

# How Sedimentary Processes Create Mineral Resources

Learning outcomes:

1. Summarize the processes that act to make sedimentary rocks.
2. Explain how sedimentary processes (especially chemical weathering, erosion and deposition, and crystallization) redistribute and concentrate mineral resources.
3. Explain how climate influences chemical weathering.
4. Give examples and uses of mineral resources that are formed by sedimentary processes.

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## Introduction

Sedimentary processes, namely weathering, erosion, crystallization, deposition, and lithification, create the sedimentary family of rocks. Most of Earth's surface is covered by sediments (like mud, sand, and gravel), and the majority of rocks you will see (the majority of rocks exposed at Earth's surface) are sedimentary rocks (like mudstone, sandstone, and limestone).

## Chemical Weathering and Mineral Resources

**Weathering** processes break rocks into smaller pieces. There are two types of weathering: chemical and mechanical. **Chemical weathering** changes the chemical makeup of minerals and hence breaks them apart. For example, when sugar is stirred into water, the sugar dissolves (the sugar crystal breaks apart into the molecules that compose it; it is no longer a crystalline solid). This is a type of chemical weathering. Rust is also an example of chemical weathering; in that case, iron minerals oxidize and become smaller minerals with different compositions.

There are several things to keep in mind about chemical weathering:

- Chemical weathering requires liquid water. There will be more chemical weathering where rainfall and humidity are high.
- Different minerals chemically weather and dissolve differently (they have different **solubilities**). Some minerals, like halite (salt), dissolve easily (quickly). Some minerals will not dissolve. Some minerals might not dissolve quickly, but they may succumb to other types of chemical weathering. **Stable** minerals do not weather very easily.
- Chemical weathering can only act on the surface of a rock or mineral or where a crack allows air and water into the mineral/rock. Therefore, more chemical weathering happens if and where the rocks have first been mechanically weathered. **Mechanical weathering** physically breaks a rock into smaller pieces of the same rock or minerals in that rock.

## A General Model of Earth's Climate

Because climate is intricately linked to chemical weathering, let's take a quick look at Earth's climate system.

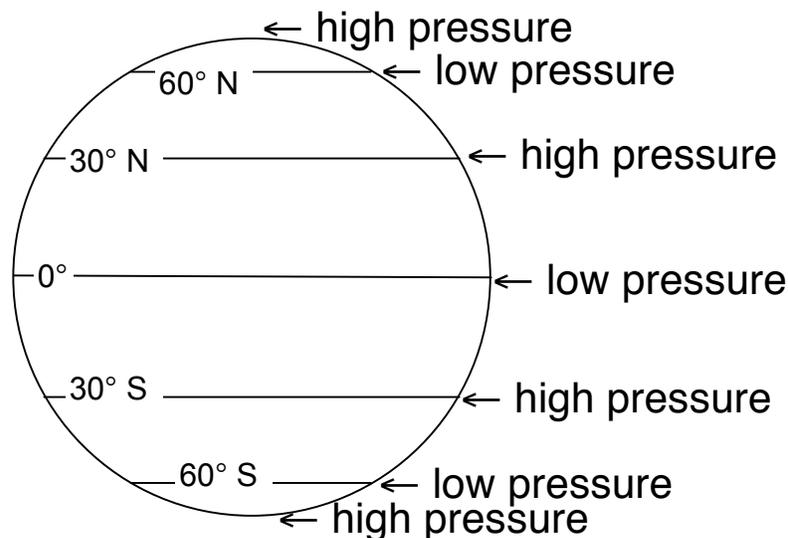
### Temperature

Temperatures are hottest in the tropics, the zone between 0° and 25° degrees N and S latitude. This is because the sun angle (the angle between incoming sun rays and Earth's surface) at these latitudes is highest, so solar radiation is more concentrated.

Temperatures are lowest at the poles but are also cold at high elevations.

### Air pressure and precipitation

The globe below shows how surface air pressure (also called atmospheric or barometric pressure) forms distinct zones that align with latitude.



*Figure 1.* Earth with idealized latitudes of high and low pressure. Rainfall/precipitation is highest where pressures are low and lowest where air pressures are high.

