A **Rock** is a solid aggregate of minerals.

Four different minerals are obvious in this piece of Granite.
Minerals are solid compounds that we use every day!

The average automobile contains:

- a ton of iron and steel,
- 240 lbs of aluminum,
- 50 lbs of carbon,
- 42 lbs of copper,
- 41 lbs of silicon,
- 22 lbs of zinc, and
- thirty other minerals including titanium, gold and platinum.
Three families of rock:

- **Igneous**
- **Sedimentary**
- **Metamorphic**

Formed through interaction, mixing, and recycling through the rock cycle.
Three ways to form:

Igneous

Sedimentary

Metamorphic
Igneous composition and texture
Sedimentary composition and texture
Metamorphic composition and texture
Plate Movement Powers the Rock Cycle
Minerals are solid crystalline compounds with a definite (but variable) chemical composition.

- Feldspar Na/Ca (Al, Si)$_4$O$_8$
- Copper C
- Hematite Fe$_2$O$_3$
- Pyrite FeS$_2$
- Gypsum CaSO$_4$-2H$_2$O
- Fluorite CaF$_2$
Hawaii’s most common mineral – volcanic **Olivine** \((\text{Mg, Fe})_2\text{SiO}_4\)

Hawaii’s second most common mineral – marine **Calcite** \(\text{CaCO}_3\)
“A mineral is a naturally occurring, inorganic, crystalline solid with a definite, but sometimes variable, chemical composition.”
Atoms are the smallest components of nature with the properties of a given substance.

- **Electrons**
  (negative charge)
- **Protons**
  (positive charge)
- **Neutrons**
  (no charge)
For any given element:

**Atomic Number** is the number of protons in the nucleus.

**Mass Number** is the number of neutrons and protons in nucleus.

Carbon 12 (\(^{12}\text{C}\))
Variations in mass number create **Isotopes**

- **Carbon 12** ($^{12}\text{C}$)
  - 6 protons
  - 6 neutrons
  - mass no. = 12
  - atomic no. = 6

- **Carbon 13** ($^{13}\text{C}$)
  - 6 protons
  - 7 neutrons
  - mass no. = 13
  - atomic no. = 6

- **Carbon 14** ($^{14}\text{C}$)
  - 6 protons
  - 8 neutrons
  - mass no. = 14
  - atomic no. = 6
Atoms bond to **achieve a stable electron configuration**. Most atoms bond to achieve 8 electrons in the outer shell - the so-called “Octet Rule”.

**TABLE 4.3** Electron Patterns of the First 20 Elements (Shaded elements are inert gases.)

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Atomic Number</th>
<th>First (2 is stable)</th>
<th>Second (8 is stable)</th>
<th>Third (8 is stable)</th>
<th>Fourth (8 is stable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium</td>
<td>Li</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beryllium</td>
<td>Be</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boron</td>
<td>B</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>8</td>
<td>2</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorine</td>
<td>F</td>
<td>9</td>
<td>2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>10</td>
<td>2</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>11</td>
<td>2</td>
<td>8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>12</td>
<td>2</td>
<td>8</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>13</td>
<td>2</td>
<td>8</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>14</td>
<td>2</td>
<td>8</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
<td>15</td>
<td>2</td>
<td>8</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>16</td>
<td>2</td>
<td>8</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl</td>
<td>17</td>
<td>2</td>
<td>8</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>18</td>
<td>2</td>
<td>8</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>19</td>
<td>2</td>
<td>8</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>20</td>
<td>2</td>
<td>8</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>
Variations in electrical charge form **Ions**

- negative charge = **Anion**
- positive charge = **Cation**
Minerals are **compounds** of atoms bonded together … “to achieve a stable electron configuration” …
COVALENT BONDING

... “[to achieve a stable electron configuration]” ...
Igneous Minerals crystallize from cooling magma.

Sedimentary Minerals crystallize from dissolved elements in water, or as a product of biological metabolism.

Metamorphic Minerals recrystallize from existing minerals where conditions in the crust cause high heat and pressure.

Ions in a dissolved state (magma, groundwater, seawater, etc.) that bond and produce a solid compound have made a mineral...the net charge must be neutral.
Silicates – Earth's most abundant mineral group
Oxygen and Silicon are the two most abundant elements in the crust.

