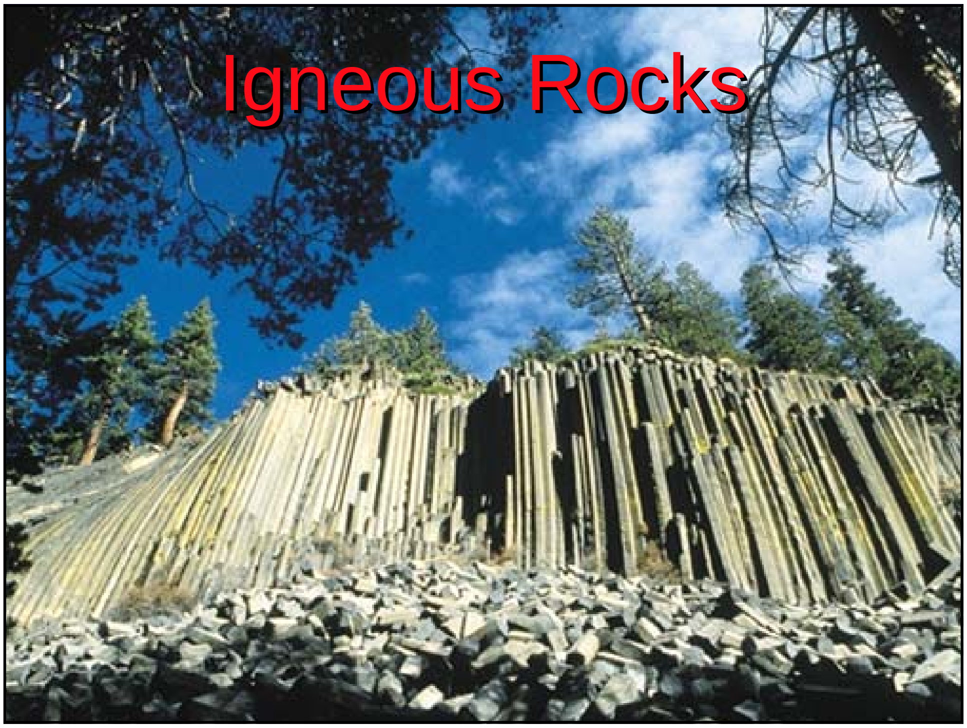
Igneous Rocks



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

- 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_2O, 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:

