Definition of Igneous Rocks

- Igneous rocks form from cooling and crystallization of molten rock—magma
  - Magma - molten rock within the Earth
  - Lava - molten rock on the Earth’s surface
- Igneous rocks form the framework for the earth’s crust
General Characteristics of Magma

- Igneous rocks form as molten rock cools and solidifies
- General characteristics of magma:
  - Parent material of igneous rocks
  - Forms from partial melting of rocks
  - Magma at surface is called lava

- General characteristics of magma:
  - Rocks formed from lava are extrusive, or volcanic rocks
  - Rocks formed from magma at depth are intrusive, or plutonic rocks
Nature of Magma

- Composed of three portions - liquid, solid and gas
  - Liquid portion = melt
    - Mobile ions in solution
      - Silicate ion, K$^{+1}$, Ca$^{+1}$, Na$^{+1}$, Fe$^{+2}$, Mg$^{+2}$
  - Solid component = silicate minerals
    - May contain silicate minerals
      - Formed early or undergoing melting
    - Slow forming produces large crystals
  - Gaseous portion = volatiles
    - Most commonly H$_2$O, CO$_2$ and SO$_2$
    - May propel magma to surface
    - Can enhance melting

Magma

Usually a silicate melt (liquid) at high temperatures (650 to 1200°C)

Mixture of all the elements that make up minerals plus volatile components:

H$_2$O, CO$_2$, Cl, F, S

These components form gases and will boil off when pressure is released
Origin of Magma

- Generating magma from solid rock
  - Role of heat
    - Temperature increases with depth in the upper crust (geothermal gradient)
      - Average between 20°C to 30°C per kilometer
    - Rocks in the lower crust and upper mantle are near their melting points
    - Additional heat may induce melting

A Typical Geothermal Gradient
Origin of Magma

- Role of pressure
  - Increases in confining pressure increases a rock’s melting temperature
  - When confining pressures drop, decompression melting occurs
- Role of volatiles
  - Volatiles (primarily water) cause melting at lower temperatures
  - Important factor where oceanic lithosphere descends into the mantle

Decompression Melting

[Diagram of decompression melting process]
Igneous rocks
Formed from the cooling and consolidation of magma
• Plutonic (intrusive) — cooled below the surface
• Volcanic (extrusive) — cooled on the surface

Classification of Igneous Rocks
Defined by texture:
• Fine-grained: extrusive or volcanic
• Coarse-grained: intrusive or plutonic
General Characteristics of Magma

• Crystallization of magma
  • Cooling of magma results in the systematic arrangement of ions into orderly patterns
  • Silicate minerals result from crystallization in a predictable order
  • Texture is the size and arrangement of mineral grains

Igneous Textures

• Texture is the overall appearance of a rock based on the size, shape, and arrangement of interlocking minerals
• Factors affecting crystal size:
  • Rate of cooling
    - Slow rate = fewer but larger crystals
    - Fast rate = many small crystals
    - Very fast rate forms glass
Classification of Igneous Rocks

Based on Mineral Composition and Texture

Textures - reflect rate of cooling

- **Phaneritic** - mineral crystals are visible e.g. Granite & Gabbro
- **Pegmatite** - exceptionally large crystals e.g. Pegmatite
- **Aphanitic** - crystals not visible e.g. Rhyolites & Basalt
- **Porphyritic** - large crystals surrounded by small crystals (indicate slow & abrupt rapid cooling) e.g. Porphyritic Granite
- **Volcanic glass** - very rapid cooling
  - Pumice (high gaseous silica rich lava) & obsidian
Coarsely Crystalline Granite
Photomicrograph of Granite

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Finely Crystalline Basalt
Photomicrograph of Basalt

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Igneous textures

**Glassy** - no minerals present

**Crystalline** - rocks made of mineral grains

**Porphyritic** - mixture of coarse and fine

**Vesicular** - with bubble holes
Pyroclastic Igneous Rocks

- Obsidian
- Pumice
- Ash
Texture of Igneous Rocks

• **Controlled by cooling rate**
  - Degree of crystallinity
  - Vesicularity

Igneous Textures

• **Types of igneous textures**
  - Pyroclastic texture
    - Fragmental appearance produced by violent volcanic eruptions
    - Often appear more similar to sedimentary rocks
  - Pegmatitic texture
    - Exceptionally coarse-grained
    - Form in late stages of crystallization of granitic magmas
Types of Igneous Rocks

Based on Silica Content

- **Ultramafic** (low silica content < 40%)
  - Peridotite
- **Mafic** (low 45-55%)
  - Gabbro (plutonic)
  - Basalt (volcanic)
- **Intermediate** (55 - 65%)
  - Diorite (plutonic)
  - Andesite (volcanic)
- **Felsic** (high silica content > 65%)
  - Granite (plutonic)
  - Rhyolite (volcanic)

Classification of Igneous Rocks

Determined by composition (both chemical and mineralogical):

- magnesium (Mg) + iron (Fe) = mafic
- feldspar + quartz (Si) = felsic
Types of Igneous Rocks
Based on Silica Content

