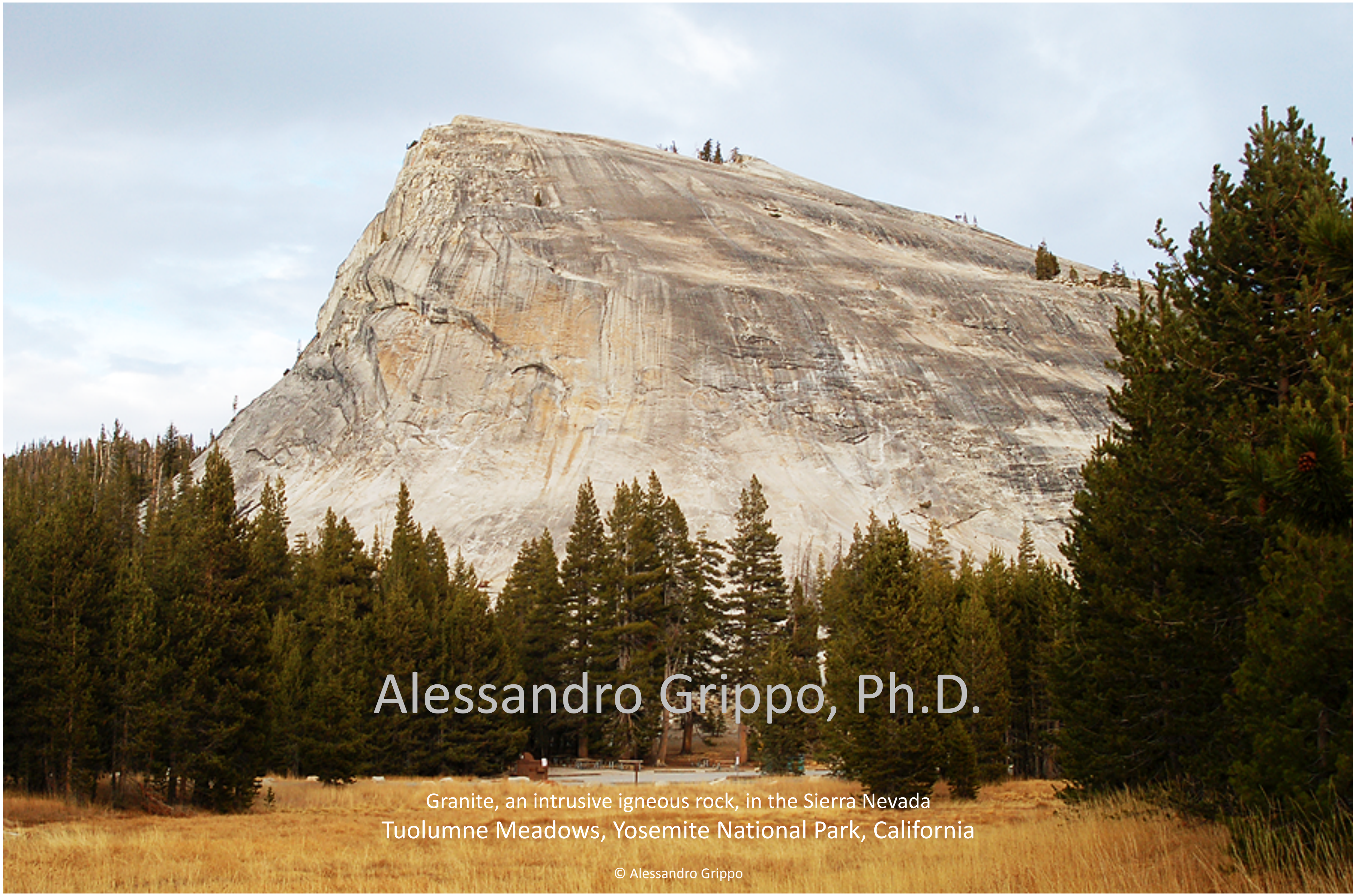
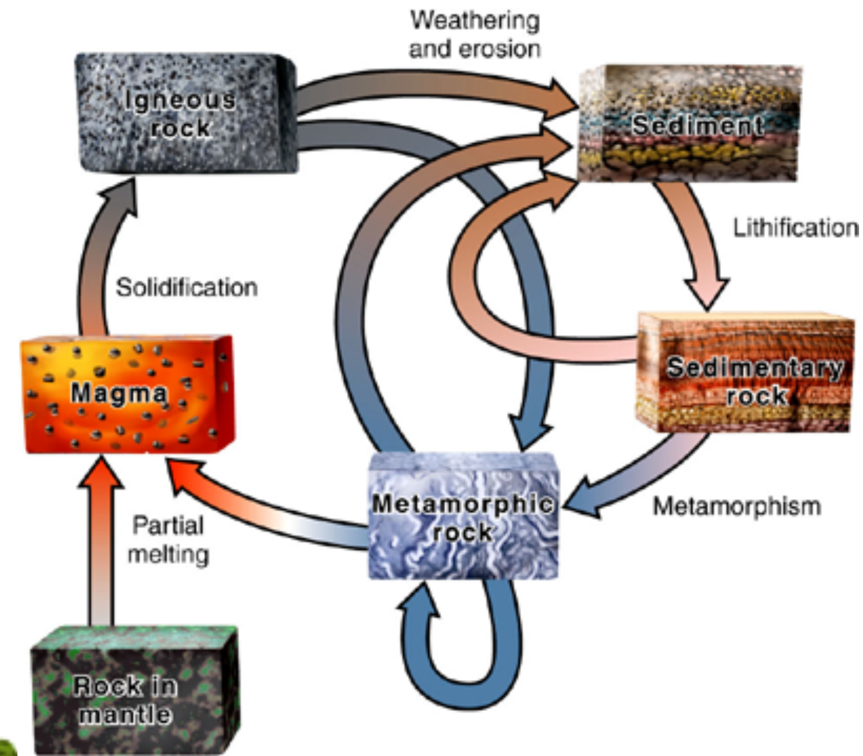
Plutonism and Intrusive Igneous Rocks

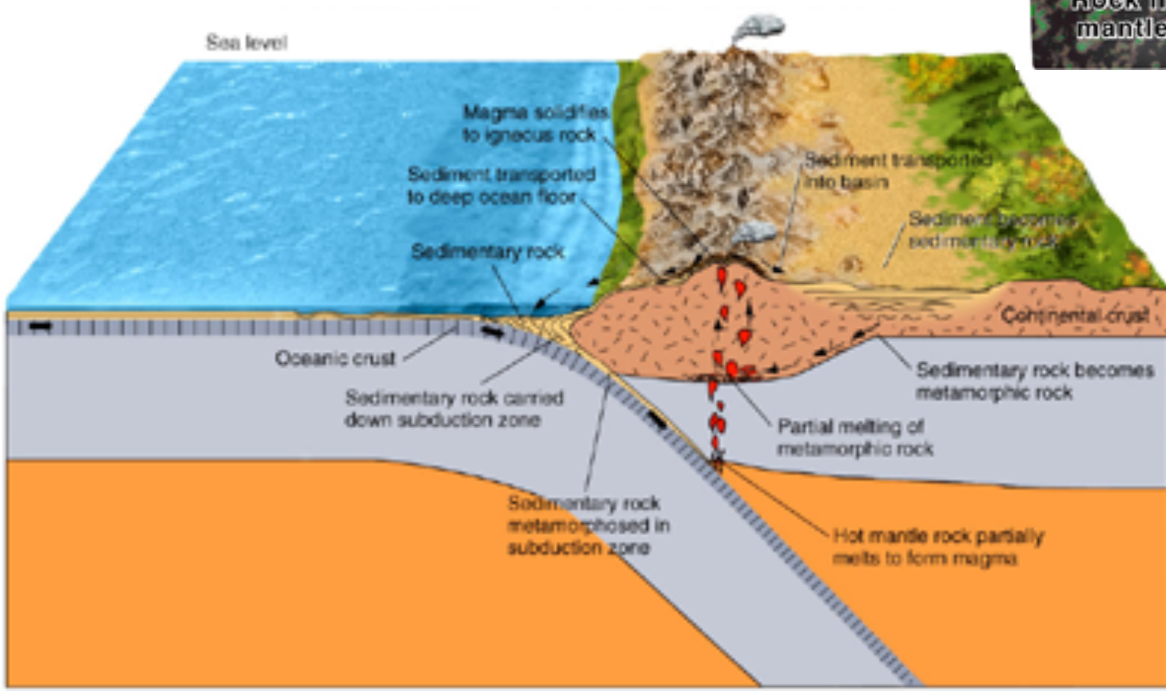
notes from the textbook, integrated with original contributions



review

- The rock cycle
- The rock cycle and Plate Tectonics



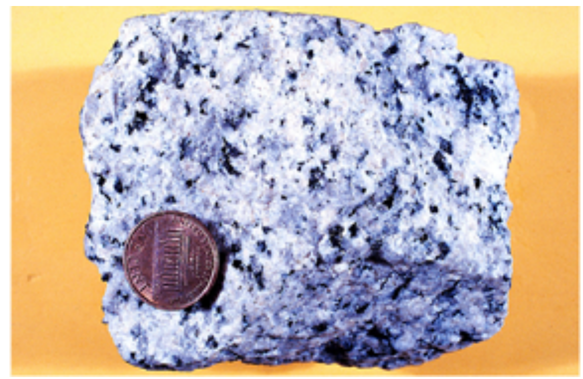


Magma

- Any rock can be melted under the right condition of pressure and temperature
- That melt is called **magma**
- Magma can contain solid, liquid, and gaseous materials

Magma vs. Lava

- When magma solidifies, it forms **igneous rocks**
  - If magma solidifies slowly within Earth’s surface it generates *intrusive igneous rocks* (e.g., granite)
  - If magma solidifies quickly at Earth’s surface it is called **lava**, and it generates *extrusive igneous rocks* (e.g., basalt)

