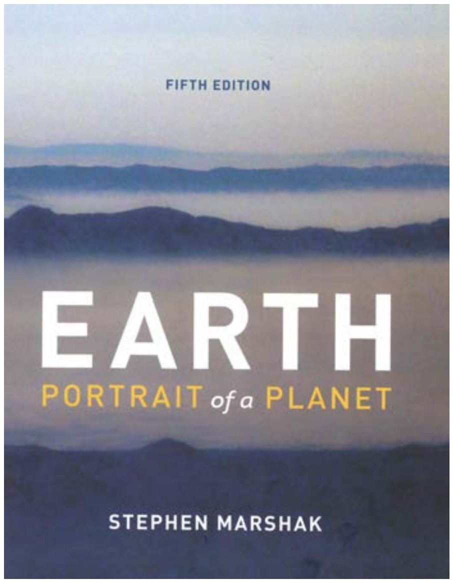
CE/SC 10110-20110

Up from the Inferno: Magma & Igneous Rocks



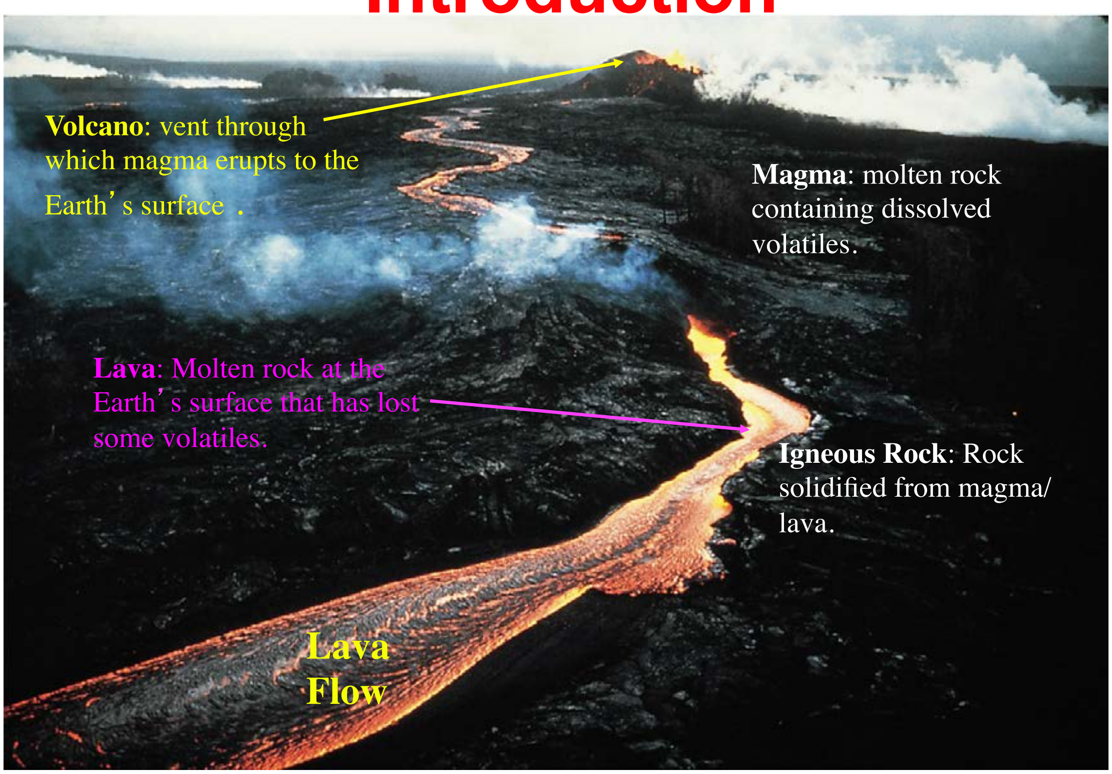
Earth

Portrait of a Planet

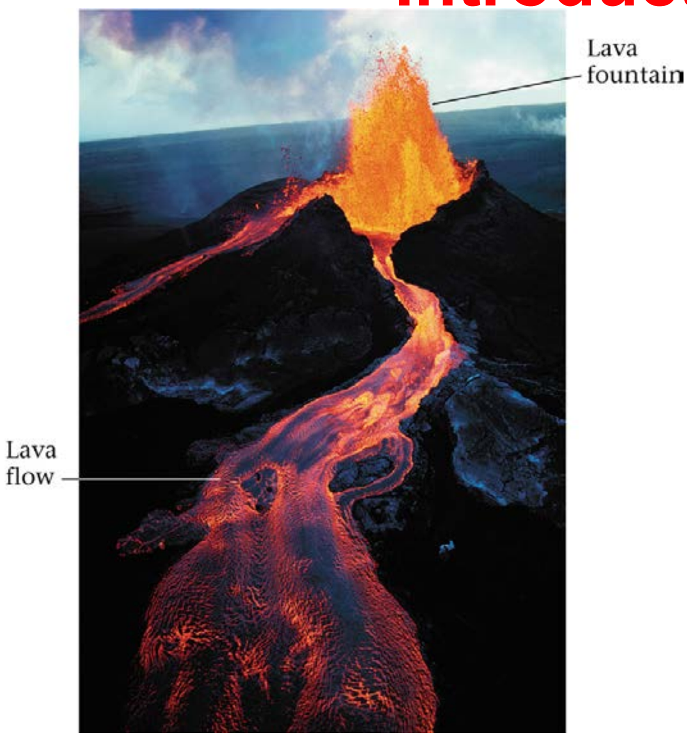
Fifth Edition

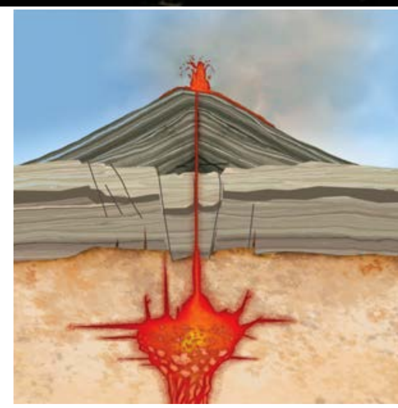
Chapter 6

Introduction



Introduction





Lava.mov

Introduction

Heat Sources:

Accretion Energy: kinetic energy --> heat on impact during Earth's formation.

Gravity: As Earth grew, gravity increased and squeezed the planet together - heated it up.

Core Formation: heavy iron sank to the center to form the core - potential energy was converted to heat.

Radioactive Decay: Generates heat and if insulated by rock, temperature increases.

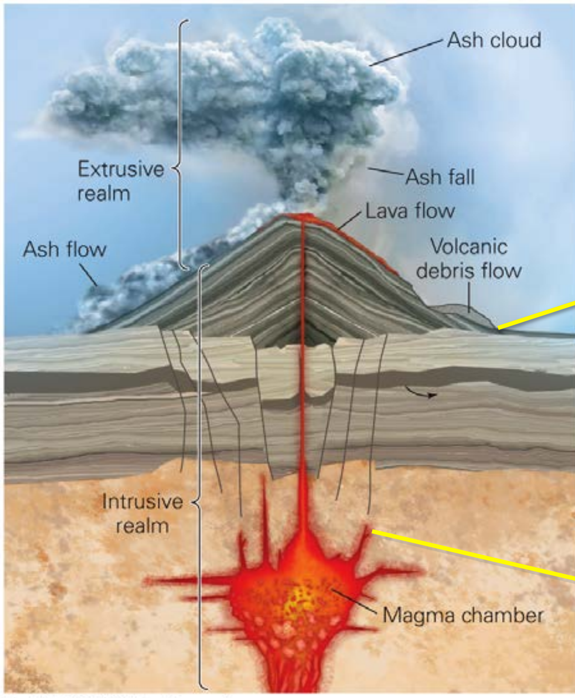
Gravitational Pull: of the Moon and Sun (mainly).

Igneous rocks broadly divided into two types:

1. Extrusive: erupted onto the Earth's surface (above ground);

2. Intrusive: magma cools within the Earth (belowground).

Introduction



Extrusive igneous rocks cool at the surface.

Intrusive igneous rocks cool underground.

Introduction

"Basalt" flows easily; two main types of basalt flow -

Aa_lava.mov

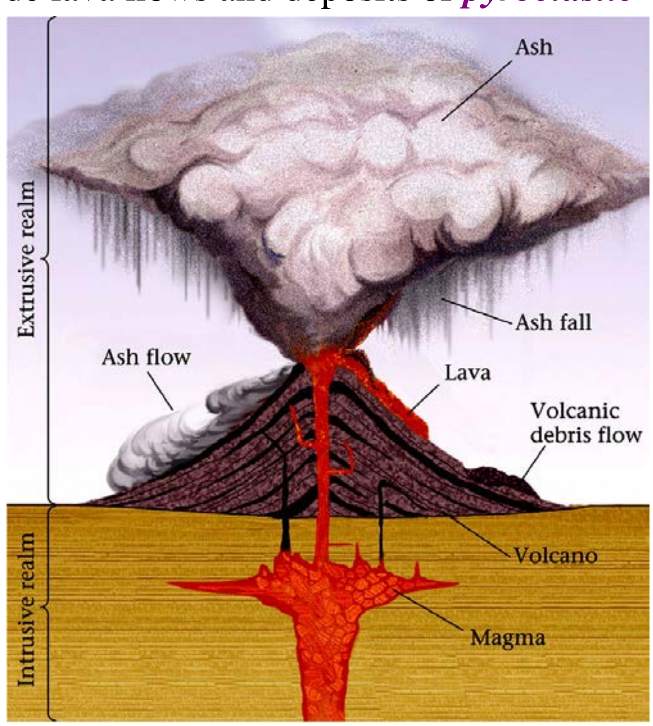
aa.mov

pahoehoe.mov

Introduction

Extrusive igneous rocks include lava flows and deposits of ***pyroclastic debris***.

Chunks of lava freeze and hit the ground.
Fine spray of lava freezes to form ***ash***.
This can billow upward and drift down as ***ash fall***.
Also it can flow down the side of the volcano as an ***ash flow*** (***nueé ardente***).
Pyroclastic debris can be remobilized into a ***volcaniclastic debris flow***.
If ash, it can become a mud flow or ***lahar***.



St. Pierre, Martinique. Mt. Peleé.

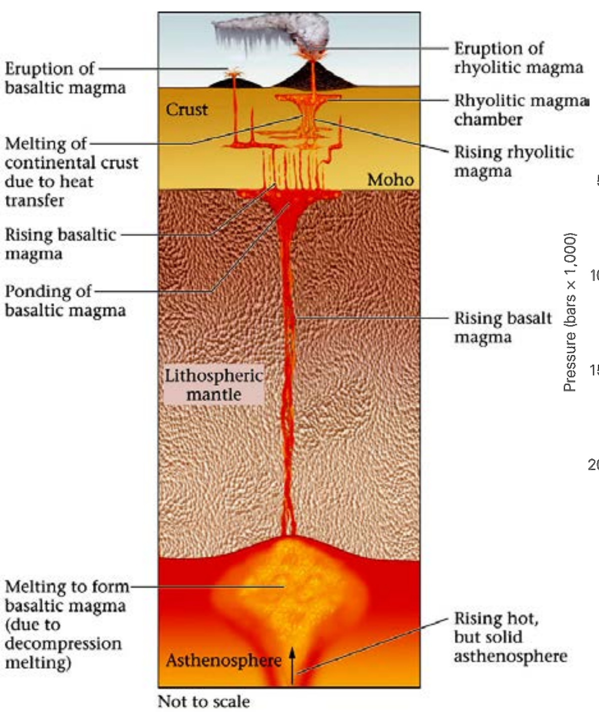
May 8th, 1902: Nueé Ardente (glowing cloud) erupted.