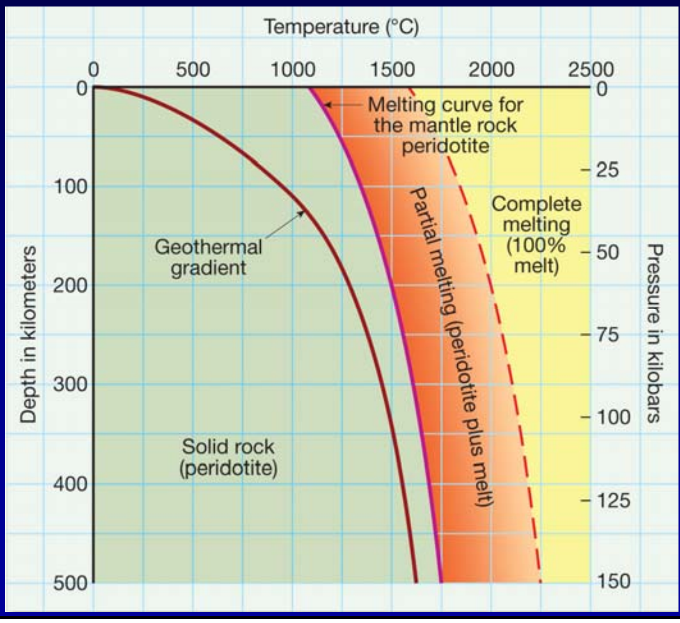
H_2O, CO_2, Cl, F, S

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

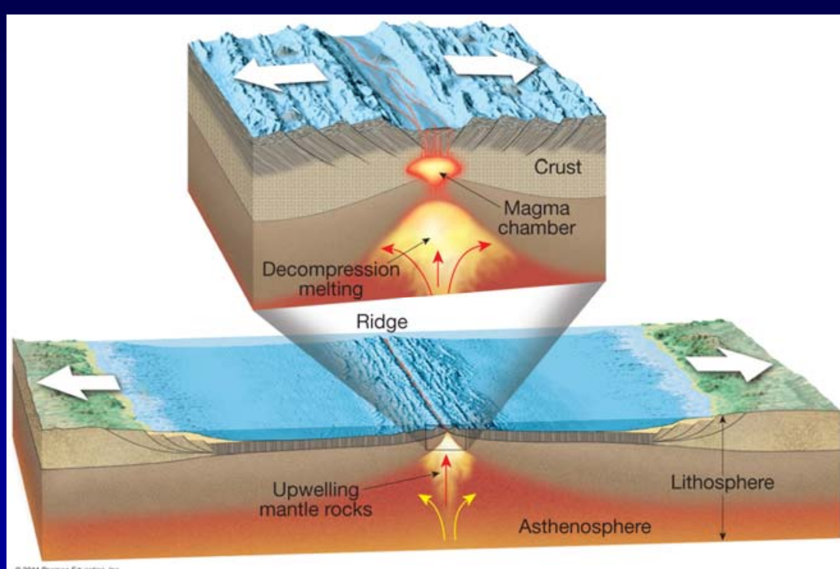
A Typical Geothermal Gradient

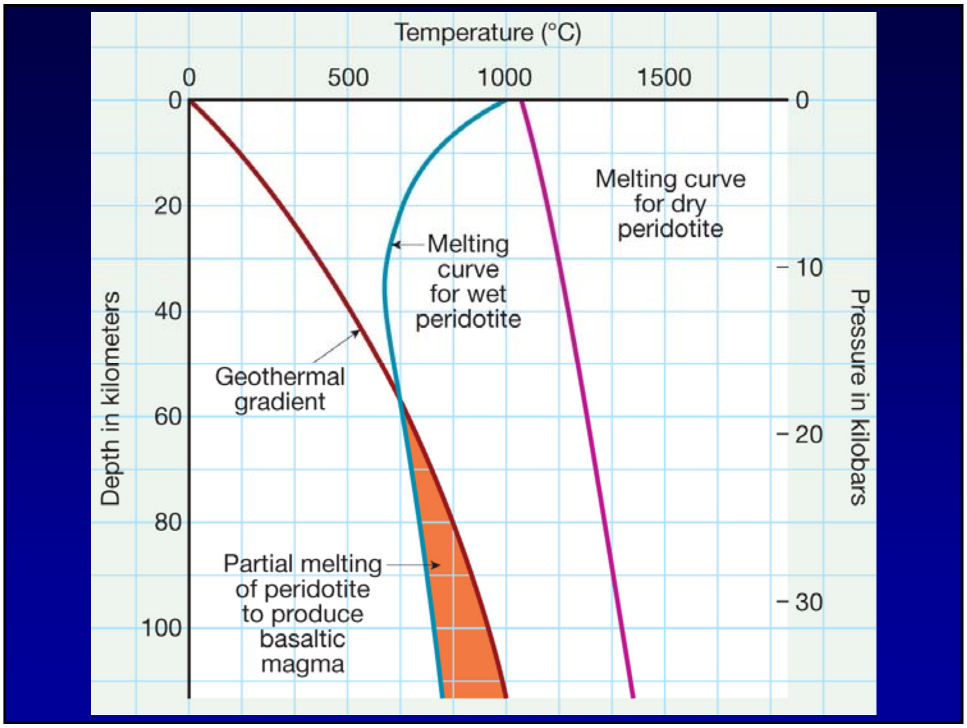


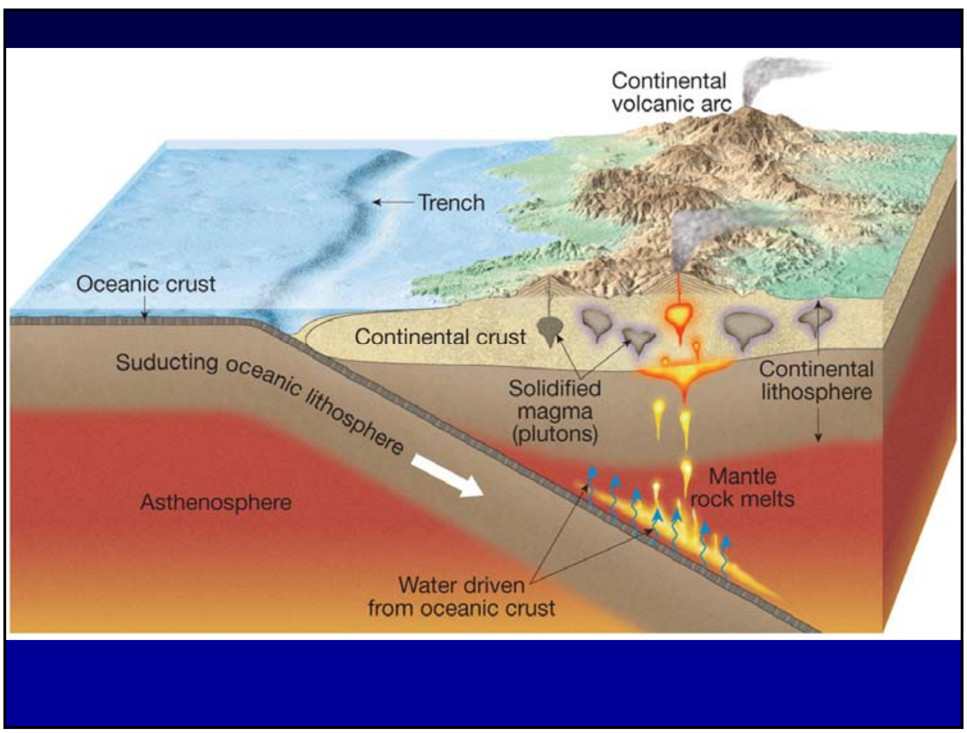
Origin of Magma

- 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




Temperature (°C)
0
500
1000
1500
0
20
40
60
80
100
0
10
20
30
Depth in kilometers
Pressure in kilobars
Melting curve for dry peridotite
Melting curve for wet peridotite
Geothermal gradient
Partial melting of peridotite to produce basaltic magma


Continental volcanic arc
Trench
Oceanic crust
Continental crust
Suducting oceanic lithosphere
Solidified magma (plutons)
Continental lithosphere
Mantle rock melts
Asthenosphere
Water driven from oceanic crust

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

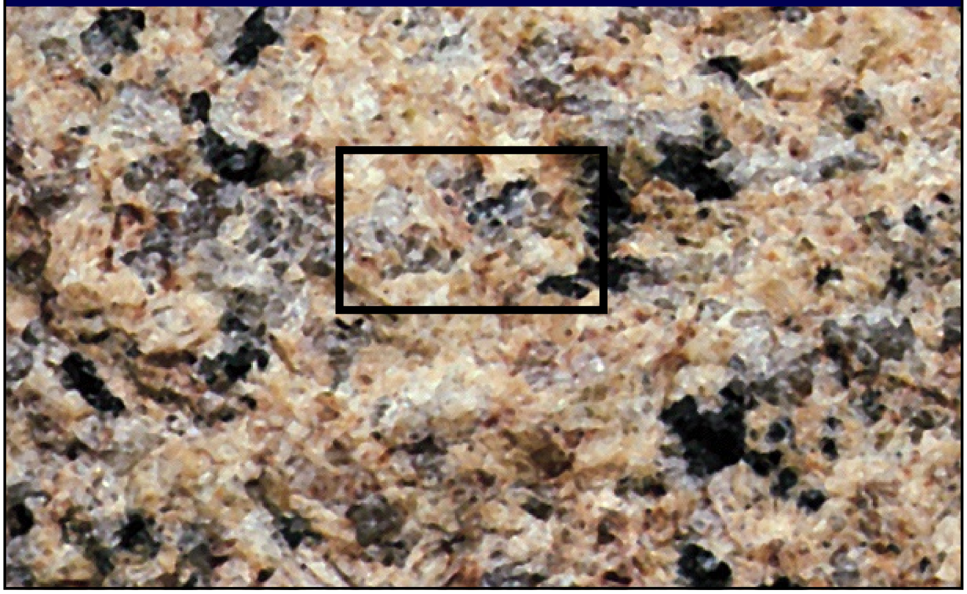
Classification of Igneous Rocks

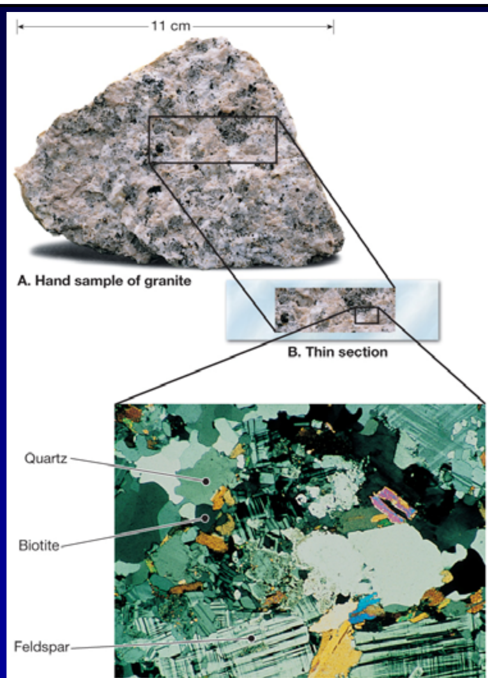
Based on Mineral Composition and Texture

