# Chapter 4

## Igneous Rocks and Intrusive Igneous Activity

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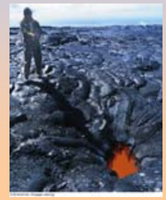
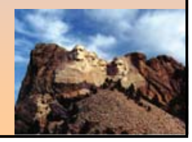
## Introduction

- Igneous rocks form by the cooling of magma (or lava).
- Large parts of the continents and all the oceanic crust are composed of Igneous Rocks.





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## The Properties and Behavior of Magma and Lava

- Molten rock material below the Earth's surface is called magma.
- If the magma reaches the surface it is called lava.
- Magma is erupted as either
  - Lava flows or
  - Pyroclastic materials (ash, etc.)

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## The Properties and Behavior of Magma and Lava

### Composition of Magma

- Silica is the primary constituent of magmas
- Magmas are differentiated based on the relative proportions of silica, iron, and magnesium.
  - Felsic – silica rich, iron and magnesium poor
  - Intermediate – intermediate between felsic and mafic
  - Mafic – silica poor, iron and magnesium rich
  - Ultramafic – even richer in magnesium and iron
- Parent magma composition largely determines the composition of igneous rocks.

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## The Properties and Behavior of Magma and Lava

### Composition of Magma

**TABLE 4.1** The Most Common Types of Magmas and Their Characteristics

| Type of Magma | Silica Content (%) | Sodium, Potassium, and Aluminum | Calcium, Iron, and Magnesium |
|---|---|---|---|
| Ultramafic | <45 | ↓ | Increase |
| Mafic | 45–52 | | ↑ |
| Intermediate | 53–65 | | |
| Felsic | >65 | Increase | |

Table 4.1, p. 87

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## The Properties and Behavior of Magma and Lava

### How Hot Are Magma and Lava?

- Measured temperatures of lavas suggest that typical
- mafic magma is somewhat hotter than 1200ºC
- felsic magma is somewhat hotter than 900ºC.

Fig. 4.2, p. 87

## The Properties and Behavior of Magma and Lava

### Viscosity – Resistance to Flow

- The viscosity of magma is controlled primarily by temperature and composition (silica and iron content).
- Other factors include loss of volatiles, crystallinity, bubble content, and shear stress during movement.

## The Properties and Behavior of Magma and Lava

### Viscosity – Resistance to Flow

- Viscosity measures a substance's resistance to flow.
  - High viscosity – thick, stiff flow
    - Examples: Tar, glacial ice, felsic magma

Fig. 4.3 b, p. 88

## The Properties and Behavior of Magma and Lava

### Viscosity – Resistance to Flow

- Viscosity measures a substance's resistance to flow.
- Low viscosity flow -
  - Examples: Water, syrup, mafic magmas
  - Mafic magmas are hotter and have less silica. This makes them flow better.

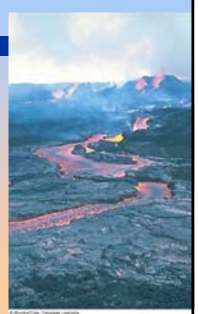


Fig. 4.3 a, p. 88

## How Does Magma Originate and Change?

- Heat increases the movement of atoms, breaks bonds, and melts rocks to form magmas
- Melting produces expanding magmas that are less dense than the parent rock
- Less dense magmas are buoyant and rise through the lithosphere

## How Does Magma Originate and Change?

- Some magmas originate at depths of 100 to 300 km.
- Most magmas, however, form at shallower depths in the upper mantle or lower crust.
- Shallow magmas often accumulate in magma chambers.
- Magma chambers beneath spreading ridges may only be a few kilometers below the surface.
- Magma chambers in convergent plate boundaries (subduction zones) are usually at depths of 10s of km.

## How Does Magma Originate and Change?

- Magma accumulates in reservoirs in the lower crust or upper mantle in magma chambers
- Molten rock is less dense than solid rock, and so it is buoyant and begins to rise thru the lithosphere.