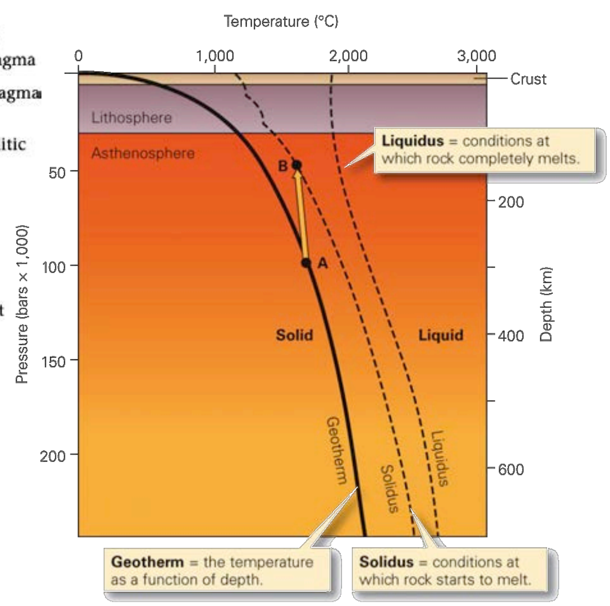
Temperature ~700 ˚C and the cloud was comprised of ash and pyroclastics (volcanic rocks fragmented by explosion) on a cushion of air.

St. Pierre was incinerated, 28,000 people killed, 2 survivors.

Formation of Magma

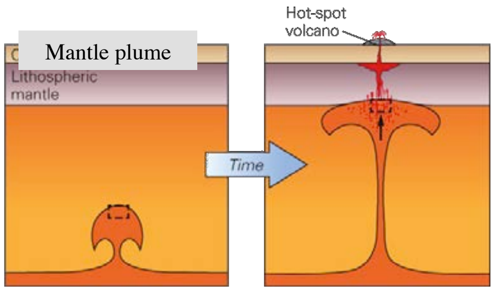
Decompression melting: P decreases, T remains constant.



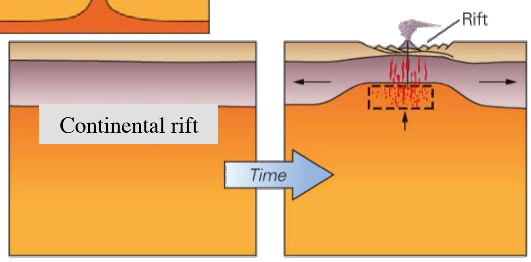


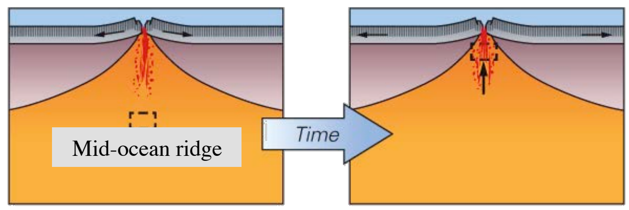
Formation of Magma

Decompression melting: P decreases, T remains constant.



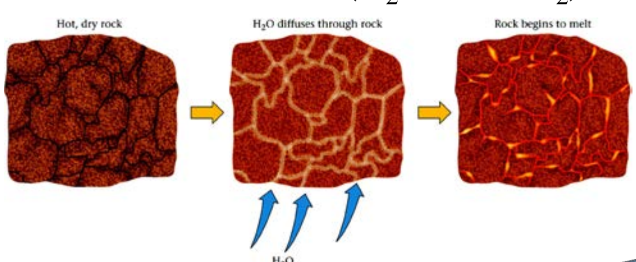
Geologic environments where decompression melting occurs



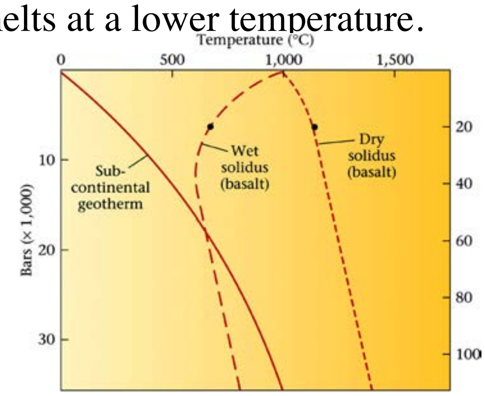


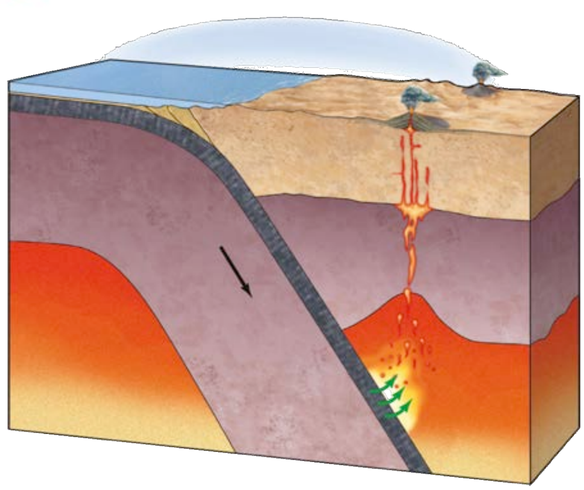
Formation of Magma

Addition of volatiles (H_2O and CO_2) – flux melting.



Help break bonds so the material melts at a lower temperature.

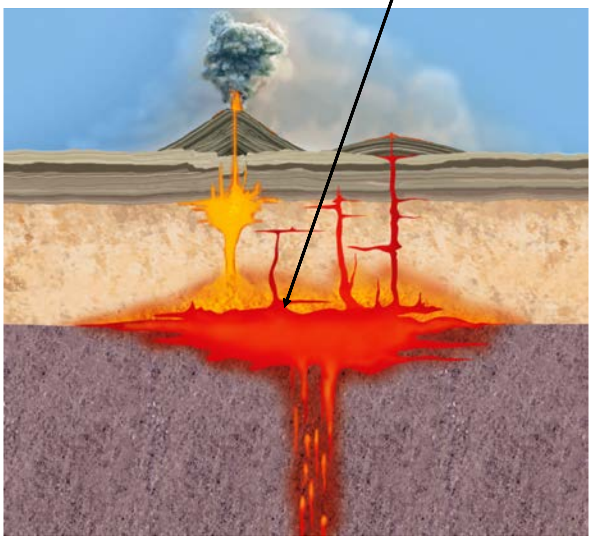


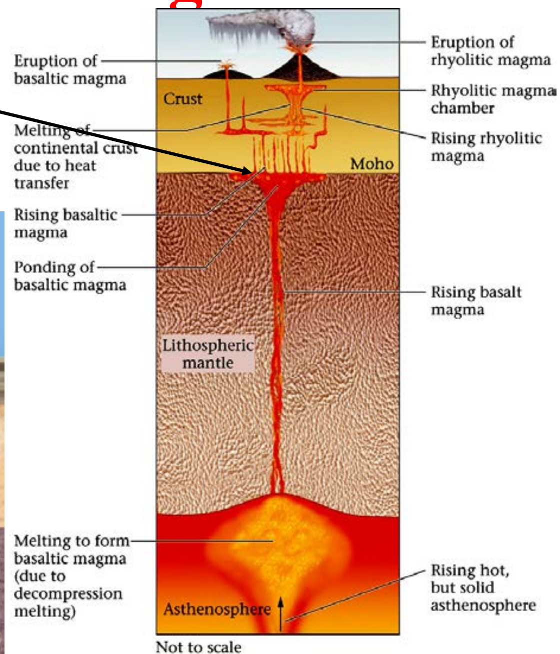


Formation of Magma

Heat transfer.

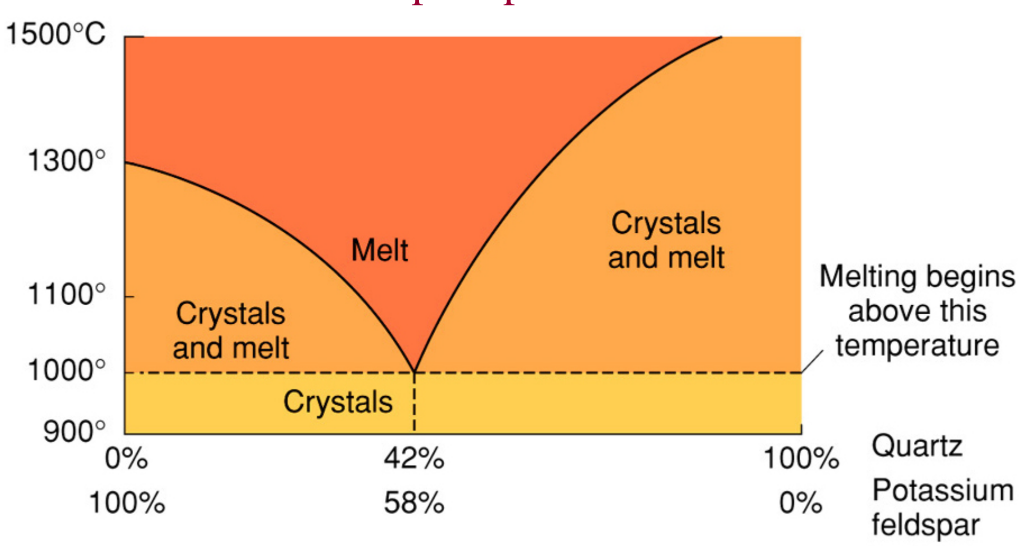
Sometimes called “heat transfer melting”, or more commonly “assimilation”.





Formation of Magma

Mixtures of Minerals can have a melting point that is lower than those of the pure phases.



What is Magma Made of?

Primarily Si and O.
Also Al, Ca, Ti, Mg, Fe, Na, and K.
Dry magmas = no volatiles (<1%).
Wet magmas = ≤15% volatiles (N_2, H_2, SO_2, **H_2O, CO_2,** etc.).

Different amounts of elements = different magma types.
Compositions reported as "weight % oxide":
SiO_2, Al_2O_3, MgO, etc.
Chemicals present can dictate minerals that form. Main magma types reflect the proportion of silica (SiO_2).

What is Magma Made of?

Felsic Magma: 66-76% SiO_2. feldspar and quartz. Sometimes called "silicic";
Intermediate Magma: 52-66% SiO_2.
Mafic Magma: 45-52% SiO_2 - "ma" = magnesian, "fic" = iron (*ferric*).
Ultramafic Magma: 38-45% SiO_2.
% = weight % - the proportion of the magma's weight that consists of silica
Magma = clusters of short Si-O chains that move around.
More SiO_2: longer the chains and the greater the viscosity.
lower melting temperature (650-800˚C = felsic; ≤1,300˚C = ultramafic.
Greater viscosity = more SiO_2 and lower temperature.