• Ultramafic (low silica content < 40%; Mg- and Fe-rich)
  - Peridotite

• Mafic (low 45- 55%; Mg- and Fe-rich)
  - Gabbro (plutonic)
  - Basalt (volcanic)

• Intermediate (55 - 65%; also rich in feldspar)
  - Diorite (plutonic)

Igneous Compositions

• Granitic versus basaltic compositions
  • Granitic composition
    - Light-colored silicates

• Termed felsic (feldspar and silica) in composition
  - High silica (SiO₂) content
  - Major constituent of continental crust
Igneous Compositions

- Granitic versus basaltic compositions
  - Basaltic composition
    - Dark silicates and calcium-rich feldspar
    - Termed mafic (magnesium and ferrum, for iron) in composition
    - Higher density than granitic rocks
    - Comprise the ocean floor and many volcanic islands
Classification by composition and texture

**Extrusive**  
- basalt  
- andesite  
- rhyolite

**Intrusive**  
- gabbro  
- diorite  
- granite
Classification of Igneous Rocks

When we talk about the chemical composition of a rock we usually speak in terms of the oxides, *e.g.*, 

<table>
<thead>
<tr>
<th></th>
<th>Typical basalt</th>
<th>Typical granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SiO}_2$</td>
<td>50%</td>
<td>70%</td>
</tr>
<tr>
<td>$\text{Al}_2\text{O}_3$</td>
<td>15%</td>
<td>12%</td>
</tr>
<tr>
<td>$\text{FeO}+\text{MgO}$</td>
<td>15%</td>
<td>3%</td>
</tr>
<tr>
<td>$\text{CaO}$</td>
<td>8%</td>
<td>2%</td>
</tr>
<tr>
<td>$\text{K}_2\text{O}+\text{Na}_2\text{O}$</td>
<td>5%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Composition of melts affects behavior while still fluid

- More $\text{SiO}_2$ will increase viscosity,
- making strong temporary bonds in magma
Factors controlling the viscosity of magmas

• **Composition:**
  - higher $\text{SiO}_2$; higher viscosity
  - lower volatiles; higher viscosity

• **Temperature:**
  - lower temperature; higher viscosity
<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>Felsic (Granitic)</th>
<th>Intermediate (Andesitic)</th>
<th>Mafic (Basaltic)</th>
<th>Ultramafic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant Minerals</td>
<td>Quartz, Potassium feldspar, Feldspar-rich plagioclase feldspar</td>
<td>Amphibole, Sodium- and Calcium-rich plagioclase feldspar</td>
<td>Pyroxene, Calcium-rich plagioclase feldspar</td>
<td>Olivine, Pyroxene</td>
</tr>
<tr>
<td>Accessory Minerals</td>
<td>Amphibole, Magnetite, Biotite</td>
<td>Pyroxene, Biotite</td>
<td>Amphibole, Olivine</td>
<td>Chromite, Calcium-rich plagioclase feldspar</td>
</tr>
</tbody>
</table>

### Texture

<table>
<thead>
<tr>
<th>Phenocrystic (coarse-grained)</th>
<th>Granite</th>
<th>Diorite</th>
<th>Gabbro</th>
<th>Peridotite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhedral (fine-grained)</td>
<td>Rhyolite</td>
<td>Andesite</td>
<td>Dacite</td>
<td>Peridotite</td>
</tr>
<tr>
<td>Porphyritic</td>
<td>&quot;Porphyritic&quot; precedes any of the above names whenever there are appreciable phenocrysts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glassy</td>
<td>Olistolith (compact glass)</td>
<td>Pumice (frothy glass)</td>
<td>Uncommon</td>
<td></td>
</tr>
<tr>
<td>Pyroclastic (fragmental)</td>
<td>Tuff (fragments less than 2 mm)</td>
<td>Volcanic Breccia (fragments greater than 2 mm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Rock Color

(based on % of dark minerals)

- 0% to 25%
- 25% to 45%
- 45% to 65%
- 65% to 100%

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**Extrusive igneous activity**

- **A.** Glassy texture produced by very rapid cooling. (Pumice, a frothy, glassy mass.)
- **B.** Pyroclastic texture produced from debris of explosive eruption
- **C.** Fine-grained (phaneritic) texture produced when magma cools quickly on Earth's surface
- **D.** Porphyritic texture produced by slow then rapid cooling
- **E.** Coarse-grained (phenocryst) texture produced when magma cools slowly at depth
**Classification of Igneous Rocks**

**Evolution of Magmas**

- A single volcano may extrude lavas exhibiting very different compositions
- Bowen’s reaction series
  - Minerals crystallize in a systematic fashion based on their melting points
  - During crystallization, the composition of the liquid portion of the magma continually changes
Bowen’s reaction series

- Series of chemical reactions that take place in silicate magmas as they cool
- First investigated in the 1920s and 1930s by N. L. Bowen
- Important experiments that help us understand the evolution of magmas
Evolution of Magmas