## How Does Magma Originate and Change?

❖Later the magma may stall out and crystallize at a level of neutral buoyancy.

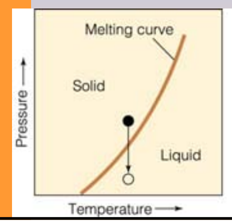

❖Stoping - A process where a large body of magma can push aside the overlying crust and assimilate blocks of crust on its way toward the surface.

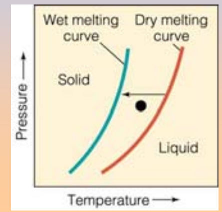
Fig. 4.9, p. 93

## How Does Magma Originate and Change?

Magma originates at depth due to partial melting.

❖The most important factors are Temperature, Pressure and Water Content

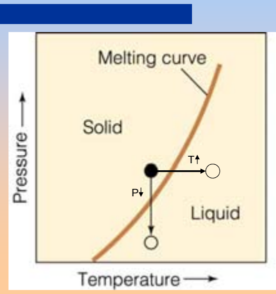



## How Does Magma Originate and Change?

Pressure-Temperature (P-T) Diagrams

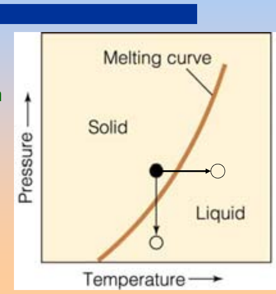
Different materials have different melting points at different temperatures and pressures. If either changes, then melting can occur. For example, an increase in temperature at the same pressure would initiate melting.




## How Does Magma Originate and Change?

Pressure-Temperature (P-T) Diagrams

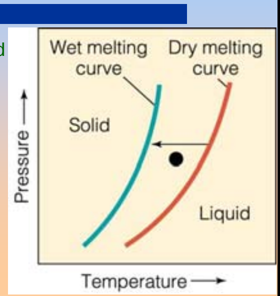
Melting can also be initiated if the Pressure Decreases. A reduction in pressure at the same temperature moves the material from the solid to liquid side of the melting curve.




## How Does Magma Originate and Change?

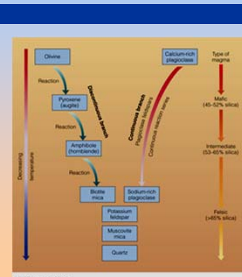
Pressure-Temperature (P-T) Diagrams

Melting can also be initiated if the Water Content Increases. An increase in water content under the same pressure and temperature conditions will cause melting to occur. Therefore, materials with water melt more easily.




## How Does Magma Originate and Change?

Bowen's reaction series



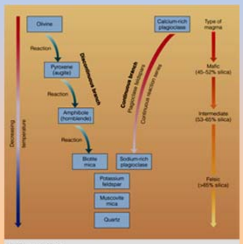
❖Bowen's reaction series describes the sequence of mineral crystallization in a cooling magma.

❖There are two branches in the reaction series.
- ❖Discontinuous series
- ❖Continuous series

Fig. 4.4, p. 89

## How Does Magma Originate and Change?

### Bowen's reaction series



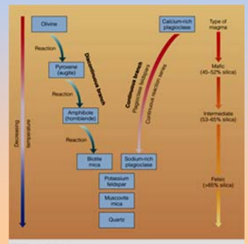
The **discontinuous series** produces ferromagnesian minerals.

- Given ideal cooling conditions, a mafic magma will yield a sequence of different minerals, each of which is stable within specific temperature ranges.
- As each mineral forms, it removes elements from the melt, leaving the remaining melt to form the next mineral in the sequence.

Fig. 4.4, p. 89

## How Does Magma Originate and Change?

### Bowen's reaction series



The **continuous series** produces a variety of plagioclase feldspars

- Substitution occurs in the crystal structure of plagioclase feldspar. Calcium is replaced with sodium during cooling.
- These minerals react continuously with the magma to adjust their compositions during cooling.