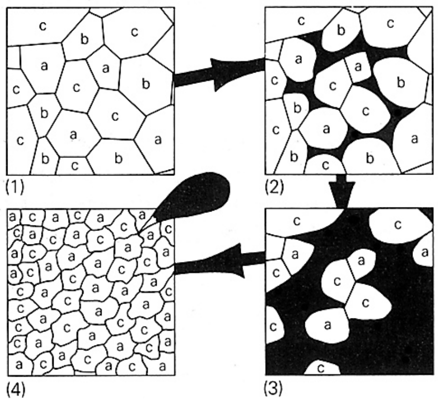
What Controls Magma Composition?

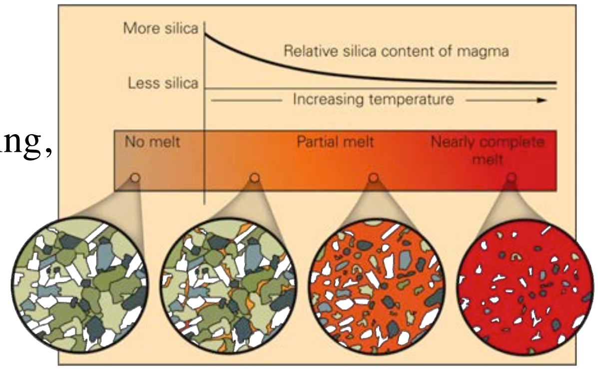
Source Rock Composition

Generally, the composition of the melt reflects the source from which it came.

Partial Melting

Higher the degree of partial melting, the more the melt resembles the source rock composition.





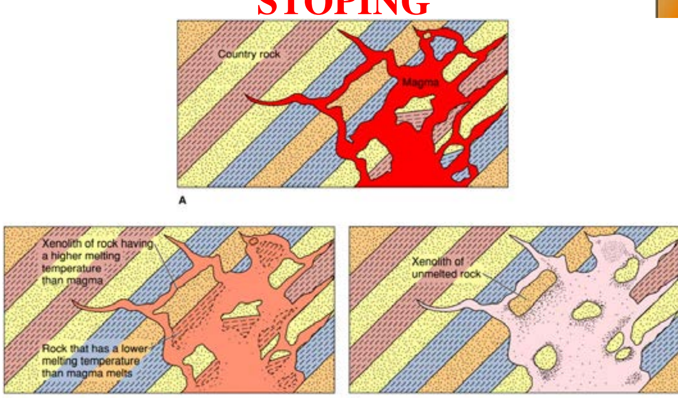
Generally, the melt is more silicic than the source: Basalt (***mafic***) is a partial melt of Mantle Peridotite (***ultramafic***).

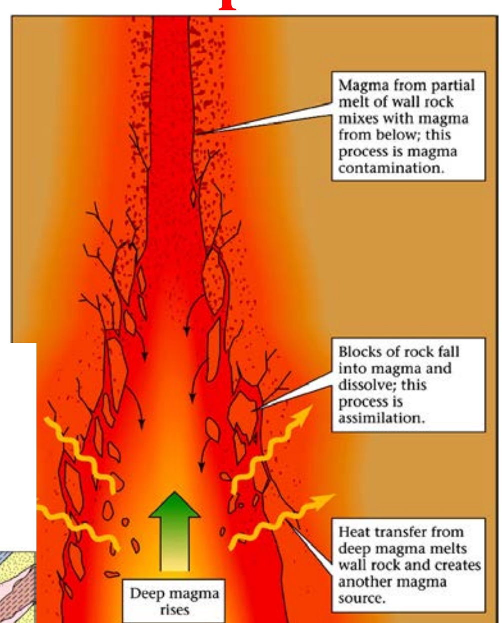
What Controls Magma Composition?

Assimilation

This commonly occurs after a magma has formed and migrated.
May selectively melt out minerals of lower melting point or if the temperature differential is high, total melt the wallrock of a magma chamber or conduit.

STOPING





NORMAN BOWEN (1887-1956)

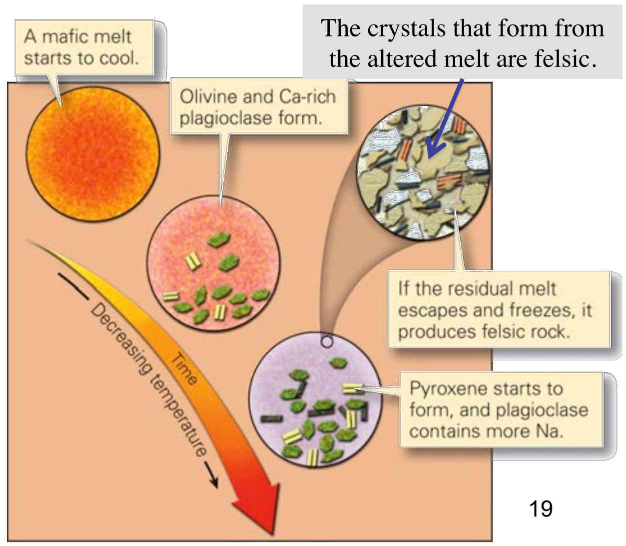
Studied crystallization of a mafic magma in the lab – The Father of Experimental Petrology.

He proposed that a granitic composition magma can be derived from a basaltic magma by ***fractional crystallization***.

Fractional Crystallization:
Crystals are isolated from magma they formed from, so the magma composition evolves (crystal settling).

Bowen: evolving magma becomes more felsic (but less volume).

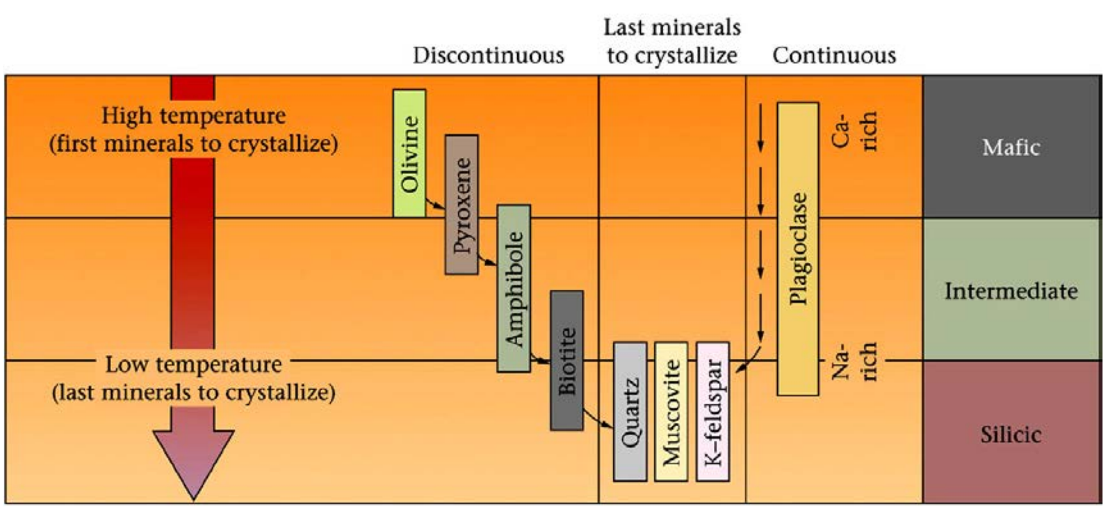
Difficult to go to completion and cannot account for the abundance of granite.



Bowens Reaction Series

Discontinuous Series – mineral phase changes. Silica polymerization is progressive down the series olivine to biotite = increase in Si from single tetrahedra, to chains to double chains to sheets.

Continuous Series – *solid solution* series (mineral phase continuously changes composition – plagioclase starts off Ca-rich and ends up Na-rich).



Bowens Reaction Series

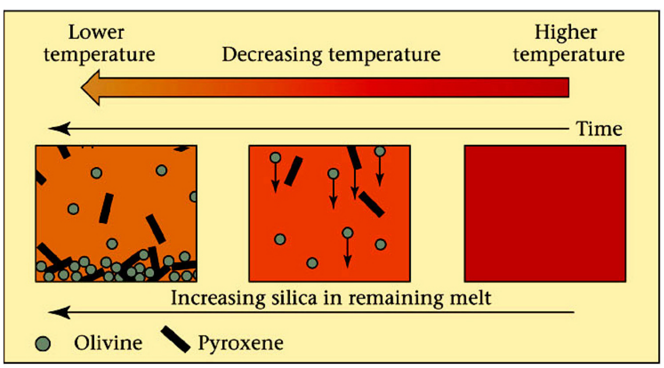
How far Bowen's Reaction Series proceeds depends upon the **initial** magma composition:

Very Mafic – stops at the top (olivine, pyroxene, Ca-plagioclase). ***Generally*** Dark Color.

Intermediate – stops lower down (pyroxene, amphibole, Ca,Na-plagioclase ± biotite). **Intermediate Color.**

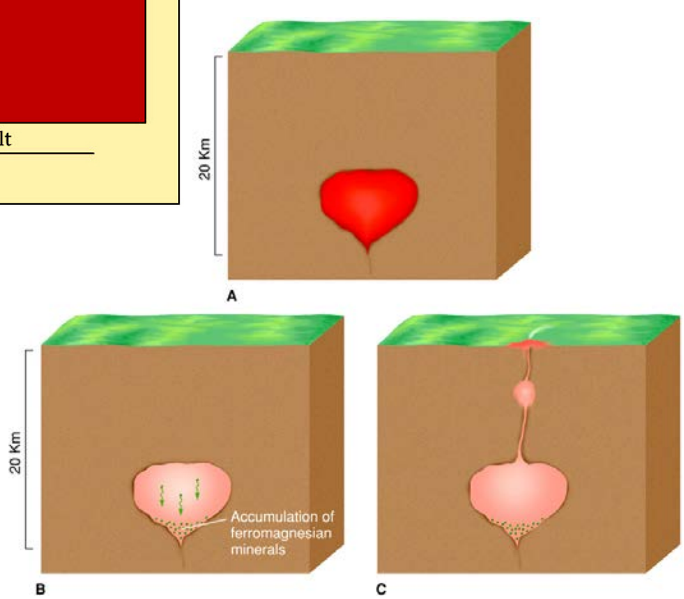
Felsic – biotite, K-feldspar, Na-plagioclase, muscovite, quartz. Light Color.

Changing a Magma Composition



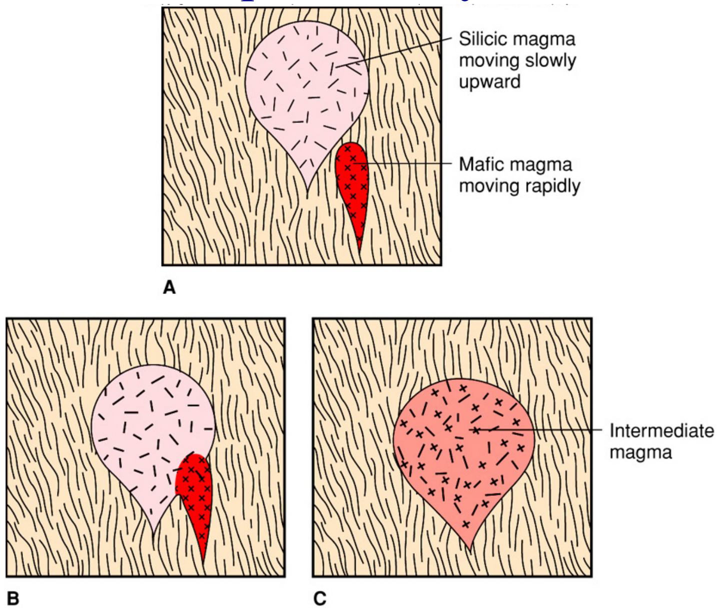
Via crystal settling.