Low-pressure zones mark where air rises and precipitation occurs. For example, due to low pressure, rain forests are found along the Equator. (The high temperature also helps, because with high temperatures comes a lot of evaporation, which provides a lot of water vapor to condense to form rain.) In zones of high pressure, air sinks, which prevents condensation. High-pressure zones tend to have low amounts of precipitation; several deserts are located along 30° N and S; the poles also have high pressure so are also deserts.

*At which latitudes do you expect the highest levels of chemical weathering?*

## How Chemical Weathering Creates Mineral Reserves

As mentioned above, different minerals dissolve at different rates.

*Table 1.* List of solution rate. From Drever, 1997 (pg. 233).

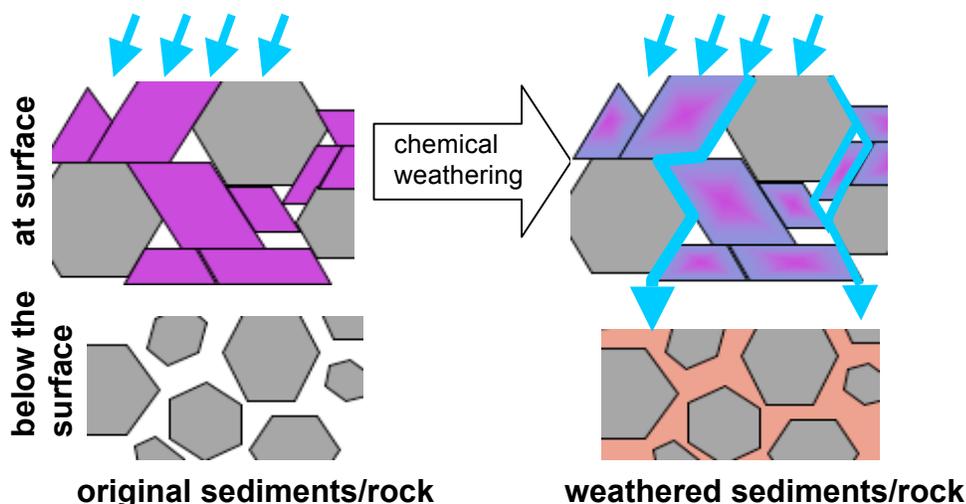
| Mineral              | Time it would take a hypothetical 1 mm sphere of this mineral to dissolve in water with pH=5 (years) |
|----------------------|--|
| calcite              | 0.1  |
| olivine (forsterite) | 2300   |
| plagioclase (albite) | 575,000  |
| mica (muscovite)     | 2,600,000  |
| clay (kaolinite)     | 6,000,000  |
| quartz               | 34,000,000   |

Table 1 lists how long it would take for very small pieces of minerals to dissolve. This list does not include halite (salt), which would dissolve in minutes instead of months or years. The minerals are listed from most soluble to least soluble. Halite and calcite have high solubilities, and quartz has a very low solubility and is thus more stable.

Not only do minerals have different solubilities, but elements within minerals dissolve differently. When minerals chemically weather, some elements in those minerals will readily dissolve in water and be removed by water. Other elements are not readily soluble, so will remain in a mineral. The mineral may not completely break into separate ions but will change composition (and hence become a different mineral) as one type of ion is removed.

For example, imagine that a rock is made of minerals X and Y (purple and gray in Figure 2, respectively). Mineral Y is made of elements C, D, and E. Mineral X is very stable and doesn't react with water, similar to quartz. Water flowing through the broken rock will alter mineral Y, but X will stay intact. In mineral Y, imagine that element C (the red element in Figure 2) is soluble, but elements D and E are not. Water will remove C. The concentrations of elements left behind (D and E, the insoluble elements) increase in the mineral; chemical weathering thus concentrated D and E (D and E would be found in **residual weathering deposits**, also called *laterite deposits*). In addition, the water containing the dissolved ions will carry element C somewhere else, where C may join with other ions and crystallize to make a mineral; in this way, C is also concentrated. Thus chemical weathering concentrates minerals and/or elements, and turns **mineral resources** into **mineral reserves**.