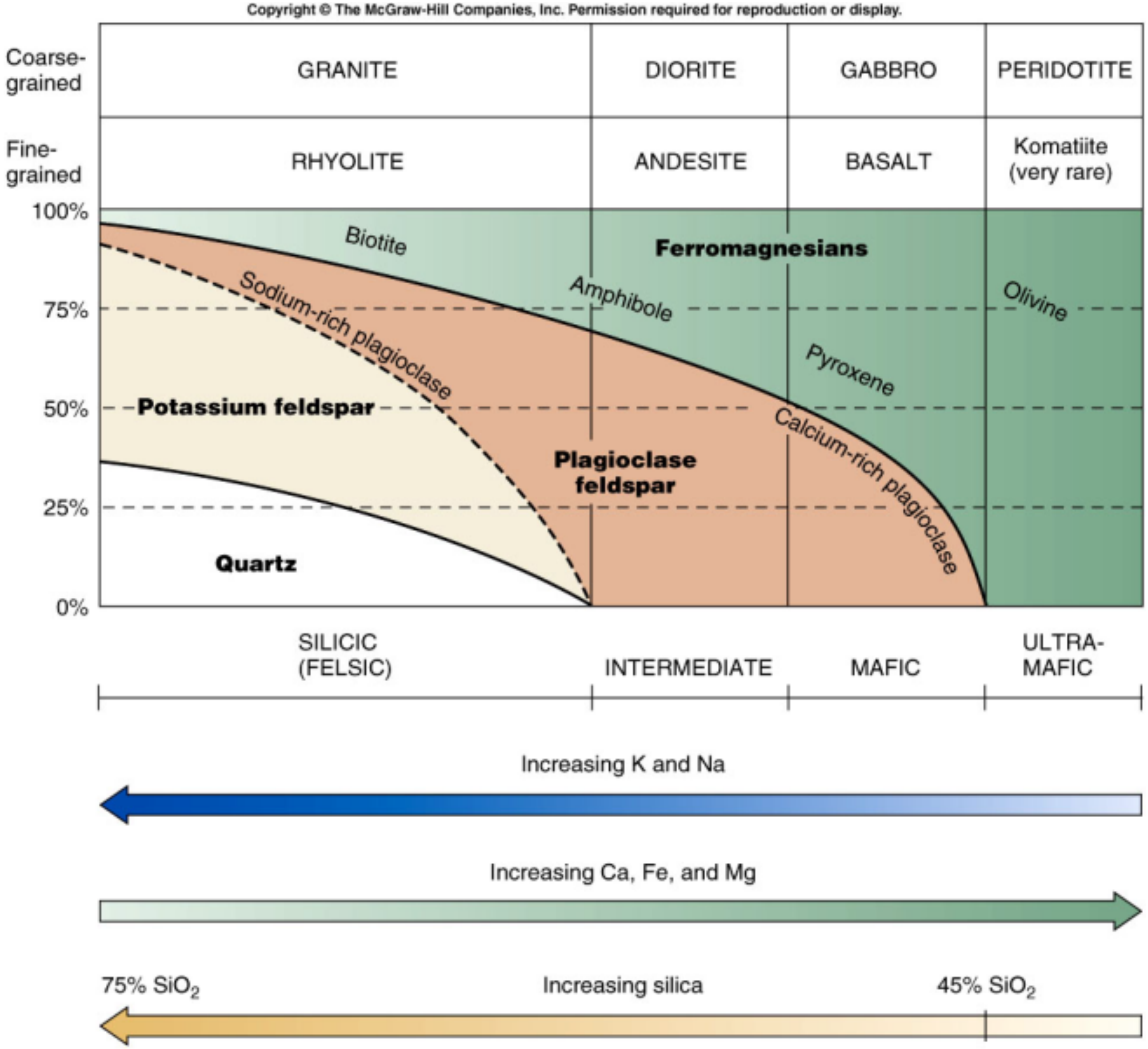


How do we classify igneous rocks?

- We use composition and texture of the rocks
- The chemical **Composition** refers mainly to their iron and silica content
- **Texture** refers to the size, shape, and arrangement of mineral grains (crystals, in the case of igneous rocks)

- *Textural classification*
  - *Plutonic* or *intrusive* rocks (gabbro-diorite-granite) are coarse-grained and cooled slowly at depth
    - Grains are visible to the naked eye
    - Two textures: pegmatitic, **phaneritic**
  - *Volcanic* or *extrusive* rocks (basalt-andesite-rhyolite) are typically fine-grained and cooled rapidly at the Earth's surface
    - Grains are not visible to the naked eye, or absent (e.g. obsidian, a volcanic glass)
    - Six textures: porphyritic, **aphanitic**, glassy, vesicular, frothy, pyroclastic

- *Compositional classification*
  - *Mafic* rocks (gabbro-basalt) contain abundant dark-colored ferromagnesian minerals
  - *Intermediate* rocks (diorite-andesite) contain roughly equal amounts of dark- and light-colored minerals
  - *Felsic* rocks (granite-rhyolite) contain abundant light-colored minerals



Coarse-grained
GRANITE
DIORITE
GABBRO
PERIDOTITE
Fine-grained
RHYOLITE
ANDESITE
BASALT
Komatiite (very rare)
100%
75%
50%
25%
0%
Biotite
Ferromagnesians
Amphibole
Olivine
Pyroxene
Sodium-rich plagioclase
Potassium feldspar
Plagioclase feldspar
Calcium-rich plagioclase
Quartz
SILICIC (FELSIC)
INTERMEDIATE
MAFIC
ULTRA-MAFIC
Increasing K and Na
Increasing Ca, Fe, and Mg
75% SiO2
Increasing silica
45% SiO2

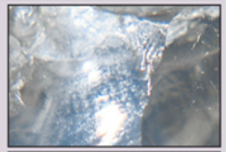
Composition

- Rock chemistry, particularly *silica* (SiO_2) content, determines mineral content and general color of igneous rocks
  - *Ultramafic* rocks have <45% silica, by weight, and are composed almost entirely of dark-colored ferromagnesian minerals
    - Most common ultramafic rock is peridotite (intrusive)
  - *Mafic* rocks have ~50% silica, by weight, and contain dark-colored minerals that are abundant in iron, magnesium and calcium
    - Intrusive/extrusive mafic rocks - gabbro/basalt
  - *Intermediate* rocks have silica contents between those of mafic and felsic rocks
    - Intrusive/extrusive intermediate rocks - diorite/andesite
  - *Felsic (silicic)* rocks have >65% silica, by weight, and contain light-colored minerals that are abundant in silica, aluminum, sodium and potassium
    - Intrusive/extrusive felsic rocks - granite/rhyolite

STEP 1 & 2: MCI and Mineral Composition

Mafic Color Index (MCI): the percent of mafic (green, dark gray, black) minerals in the rock. See the top of Figure 5.2 and GeoTools Sheets 1 and 2 for tools to visually estimate MCI.

FELSIC MINERALS



Quartz
hard, transparent, gray, crystals with no cleavage

Plagioclase Feldspar
hard, opaque, usually pale gray to white crystals with cleavage, often striated

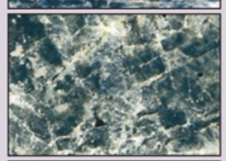
Potassium Feldspar
hard, opaque, usually pastel orange, pink, or white crystals with exsolution lamellae

Muscovite Mica
flat, pale brown, yellow, or colorless, crystals that scratch easily and split into sheets

MAFIC MINERALS

Biotite Mica
flat, glossy black crystals that scratch easily and split into sheets

Amphibole
hard, dark gray to black, brittle crystals with two cleavages that intersect at 56 and 124 degrees



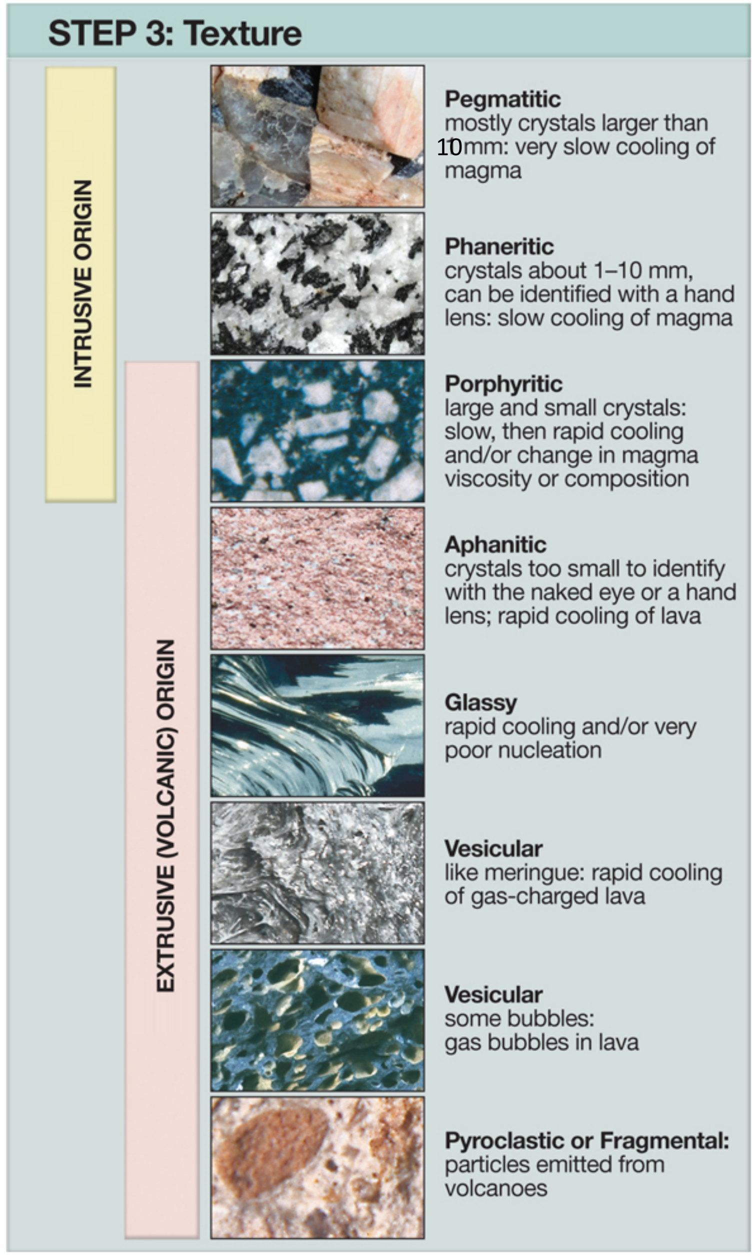
Pyroxene (augite)
hard, dark green to green-gray crystals with two cleavages that intersect at nearly right angles