Fractional crystallization



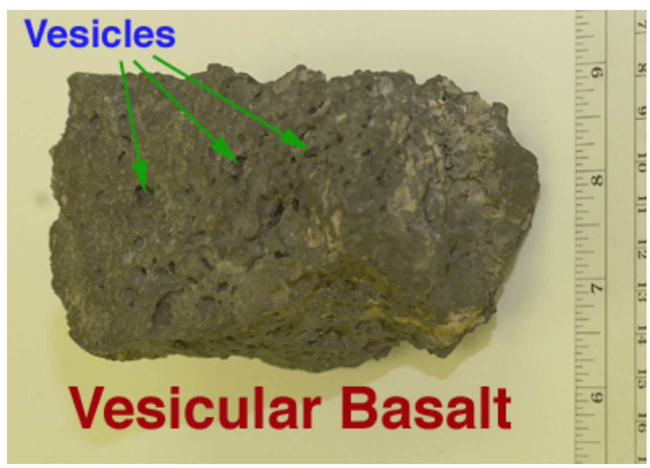
Changing a Magma Composition

Mixing of two compositionally distinct magmas:



Magma Rise

Magma is less dense than rock.
Magma is hotter and molecules are farther apart.
Contains dissolved gas under pressure - gas exsolves at lower pressures. Magma contains bubbles so density is lower still.



Pressure of overlying rock squeezes the magma out.
Rate of rise depends on viscosity.
Viscosity dependent upon temperature, volatile content, and silica content: hotter mafic lavas are less viscous than cool silicic lavas.

Extrusive Igneous Settings

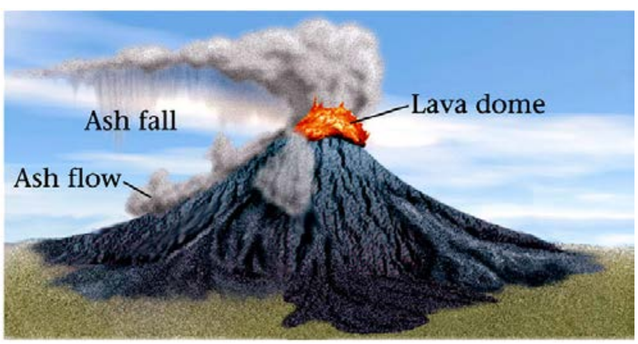
Fluid lava flow eruptions or explosive ash flow/fall eruptions depend upon silica and volatile content.

Fluid eruption = lava flows = mafic (basaltic) & volatile poor. Eruptions through shield volcanoes, fissures.

LavaFlowCreation.mov

Spatter1.mov

Extrusive Igneous Settings

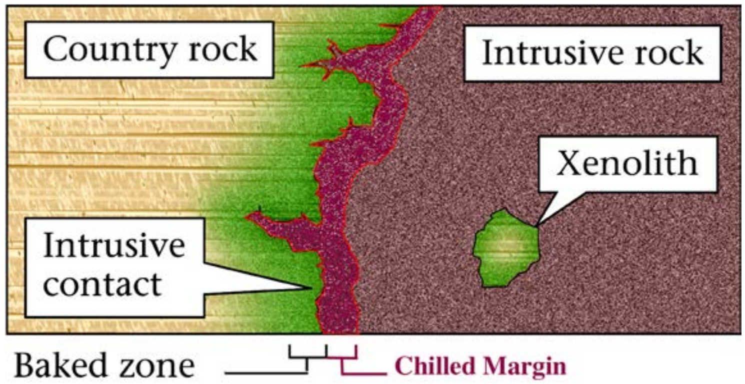


St_Helen.mov

Explosive eruption = ash flow/fall = silicic and volatile rich.

Intrusive Igneous Settings

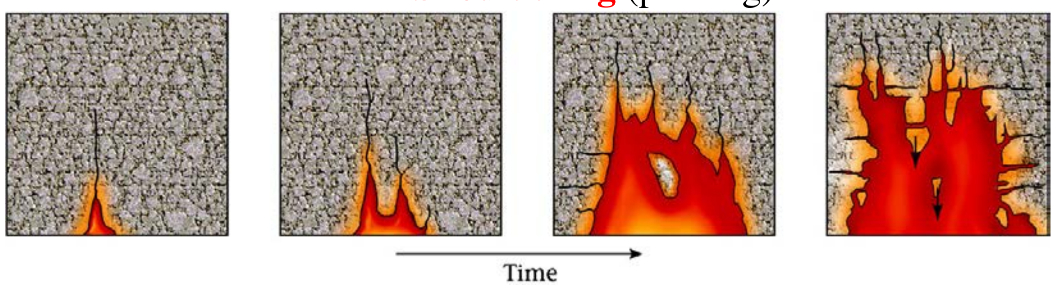
Intrude older rocks (generically known as "***countyrock***" – can be igneous, sedimentary, or metamorphic) and bake them = ***contact metamorphism***. Intrusion also has a chilled margin.



Intrusion creates space by:

Stoping (fracturing and assimilation)

Shouldering (pushing)



Intrusive Rocks

Intrusive rocks recognized by:

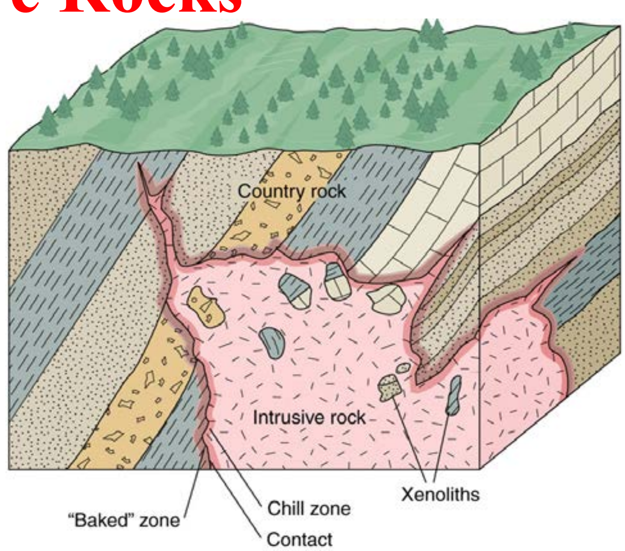
Coarse grain size, interlocking crystals, typically lacking a fabric (oriented texture).

Baked contacts (country rock) and chill zone (finer grain size) at the edges of the intrusion.

Inclusions of country rock = "***xenoliths***".

They cross-cut features in the country rock.

Veins protrude outward into country rock.



Intrusion Types

CYLINDRICAL: Volcanic neck – removal of more easily weathered volcano leaves more resistant intrusion.

LENTICULAR: ***Laccolith***, < 2 Km, concordant.

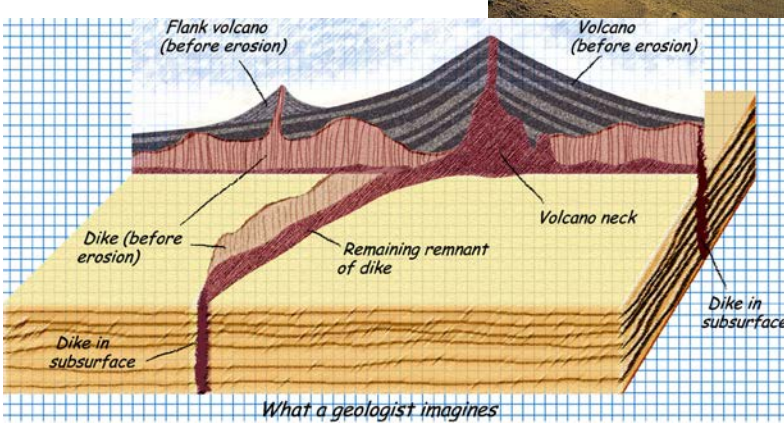
IRREGULAR:

Stock: outcrop < 100 km^2
Batholith: outcrop > 100 km^2

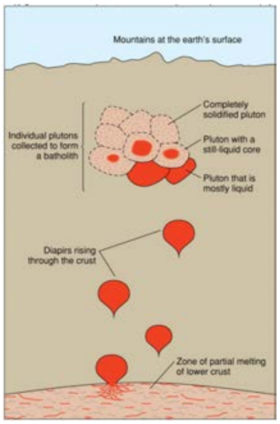
Both are deep.

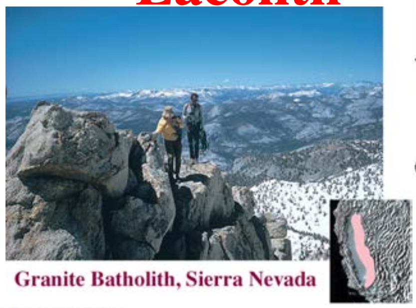
Intrusive rocks currently exposed at the surface were intruded at depth (i.e., in the roots of mountains, which were eroded). Larger intrusions (laccolith, stock, batholith) = have the generic term "**Plutons**".