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



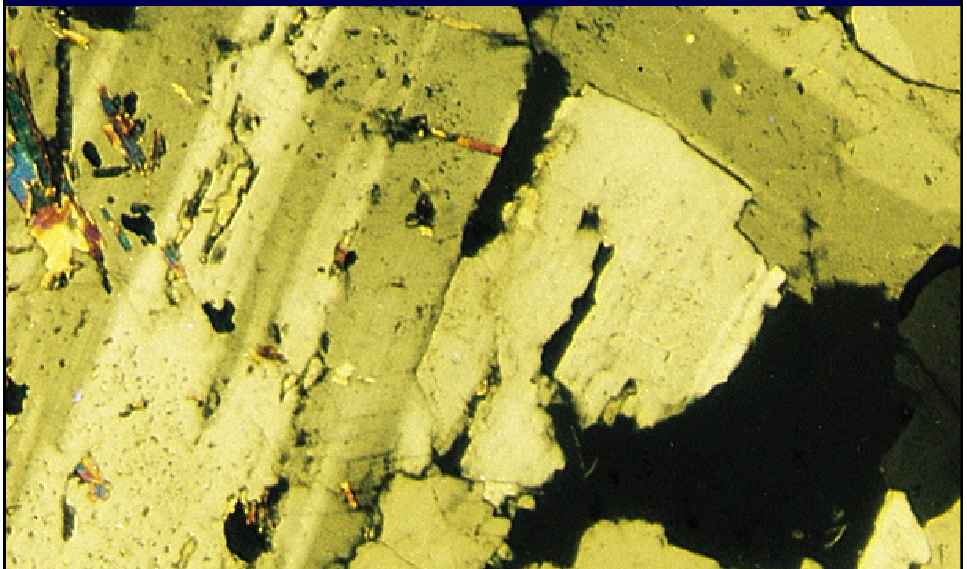


A. Hand sample of granite

B. Thin section

C. Photomicrograph taken with polarized light magnified about 27 times.

Photomicrograph of Granite



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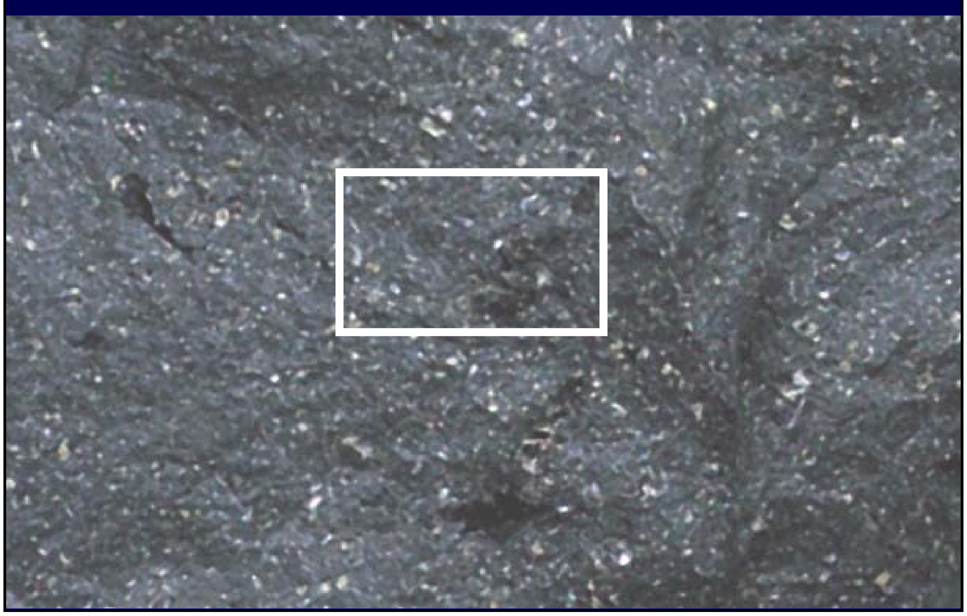
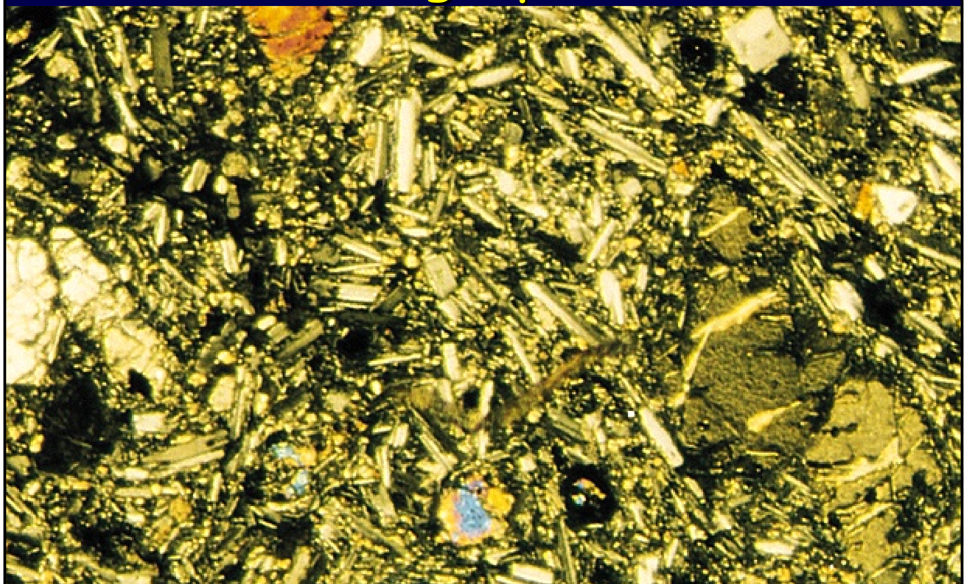
Finely Crystalline Basalt



