GEOLOGIC PRINCIPLES corresponds to Chapter 2: *Getting Around in Geology*

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Summary of Important Concepts

• The Earth consists of five interconnected systems: the solid earth (rock and soil); the atmosphere; the hydrosphere; the biosphere; and the extraterrestrial system. These systems interact and influence each other.

• The earth’s crust consists of rocks made of various types of minerals. Minerals are classified into different groups according to their chemistry. The silicate mineral group makes up most rock of the crust.

• Rocks are composed on one or more minerals. There are three main classes of rocks:
  – Igneous rocks form from solidification of magma (molten rock)
  – Sedimentary rocks form from solidification of sediment (particles formed from the erosion of older rocks, or by chemical or biological processes at the earth’s surface).
  – Metamorphic rocks form from other rocks changed by heat and pressure
One type of rock can be transformed into another type over geologic time; a process known as the **rock cycle**.

Two concepts are used to determine geologic time and age:

- **Relative time** describes the sequence of geologic events, using principles such as superposition and cross-cutting.
- **Absolute age** uses radioactive decay as a natural “clock” to determine when a rock formed. This is called **radiometric dating**. Based on radiometric dating, the earth is estimated to have formed 4.6 billion years ago.

The Earth, along with the rest of the solar system (the Sun, the planets, and meteorites) formed from the gravitational contraction of a **nebula** - a spinning cloud of gas and dust - about 4.6 billion years ago.
The Earth System

The earth can be thought of as a system of interconnected parts, often called “spheres”. These spheres influence one another in important ways. The interconnected spheres of the Earth System are:

• the solid earth, which includes soil and rock
• the hydrosphere, which includes all the water on earth
• the biosphere, which includes all living things
• the atmosphere - the layer of gas that surrounds the earth
• the extraterrestrial sphere, which includes energy and objects which come from outside the earth. This includes the Sun’s energy, the effects of the Sun’s and Moon’s gravity on the earth, and meteorites.
This figure shows that the processes in the earth’s various spheres happen over a huge range of time, from seconds to millions or billions of years, depending on the process.
Earth Materials: MINERALS

The earth’s crust is made of various kinds of rock, and rock is composed of one or more minerals. For example, as this picture shows, the rock granite is composed mostly of the minerals quartz, biotite, and feldspar.

Minerals, by definition:
- are naturally occurring crystalline substances
- have a narrow range of chemical composition
- have characteristic physical properties
Minerals are made of various chemical **elements**, or **atoms**. Atoms, which form all matter, consist of three kinds of particles. Two of these particles -- **protons** with a positive charge and **neutrons** with a neutral charge -- occupy the center, or **nucleus**, of the atom. The nucleus contains nearly all the **mass** of the atom. The third particle -- **electrons** with a negative charge -- orbit around the nucleus. Electrons have almost zero mass.

All atoms all have this same general structure. By changing the **numbers** of protons, electrons, and neutrons, we make **different chemical elements**! For example, the element Oxygen has 8 protons; the element Gold has 79 protons, etc..
Chemical bonding between elements forms minerals.

In the earth’s crust, chemical elements rarely occur by themselves. It is much more common for two or more elements to combine by forming chemical bonds. Bonding occurs because elements commonly have opposite net electrical charges. For example, the figure shows how positively charged Sodium atoms (Na+) and negatively charged Chlorine atoms (Cl-) form bonds to make the mineral halite (Na Cl), which is table salt. (Yes, you eat this mineral every day!)
Minerals take the form of **crystals** of different colors and shapes.

The different colors result from the ways that different atoms absorb and reflect light.

The different shapes result from the different ways that bonded atoms pack together in particular geometric arrangements.
The **silicates** are the most abundant and important mineral group.

Geologists classify minerals into groups that share the same negatively charged atoms or molecules.

*For example:*
The **oxide** group consists of all minerals formed from various elements bonded to negatively charged oxygen (O\(^{-2}\)) atoms.
The **carbonate** group consists of all minerals formed from elements bonded to negatively charged carbonate ((CaCO\(_3\))\(^{-2}\)) molecules.

By far the most important group of rock-forming minerals in the earth’s crust is the **silicates**: minerals composed of **silicate tetrahedra** (SiO\(_4\))\(^{-4}\) bonded to each other and/or to other elements. A single silicate tetrahedron consists of 1 silicon (Si) atom surrounded by 4 oxygen (O) atoms, forming a tetrahedron shape. These tetrahedra bond readily to each other, and to other elements, forming several kinds of abundant minerals, including quartz and feldspar.
The figure shows the shape of the silicate tetrahedron, and shows how progressively more complex bonding between silicate tetrahedra forms the different types of common silicate minerals.