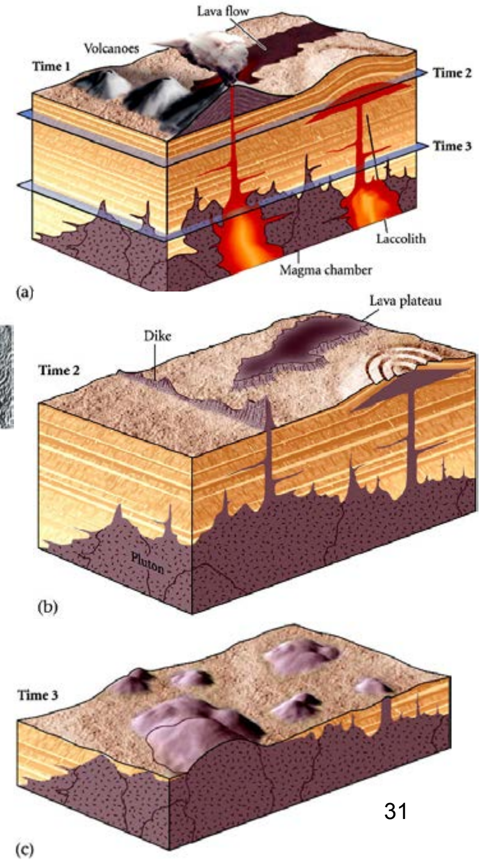
Ship Rock, New Mexico

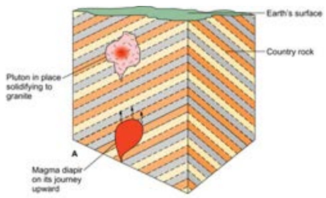


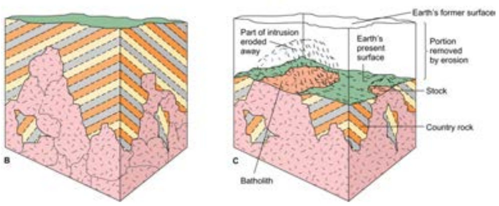
Batholith + Lacolith



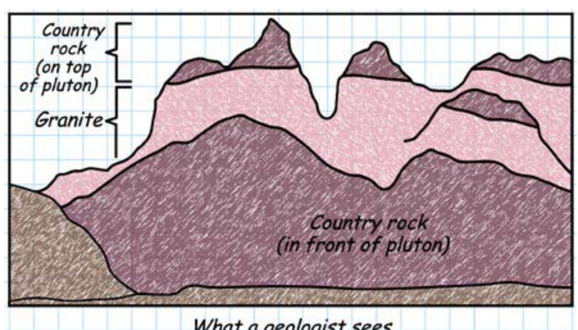

Granite Batholith, Sierra Nevada

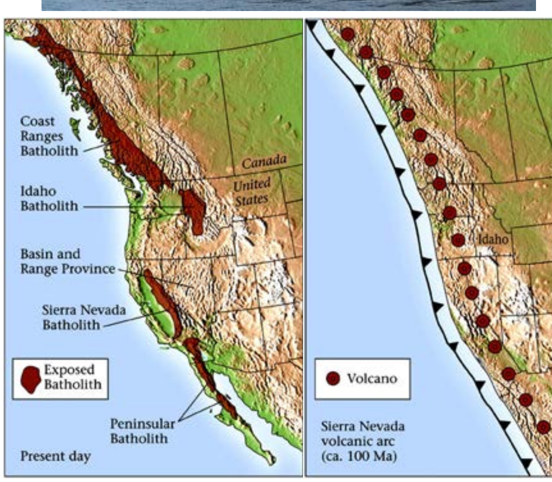


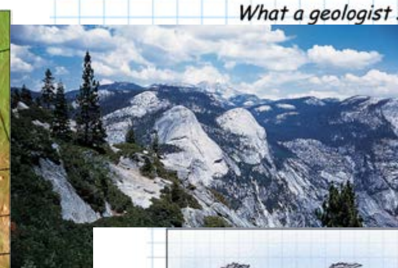


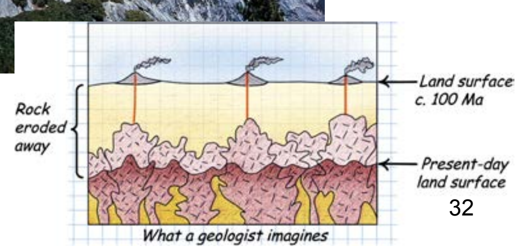


Batholiths and Volcanoes





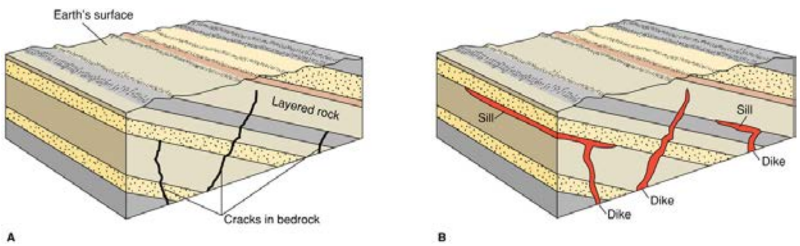


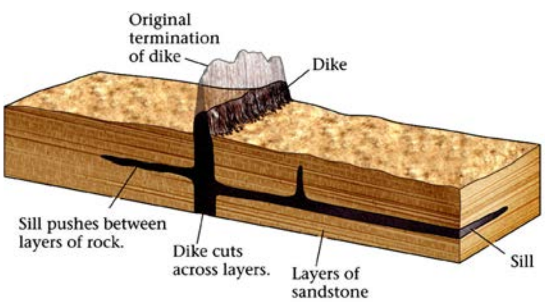


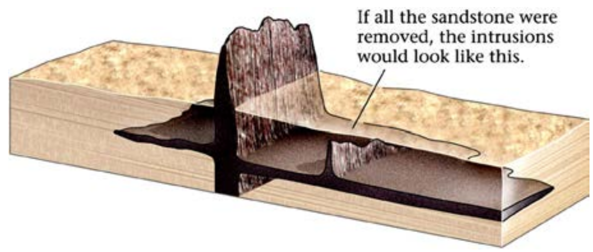
Intrusion Types

TABULAR: typically shallow, < 2 km.

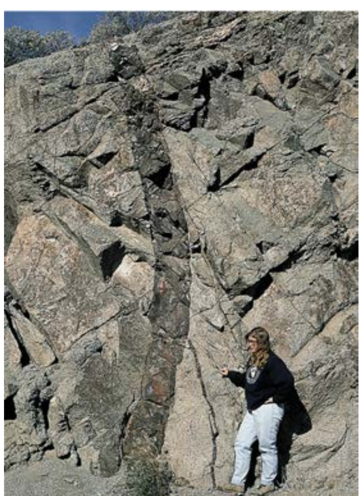
Discordant = dike; **Concordant** = sill

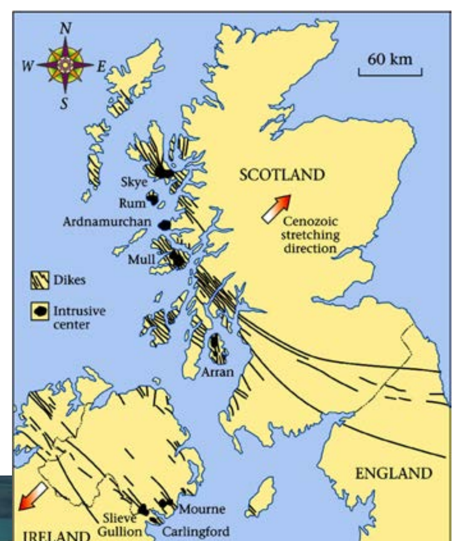




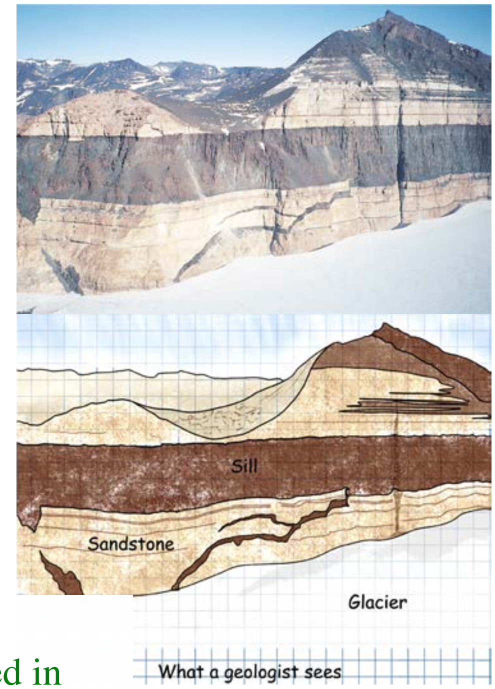


Dikes





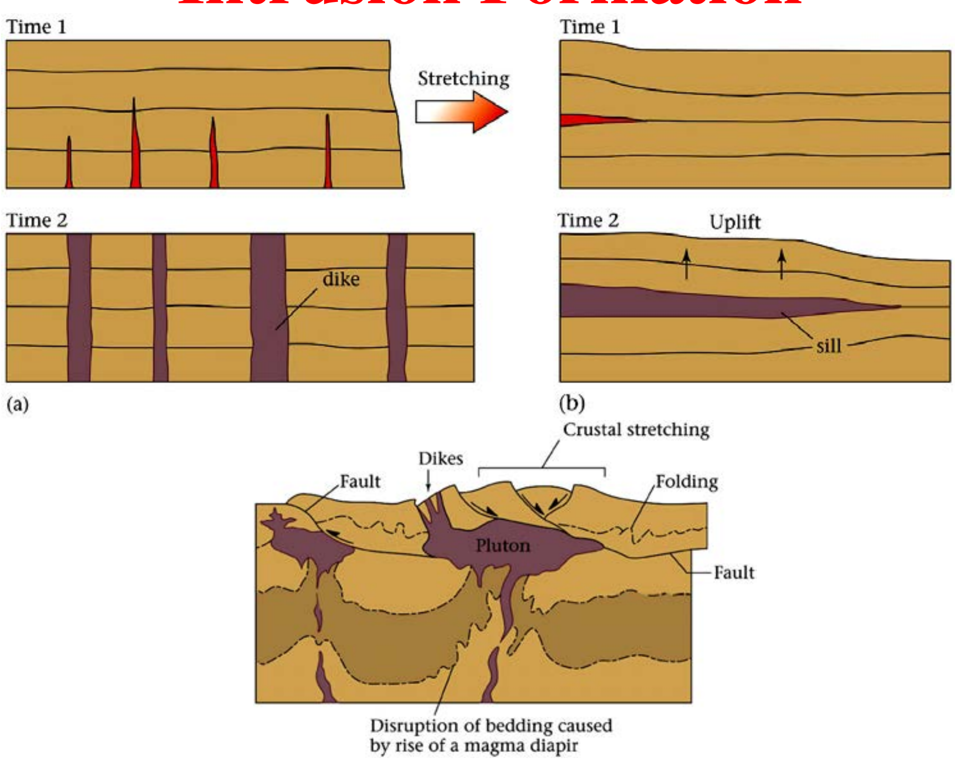
Sills



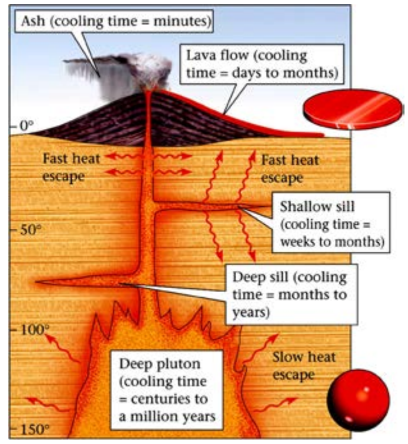
How to distinguish a sill from a flow:

- baked contacts above and below;
- vesicles (gas bubbles) in flow often filled in with flows;
- smaller dikes present above sill and emanating from it intruding the overlying countryrock.

Intrusion Formation



Controls on Cooling Rate



Extrusive = fast = small grain size;
Intrusive = slow = larger grain size.

Three factors control cooling rate:

- Depth of intrusion;
- Size and shape of intrusion;
- Presence of circulating groundwater.

Textures also related to cooling rate:

Glassy = fast cooling. Conchoidal fracture.