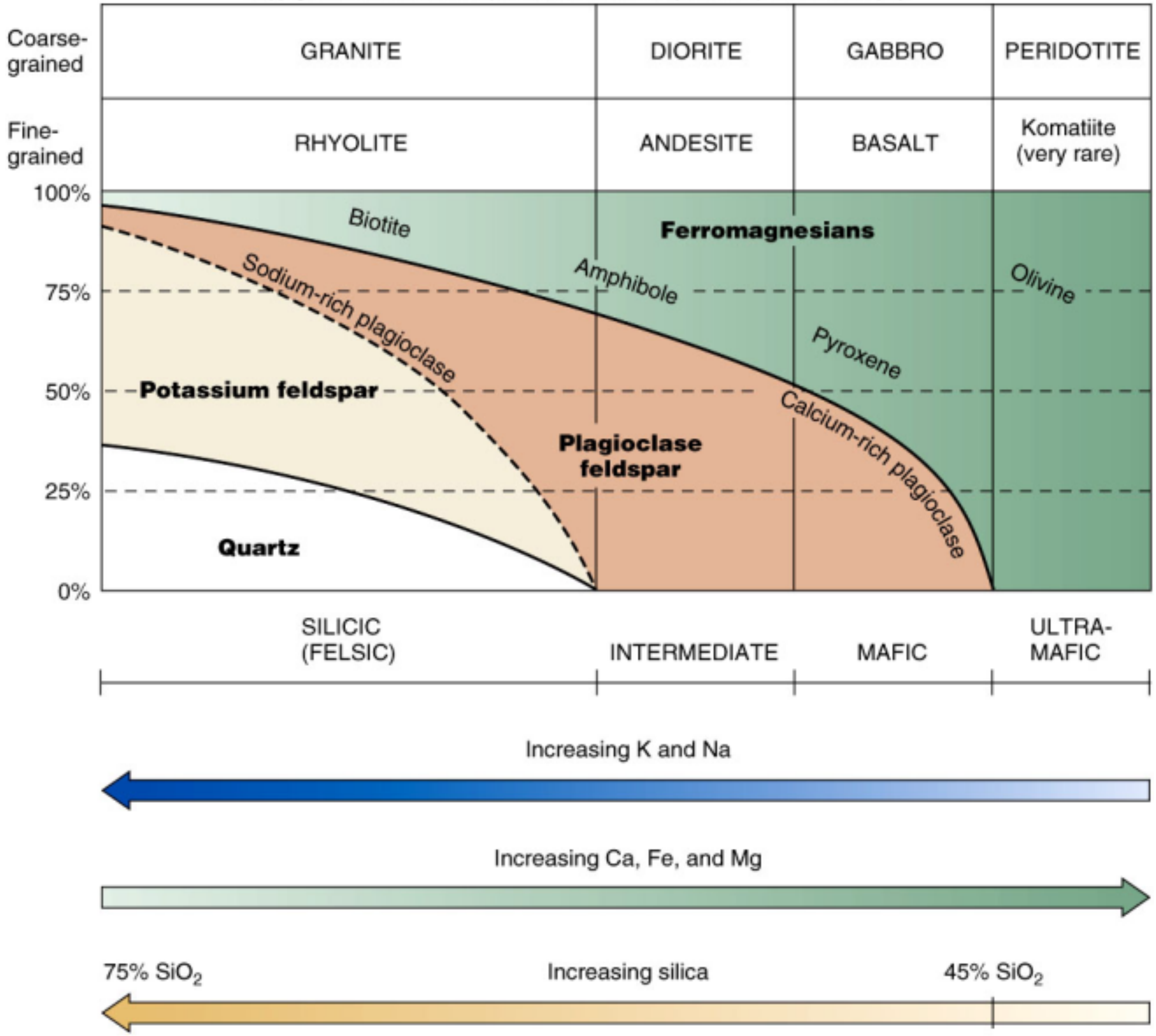
Olivine (gemstone peridot)
hard, transparent to opaque, pale yellow-green to dark green crystals with no cleavage

Eight Textures

- Pegmatitic
  - Visible crystals bigger than 1 cm in size
- **Phaneritic** (Coarse-grained)
  - Visible crystals smaller than 1 cm in size (most common)
- Porphyritic
  - Two crystal sizes together in the same rock
- **Aphanitic** (Fine-grained)
  - Invisible crystals (most common)
- Glassy
  - No crystals (e.g., obsidian)

- Vesicular
  - vesicles left in the rock by escaping gases; e.g., vesicular basalt
- Frothy
  - a variety of vesicular that applies to felsic, viscous magmas; e.g., pumice
- Pyroclastic, or Fragmental
  - after volcanic explosions; e.g., volcanic breccia and volcanic tuff


STEP 3: Texture
INTRUSIVE ORIGIN
EXTRUSIVE (VOLCANIC) ORIGIN
Pegmatitic
mostly crystals larger than 10mm: very slow cooling of magma
Phaneritic
crystals about 1–10 mm, can be identified with a hand lens: slow cooling of magma
Porphyritic
large and small crystals: slow, then rapid cooling and/or change in magma viscosity or composition
Aphanitic
crystals too small to identify with the naked eye or a hand lens; rapid cooling of lava
Glassy
rapid cooling and/or very poor nucleation
Vesicular
like meringue: rapid cooling of gas-charged lava
Vesicular
some bubbles: gas bubbles in lava
Pyroclastic or Fragmental:
particles emitted from volcanoes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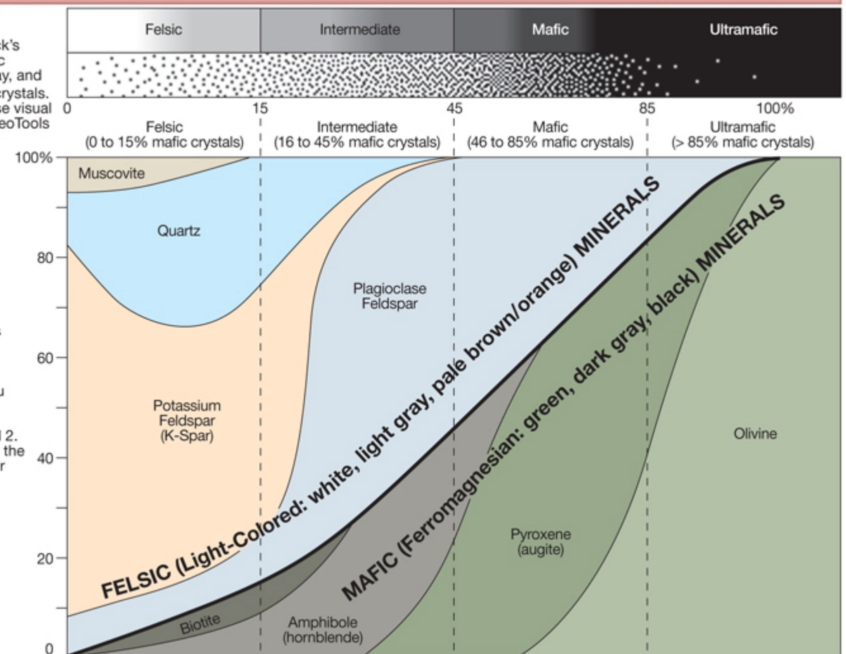
Potassium feldspar
Plagioclase feldspar
Calcium-rich plagioclase
Quartz
SILICIC (FELSIC)
INTERMEDIATE
MAFIC
ULTRA-MAFIC
Increasing K and Na
Increasing Ca, Fe, and Mg
75% SiO2
Increasing silica
45% SiO2

IGNEOUS ROCKS CLASSIFICATION

1. Mafic Color Index (MCI)
Estimate the rock's percent of mafic (green, dark gray, and black) mineral crystals. You can also use visual estimators in GeoTools 1 and 2.

2. Minerals
Identify minerals in the rock, if possible, and the percent of each one. You can use visual estimators in GeoTools 1 and 2. Skip this step if the rock is glassy or aphanitic.



3. Texture(s) Identify the rock's texture(s).

4. Rock Name: Select name below, based on data from steps 1–3.

Origin	Texture	Felsic	Intermediate	Mafic	Ultramafic
INTRUSIVE ORIGIN	Pegmatitic: very coarse-grained	PEGMATITIC GRANITE	PEGMATITIC DIORITE	PEGMATITIC GABBRO	PEGMATITIC PERIDOTITE
INTRUSIVE ORIGIN	Phaneritic: coarse-grained	**GRANITE** (SYENITE, if no quartz)	**DIORITE**	**GABBRO**	**PERIDOTITE**
INTRUSIVE ORIGIN	Phenocrysts[1] in a phaneritic groundmass	PORPHYRITIC GRANITE	PORPHYRITIC DIORITE	PORPHYRITIC GABBRO	PORPHYRITIC PERIDOTITE
EXTRUSIVE ORIGIN	Phenocrysts[1] in an aphanitic groundmass	PORPHYRITIC RHYOLITE	PORPHYRITIC ANDESITE	PORPHYRITIC BASALT	KOMATIITE (resembles basalt but has 1–10 cm long criss-crossing needles of olivine or pyroxene)
EXTRUSIVE ORIGIN	Aphanitic: fine-grained	**RHYOLITE**	**ANDESITE**	**BASALT**	
EXTRUSIVE ORIGIN	Glassy	OBSIDIAN			
EXTRUSIVE ORIGIN	Vesicular	PUMICE (abundant tiny vesicles–like meringue; very lightweight; white or gray; floats in water)		SCORIA (resembles a sponge) VESICULAR BASALT (has few scattered vesicles)	
EXTRUSIVE ORIGIN	Pyroclastic or Fragmental	VOLCANIC TUFF (fragments < 2 mm) VOLCANIC BRECCIA (fragments > 2 mm)			

[1]Phenocrysts are crystals conspicuously larger than the finer grained groundmass (main mass, matrix) of the rock.