Photomicrograph of Basalt



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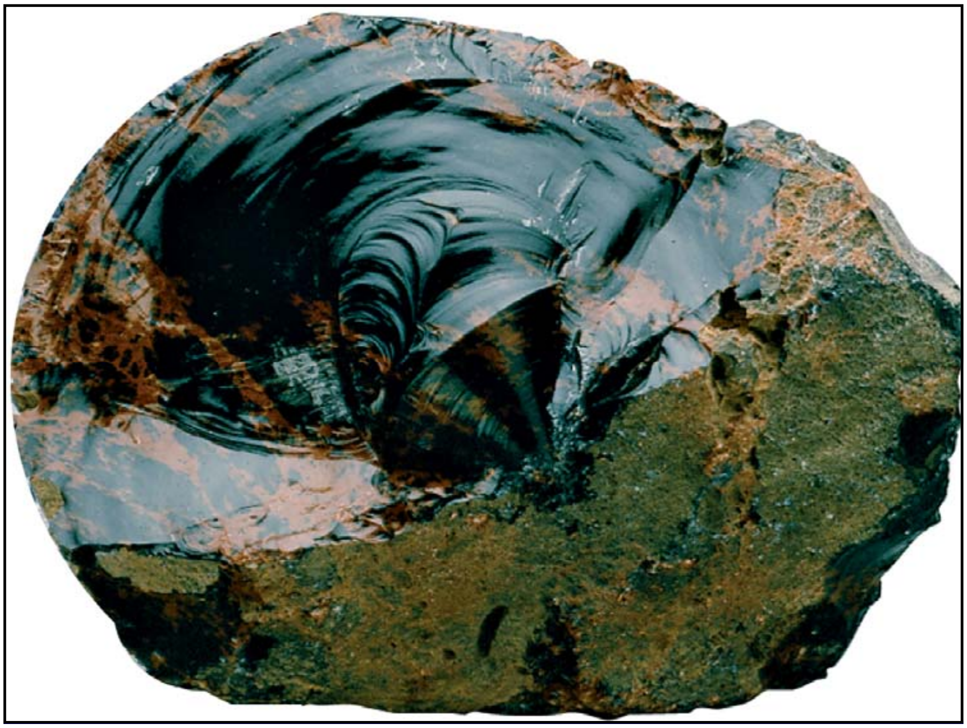


Igneous textures

Glassy – no minerals present

Crystalline – rocks made of mineral grains

Porphyritic - mixture of coarse and fine

Vesicular - with bubble holes

Pyroclastic Igneous Rocks

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

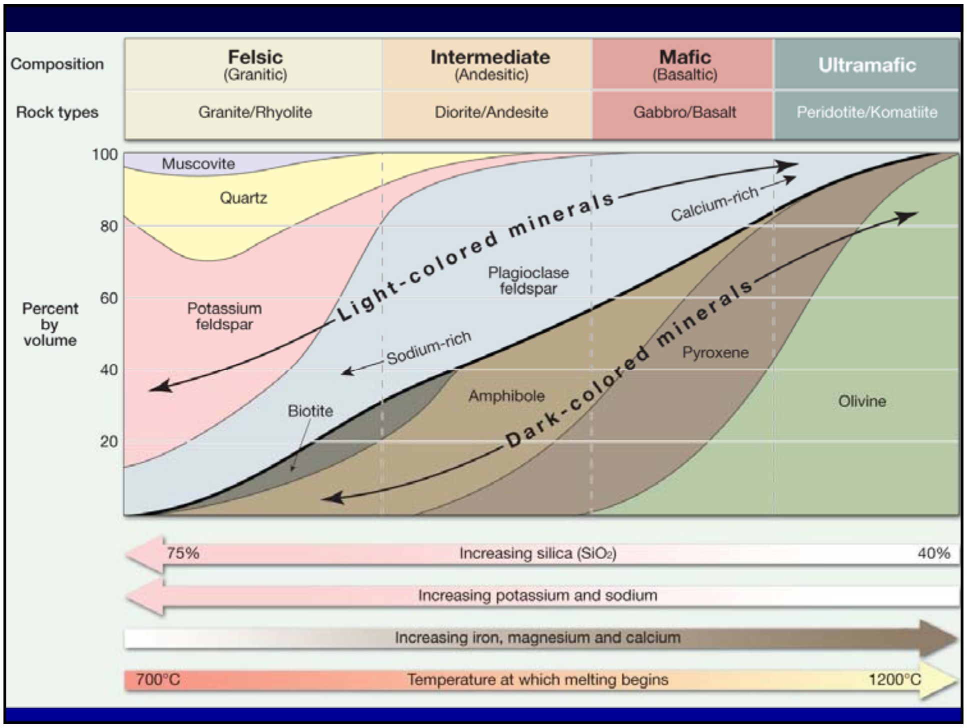
- Ultramafic (low silica content < 40%; Mg- and Fe-rich)
  - Peridotite
- Mafic (low 45- 55%; Mg- and Fe-rich)
  - Gabbro (plutonic)
  - Basalt (volcanic)
- Intermediate (55 - 65%; also rich in feldspar)
  - Diorite (plutonic)

Igneous Compositions

- Granitic versus basaltic compositions
  - Granitic composition
    - Light-colored silicates
- Termed felsic (feldspar and silica) in composition
    - High silica (SiO_2) content
    - Major constituent of continental crust

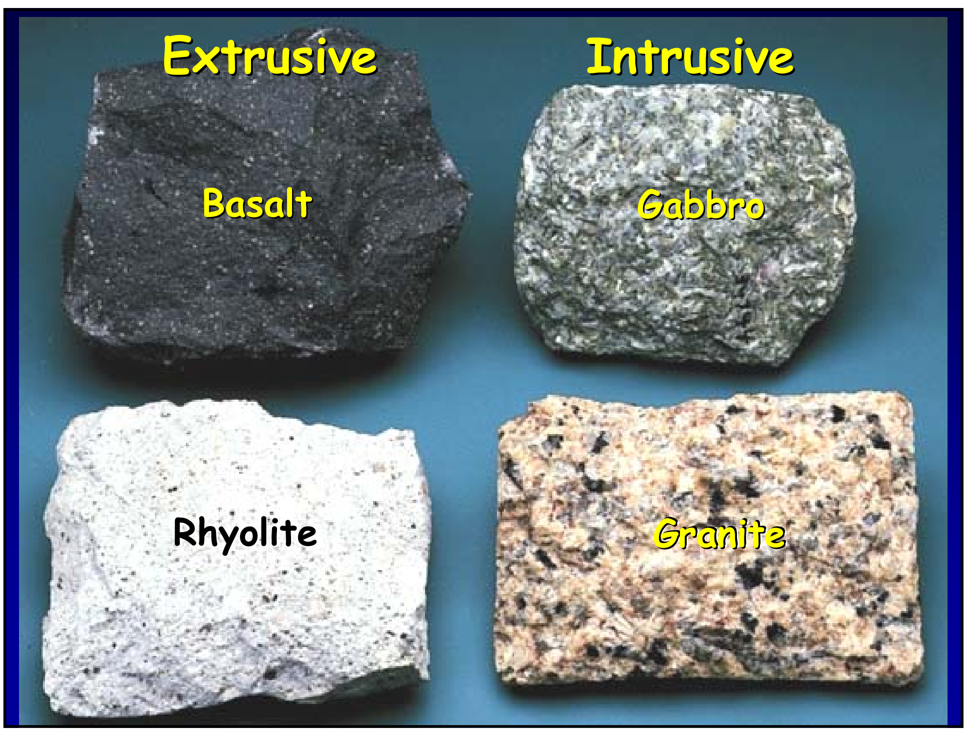
Igneous Compositions

- 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	*Intrusive*
basalt	gabbro
andesite	diorite
rhyolite	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.*,