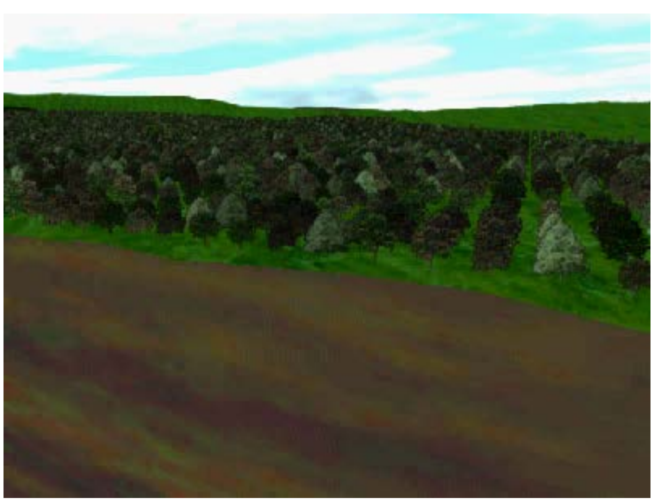
Interlocking texture = slower cooling = crystalline igneous rocks.

- **Phaneritic** = coarse grained - crystals seen with naked eye;
- **Aphanitic** = fine grained - need hand lens/microscope.
- **Porphyritic** = two cooling regimes - slow then fast.

Fragmental = fragmental - welded/cemented volcanic fragments.

Controls on Cooling Rate

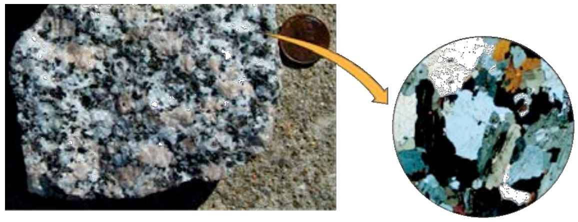
Pegmatite: very coarse grained, but crystallized from a water-rich magma. Doesn't quite fit in the cooling rate-grain size scheme.



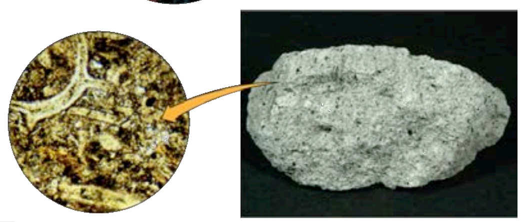
PEGMATIT.MOV

Describing Igneous Rocks

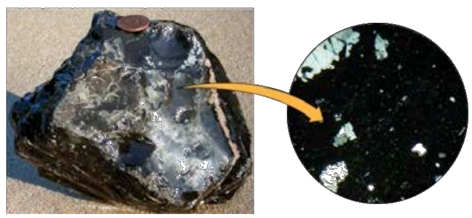
Crystalline texture



Fragmental texture



Glassy texture

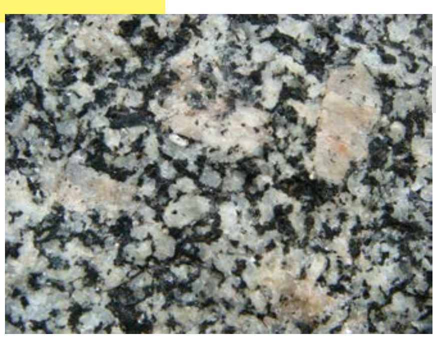


Describing Igneous Rocks

Crystalline Texture: Aphanitic vs. Phaneritic

Aphanitic – fast cooling

Phaneritic – slow cooling

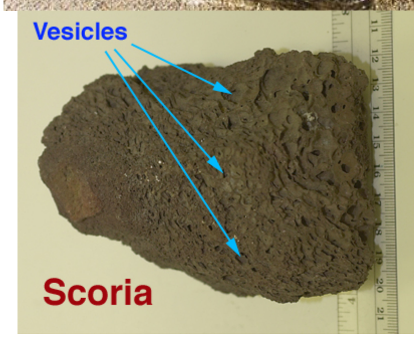


Porphyritic – slow & fast cooling

Glassy Textures

Obsidian: felsic glass.

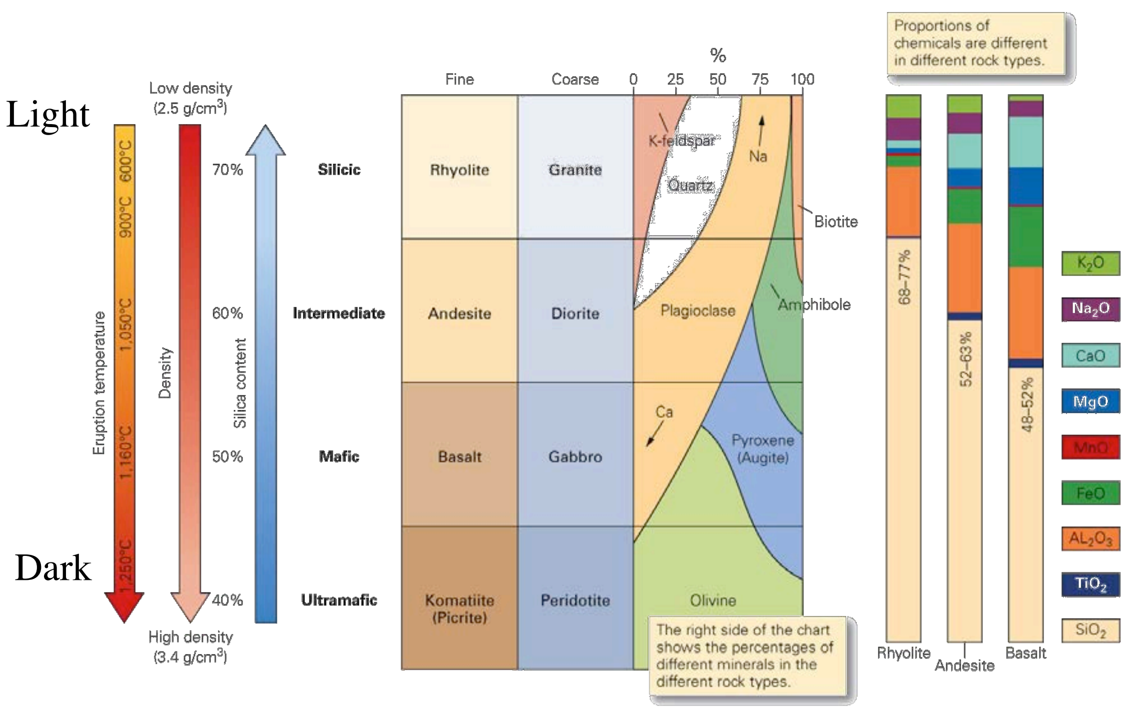
Pumice: glassy, felsic, with abundant pores or bubbles (vesicles). Floats on water.



Scoria: glassy, mafic rock with >30% vesicles. Bubbles are bigger than in pumice.

Tachylite: mafic, bubble-free mass >80% glass. Rare compared to obsidian.

Crystalline Igneous Rock Classification



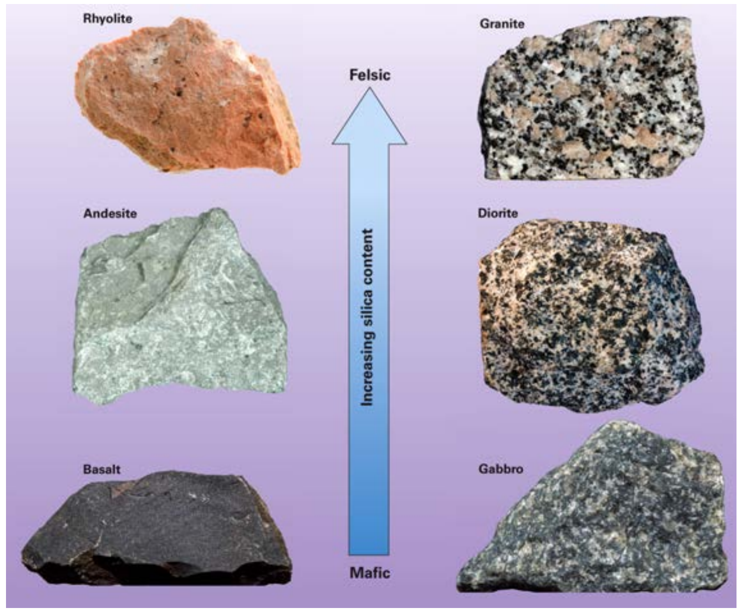
Crystalline Igneous Rock Classification

Aphanitic texture | Phaneritic texture

Felsic composition

Intermediate composition

Mafic composition



Fragmental Rocks

Pyroclastic or Volcaniclastic Rocks.

Table 4.1 Summary of Textures in Volcanic Rocks

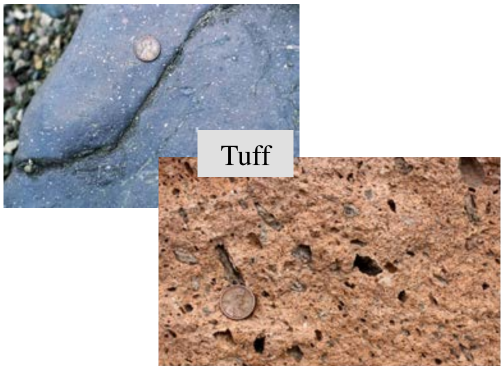
Name	Description
Fine-grained (adjective)	Mosaic of interlocking minerals that are smaller than 1 mm.
Porphyritic (adjective)	Some crystals, phenocrysts, are larger than 1 mm (usually considerably larger). Most grains are smaller than 1 mm. Or phenocrysts are enclosed in glass.
Obsidian	Glass. Atoms are disordered.
Vesicular (adjective)	Holes in rock due to trapped gas.
Pumice	Frothy glass.
Tuff	Consolidated fine pyroclastic material.
Volcanic breccia	Consolidated pyroclastic debris that includes blocks or bombs.

Pyroclastic Fragmental Textures

Dust/ash = finest.

Cinders = sand grains.

Bombs/blocks = largest. Bomb = ejected as lava and streamlined in air as it cools.



Tuffs = rock composed of fine-grained pyroclastic particles. Can be cemented or welded. Air fall tuff or water lain.

Hyaloclastite = Lava erupts under water/ice and shatters. Fragments become cemented/welded.

