 and 7 km depth, depending mostly on the rate of calcite and aragonite production in surface waters (higher carbonate production increases the depth of the CCD).

Evaporites

Evaporites are inorganic precipitates from aqueous solutions, composed primarily of the minerals anhydrite (CaSO₄), gypsum (CaSO₄*2H₂O) and halite (NaCl). They are deposited mainly in arms of the sea that have limited communication with the open ocean. The bottom of the Mediterranean Sea, for example, is draped by a thick sequence of evaporites. Evaporite minerals become saturated only in solutions that are considerably more concentrated than the water in the open ocean. Gypsum is the first mineral to saturate from evaporating seawater—it crystallizes from solutions ~3X as concentrated as seawater. Halite is saturated in solutions ~10X the concentration of seawater.