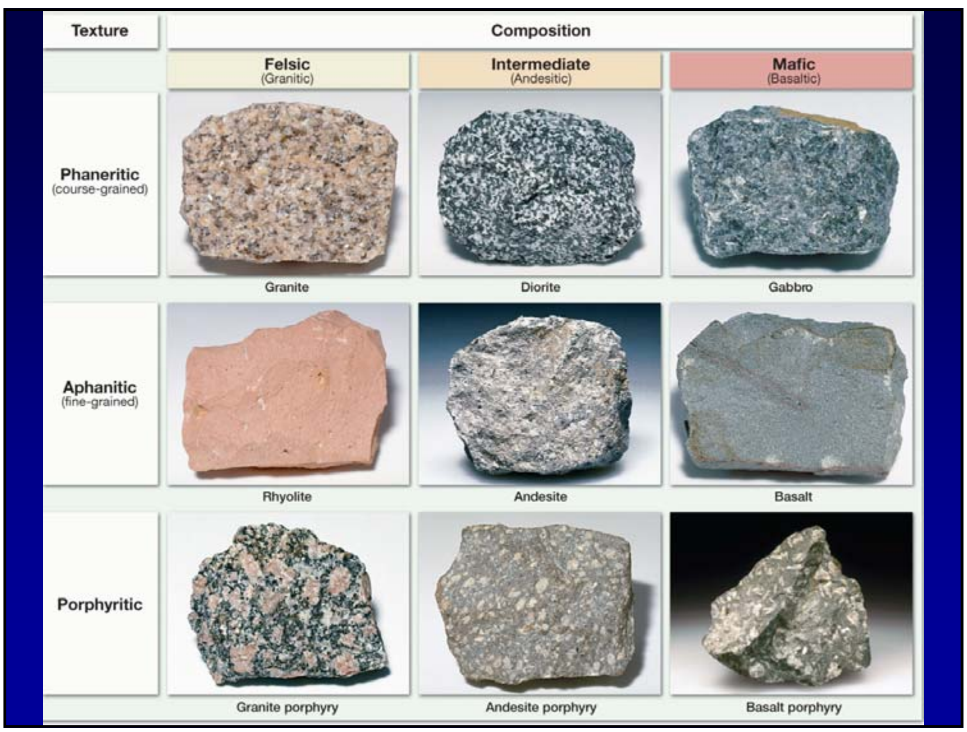
	Typical basalt	*Typical granite*
SiO_2	50%	70%
Al_2O_3	15%	12%
FeO+MgO	15%	3%
CaO	8%	2%
K_2O+Na_2O	5%	8%

Composition of melts affects behavior while still fluid

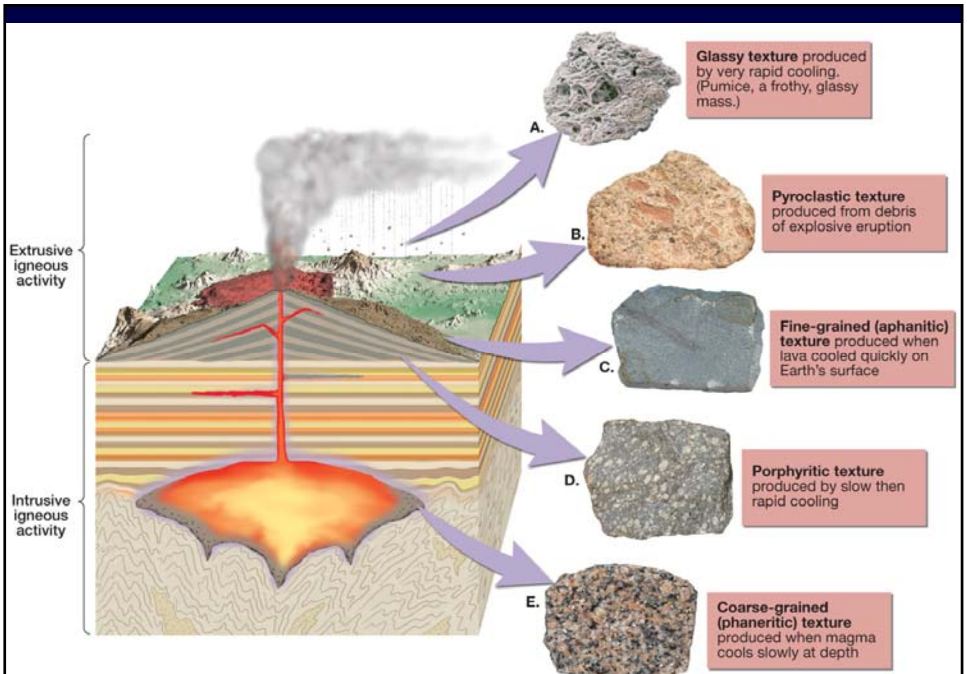
- More SiO_2 will increase viscosity,
  - making strong temporary bonds in magma

Factors controlling the viscosity of magmas

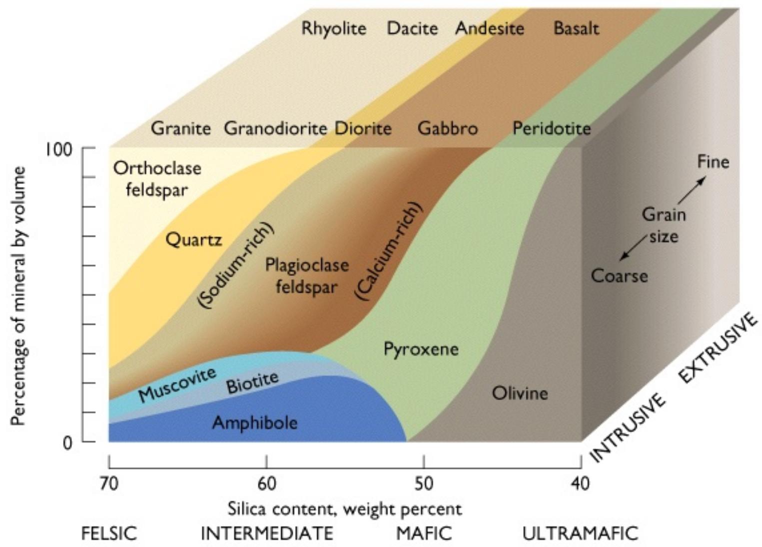
- Composition:
  - higher SiO_2; higher viscosity
    lower volatiles; higher viscosity
- Temperature:
  - lower temperature; higher viscosity