Because they form right at the surface, residual weathering deposits are likely to erode away. Therefore, residual weathering deposits tend to be found in fairly young sediment layers, as older deposits will have already eroded.



*Figure 2.* The colored shapes represent minerals, and white space is pore space (space in rock that is filled with air or water). The original sediment (or rock, on left) at the surface is exposed to rain (the arrows from above) and, hence, chemical weathering. The gray minerals are not soluble, so remain unchanged. The purple minerals are made of red and blue elements. The purple minerals react with the water, which preferentially removes one element (the red) from the mineral and carries that element deeper into the ground, where it crystallizes as a new mineral. Weathering therefore separated the blue from the red elements and concentrated those elements. A mining company interested in the blue element will mine rocks/sediments right at the surface, whereas a mining company interested in the red element will extract deeper rocks/sediments.

*Table 2.* Mineral resources derived from chemical weathering.

| Mineral   | Commodity         | How the mineral forms  | Some uses  |
|---|-------------------|--|--|
| gibbsite, boehmite (in the rock called bauxite)  | aluminum          | chemical weathering of aluminum-rich sediments, igneous rocks, or volcanic ash | food and beverage packaging, parts in airplanes and cars |
| garnierite and goethite   | nickel            | chemical weathering of ultramafic (low silica content) igneous rocks           | stainless steel, batteries                               |
| goethite and hematite   | iron oxides, iron | not currently mined for iron but is a potential reserve                        | steel, pigment (paint, makeup)                           |
| clay minerals   | clay              | chemical weathering of feldspar minerals                                       | ceramics, paper, cat litter                              |



*Figure 3.* The characteristic red color of the Waimea Canyon on the island of Kauai, Hawaii, results from chemical weathering. The original lava flows were chemically weathered by rainwater and the Waimea River, dissolving out the soluble elements and concentrating relatively insoluble rust-red iron oxide (hematite) on the surface. The red mud of the Waimea Canyon is used today as a resource by a local company to color their t-shirts.

## **Mechanical Weathering, Erosion, Deposition, and Mineral Resources**

### **Erosion and deposition**

Mechanical weathering processes break rocks into smaller pieces without changing their compositions. The rock and mineral fragments created by mechanical weathering are called **clastic** sediments and may be **eroded** (picked up and carried) and **deposited** elsewhere. Thousands or millions of years of erosion can deposit large quantities of a certain mineral in one spot, so even though the concentration of the mineral might have been low in the weathered rock, the concentration can be much higher in the sedimentary deposit. These mineral deposits are called **placer deposits**.

Streams are often the agents that erode (transport) these minerals. Streams can deposit sediments along the stream bank (in sand or gravel bars) and in alluvial fan or delta deposits. Once the sediments deposit in the ocean, they can be eroded further by waves and deposited in beaches. Wind can also pick up clastic sediment and concentrate placer deposits.



*Figure 4.* The sand on this Lake Superior beach is clastic sediment. The sand was created when a rock mechanically weathered (broke into pieces) and then was eroded (carried) by streams to Lake Superior, where it deposited. Further erosion by the waves concentrates the sand on the beach.

Sediments deposited by wind, streams, and waves are **sorted** by size and density. Gravity pulls sediments to the ground (or bottom of the stream or ocean), but the wind or rushing water (or waves) pulls sediments sideways, attempting to keep them aloft. Larger and denser (higher specific gravity) sediments require more wind, stream, or wave energy to stay afloat.

If we know the size and specific gravity (density) of the mineral that we are looking for, and we know the energy levels of a stream (or wave), then we can predict where in the stream (or shoreline) we should look for that mineral.

For example, gold tends to form small clastic sediments, but it is very dense. Therefore, small pieces of gold may deposit with large pieces of less dense clastic sediment (gravel) along streams. Therefore we should look for gold in gravel bars in modern streams or in deposits of conglomerate that were once gravel bars.

Before you go to the local stream to pan for gold, remember that the rock that weathered to begin with is important. If the rock that mechanically weathered to make the gravel did not contain any gold, then we will not find gold in the gravel. Gold is found mostly in igneous or metamorphic rocks. So, a gravel bar along the Meramec River in Missouri that contains only the chemical sedimentary rock chert is not likely to contain gold. A river flowing from a granite outcrop in the Rocky Mountains, however, might have visible gold flakes in its gravel bars.