<table>
<thead>
<tr>
<th>Isolated tetrahedra</th>
<th>Formula of negatively charged ion group</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((\text{SiO}_4)^{-4})</td>
<td>Olivine</td>
</tr>
<tr>
<td>Continuous chains of tetrahedra</td>
<td>((\text{SiO}_3)^{-2})</td>
<td>Pyroxene group (augite)</td>
</tr>
<tr>
<td>Continuous sheets</td>
<td>((\text{Si}<em>4\text{O}</em>{11})^{-6})</td>
<td>Amphibole group (hornblende)</td>
</tr>
<tr>
<td>Three-dimensional networks</td>
<td>Too complex to be shown by a simple two-dimensional drawing</td>
<td>Mica (muscovite)</td>
</tr>
<tr>
<td></td>
<td>( \left(\text{SiO}_2\right)^0 ) ( \left(\text{Si}_3\text{AlO}_8\right)^{-1} ) ( \left(\text{Si}_2\text{Al}_2\text{O}_8\right)^{-2} )</td>
<td>Quartz Orthoclase feldspar Plagioclase feldspar</td>
</tr>
</tbody>
</table>

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Some examples of common rock-forming silicate minerals:

- **FELDSPAR** (plagioclase)
  - MICA (muscovite)
  - QUARTZ
Most rocks consist of one or more minerals (although volcanic glass and organic matter can also form rocks, even though technically neither are minerals). There are three main groups of rocks:

1. **IGNEOUS rocks** form from solidification of magma (molten rock).

2. **SEDIMENTARY rocks** form from solidification of sediment (particles formed from the erosion of older rocks, or by chemical or biological processes at the earth’s surface).

3. **METAMORPHIC rocks** form from other rocks changed in a solid state by heat, fluids, and pressure.
One type of rock can be transformed over geologic time into another type. This process is known as the **rock cycle**.

For example, an **igneous rock** may form from cooling of some magma. Later it may become eroded into pieces that are washed down rivers, eventually settling and becoming buried and compacted into a **sedimentary rock**. This rock may then eventually be buried so deeply under other layers that it becomes changed by heat and pressure into a **metamorphic rock**. This rock might then get exposed at the earth’s surface and eroded to eventually become a sedimentary rock. Or it might get buried deeply enough to melt, forming magma that will eventually form a new igneous rock. And on and on it goes.....
The Rock Cycle

- Weathering
- Transportation
- Deposition
- Uplift and exposure
- Lithification (compaction and cementation)
- Sedimentary rocks
- Metamorphism
- Metamorphic rocks
- Melting
- Magma
- Consolidation
- Igneous rocks (extrusive)
- Igneous rocks (intrusive)
- Crystallization
IGNEOUS ROCKS

Igneous rocks are classified using two criteria: **texture** (the size and shape of the minerals) and **mineral composition** (the types and abundance of minerals present).

**TEXTURE:** If magma cools **slowly**, deep underground, the minerals will grow large, giving the rock a **phaneritic texture** (large crystals). In contrast, if the magma cools **quickly**, like when it erupts on the earth’s surface as lava or as a mixture of gas and hot particles, the minerals will all be small, producing an **aphanitic texture** (small crystals).

**MINERAL COMPOSITION:** The chemical composition of the magma determines which types of silicate minerals will form. Magma rich in **silicon** (called **felsic magma**) will form light-colored rocks, while magma rich in **iron and magnesium** (called **mafic magma**) will form dark-colored rocks.
This diagram shows how texture and mineral composition are used together to determine the type of igneous rock. For example, a rock rich in the minerals olivine and pyroxene, with a phaneritic texture (large crystals), is called **peridotite**. A rock rich in the minerals quartz and potassium feldspar, with an aphanitic texture (small crystals) is called **rhyolite**.
The rock of the Sierra Nevada, CA, is granite – an igneous rock that is light-colored, rich in silicon, with a phaneritic texture. Granite forms from felsic magma that cools slowly deep underground.

Famous **Half Dome**, in Yosemite National Park, is made of same granite that makes up the rest of the Sierra Nevada. *(Photograph by Ansel Adams.)*
“Sediment” is made up of particles formed at the earth’s surface. Sediment can form in several ways, giving us three main classes of sedimentary rocks:

1. **Detrital (or clastic) sedimentary rocks** form from fragments of older rocks. These pieces may be transported some distance by water, wind, or glacial ice, then deposited, buried, and turned into rock. Examples include sandstone and conglomerate.

2. **Chemical sedimentary rocks** form from chemical precipitation, generally precipitation from a solution of water and dissolved ions. Examples include rock salt and gypsum.

3. **Biogenic sedimentary rocks** form from the remains of living things. For example, coal is the altered remains of wood, and most limestone and chalk comes from the shells of marine animals.
This figure shows how clastic sediment of various sizes will, after compaction and cementation, form different types of detrital sedimentary rocks.