Chemical Composition	Felsic (Granitic)	Intermediate (Andesitic)	Mafic (Basaltic)	Ultramafic
Dominant Minerals	Quartz Potassium feldspar Sodium-rich plagioclase feldspar	Amphibole Sodium- and calcium-rich plagioclase feldspar	Pyroxene Calcium-rich plagioclase feldspar	Olivine Pyroxene
Accessory Minerals	Amphibole Muscovite Biotite	Pyroxene Biotite	Amphibole Olivine	Calcium-rich plagioclase feldspar
TEXTURE: Phaneritic (coarse-grained)	**Granite**	**Diorite**	**Gabbro**	**Peridotite**
TEXTURE: Aphanitic (fine-grained)	**Rhyolite**	**Andesite**	**Basalt**	**Komatiite** (rare)
TEXTURE: Porphyritic	"Porphyritic" precedes any of the above names whenever there are appreciable phenocrysts			Uncommon
TEXTURE: Glassy	**Obsidian** (compact glass) **Pumice** (frothy glass)			
TEXTURE: Pyroclastic (fragmental)	**Tuff** (fragments less than 2 mm) **Volcanic Breccia** (fragments greater than 2 mm)			
Rock Color (based on % of dark minerals)	0% to 25%	25% to 45%	45% to 85%	85% to 100%