Granite

Rhyolite

Diorite

Andesite (porphyritic)

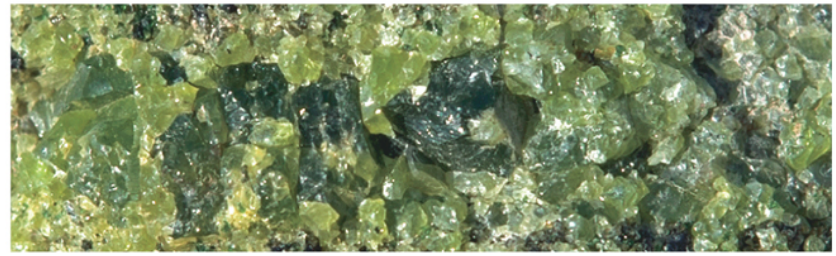
Fig. 3.7e

Gabbro

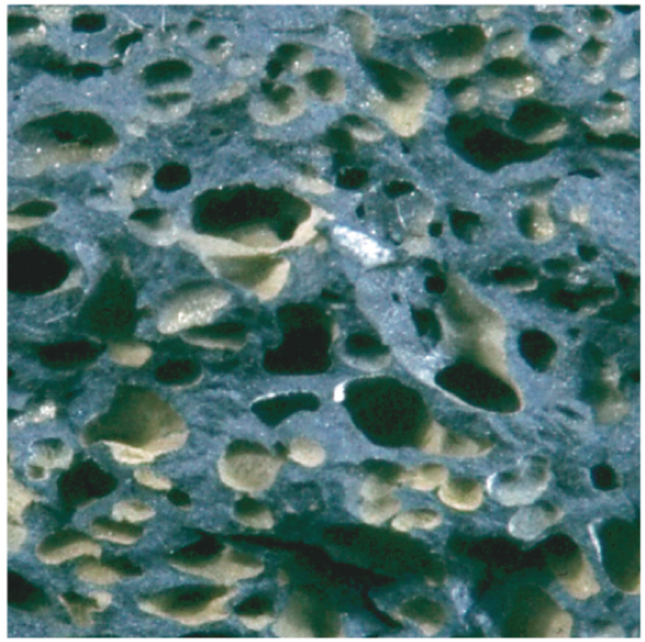
Fig. 3.7f

Basalt

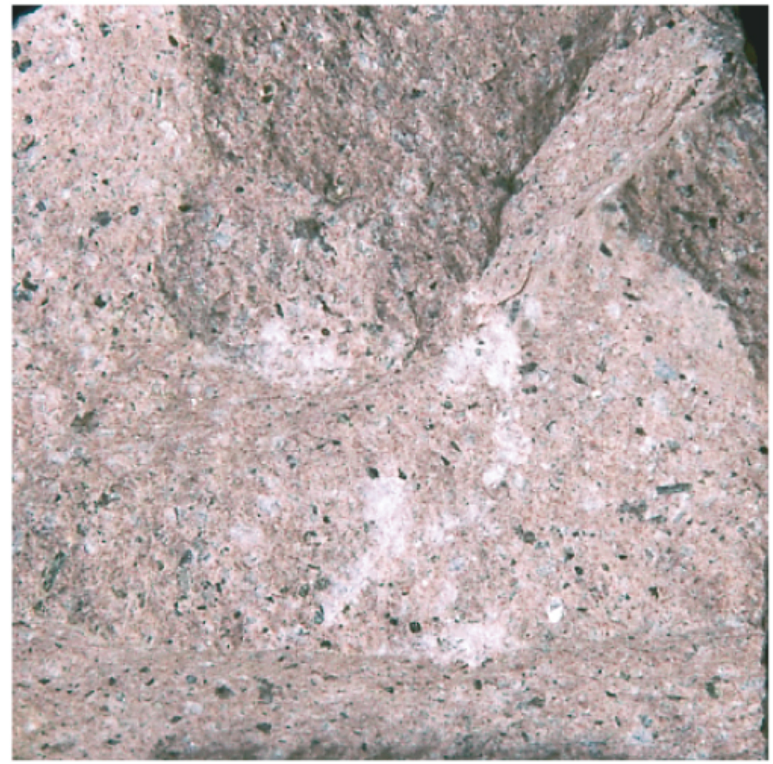
Hand sample
(actual size)



10× close-up of peridotite

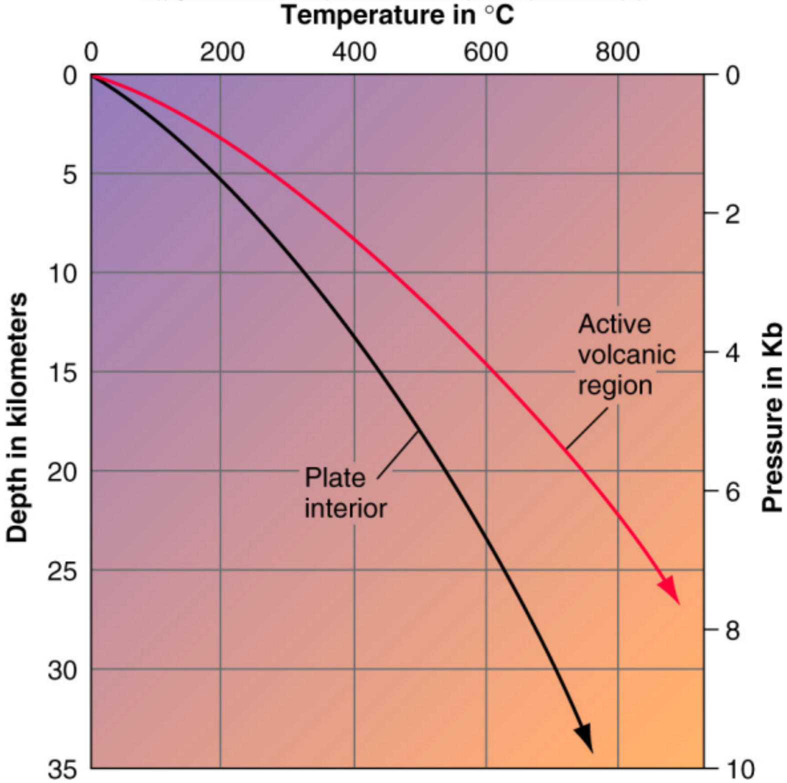


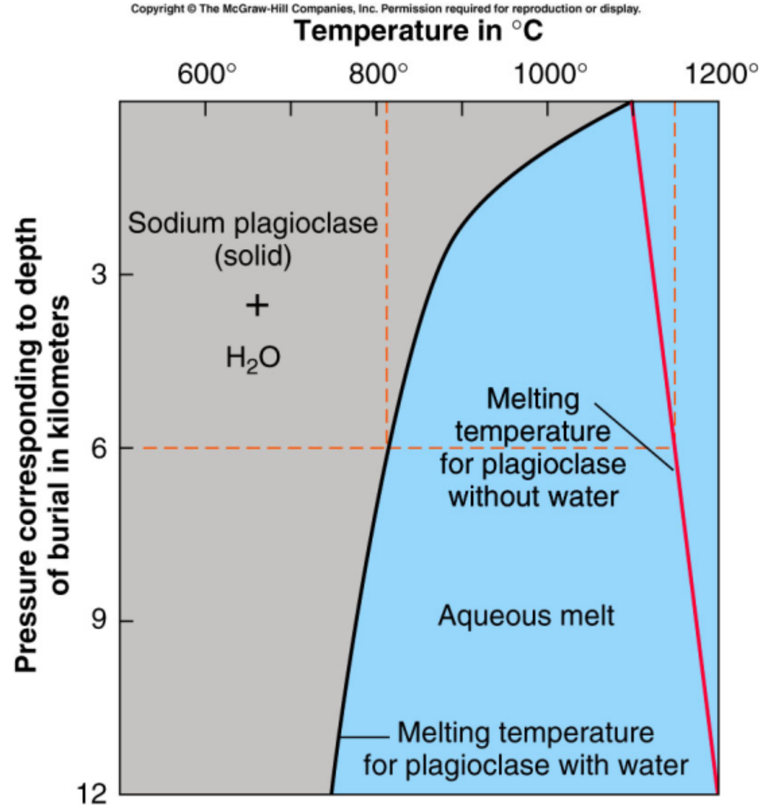

×1

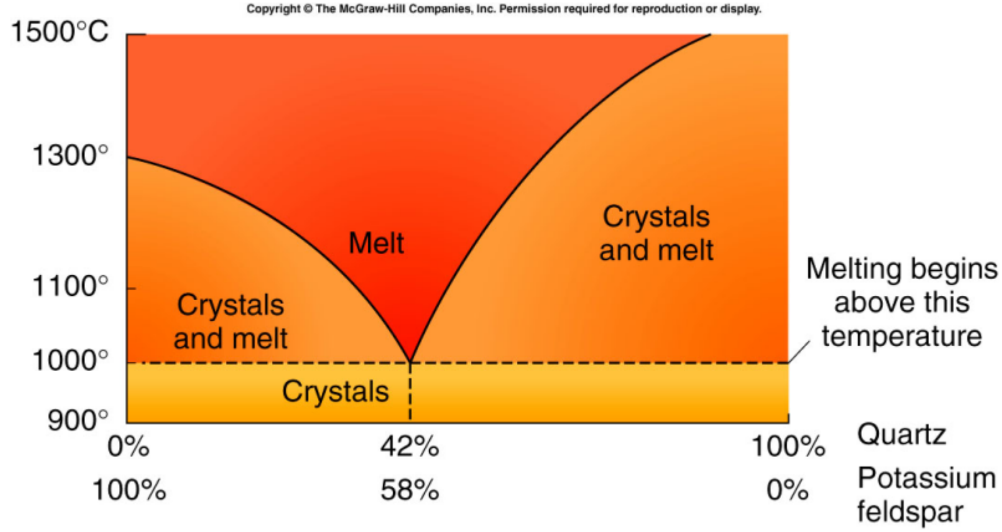


How Magma Forms

- *Heat from below*
  - Heat upward (by conduction and convection) from the very hot (>5000°C) core through the mantle and crust
- *Heat vs. pressure*
  - Melting point of minerals increases with increasing pressure
  - In the hottest regions within the upper mantle and crust, pressure can be low enough for melting to occur
- *Hot water under pressure*
  - Water becomes increasingly reactive at higher temperatures
  - At sufficient pressures and temperatures, highly reactive water vapor can reduce the melting point of rocks by over 200°C
- *Mineral mixtures*
  - Mixtures of minerals, such as quartz and potassium feldspar, can result in the melting of both at temperatures hundreds of degrees lower than either mineral would melt on its own