Volcanic Breccia = rock composed of larger pyroclastic materials

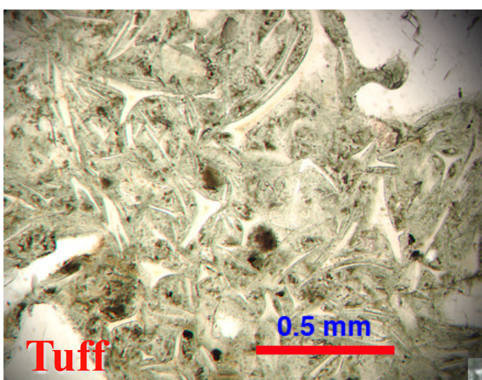


Plate Tectonics and Igneous Rocks

Table 3.2 Relationships between Rock Types and Their Usual Plate Tectonic Setting

Rock	Original Magma	Final Magma	Processes	Plate Tectonic Setting
basalt & gabbro	mafic	mafic	partial melting of mantle (asthenosphere)	1. divergent boundary—oceanic crust created 2. Intraplate • plateau basalt • volcanic island chains (e.g., Hawaii)
andesite & diorite	mafic (usually)	intermediate	partial melting of mantle (asthenosphere) followed by: • differentiation or • assimilation or • magma mixing	convergent boundary
granite & rhyolite	silicic	silicic	partial melting of lower crust	1. convergent boundary 2. intraplate • over mantle plume

Igneous Rocks and Plate Tectonics

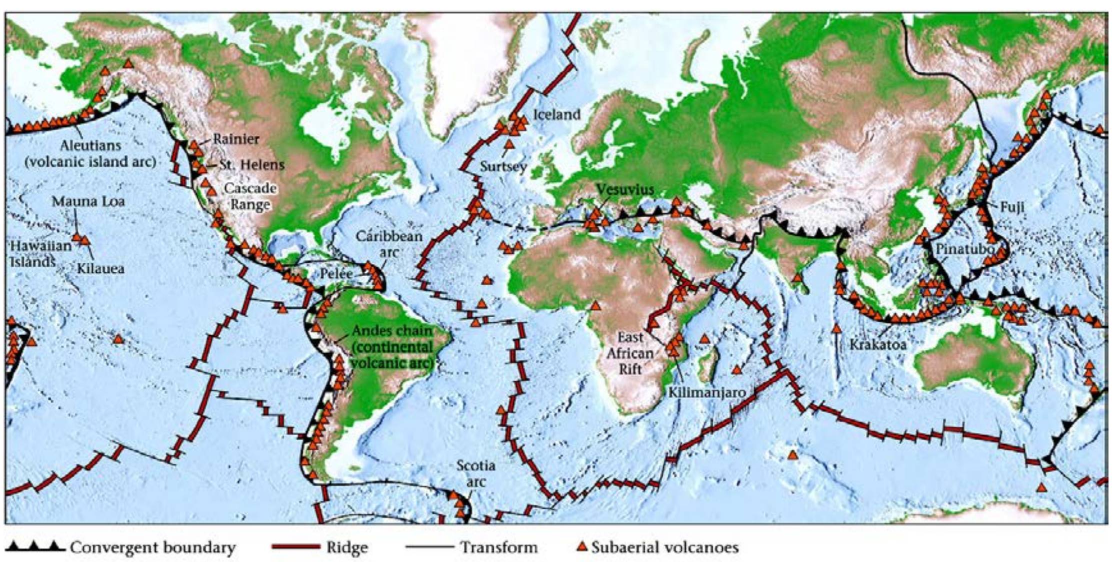
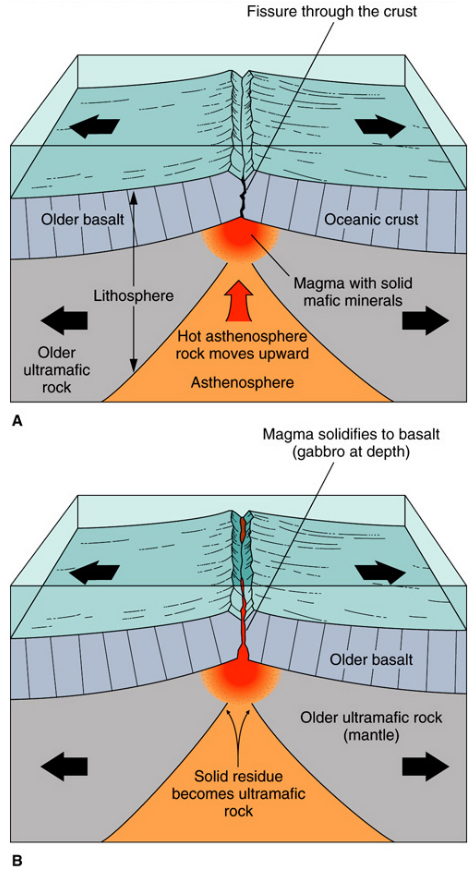
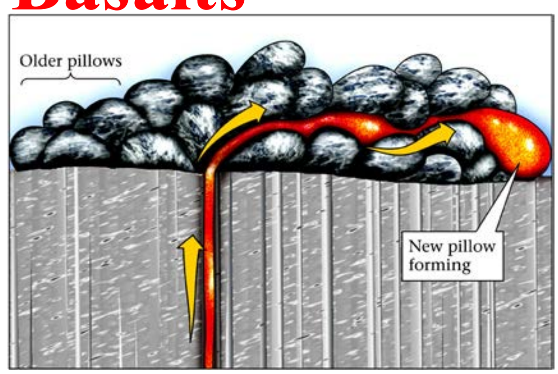


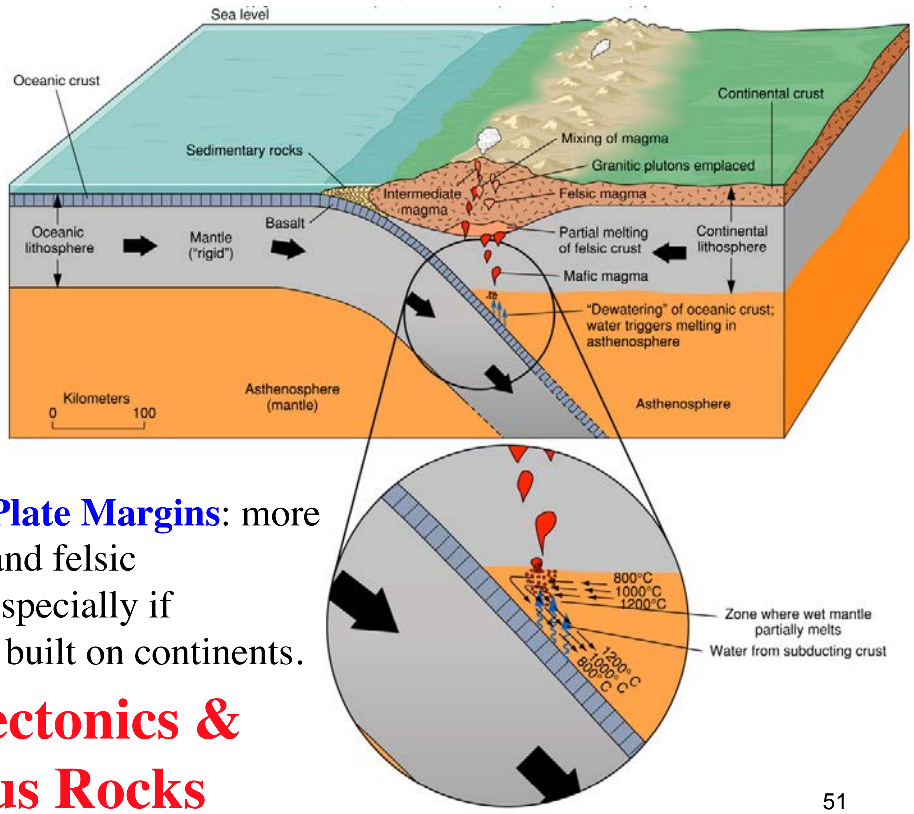
Plate Tectonics & Igneous Rocks

Divergent Plate Margins – lithosphere and asthenosphere; pressure-release, almost all mafic magmatism.



Pillow Basalts

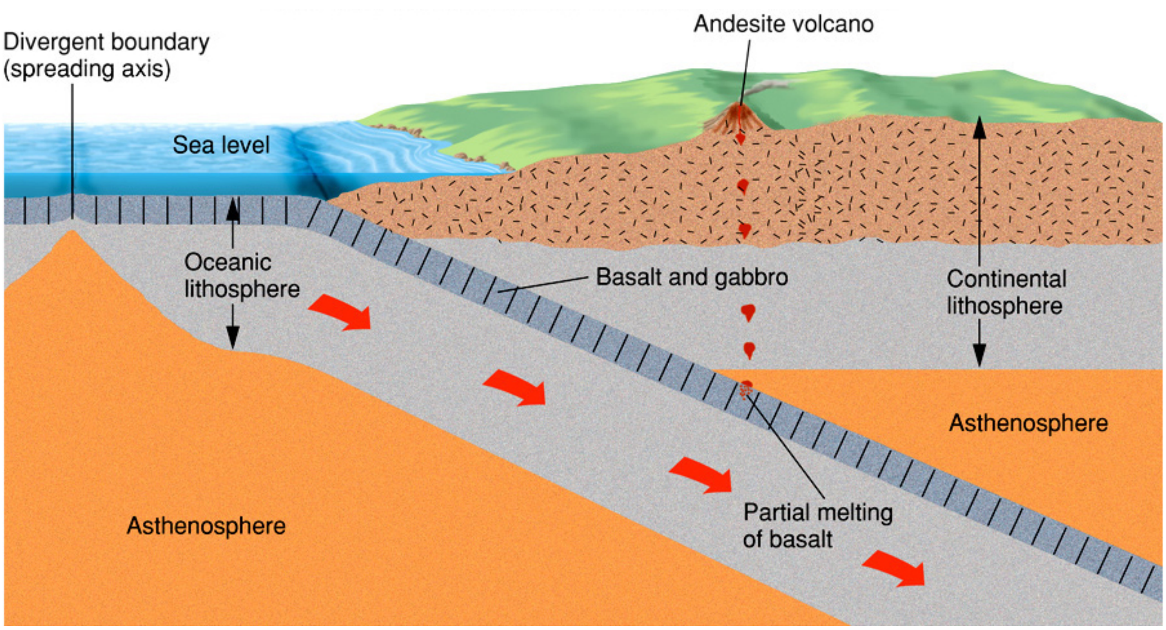




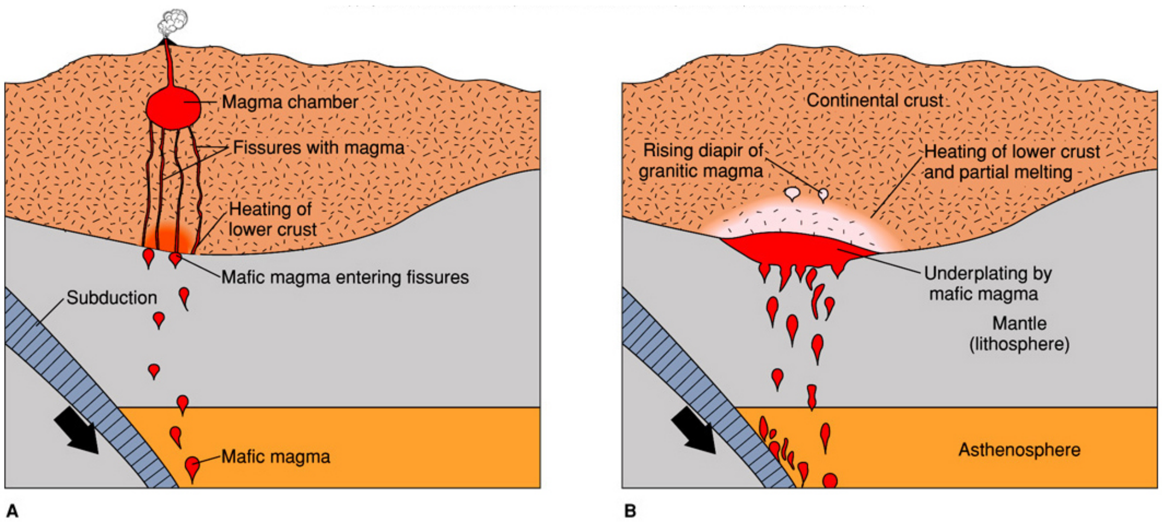
Convergent Plate Margins: more intermediate and felsic magmatism, especially if volcanoes are built on continents.