Classification of Igneous Rocks



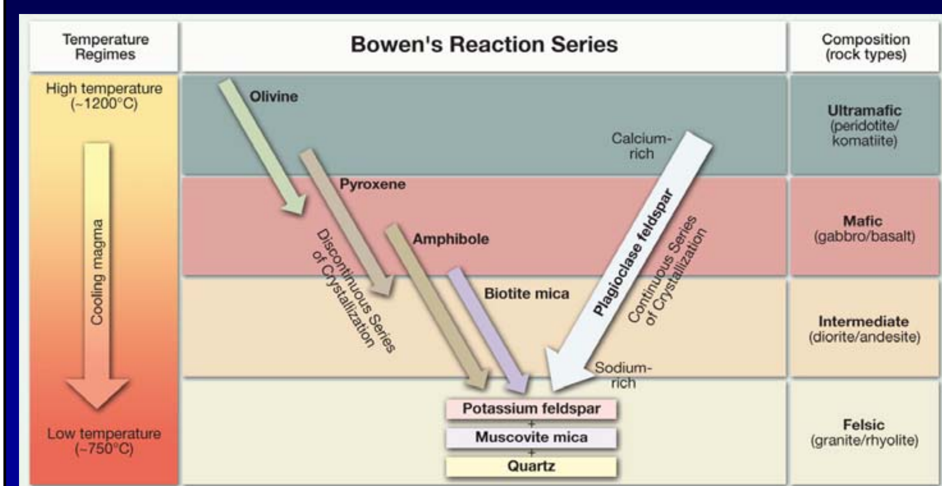
Evolution of Magmas

- 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

Bowen's Reaction Series



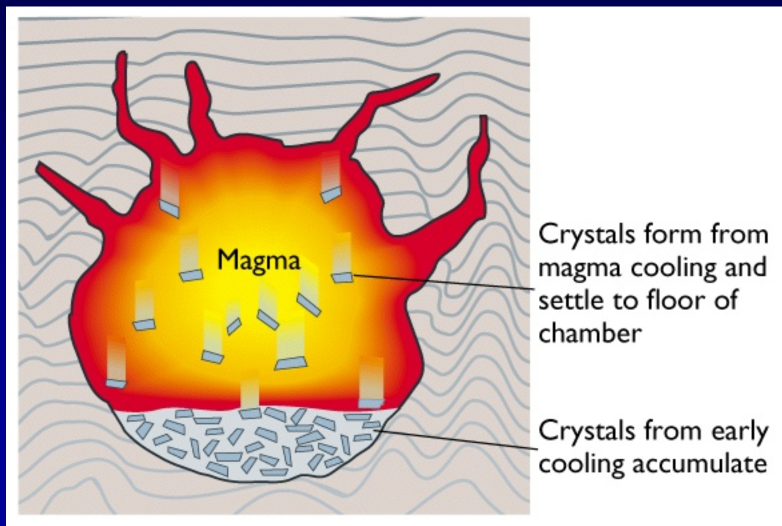
Evolution of Magmas

- 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

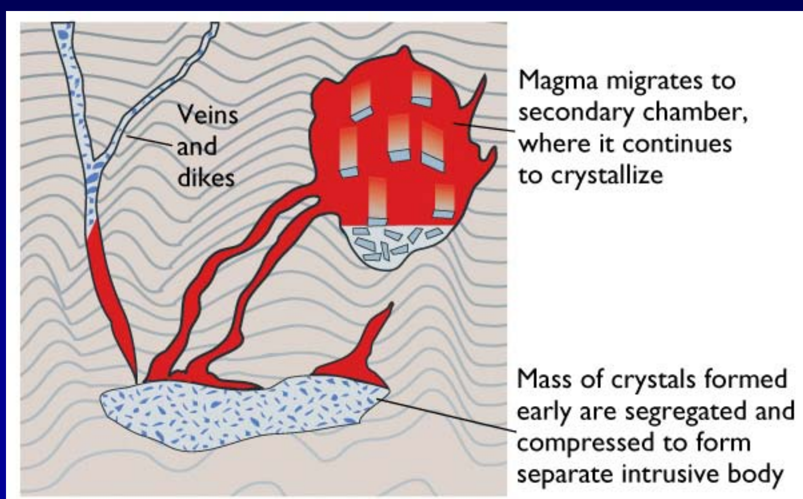
Evolution of Magmas

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

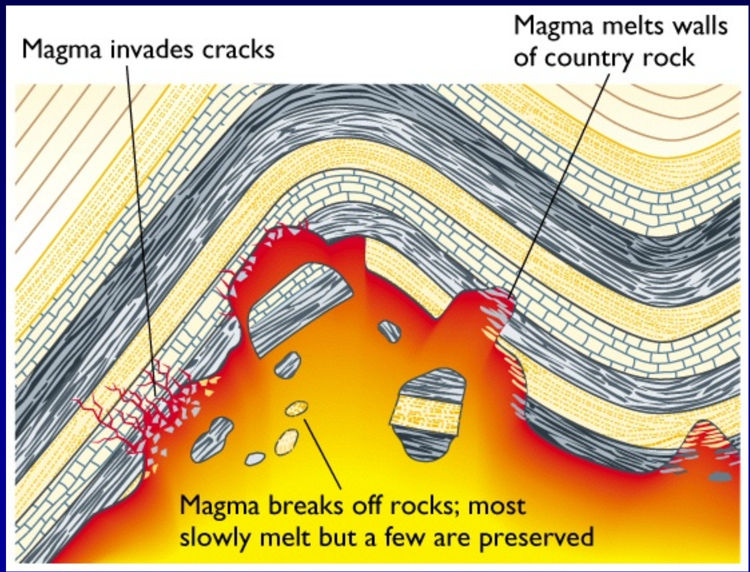
Early Crystallization



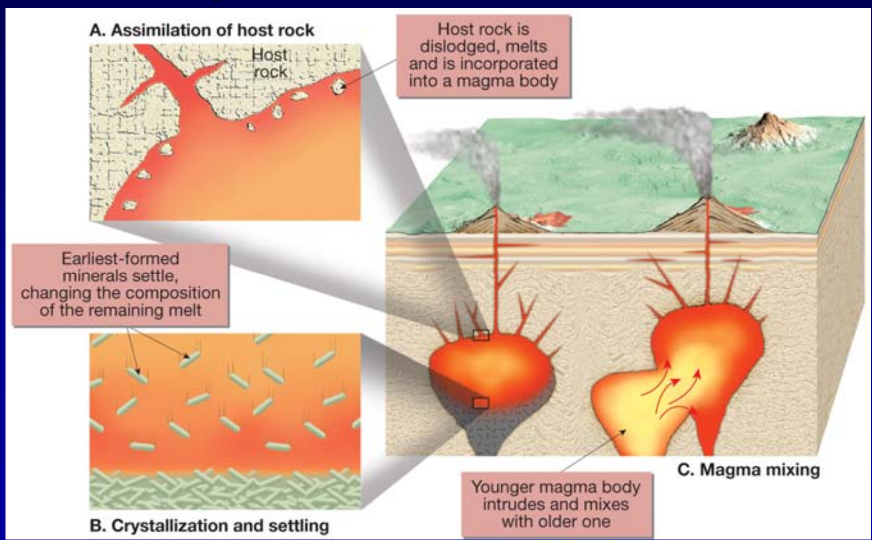
Liquids Squeezed from Crystals



Methods of Intruding Magma



Assimilation, Magma Mixing, and Magmatic Differentiation



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

Evolution of Magmas

- 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

Intrusive Igneous Activity

- Emplacement of magma
  - 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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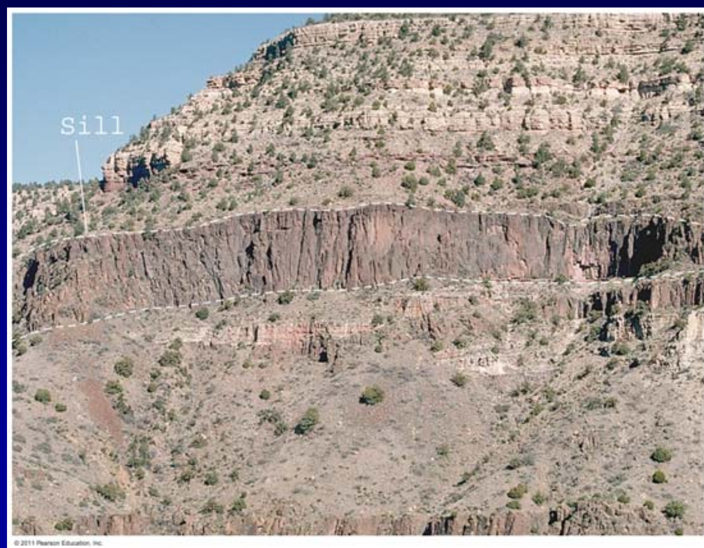
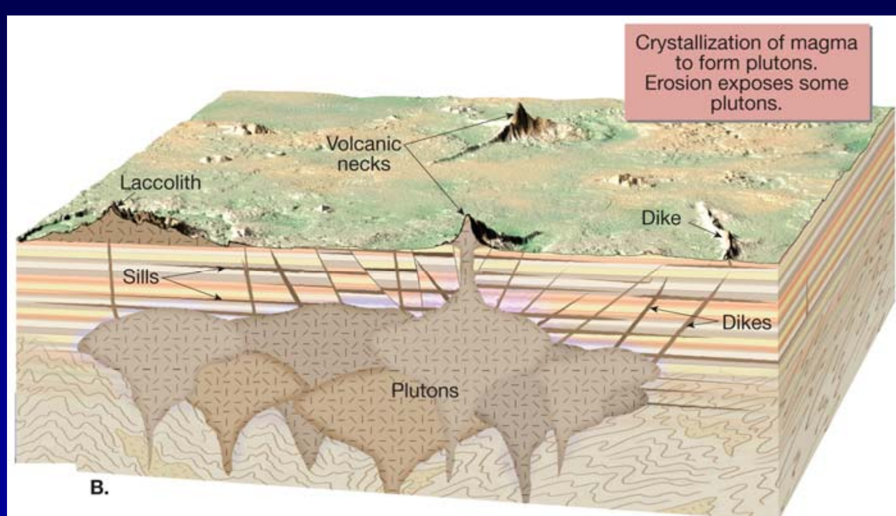
The Palisades Sill