• Processes responsible for changing a magma’s composition
  • Magmatic differentiation
    - Separation of a melt from earlier formed crystals
  • Assimilation
    - Changing a magma’s composition by incorporating surrounding rock bodies into a magma

Evolution of Magmas

• Processes responsible for changing a magma’s composition
  • Magma mixing
    - Two chemically distinct magmas may produce a composition quite different from either original magma
Early Crystallization

Liquids Squeezed from Crystals
Methods of Intruding Magma

- Magma invades cracks
- Magma melts walls of country rock
- Magma breaks off rocks; most slowly melt but a few are preserved

Assimilation, Magma Mixing, and Magmatic Differentiation

- A. Assimilation of host rock
- Host rock is dislodged, melts and is incorporated into a magma body
- Earliest-formed intrusives alter, changing the composition of the remaining melt

- B. Crystallization and settling

- C. Magma mixing
- Younger magma body intrudes and mixes with older one
Evolution of Magmas

• Partial melting and magma formation
  • Incomplete melting of rocks is known as partial melting
  • Formation of basaltic magmas
    - Most originate from partial melting of mantle rocks at oceanic ridges
    - Large outpourings of basaltic magma are common at Earth’s surface

• Partial melting and magma formation
  • Formation of andesitic magmas
    - Produced by interaction of basaltic magmas and more silica-rich rocks in the crust
    - May also evolve by magmatic differentiation
Evolution of Magmas

• Partial melting and magma formation
  • Formation of granitic magmas
    - Most likely form as the end product of crystallization of andesitic magma
    - Granitic magmas are more viscous than other magmas—tend to lose their mobility before reaching the surface.
    - Produce large plutonic structures

How Different Magmas Form

• Factors affecting melting of rocks- thus magma creation
  - Heat - radioactive isotopes, friction, original Earth heat
  - Pressure - increases melting point of minerals/rocks
  - Water - lowers melting point of minerals
• Fractional Crystallization (Magma Differentiation)
  - Bowen reaction series
• Magma - Assimilation
• Magma - Mixing
Intrusive Igneous Activity

- Emplacement of magma
  - Magma at depth is much less dense than the surrounding rock
    - Increased temperature and pressure causes solid rock to deform plastically
    - The more buoyant magma pushes aside the host rock and forcibly rises in the Earth as it deforms the "plastic" host rock

- At more shallow depths, the host rock is cooler and exhibits brittle deformation
  - Movement of magma here is accomplished by fractures in the host rock and stoping
  - Melting and assimilation of the host rock is greatly limited by the availability of thermal energy
Intrusive Igneous Activity

- Most magma is emplaced at depth in the Earth
  - An underground igneous body, once cooled and solidified, is called a pluton

- Classification of plutons
  - Shape
    - Tabular (sheet-like)
    - Massive

Intrusive Igneous Activity

- Classification of plutons
  - Orientation with respect to the host (surrounding) rock
    - Discordant—cuts across sedimentary rock units
      » Provides an important age relationship
    - Concordant—parallel to sedimentary rock units
Intrusive Igneous Activity

• Types of intrusive igneous features
  • Dike—a tabular, discordant pluton
    - e.g., Ka‘ihalulu (Red Sand) Beach, Hana, Maui
  • Sill—a tabular, concordant pluton
    - e.g., Palisades Sill in New York
  • Laccolith
    - Similar to a sill
    - Lens or mushroom-shaped mass
    - Arches overlying strata upward
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The Palisades Sill
A Sill in the Salt River Canyon, Arizona

Some Intrusive Igneous Structures
Intrusive Igneous Activity

- Intrusive igneous features
  - Batholith
    - Largest intrusive body
    - Surface exposure of 100+ square kilometers (smaller bodies are termed stocks)
    - Frequently form the cores of mountains

Sierra Nevada Batholith

- Core of the Sierra Nevada mountain range in California
- Composed of many individual plutons
- Includes familiar granite peaks of the High Sierra
  - Mount Whitney, Half Dome, and El Capitan
- Formed when Farallon Plate subducted below the North American Plate
  - Approximately 210-80 mya
Types of Igneous Structures
Cooling Structure - Columnar Jointing

- Form when igneous rock cool near surface
  - Develop shrinkage fractures that produce these elongate pillar-like columns
    - Giant’s Causeway, Ireland; Sampson’s Ribs, Scotland
Plate Tectonic & Igneous Rocks

Plate tectonic can be used to account for the global distribution of igneous rock types

- Basalt/Gabbros
  - most abundant igneous rocks in oceanic crust
    - divergent plate boundary

- Andesite/Diorite
  - found in subduction zones

- Rhyolites/Granite
  - most abundant in continental crust
    - subduction zone

Economic values of Igneous rocks - gemstones, road construction, building decoration, etc.
Tectonic Settings of Igneous Activity

Volcanic Island Arc, Indonesia
Fig. 4.8

Oceanic Hot Spot

Hawaii

Continental Volcanic Arc

N. Cascades