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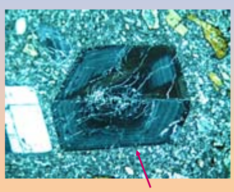
Fig. 4.4, p. 89

## How Does Magma Originate and Change?

### Bowen's Reaction Series – Zoning

Zoned minerals indicate changing conditions during formation.

Rimmed Olivine

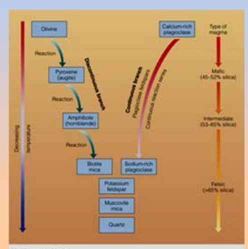


Zoned Plagioclase

Images from: http://www.union.edu/PUBLIC/GEODEPT/hollocher/skaergaard/geologic_features/micrographs.htm
And http://www.und.nodak.edu/instruct/mineral/320petrology/opticalmin/plagioclase.htm

## How Does Magma Originate and Change?

### Bowen's reaction series



- Bowen's reaction series predicts that
  - olivine will form first at high temperatures and
  - quartz ($SiO_2$) is the last mineral to crystallize from a cooling magma.

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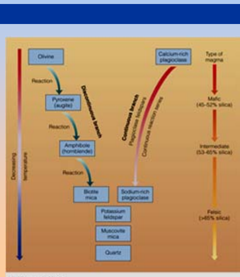
Fig. 4.4, p. 89

## How Does Magma Originate and Change?

### Bowen's reaction series



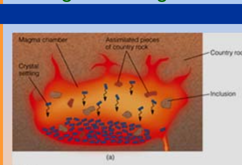
The reverse of Bowen's reaction series describes the melting of rock

- The first mineral to melt would be quartz.
  - followed by muscovite
  - followed by potassium feldspar
  - followed by biotite and Na-rich plagioclase feldspar

Fig. 4.4, p. 89

## How Does Magma Originate and Change?

### Processes That Bring About Compositional Changes in Magma

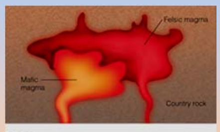


- 1. Crystal settling - the first formed ferromagnesian minerals can settle to the base of a magma chamber or body, withdrawing some of the iron and magnesium and enriching the remaining magma in other elements.
- During crystallization, the remaining melt becomes progressively more silica-enriched.

Fig. 4.7a, p. 92

## How Does Magma Originate and Change?

### Processes That Bring About Compositional Changes in Magma




- 2. Assimilation of country rock, sometimes by stoping, can change a magma's composition, but usually only to a limited extent.
- 3. Magma mixing can also result in compositional change.
  - Two different magmas can blend together (mix) if their viscosities are very similar, or
  - they can mingle without blending if their viscosities are very different.

Fig. 4.8, p. 93

## Igneous Rocks Their Characteristics and Classification

### Igneous Rock Textures

- Minerals begin to crystallize from magma and lava after small crystal nuclei form and grow.
- Two broad groups based on texture are:
  - volcanic (extrusive) rocks which have an aphanitic texture
  - plutonic (intrusive) rocks which have a phaneritic texture.
  - Rocks with more complex cooling histories are characterized by porphyritic textures.

## Igneous Rocks Their Characteristics and Classification

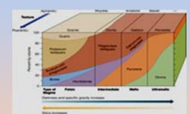
### Igneous Rock Textures

- Rapid cooling typifies volcanic rock and produces aphanitic textures.
- Slow cooling of plutonic magmas produces phaneritic textures with mineral grains that are easily visible without magnification.
- Porphyritic textures are characteristic of rocks with complex cooling histories and contain mineral grains of different sizes.
- Other igneous rock textures include vesicular, glassy, and pyroclastic.