Sand and gravel are important **industrial mineral resources**. Sand and gravel are clastic sediments, so will be eroded and deposited in environments (e.g., along streams and beaches) that can later be mined for these resources.

*Table 3.* Some economic minerals found in clastic sedimentary deposits and common uses.

| <b>Mineral</b>    | <b>Commodity</b>          | <b>Specific gravity</b>               | <b>Some uses</b>  |
|-------------------|---------------------------|---------------------------------------|---|
| various           | gravel                    |                                       | construction  |
| quartz            | sand, silica              | 2.65 (quartz)                         | construction, glass, computer chips   |
| rutile, ilmenite  | titanium                  | 4.18–4.25 (rutile),<br>4.7 (ilmenite) | white pigment (paint),<br>titanium metal (airplanes)  |
| chromite          | chromium                  | 4.6                                   | stainless steel   |
| rare-earth oxides | rare-earth elements (REE) |                                       | computer and television displays, fiber optic cables, magnets, catalytic converters in cars |
| cassiterite       | tin                       | 6.8–7.1                               | coating for tin cans, bronze  |
| cinnabar          | mercury                   | 8.10                                  | fluorescent lights, thermometers, production of chlorine                                    |
| diamond           | diamond                   | 3.5                                   | gemstones, abrasives  |
| native copper     | copper                    | 8.9                                   | wiring, antifungal and antibacterial chemicals  |
| native silver     | silver                    | 10.5                                  | mirrors, photography, electronics   |
| native gold       | gold                      | 15–19.3                               | jewelry, electronics, currency  |
| native platinum   | platinum                  | 14–19                                 | jewelry, catalytic converters in cars, dental equipment                                     |



*Figure 5.* This lake in Edwardsville, Illinois, fills an abandoned shale quarry. This shale is a clastic sedimentary rock formed from mud deposited in a swampy area about 300 million years ago and since lithified. Before reclamation laws were in place, the shale was mined to make bricks. The quarry was not filled in and returned to its pre-mining state, but left as a lake.

## Chemical Sedimentary Rocks and Mineral Resources

Water contains the dissolved ions derived from chemical weathering. When water evaporates, only pure water will turn to vapor and enter the atmosphere. Any ions are left behind, and the concentration of ions in the remaining water increases. When the water becomes saturated in ions, those ions will combine to form new minerals (crystallization will occur). The new mixture of minerals is a chemical sedimentary rock. Chemical sedimentary rocks that form when water evaporates are called **evaporite deposits**.

*Table 4.* The concentrations of ions in average seawater, brine from Great Salt Lake, Utah (from Drever, 1997), and freshwater (rain and river water; from Hem, 1985). In the ocean and the Great Salt Lake, evaporation removes water, leaving other ions behind. This concentrates the ions (as you can see by comparing the amounts of ions in seawater and the Great Salt Lake with the ions in rain water and the Mississippi River). Note that brines, like that in the Great Salt Lake, are saltier than seawater; and while all brines are saltier than seawater, different brines will contain different amounts of certain ions.

| Ion         | Average seawater (mg/kg) | Great Salt Lake (mg/kg) | Rain water from Menlo Park, CA (mg/kg) | Mississippi River (mg/kg) |
|-------------|--------------------------|-------------------------|--|---------------------------|
| chloride    | 19,350                   | 140,000                 | 0.8–17                                 | 24                        |
| sodium      | 10,760                   | 85,600                  | 0–9.4                                  | 20                        |
| sulfate     | 2,710                    | 16,400                  | 0.7–7.6                                | 51                        |
| magnesium   | 1,290                    | 7,200                   | 0.7–1.2                                | 10                        |
| calcium     | 411                      | 241                     | 0.8–1.2                                | 38                        |
| potassium   | 399                      | 4,070                   | 0                                      | 2.9                       |
| bicarbonate | 142                      | 251                     | 4–7                                    | 113                       |
| silica      | .5–10                    | 48                      | 0.3–1.2                                | 7.9                       |