<table>
<thead>
<tr>
<th>Element</th>
<th>Average Abundance</th>
<th>Typical Ionization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>46%</td>
<td>(O${^{2-}}$)</td>
</tr>
<tr>
<td>Silicon</td>
<td>28%</td>
<td>(Si${^{4+}}$)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>8%</td>
<td>(Al${^{3+}}$)</td>
</tr>
<tr>
<td>Iron</td>
<td>6%</td>
<td>(Fe${^{2+}}$ or Fe${^{3+}}$)</td>
</tr>
<tr>
<td>Magnesium</td>
<td>4%</td>
<td>(Mg${^{2+}}$)</td>
</tr>
<tr>
<td>Calcium</td>
<td>2.4%</td>
<td>(Ca${^{2+}}$)</td>
</tr>
<tr>
<td>Potassium</td>
<td>2.3%</td>
<td>(K+)</td>
</tr>
<tr>
<td>Sodium</td>
<td>2.1%</td>
<td>(Na${^{+}}$)</td>
</tr>
</tbody>
</table>
Silica - 4 oxygen atoms surround a single silicon atom, forming \((\text{Si}^{4+}\text{O}^{2-})^4\). Each oxygen atom covalently shares 1 electron with the silicon atom, jointly filling its outermost shell.
Types of Silicate Structures

- **Single Tetrahedron**
- **Independent Tetrahedra**
- **Single Chain**
- **Double Chain**
- **Sheet**
- **Three-Dimensional Network**

- $\text{Si}^{4+}$
- $\text{O}^{2-}$
- $\text{Na}^+$
- $\text{Ca}^{2+}$
- $\text{Al}^{3+}$
- $\text{Fe}^{2+}$ (3+)
- $\text{Mg}^{2+}$
- $\text{K}^+$
- Metallic Cations
http://www.youtube.com/watch?v=Jd9C40Svt5g
Metallic Cations Join Silicate Structures to Form Neutral Compounds.

- Cations of like size and charge substitute within silicate structures.
  - This forms a wide variety of minerals.
- Most substituted Cation pairs are $\text{Na}^+$/Ca$^{2+}$, $\text{Al}^{3+}$/$\text{Si}^{4+}$, and Fe$^{2+}$/Mg$^{2+}$.
- Olivine forms by Single Cation Substitution.
- Plagioclase Feldspar forms by Double Cation Substitution.

\[(\text{Mg}^{2+}\text{or Fe}^{2+})_2\text{Si}^{4+}\text{O}^{2-}_4\]
**Single Substitution**

- Mg$^{2+}$

**Double Substitution**

- Al$^{3+}$
- Si$^{4+}$

### Minerals

- **Forsterite (Mg$^{2+}$)**
  - Mg$_2^{2+}$(Si$^{4+}$O$_{4}^{2-}$)$_4^{-}$

- **Fayalite (Fe$^{2+}$)**
  - Fe$_2^{2+}$(Si$^{4+}$O$_{4}^{2-}$)$_4^{-}$

- **Olivine**

- **Magnetite**
  - Fe$^{3+}$

- **Albite (Na$^{+}$)**
  - Na$^{1+}$Al$^{3+}$Si$_3^{4+}$O$_8^{2-}$

- **Anorthite (Ca$^{2+}$)**
  - Ca$^{2+}$Al$_2^{3+}$Si$_2^{4+}$O$_8^{2-}$

### Structures

- Plagioclase Feldspar
- Single Substitution
- Double Substitution
Olivine: single tetrahedron \((\text{SiO}_4)^{4-}\) 
\([\text{Fe}_2^{2+}(\text{Si}^{4+}\text{O}_4^{2-})^{4-}] \text{ or } [\text{Mg}_2^{2+}(\text{Si}^{4+}\text{O}_4^{2-})^{4-}]\) 
\(+4\ +4\ -8 = 0\) \text{ or } \(+4\ +4\ -8=0\)

\textit{Fayalite (Fe}_2\text{SiO}_4) \quad \textit{Forsterite (Mg}_2\text{SiO}_4)

Feldspar: 3-D framework \((\text{Si}_3\text{O}_8)^{4-}\) 
\([\text{Na}^{1+}\text{Al}^{3+}\text{Si}_3^{4+}\text{O}_8^{2-}] \text{ or } [\text{Ca}^{2+}\text{Al}_2^{3+}\text{Si}_2^{4+}\text{O}_8^{2-}]\) 
\(+1\ +3\ +12\ -16=0\) \text{ or } \(+2\ +6\ +8\ -16=0\)

\textit{Albite NaAlSi}_3\text{O}_8 \quad \textit{Anorthite CaAl}_2\text{Si}_2\text{O}_8
As the Si and O build crystalline structures and the metallic cations play single and double substitution, the entire magma chamber grows into a solid mass of minerals....
“A mineral is a naturally occurring, inorganic, crystalline solid with a definite, but sometimes variable, chemical composition.”
There are seven common rock-forming minerals.