Plate Tectonics & Igneous Rocks

Origin of Andesite: subduction zone generates ultramafic/mafic magmas through "dewatering", which evolve to andesite through differentiation, assimilation and magma-mixing.



Origin of Granite: magmatic underplating.



FISSURE ERUPTIONS

Flood lavas from long fissures.

Very hot mafic lavas = flood basalts, which form plateaus (e.g., Columbia Plateau – Oregon and Idaho; Deccan Traps, India).

Can form on land (*continental flood basalts*) or in the sea (*oceanic plateaus*). For example, Ontong Java Plateau, SW Pacific; Iceland.

Environmental Effects.

Often flows have columnar jointing upon cooling (relatively slow cooling in thick lava flows (e.g., Giants Causeway, Ireland; Fingles Cave, Scotland).

Plate Tectonics & Igneous Rocks

Intraplate: Hawaii, Yellowstone, LIPs – mantle plume activity.

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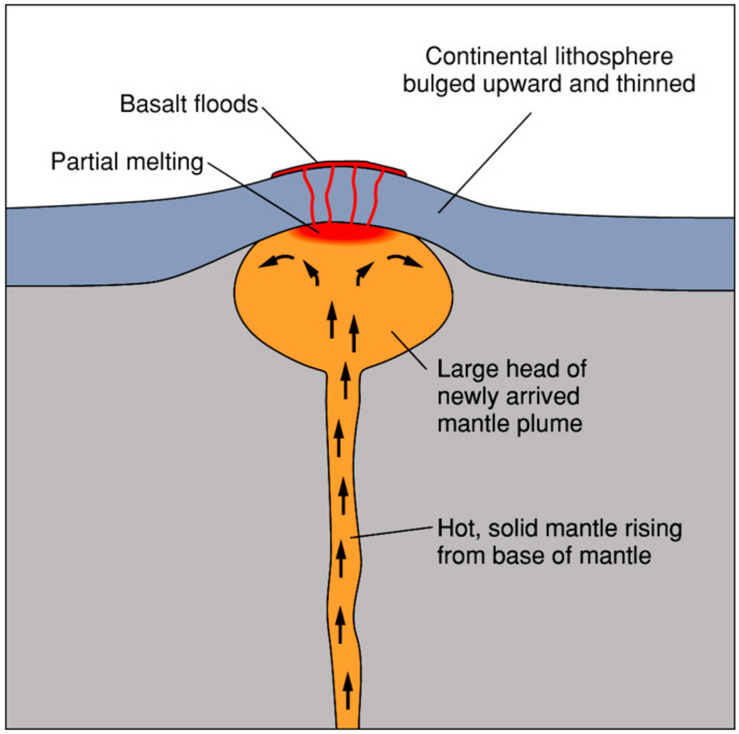
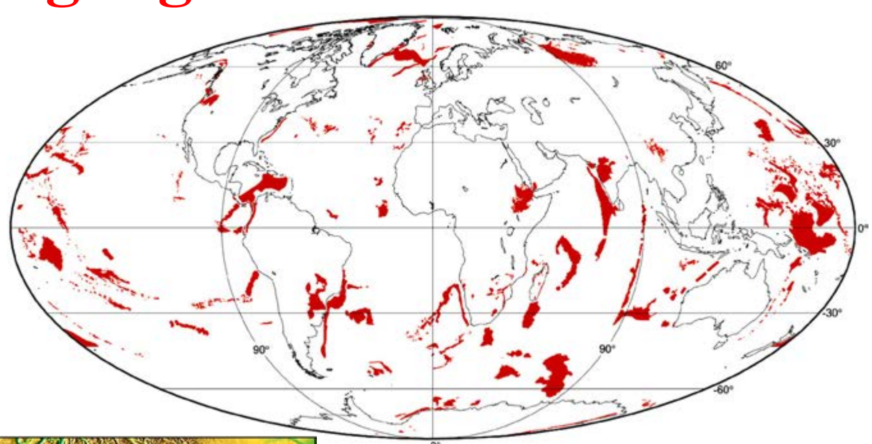
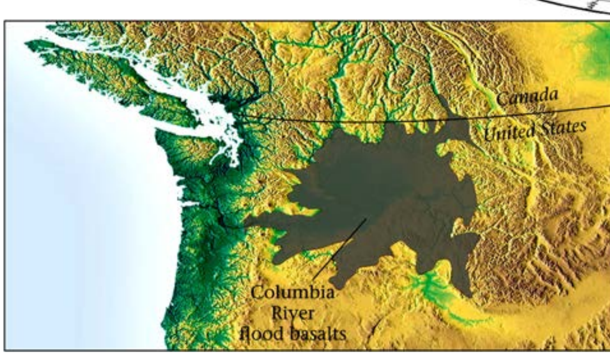
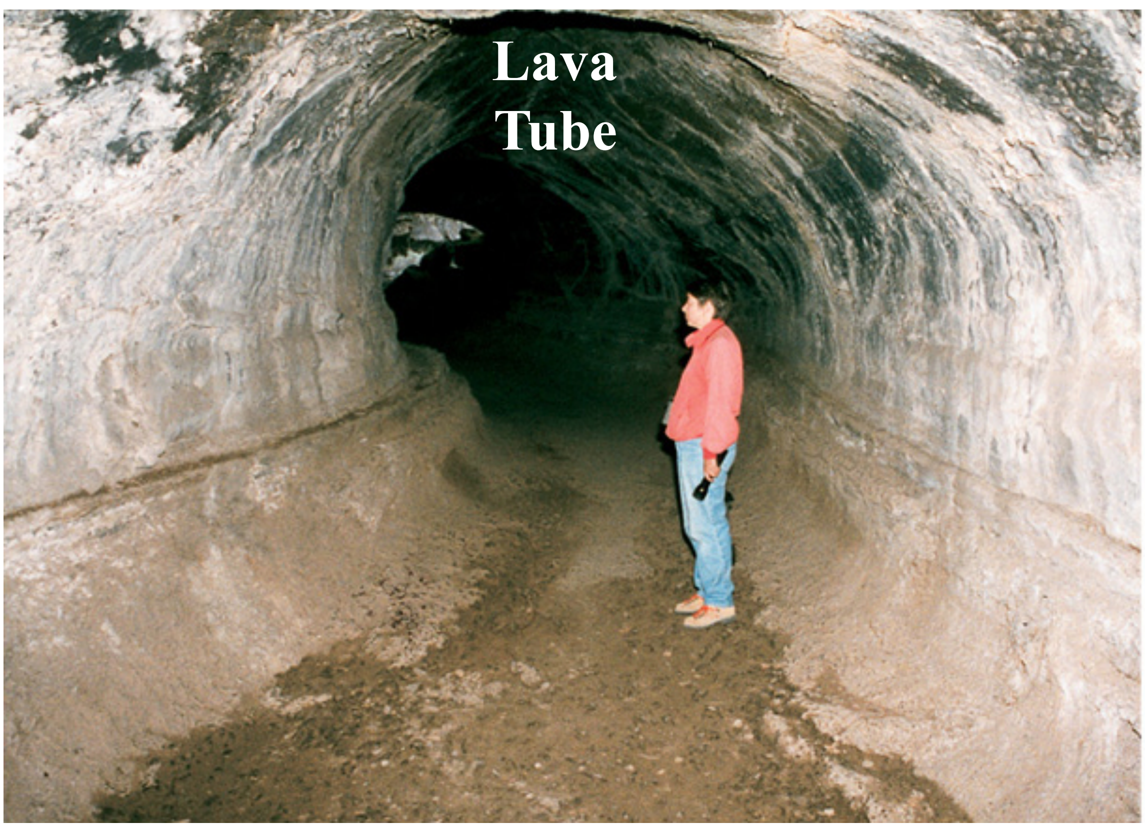


Large Igneous Provinces



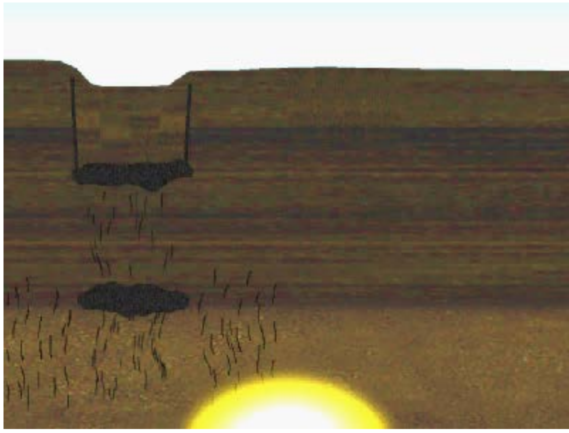


Flood Basalt Flows



Giants Causeway, Co. Antrim, Ireland

Hot Spot Tracks



hotspot.MOV

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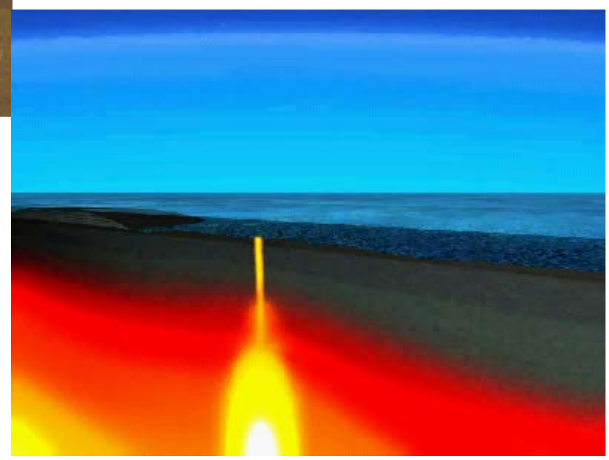

Summary

Introduction: Volcano, Magma, Lava, Lava Flow, Lava Fountain, Igneous Rock.
Basalt Flows: A’s, Pahoehoe.
Heat Sources: Accretion, Gravity, Gravitational Pull, Radioactive Decay, Core Formation.
Igneous Rocks: Intrusive, Extrusive.
Extrusive: Pyroclastic Debris, Ash, Ash Fall, Ash Flow (Nueé Ardente), Volcanic Debris Flow, Lahar.
Formation of Magma: Decompression, Volatile Addition, Heat Transfer, Mixing of Minerals.
What is a Magma Made of? Felsic, Intermediate, Mafic, Ultramafic.
What Controls Magma Composition? Source Rock Composition, Partial Melting, Assimilation, Fractional Crystallization (Bowen’s Reaction Series), Magma Mixing.
Magma Rise: Heat, Less Dense, Vesicles, Pressure of Overlying Rocks, Viscosity.
Extrusive Igneous Settings: Mafic and Felsic volcanoes.
Intrusive Igneous Settings: Stoping and Shouldering, Country Rock, Chilled Margin, Baked Zone, Xenoliths.
Intrusion Types: Cylindrical, Lenticular, Irregular, Tabular (Dike and Sill)
Controls on Cooling Rate: Depth of Intrusion, Size of Intrusion, Presence of Circulating Groundwater.
Plate Tectonics and Igneous Rocks: Divergent Margins (Pillow Basalts), Convergent Margins, LIPs, Hotspots.