*Which brine in the table has the highest salinity (contains the highest concentration of dissolved ions)?*

*Evaporite minerals readily form in the Great Salt Lake and in the ocean. Why do minerals crystallize in these places?*

As water evaporates, different ions reach saturation, and thus crystallize, at different times. The most insoluble minerals crystallize first, and the most soluble crystallize last. So, as salt water evaporates, calcite will crystallize first (using up the carbonate and bicarbonate ions), then gypsum (using up the sulfate), then halite (using up the sodium), and lastly potassium and magnesium salts. The minerals (and rocks they comprise) form in distinct layers, with calcite (which forms the rock limestone) on the bottom and potassium and magnesium salts on top. Because these chemical sedimentary rocks contain only one mineral, beneficiation of the mined reserve (where minerals have to be separated from other minerals) can be quite easy.

Because high evaporation rates are needed for crystallization, climate is important. For example, limestone (the sedimentary rock made of calcite) is presently forming in the shallow seas off the Bahamas. Also, natural highs and lows in the seafloor and/or coral reefs can create basins that favor chemical sedimentary rock formation.

*What temperature would favor evaporite formation? What amount of precipitation would favor evaporite formation? Based on these answers, at what latitudes should evaporites form?*



*Figure 3.* A limestone quarry in Dupou, Illinois. Illinois is nowhere near the ocean today but was covered by a shallow sea when this limestone formed about 300 million years ago. The limestone is mined to make cement.

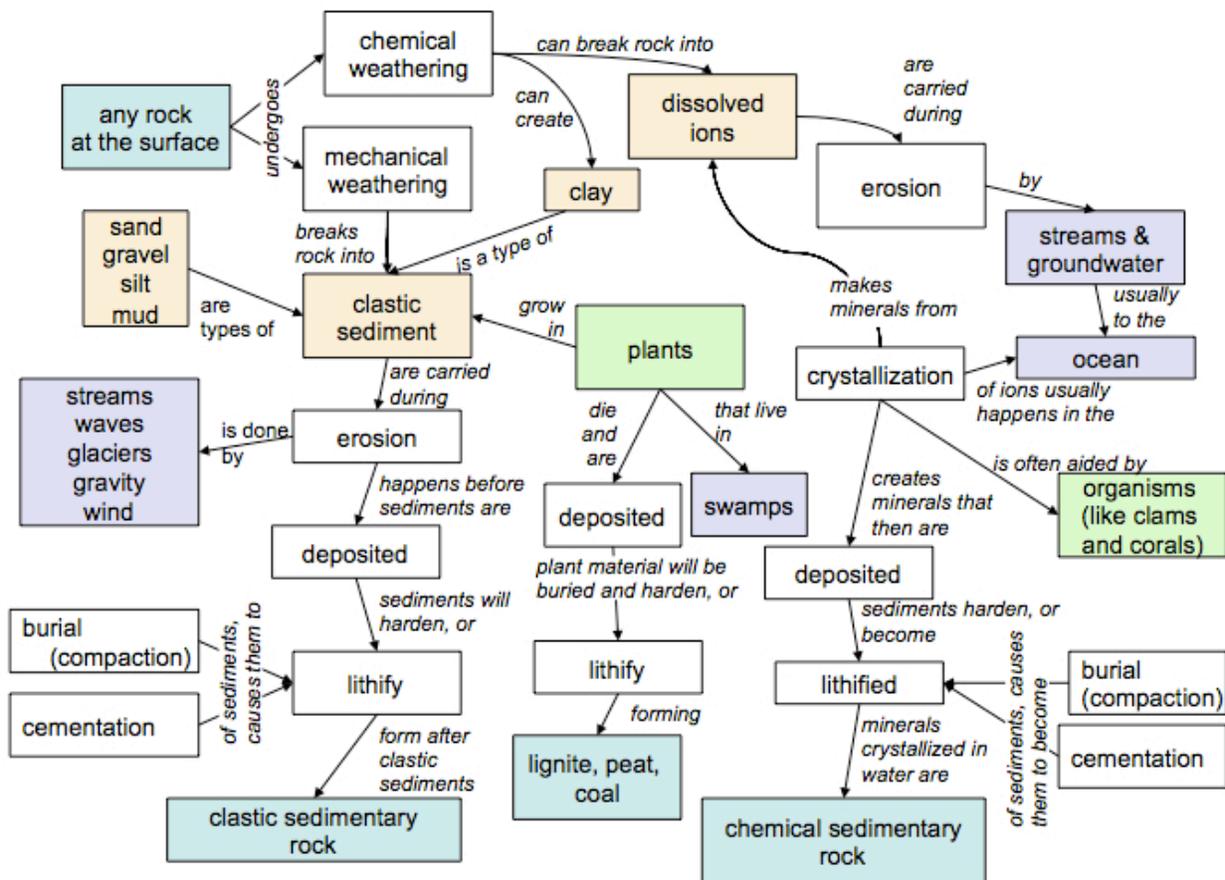
Table 5. Mineral resources that are chemical sedimentary rocks.