- Olivine
- Pyroxene
- Amphibole
- The Feldspar Group: Orthoclase and Plagioclase
- Biotite
- Quartz
- Calcite
• Earth’s crust is 4/5 igneous rock.
• Every igneous rock begins life as magma.
• As magma migrates toward the surface, some of it chills and hardens underground into various types of igneous rocks.
• Magma that makes it to the surface erupts in either flowing or explosive volcanoes, generating lava or pyroclastic debris.
Igneous rock is formed when molten, or partially molten, rock solidifies.
Igneous rock-forming environments
Igneous Rocks (two categories)

**Intrusive**

*Magma* crystallized slowly within the crust. No exposure to the cool atmosphere.  
**Plutonic** – intrusive igneous rock at great depth within crust or mantle.

**Extrusive**

*Lava* and *Pyroclastic Debris* Extruded at surface or at very shallow levels.

Granite is Intrusive

Basalt is Extrusive
Igneous Rocks

• Igneous Rocks are named on the basis of their texture and composition.

  **Texture** of a rock is the **size and arrangement** of the minerals it contains.

  **Composition** of a rock is the **assemblage** of minerals it contains.
As magma crystallizes a network of interlocking minerals develops.

The **composition** and **texture** of the resulting rock is determined by these minerals.
Phaneritic texture - with large minerals (Granite)

Large crystals had a long time to crystallize. Therefore, this is an intrusive rock.
Texture

Aphanitic texture - mineral grains too small to see with the unaided eye (Basalt)

Small crystals had a short time to crystallize. Therefore, this is an extrusive rock.
Texture

Vesicular texture – many pits from gas escape (Basalt)

Extrusive rock.
Texture

Porphyritic texture - with 2 distinct grain sizes, large and small (Andesite Porphyry)

What is the cooling history?
Texture

Glassy texture - without obvious minerals (Obsidian)

No crystals. This is an extrusive rock.
Texture is estimated using visual grain size

(depends on crystallization history)

<table>
<thead>
<tr>
<th>Texture</th>
<th>Definition</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aphanitic</td>
<td>Minerals too small to see</td>
<td>Rhyolite</td>
</tr>
<tr>
<td>Phaneritic</td>
<td>Minerals large enough to see with unaided eye</td>
<td>Granite</td>
</tr>
<tr>
<td>Glassy</td>
<td>No obvious minerals</td>
<td>Obsidian</td>
</tr>
<tr>
<td>Pyroclastic</td>
<td>Fused, glassy volcanic rock fragments and ash from explosive volcanic eruption</td>
<td>Tuff</td>
</tr>
<tr>
<td>Vesicular</td>
<td>Many holes or pits in rock surface caused by escaping gas</td>
<td>Vesicular Basalt</td>
</tr>
<tr>
<td>Porphyrytic</td>
<td>Two distinct mineral sizes</td>
<td>Porphyritic Basalt</td>
</tr>
</tbody>
</table>

Pyroclastic texture

Phaneritic texture

Aphanitic texture

Pyroclastic flow

Lava bed

Magma chamber
Composition

Igneous color (gray scale) is used to estimate chemical composition

<table>
<thead>
<tr>
<th>Felsic</th>
<th>Intermediate</th>
<th>Mafic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Fe/Mg content</td>
<td>High Si/O content</td>
<td>Low Si/O content</td>
</tr>
<tr>
<td>High Fe/Mg content</td>
<td>High Si/O content</td>
<td>Low Si/O content</td>
</tr>
</tbody>
</table>
**Felsic** – oxygen, silicon, sodium enriched, iron, magnesium, calcium depleted

Source – partial melting, continental crust

**Intermediate**

**Mafic** - iron, magnesium, calcium enriched, oxygen, silicon, sodium depleted

Source – mantle, oceanic crust

**Ultramafic**

**Granite** - (pink is considered felsic)

**Peridotite**
Composition

How do igneous rocks form in a cooling magma chamber?

Remember partial melting?

Silica (felsic) compounds melt first – therefore in a cooling magma chamber they must crystallize last.