The process of sediment turning into rock is called lithification.
COQUINA (a form of limestone): an example of a biogenic sedimentary rock.

CONGLOMERATE: an example of a detrital sedimentary rock.
Sedimentary rocks are particularly useful for geologists because various features of the rock can tell you something about the original environment in which the rock formed.

For example, if you found these **mudcracks** in ancient sedimentary rocks, it would tell you that the environment was subject to periodic wetting and drying out. Perhaps the environment was a river flood plain, or a tidal area at the edge of the sea.
Here is another example of what sedimentary rocks tell you about the ancient environment. Many sedimentary rocks form in areas with blowing wind or moving water (currents or waves). Moving water or wind forms ripples in the sediment, and these are preserved as cross-bedding in the rock. The large inclined layers shown here are cross-bedding formed by wind-blown sand forming huge sand dunes in an ancient desert!
METAMORPHIC ROCKS

Metamorphic rocks form from other rocks that have been changed in a solid condition by heat, pressure, and/or fluids moving through the rock deep underground. One common feature of metamorphic rocks is foliation -- a layering that forms within the rock perpendicular to the direction of maximum pressure. Nearly all metamorphic rocks have this layered appearance, or foliation, not to be confused with the layering present in sedimentary rocks.
GEOLOGIC TIME

Geologic time involves events ranging in time from a few seconds (earthquakes, meteorite impacts) to millions and even billions of years (the movement of tectonic plates, the formation of the earth itself).

Geologists use two different methods to determine geologic time and the ages of geologic features and events:

1. **Relative age dating** involves establishing the order of features and events, without necessarily determining their actual age in years.

2. **Absolute age dating** involves determining the actual age (in thousands, millions, or billions of years) of a rock or other geologic feature.
Relative Age Dating - an example

• Layer #1 is younger than the other layers because it is on top, while Layer #5 is older than Layers #1-#4, because it is below them.

• The fault is younger than all the layers, because it cuts through all the layers.

• The blue layer is the same age in both places, because it contains the same fossils.
Absolute Age Dating

Determining the actual age of a rock, in years, requires some sort of natural “clock”. The clock that geologists use is the **radioactive decay** of certain elements within rocks.

Radioactive decay is when an unstable element changes (decays) into another element, or a new variation of itself. This change occurs at a **precise rate** that can be determined by experimentation. By convention, the unstable element is called the “**parent**”, while the element resulting from the decay of the parent is called the “**daughter**”. The speed (rate) at which a particular parent element changes into a daughter element is expressed as the **half-life**: the time required for half of the parent atoms to change into daughter atoms.

To determine the age when a rock formed, you need to know two things:
- the percentage of parent and daughter atoms in the rock
- the half-life (rate of decay)
An example follows on the next slide.....
Notice in this figure how the percentage of parent atoms decreases, and the percentage of daughter atoms increases, as time goes by. By measuring the rate at which this occurs (the half-life), and measuring the percentage of parent and daughter atoms in the rock, we can determine the age of the rock!
Two types of radioactive decay are common.

**Alpha decay** is when an unstable parent atom emits an alpha particle (a small atom consisting of 2 protons and 2 neutrons).

**Beta decay** is when an unstable parent emits a beta particle (an electron).

Both types of decay produce a new, stable daughter atom.
A form of radioactive decay that is particularly useful for determining the ages of the remains of plants and animals is the decay of carbon-14 to carbon-12.

C-14 is made continuously in the upper atmosphere, so all living things absorb a fraction of C-14 in their tissues as they grow. After death, C-14 decays gradually to C-12. By measuring the percentage of C-14 versus C-12 in plant and animal remains, we can determine their age.

Carbon-14 radiometric dating can be used to determine ages of organic material up to 50,000 years old.
FORMATION and AGE of the EARTH

Our solar system consists of 8 planets (not including Pluto) orbiting the Sun in a single plane, all traveling in the same direction. Most scientists think this reflects the formation of the solar system from a nebula - a spinning cloud of gas and dust that slowly contracted under its own gravity, flattened into a disc, and eventually coalesced into the Sun and the planets, including Earth.
When did the Earth and the rest of the solar system form?

Radiometric dating (based on the decay of uranium into lead) shows us that the oldest rocks yet found on earth are nearly 4.0 billion years old. Furthermore, certain isolated mineral grains (eroded out of rocks that are no longer present) have been dated as old as 4.3 billion years.

However, scientists presently accept 4.6 billion years as the age of formation of the earth. This is the age (based again on the decay of uranium into lead) of the oldest moon rocks and meteorites. Since we assume that all objects in the solar system formed at about the same time (see previous slide), we assume that the earth is about as old as the moon and meteorites.

*Our earth today is a result of geologic processes that have acted over an immense span of geologic time!*