| <b>Rock</b>           | <b>Mineral</b>      | <b>Commodity</b>                       | <b>Some uses</b>   |
|-----------------------|---------------------|--|--|
| limestone, dolostone  | calcite, dolomite   | limestone, calcite (calcium carbonate) | cement, calcium in food and supplements  |
| rock gypsum           | gypsum              | gypsum                                 | dry wall   |
| rock salt             | halite              | salt                                   | food additive, road deicer, source of chlorine (water treatment, bleach, etc.) |
| rock salt             | sylvite             | potassium salt                         | food additive, road deicer, source of potassium (fertilizer)                   |
| banded iron formation | magnetite, hematite | iron                                   | steel  |

One nice thing about evaporite minerals is that most are readily soluble. Therefore, it's easy to remove the desired element from the solid. For example, if soybean plants need sulfur, powdered gypsum (a mineral) can be added to the soil and the soybeans can readily remove the sulfur from the gypsum. Humans need sodium. If we eat the mineral halite, then our bodies easily remove the sodium from the salt. It would be almost impossible to remove sodium from a silicate mineral like albite (feldspar), for example.

Instead of mining the crystallized evaporite deposits, salt water or brines (even saltier water) can be mined. Salt water is, of course, found in the oceans. Brines are found in terminal lakes (lakes into which rivers flow but which have no outlets) as well as underground (the deepest groundwater is often brine).

### Sedimentary Rocks and Processes: A Summary



The above concept map shows how all sedimentary rocks form. The blue and tan boxes contain substances, the purple boxes show places or forces, and white boxes contain **sedimentary processes** (the actual events that create sedimentary rocks). These processes are further defined in the glossary. Some sedimentary rocks form with the help of living things (green boxes). (Rocks that form from or with the help of organisms are sometimes called biochemical or bioclastic sedimentary rocks.)

The different sedimentary processes can concentrate elements, making them economical to mine. In other words, sedimentary processes can turn a **mineral resource** into a **mineral reserve**.

### **Weathering practice**

*Which of the following are examples of mechanical weathering and which are examples of chemical weathering?*

- *Water fills a crack in the pavement. Overnight, the water freezes (and expands), so the pavement cracks even more.*
- *A road crew uses dynamite to blast away a hillside.*
- *A teaspoon of salt dumped into a pot of boiling water dissolves.*
- *The bumper of a 1989 Honda rusts.*
- *Sediments (rocks) carried in a stream smash against each other, breaking off edges and corners.*

### **References**

Drever, James I. 1997. *The Geochemistry of Natural waters: Surface and Groundwater Environments*, 3rd Edition. Prentice Hall.

Hem, John D. 1985. *Study and Interpretation of the Chemical Characteristics of Natural Water*, 3rd Edition. USGS Water Supply Paper 2254

### **Images credits**

Sketches and concept map by J. Branlund

Table 2: Photo of bauxite taken by J. Branlund

Figure 3: Photos of Waimea Canyon and t-shirt by P. Bhattacharrya

Figures 4–6: Photos of Lake Superior beach, Edwardsville quarry lake, and Dupo limestone quarry by J. Branlund