Iron-rich (mafic) compounds melt last – therefore in a cooling magma chamber they must crystallize first.

Therefore cooling magma will become enriched in Si/O as crystallization proceeds.
Igneous Rock-Forming Minerals

Mafic Minerals
- Olivine
- Pyroxene
- Amphibole
- Biotite Mica

Felsic Minerals
- Plagioclase Feldspar (Ca/Na)
- Orthoclase Feldspar
- Muscovite Mica
- Quartz
How do igneous rocks form?

Bowen's Reaction Series

**Hot**
- Olivine
- Pyroxene
- Amphibole
- Biotite

Ultramafic
- Ca-plagioclase

Mafic
- Plagioclase feldspar
- Na-plagioclase

Intermediate
- Orthoclase feldspar
- Muscovite
- Quartz

**Cool**

Felsic

Rhyolite Granite

Basalt Gabbro

Andesite Diorite

Types of Rocks formed
The Igneous Minerals

The Igneous Rocks

Composition

Felsic
Intermediate
Mafic
Ultramafic

Texture

Intrusive
Extrusive

Granite
Diorite
Gabbro
Rhyolite
Andesite
Basalt
Peridotite
Igneous rock is a ubiquitous component of Earth’s crust because it evolves as a product of tectonic processes.
Can you predict the location of volcanoes?
A volcano is any landform from which lava, gas, or ashes, escape from underground or have done so in the past.

What is causing this eruption?
What factors influence its character?

“A volcano is any landform from which lava, gas, or ashes, escape from underground or have done so in the past.”
We learned from Chapter 5 that magma (and lava) can be felsic, intermediate, or mafic. How does magma chemistry influence the nature of volcanic eruptions?
There are three common types of magma:

**BASALTIC**

Basaltic lava flows easily because of its low viscosity (low gas content). The low viscosity is due to low silica content.

**ANDESITIC**

**RHYOLITIC**

Pahoehoe - smooth, shiny, and ropy surface
There are three common types of magma:

**BASALTIC**

**ANDESITIC**

Andesitic magma erupts *explosively* because it tends to have high gas content. It is viscous and therefore traps gas, builds pressure and explosively erupts. High Viscosity is related to high silica content.

**RHYOLITIC**

Mount St. Helens, 1980
There are three common types of magma:

**BASALTIC**

**ANDESITIC**

**RHYOLITIC**

Rhyolitic magma erupts *catastrophically* because it has high gas content. It is viscous and therefore traps gas, builds pressure and explosively erupts. High viscosity is related to high silica content – an abundance of silica polymers (chains etc.) leads to the high viscosity.
Comparison of common magma types

<table>
<thead>
<tr>
<th>Magma Type</th>
<th>Composition</th>
<th>Silica Content and Viscosity</th>
<th>Gas Content</th>
<th>Explosivity</th>
<th>Lava Temperature</th>
<th>Examples of Volcanoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basaltic</td>
<td>Mafic</td>
<td>Least, ~50% (thin, runny)</td>
<td>0.5%–2%</td>
<td>Least</td>
<td>Hottest ~1100°C to 1200°C</td>
<td>Mid-ocean ridges; plateau basalts like Columbia Plateau; Hawaiian Islands</td>
</tr>
<tr>
<td>Andesitic</td>
<td>Intermediate</td>
<td>Intermediate, ~60%</td>
<td>3%–4%</td>
<td>Intermediate</td>
<td>Cooler ~900°C to 1000°C</td>
<td>Mount St. Helens, Mount Rainier</td>
</tr>
<tr>
<td>Rhyolitic</td>
<td>Felsic</td>
<td>Greatest, &gt;70% (thick, stiff)</td>
<td>4%–6%</td>
<td>Greatest</td>
<td>Coolest ~700°C to 800°C</td>
<td>Yellowstone volcano</td>
</tr>
</tbody>
</table>

TABLE 6.1 Magma Types
Pillow Basalt
EXPLOSIVE ERUPTIONS are fueled by violent releases of volcanic gas.
A cataclysmic Plinian-style eruption (schematic drawing)
Pyroclastic debris is produced by explosive eruption

Tephra = airborne
Pyroclastic Flow = gravity-driven down the slopes

http://www.youtube.com/watch?v=yjL7UjogUaI
EFFUSIVE ERUPTIONS

RELATIVELY FLUID LAVA FLOW

DETERMINED BY:
• viscosity (low)
• temperature (high)
• gas content of magma (low)