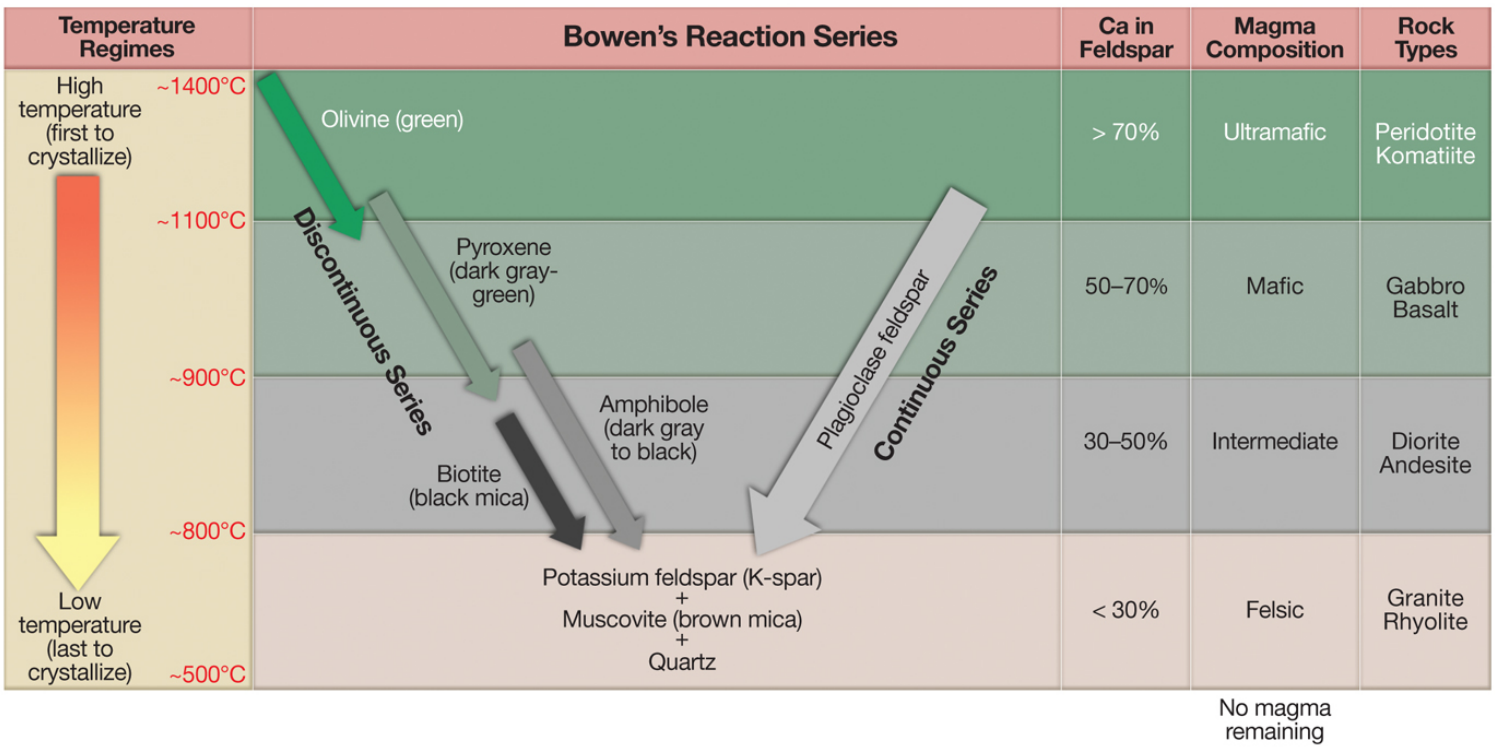

Temperature in °C
0
200
400
600
800
Depth in kilometers
0
5
10
15
20
25
30
35
Pressure in Kb
0
2
4
6
8
10
Active volcanic region
Plate interior


Temperature in °C
600°
800°
1000°
1200°
Pressure corresponding to depth of burial in kilometers
3
6
9
12
Sodium plagioclase (solid)
+
H2O
Melting temperature for plagioclase without water
Aqueous melt
Melting temperature for plagioclase with water


1500°C
1300°
1100°
1000°
900°
Melt
Crystals and melt
Crystals and melt
Crystals
Melting begins above this temperature
0%
42%
100%
Quartz
100%
58%
0%
Potassium feldspar

Bowen’s Reaction Series

- Minerals crystallize in a predictable order, over a large temperature range



- *Discontinuous series of crystallization*
  - Mafic minerals (olivine, pyroxene, amphibole, biotite) crystallize in sequence with decreasing temperature
  - As one mineral becomes chemically unstable in the remaining magma, another begins to form

- *Continuous series of crystallization*
  - Plagioclase feldspar forms with a chemical composition that evolves
  - (from Ca-rich to Na-rich) with decreasing temperature

- *Final stages of crystallization*
  - At lower temperatures, if there is still magma left, cooling will not affect the two end terms of the series (biotite and Na-plagioclase)
  - It will form quartz and K-feldspar directly out of magma

- A large variety of igneous rocks is produced by a large variety of *magma compositions*
- *Mafic magmas* will crystallize into *basalt* or *gabbro* if early-formed minerals are not removed from the magma
- *Intermediate magmas* will similarly crystallize into *diorite* or *andesite* if minerals are not removed
- Separation of early-formed ferromagnesian minerals from a magma body increases the silica content of the remaining magma
- Minerals melt in the reverse order of that in which they crystallize from a magma

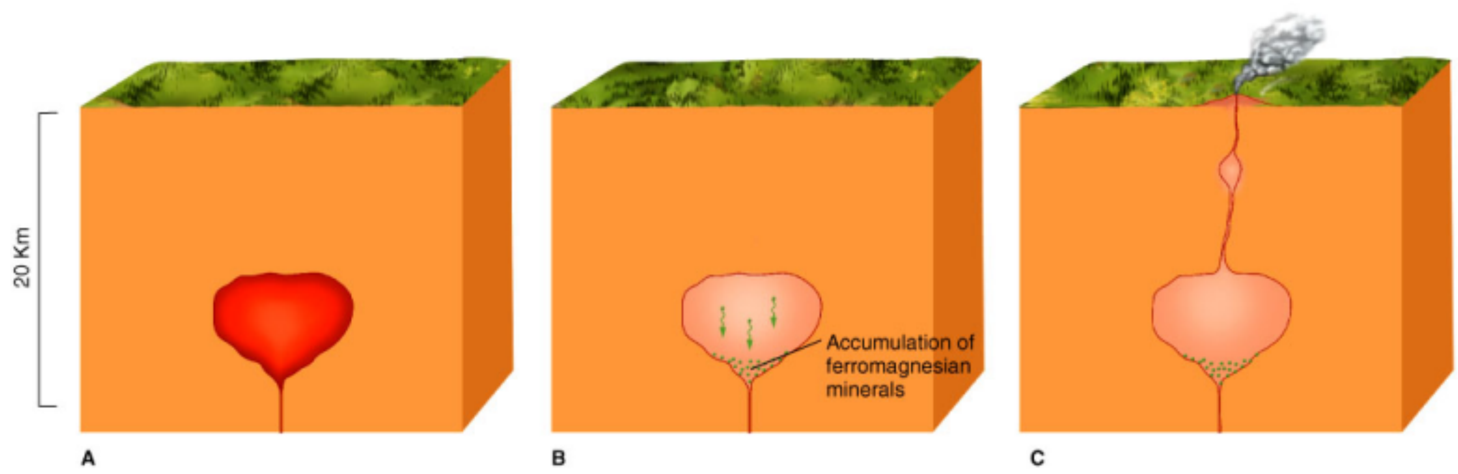
Magma Evolution

- A change in the composition of a magma body is known as *magma evolution*

- Magma evolution can occur by *differentiation*, *partial melting*, *assimilation*, or *magma mixing*

Differentiation

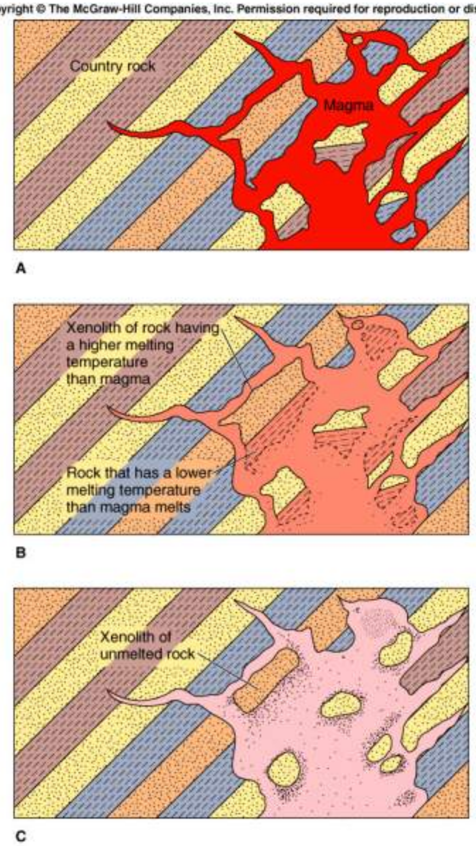
- *Differentiation* involves the changing of magma composition by the removal of denser early-formed ferromagnesian minerals by *crystal settling*

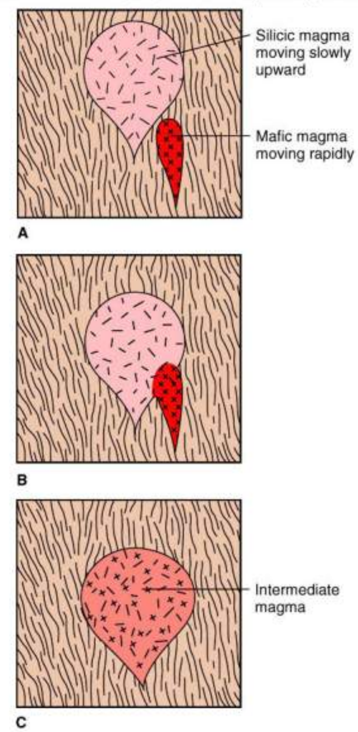


- *Partial melting* produces magmas less mafic than their source rocks, because lower melting point minerals are more felsic in composition