## Igneous Rocks Their Characteristics and Classification

### Composition of Igneous Rocks

- Mg-Fe-rich magma is called "mafic,"
  - Gabbros and basalts are products of mafic magmas
- Na, K, Al and $H_2O$ rich magma is "felsic."
  - Granites and rhyolites are products of felsic magmas



Most magma, like most minerals, consists of silicon and oxygen with lesser amounts of other elements, such as magnesium (Mg), iron (Fe), sodium (Na), potassium (K), and aluminum (Al).

Fig. 4.11, p. 95

## Igneous Rocks Their Characteristics and Classification

### Classifying Igneous Rocks

Depending on whether magma erupts, it can produce

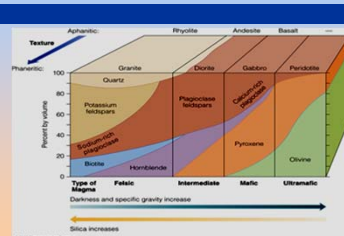
- Plutonic / Intrusive (deep-seated) or
- Volcanic / Extrusive (eruptive) rocks.

It is best to learn the different kinds of igneous rocks as *pairs* of equivalent plutonic and volcanic compositions; that is, each plutonic rock has its volcanic compositional equivalent, and visa versa.

- For example, gabbro is chemically equivalent to basalt.
- Gabbro is a plutonic rock. Basalt is a volcanic rock.

## Igneous Rocks Their Characteristics and Classification

### Composition of Igneous Rocks




After geologists identify a rock as plutonic or volcanic, the name it is given depends on the relative percentages of certain key minerals, such as quartz, orthoclase (K-Feldspar), plagioclase, olivine, and pyroxene.

Fig. 4.11, p. 95

## Igneous Rocks
## Their Characteristics and Classification

### Classifying Igneous Rocks

**Ultramafic Rocks**

- Peridotite is an ultramafic rock, meaning that it contains more iron and magnesium than basalt and gabbro which are mafic. Its composition is close to that of the upper mantle.
- Key Mineral - Olivine

Peridotite

Figure 4.12, p. 95

## Igneous Rocks
## Their Characteristics and Classification

### Classifying Igneous Rocks

- Gabbro/basalt, and granite/rhyolite are pairs of common rock types
- They represent two ends of the compositional range of most igneous rocks at Earth's surface.
  - Gabbro/basalt are mafic
  - Granite/rhyolite are felsic

Fig. 4.13, p. 96
Fig. 4.15, p. 97

## Igneous Rocks
## Their Characteristics and Classification

### Classifying Igneous Rocks

**Basalt-Gabbro** – Mafic composition

- Gabbro is chemically equivalent to basalt.
- Gabbro is a plutonic rock. Basalt is a volcanic rock.
- Key Minerals: Pyroxene and/or Ca-Plagioclase

Fig. 4.13, p. 95

## Igneous Rocks
## Their Characteristics and Classification

### Classifying Igneous Rocks

**Rhyolite-Granite** – Felsic composition

- Granite is chemically equivalent to rhyolite.
- Granite is a plutonic rock. Rhyolite is a volcanic rock.
- Key Minerals: Quartz and/or K-Feldspar and/or Na-Plagioclase

Fig. 4.15, p. 97

## Igneous Rocks
## Their Characteristics and Classification

### Classifying Igneous Rocks

**Andesite-Diorite** – Intermediate composition

- Diorite is chemically equivalent to andesite.
- Diorite is a plutonic rock. Andesite is a volcanic rock.
- Key Minerals – Amphibole, Plagioclase

Fig. 4.14, p. 96

## Igneous Rocks
## Their Characteristics and Classification

### Classifying Igneous Rocks

It is best to learn the different kinds of igneous rocks as *pairs* of equivalent plutonic and volcanic compositions