A Sill in the Salt River Canyon, Arizona



Some Intrusive Igneous Structures

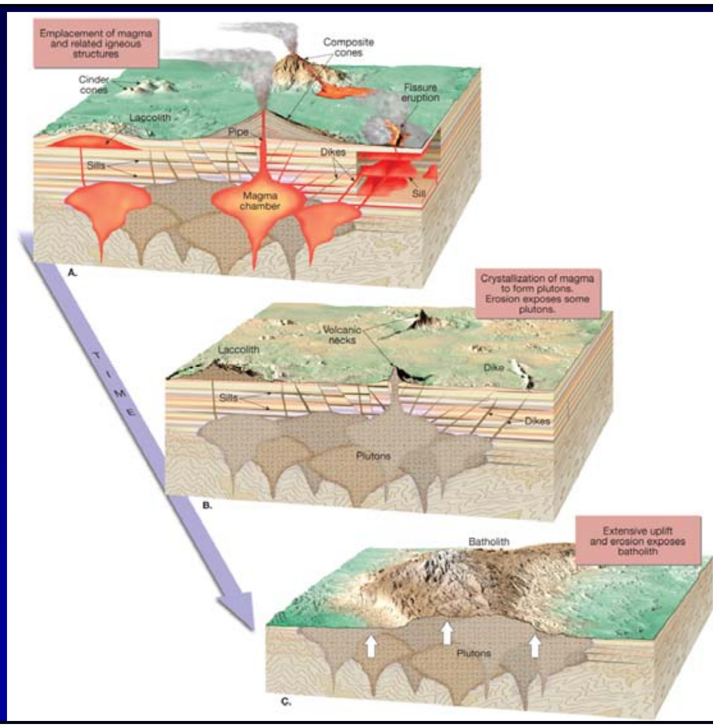


Intrusive Igneous Activity

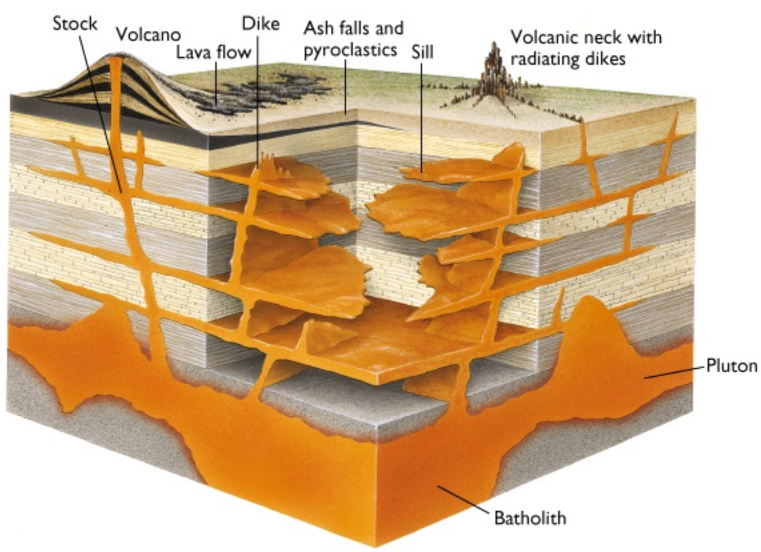
- Intrusive igneous features
  - Batholith
    - Largest intrusive body
    - Surface exposure of 100+ square kilometers (smaller bodies are termed stocks)
    - Frequently form the cores of mountains

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

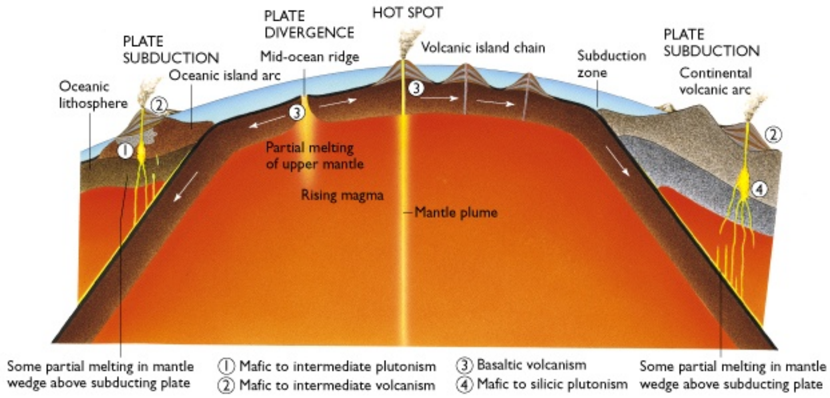
Plate Tectonic & Igneous Rocks

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

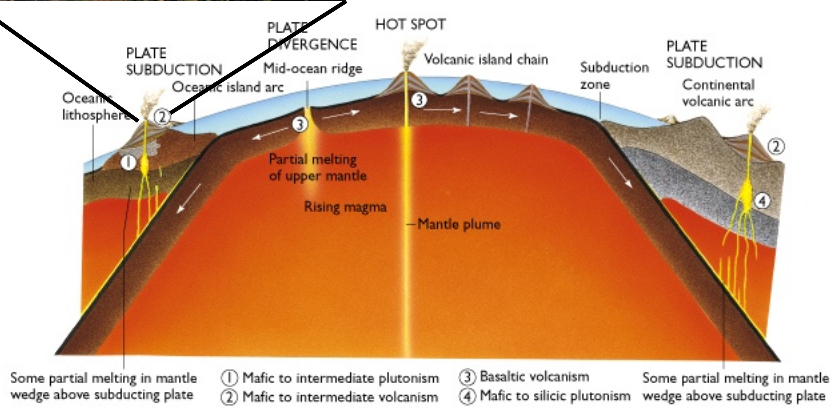
- Basalt/Gabbros
  - most abundant igneous rocks in oceanic crust
    - divergent plate boundary
- Andesite/Diorite
  - found in subduction zones
- Rhyolites/Granite
  - most abundant in continental crust
    - subduction zone

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

Tectonic Settings of Igneous Activity

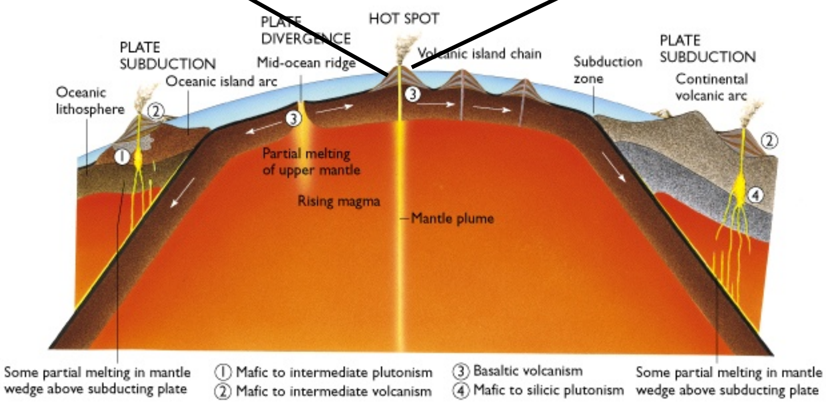


Volcanic Island Arc, Indonesia



Oceanic Hot Spot

Hawaii



Continental Volcanic Arc N. Cascades

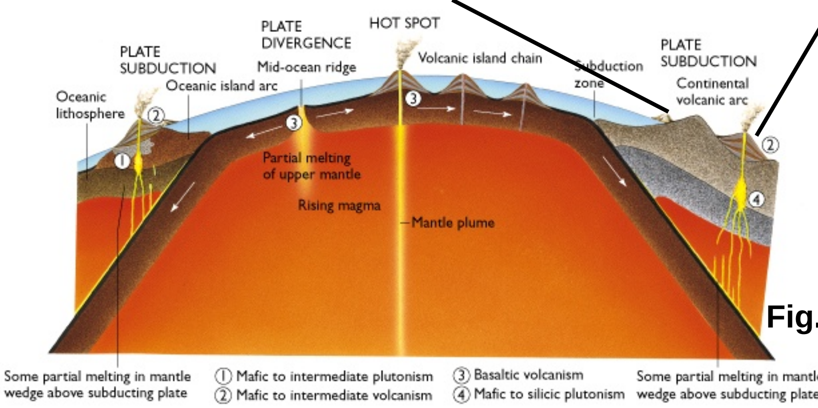


Fig. 4.8