- *Assimilation* occurs when a hot magma melts and incorporates more felsic surrounding country rock

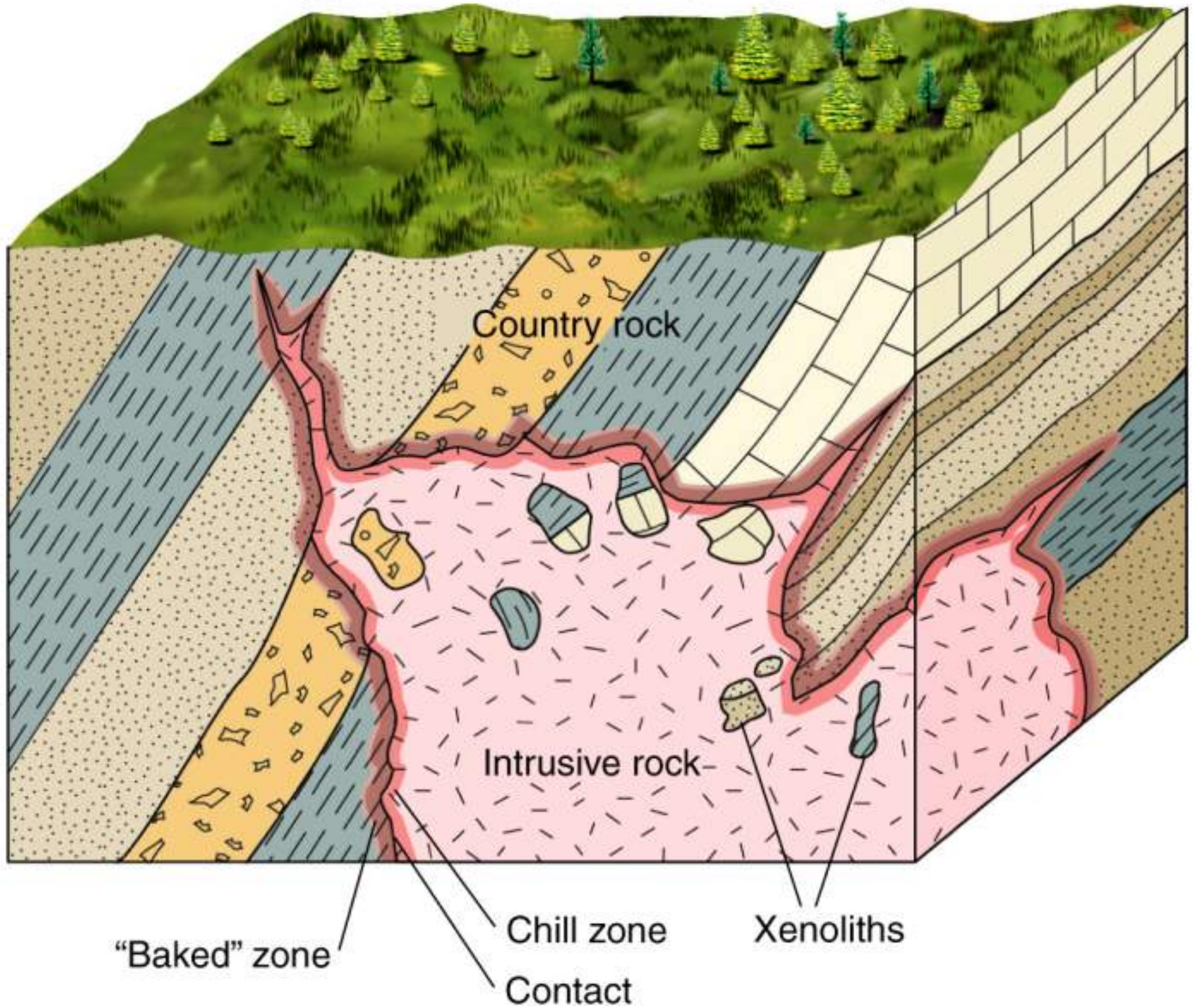
- *Magma mixing* involves the mixing of more and less mafic magmas to produce one of intermediate composition

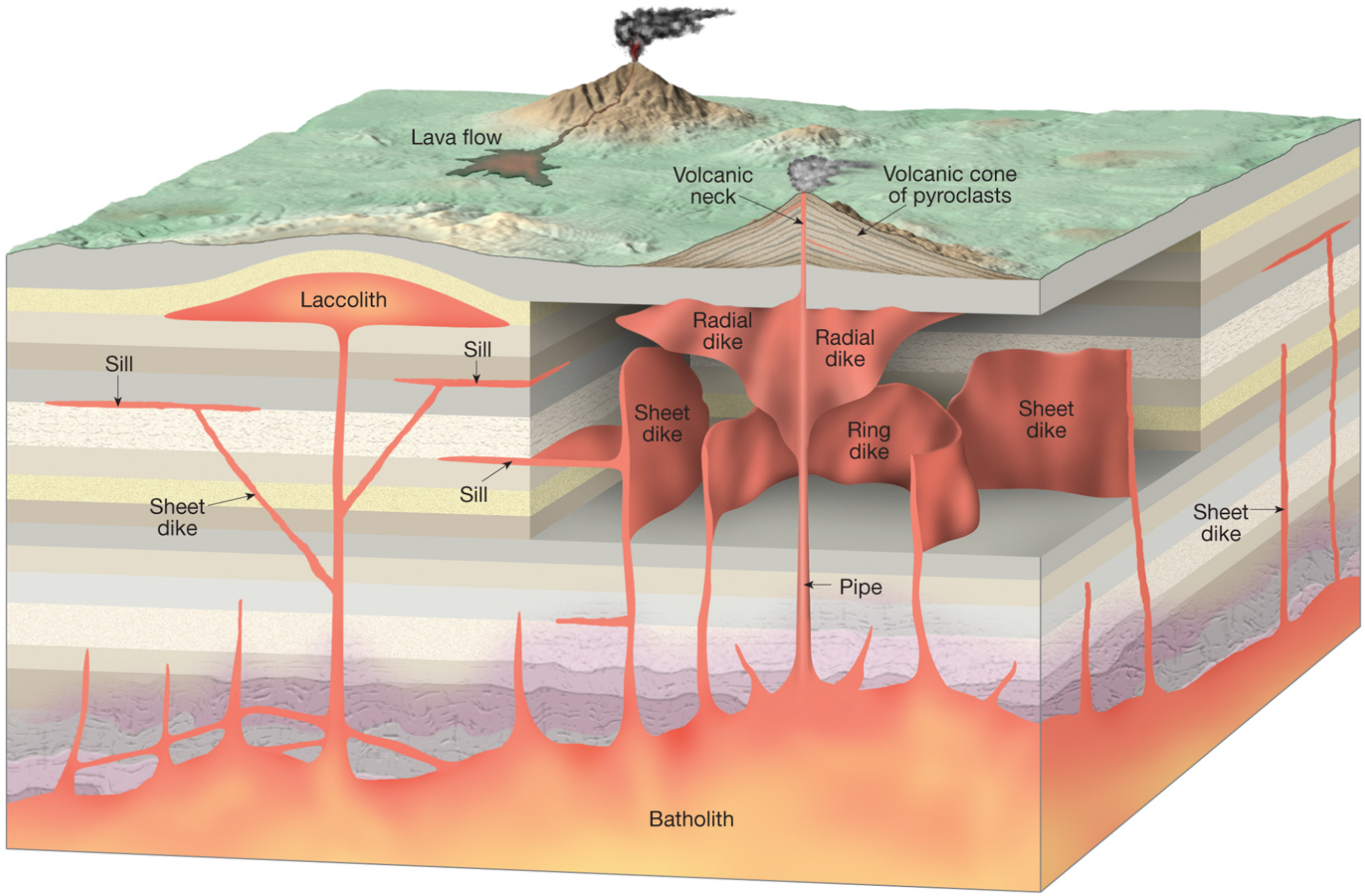




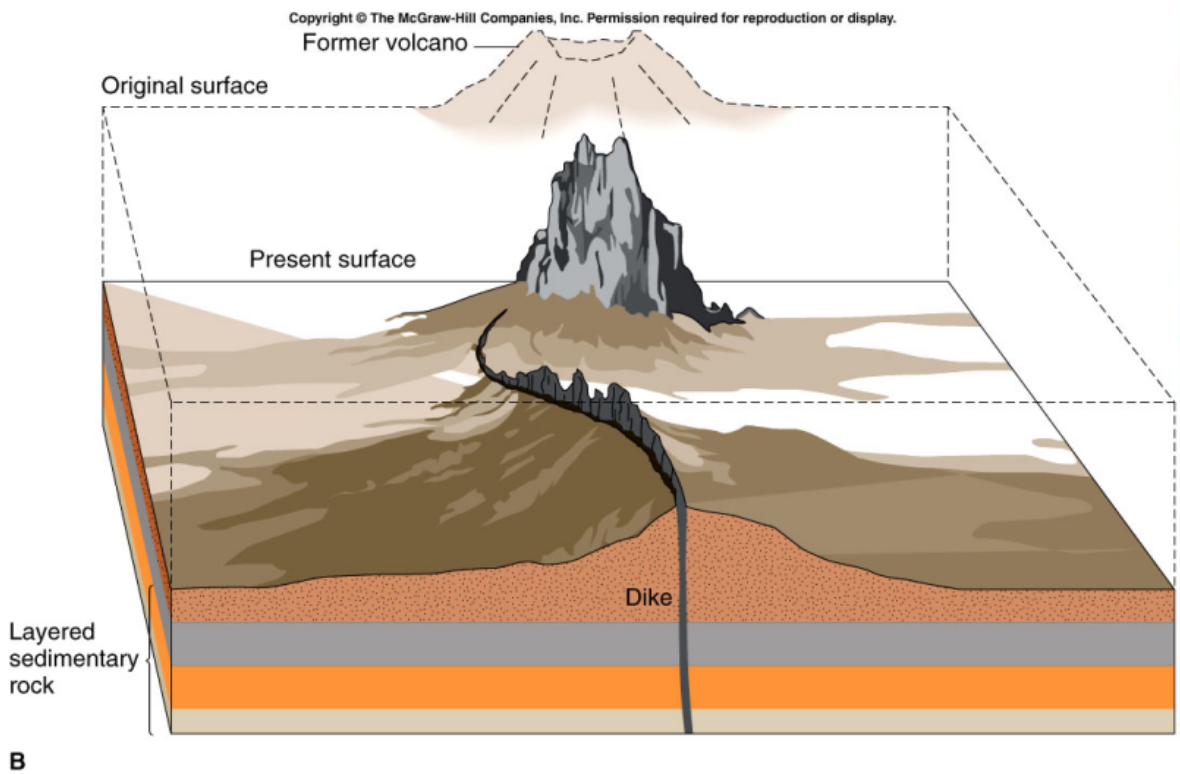
Intrusive Rock Bodies

- Intrusive rocks exist in bodies or structures that penetrate or cut through pre-existing *country rock*
- *Intrusive bodies* are given names based on their size, shape and relationship to country rock
  - Shallow intrusions
    - Form <2 km beneath Earth's surface
    - Chill and solidify fairly quickly in cool
    - country rock
    - Generally composed of fine-grained rocks
  - Deep intrusions: *Plutons*
    - Form at considerable depth beneath Earth's surface when rising blobs of magma (*diapirs*) get trapped within the crust
    - Crystallize slowly in warm country rock
    - Generally composed of coarse-grained rocks