Rhyolite porphyry

Andesite porphyry

Basalt

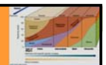
Granite

Diorite

Gabbro

Fig. 4.13, p. 96
Fig. 4.14, p. 96
Fig. 4.15, p. 97

## Igneous Rocks
## Their Characteristics and Classification



### Classifying Igneous Rocks

**Pegmatite**

- ❖Pegmatite is a rock type closely related to granite that contains many minerals not ordinarily found in other igneous rocks.
- ❖By definition, pegmatites contain crystals that measure at least 1 cm across.
- ❖Typically they form from water-rich magmas

Pegmatite

4.16, p. 98

## Igneous Rocks
## Their Characteristics and Classification

### Classifying Igneous Rocks

**Other Igneous Rocks**

Tuff

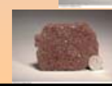
- ❖Composed of volcanic ash.

Obsidian

- ❖Composed of volcanic glass.

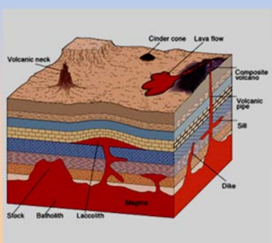
Pumice & Scoria

- ❖Composed of volcanic glass
- ❖Vesicular



## Intrusive Igneous Bodies - Plutons

- ❖Plutons are bodies of igneous rock which have been intruded in country rock or have formed in place far beneath the surface.




- ❖Concordant plutons include sills and laccoliths.
- ❖Discordant plutons include dikes, volcanic necks, batholiths and stocks.
- ❖Each of these plutons is defined by volume and geometry.

Fig. 4.19, p. 101

## Plutons

### Aerial View of a Pluton

From Earth Science Slides by Skelton

## Intrusive Igneous Bodies - Plutons

- ❖Dikes and Sills

  Dikes and sills are the most common sheet-like igneous intrusions.

- ❖Dikes are discordant features (meaning they cut across layering in the country rock)
- ❖Sills are concordant (parallel to the rock layers).

Fig. 4.20, p. 101

## Dikes and Sills

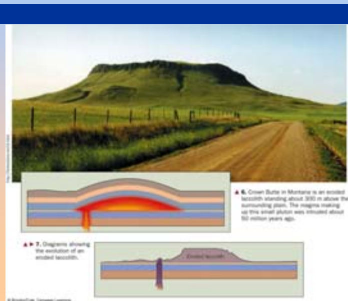
### Intersecting Dikes and Veins, California

From Earth Science Slides by Skelton

## Intrusive Igneous Bodies - Plutons

Laccoliths, Volcanic pipes and necks

- ❖Laccoliths are sill-like bodies with inflated cores.



## Intrusive Igneous Bodies - Plutons

Laccoliths, Volcanic pipes and necks

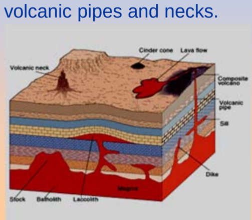
- ❖Volcanic pipes are magma-filled, cylindrical feeder channels beneath volcanoes.
- ❖ Pipes can become volcanic necks with deep erosion.

Fig. 4-21,p. 102

## Intrusive Igneous Bodies - Plutons

Laccoliths,
Volcanic pipes and necks

Dikes, sills, and laccoliths radiate from many volcanic pipes and necks.



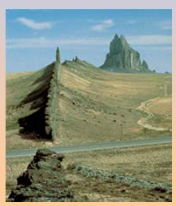



Fig. 4-21, p. 102

## Intrusive Igneous Bodies - Plutons

Batholiths and Stocks

- ❖Batholiths are plutons that have more than 100 km² in area of exposure.
- ❖Stocks are somewhat smaller plutonic bodies.

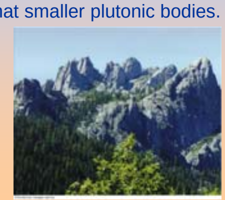


Fig. 4-22, p. 103

## Western Batholiths

Large Intrusive Complexes formed by multiple injections of magma.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