Country rock
Intrusive rock
"Baked" zone
Chill zone
Contact
Xenoliths

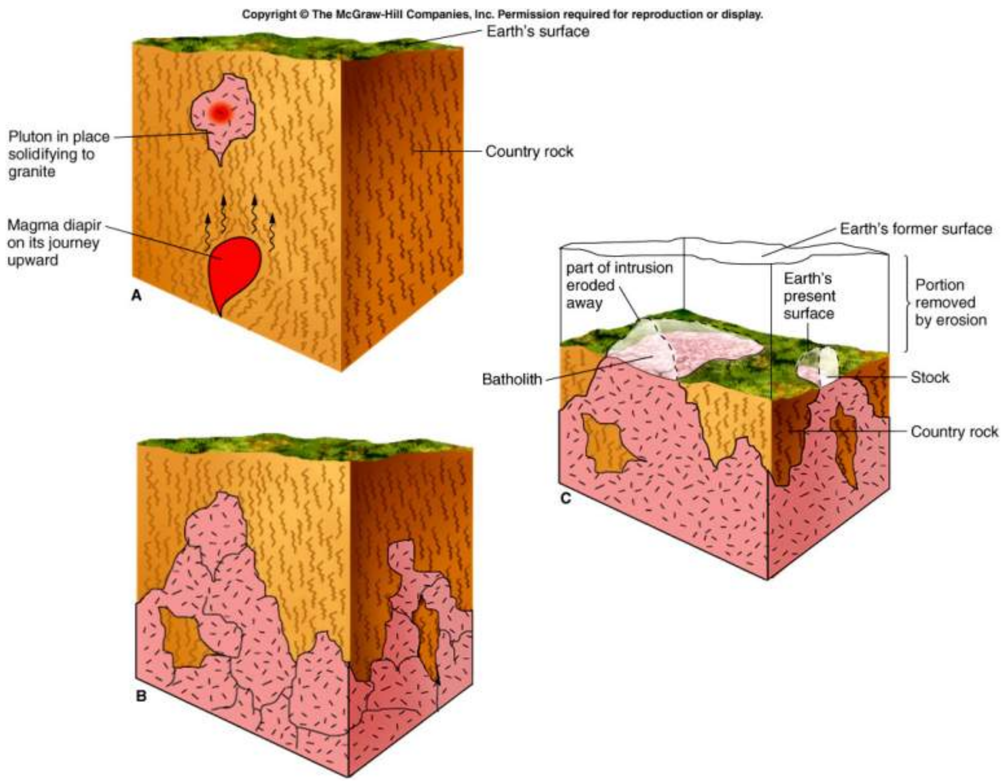

Lava flow
Volcanic neck
Volcanic cone of pyroclasts
Laccolith
Radial dike
Radial dike
Sill
Sill
Sheet dike
Ring dike
Sheet dike
Sill
Sheet dike
Sheet dike
Pipe
Batholith

Volcanic Necks



Shiprock, Farmington, New Mexico

Plutons



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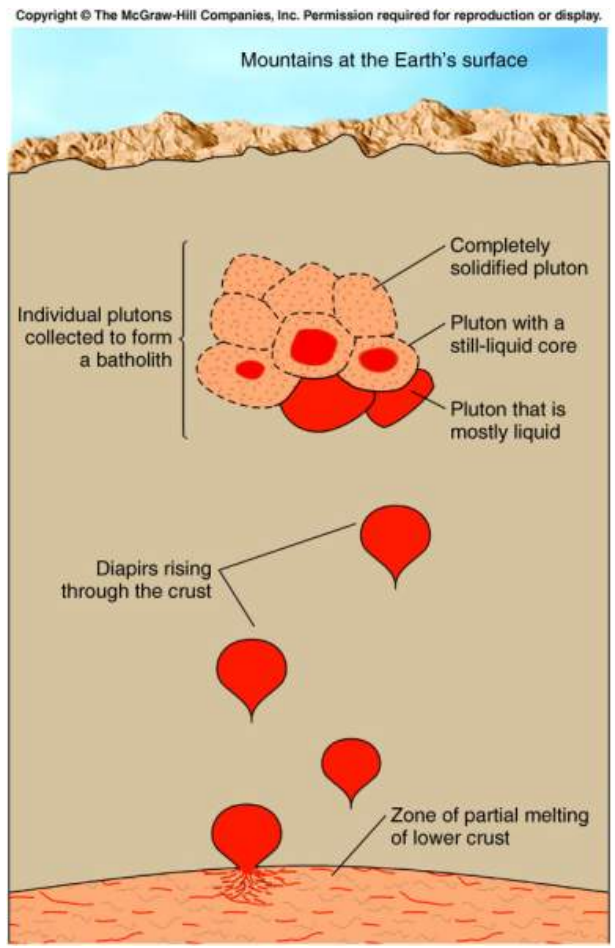
Earth's surface
Pluton in place solidifying to granite
Country rock
Magma diapir on its journey upward
A
B
Earth's former surface
part of intrusion eroded away
Earth's present surface
Portion removed by erosion
Batholith
Stock
Country rock
C



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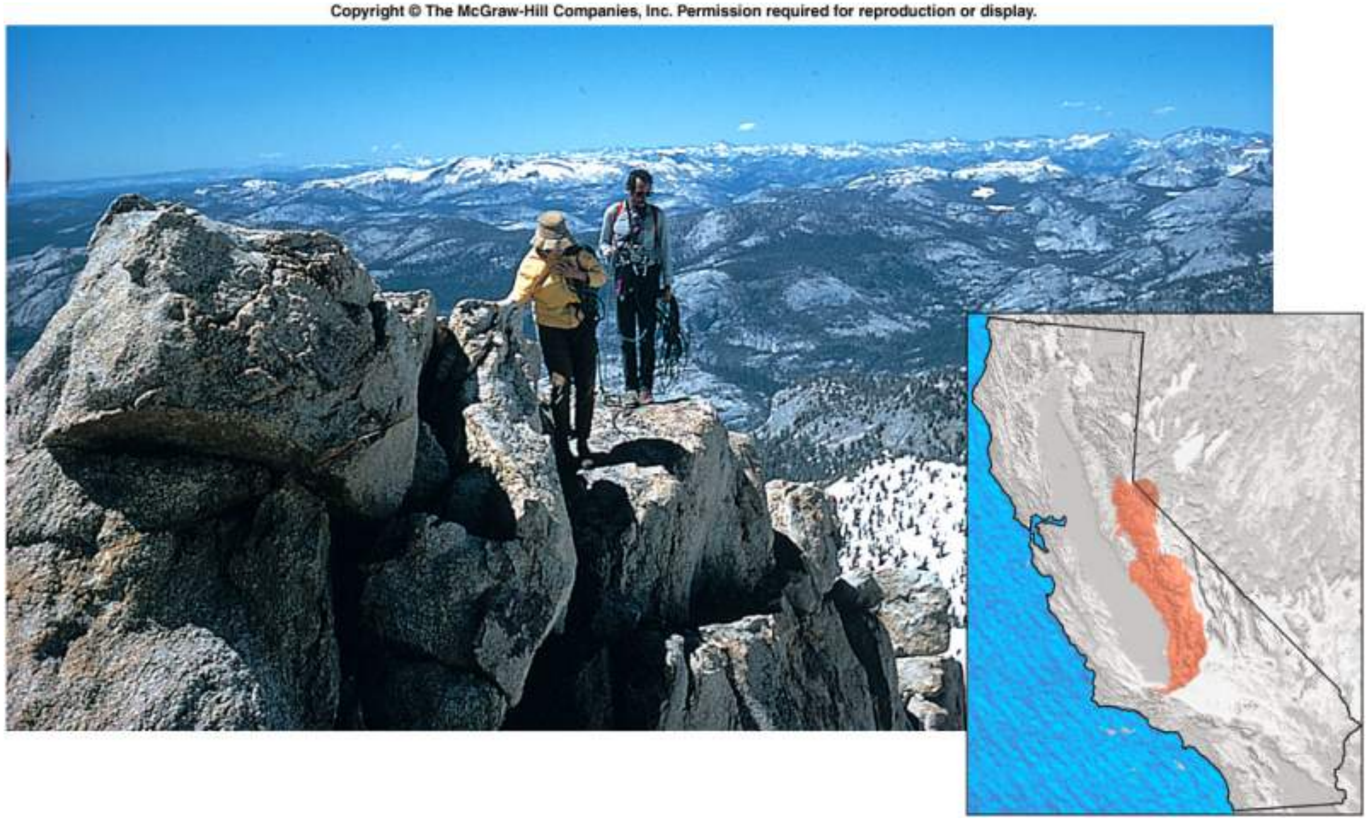
Mountains at the Earth's surface
Individual plutons collected to form a batholith
Completely solidified pluton
Pluton with a still-liquid core
Pluton that is mostly liquid
Diapirs rising through the crust
Zone of partial melting of lower crust

Sierra Nevada batholith

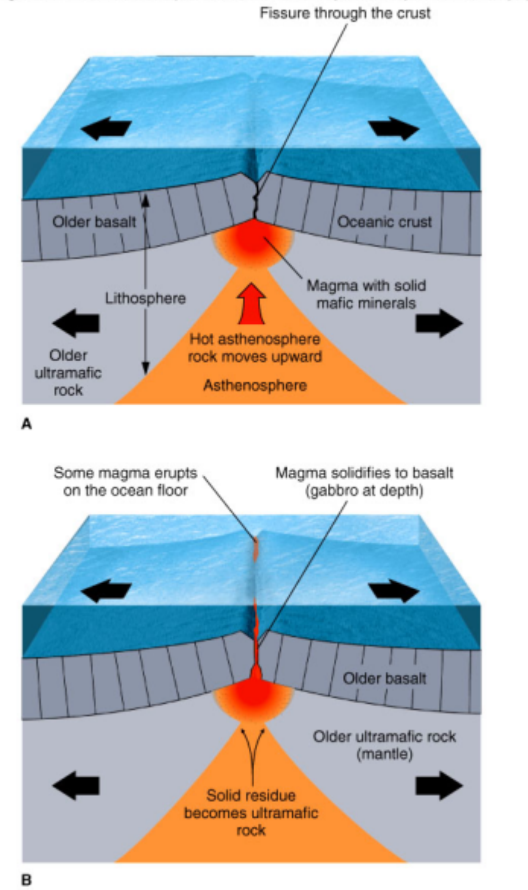


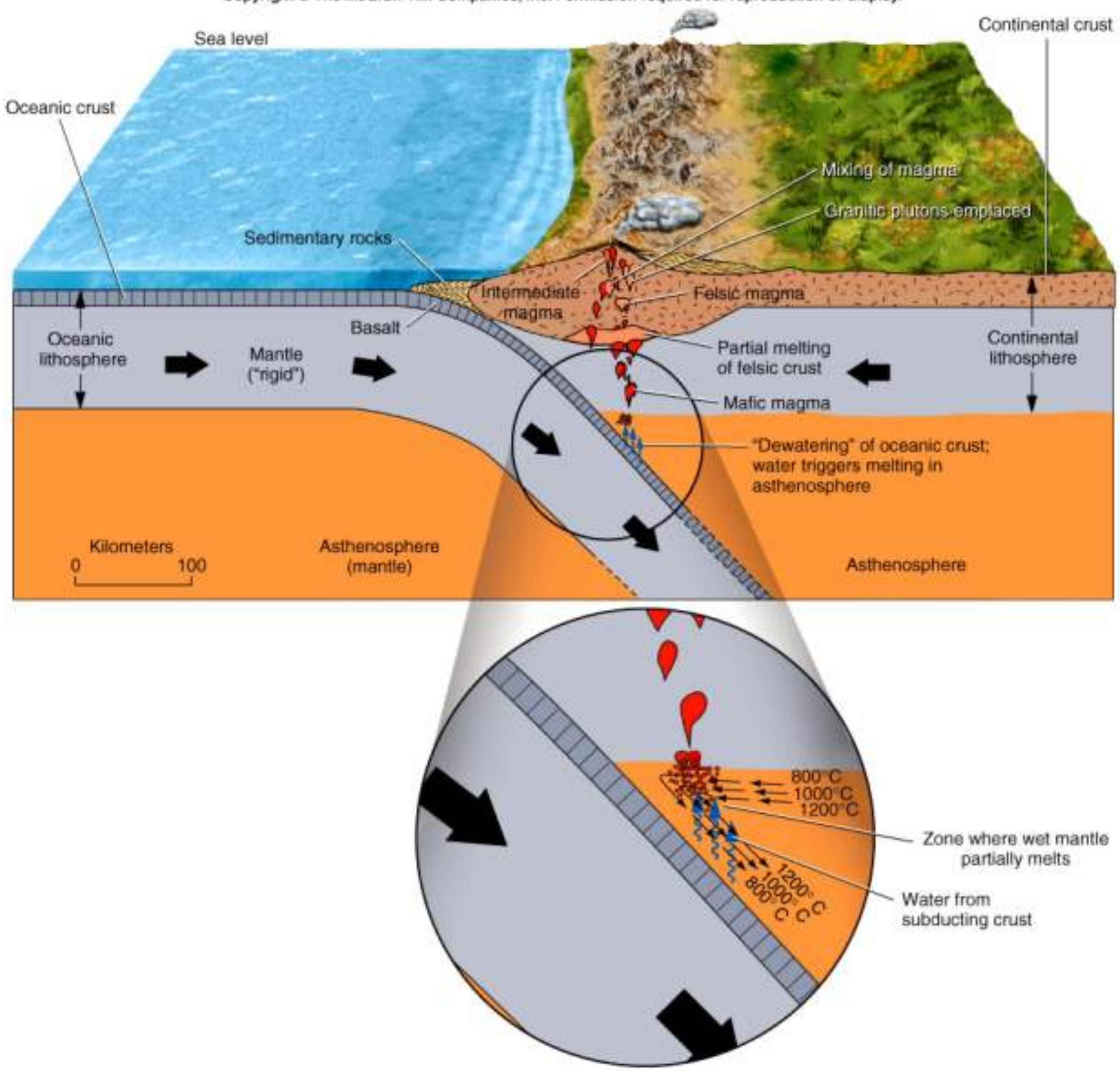
Igneous Activity and Plate Tectonics

- Igneous activity occurs primarily at or near tectonic plate boundaries

- Mafic igneous rocks are commonly formed at *divergent boundaries*
  - Increased heat flow and decreased overburden pressure produce mafic magmas from partial melting of the asthenosphere

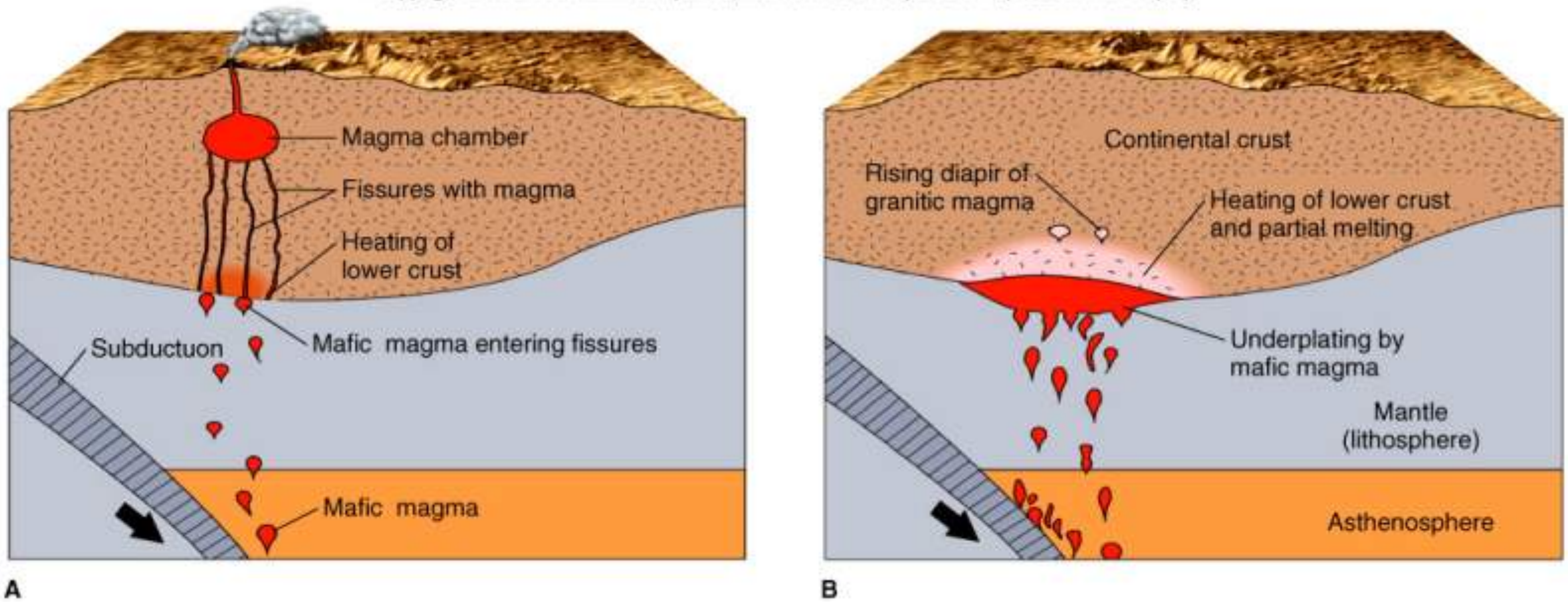
- Intermediate igneous rocks are commonly formed at *convergent boundaries*
  - Partial melting of basaltic oceanic crust produces intermediate magmas





Sea level
Continental crust
Oceanic crust
Mixing of magma
Granitic plutons emplaced
Sedimentary rocks
Intermediate magma
Felsic magma
Basalt
Oceanic lithosphere
Mantle ("rigid")
Partial melting of felsic crust
Continental lithosphere
Mafic magma
"Dewatering" of oceanic crust; water triggers melting in asthenosphere
Kilometers
0
100
Asthenosphere (mantle)
Asthenosphere
800°C
1000°C
1200°C
Zone where wet mantle partially melts
1200° C
1000° C
800° C
Water from subducting crust

- Felsic igneous rocks are commonly formed adjacent to *convergent boundaries*
  - Hot rising magma causes partial melting of the granitic continental crust
- *Intraplate volcanism*
  - Rising mantle plumes can produce localized hotspots and volcanoes when they produce magmas that rise through oceanic or continental crust
  - Hawaii is an example


Magma chamber
Fissures with magma
Heating of
lower crust
Subductuon
Mafic magma entering fissures
Mafic magma
A
Continental crust
Rising diapir of
granitic magma
Heating of lower crust
and partial melting
Underplating by
mafic magma
Mantle
(lithosphere)
Asthenosphere
B

The End