Lecture 2
Igneous rocks
Ch.4 text, pg. 142

- Photograph by J.D. Griggs on June 3, 1990
- Pahoehoe lava "toe" spills over a cobble beach into the sea, Kilauea Volcano, http://hvo.wr.usgs.gov

Why study igneous rocks?

- Igneous rocks constitute one of the three rock families
- Continental and oceanic crust are made of igneous rock
- Intrusive igneous activity, the cooling of magma within Earth, forms one of the most common igneous rocks, granite. At Mt. Rushmore, images of four presidents were carved in granite
- Several types of important mineral deposits are the result of intrusive igneous activity

Wicander and Monroe (2002)

Molten rocks - magma

- The majority of rocks we see on the surface are solid
- Only at active volcanoes are we lucky enough to see rocks in their molten state
- Understanding how rocks melt is important

Popocateptl, Mexico, December 2000

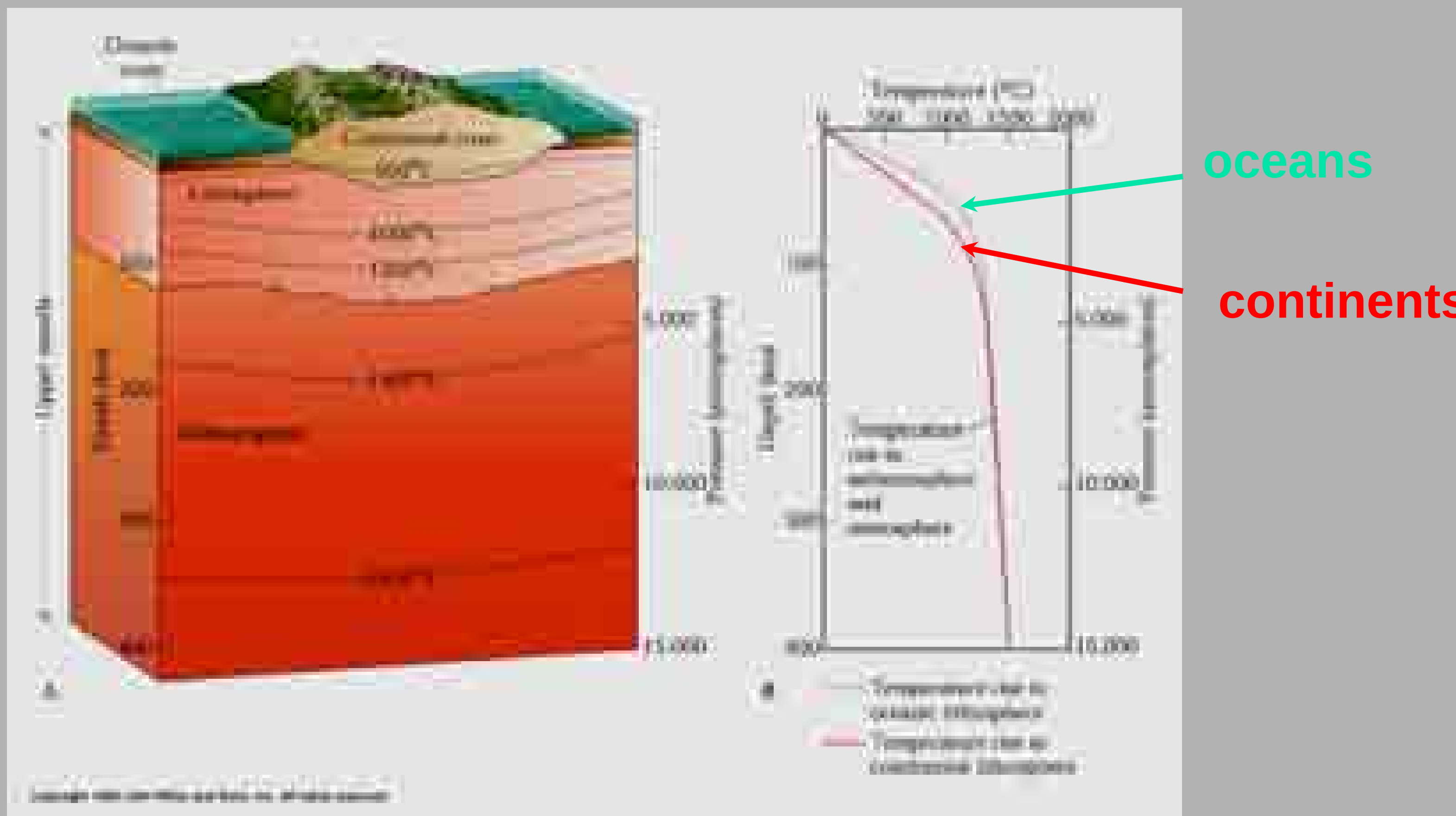
Why do rocks melt?

- In theory if you get rocks hot enough, just like ice, they will melt (>800°C)
- But as usual with geology it isn't that simple
- Minerals melt at different temps
- Pressure & water also complicate things


Popocateptl, Mexico, December 2000

Earth’s Internal Heat

Earth’s temperature increases with depth. This geothermal gradient is about 2.5°C per km near the surface but varies from area to area. The geothermal gradient decreases markedly at greater depths and is thought to be only 1°C per km in the mantle



Murck and Skinner (1999)

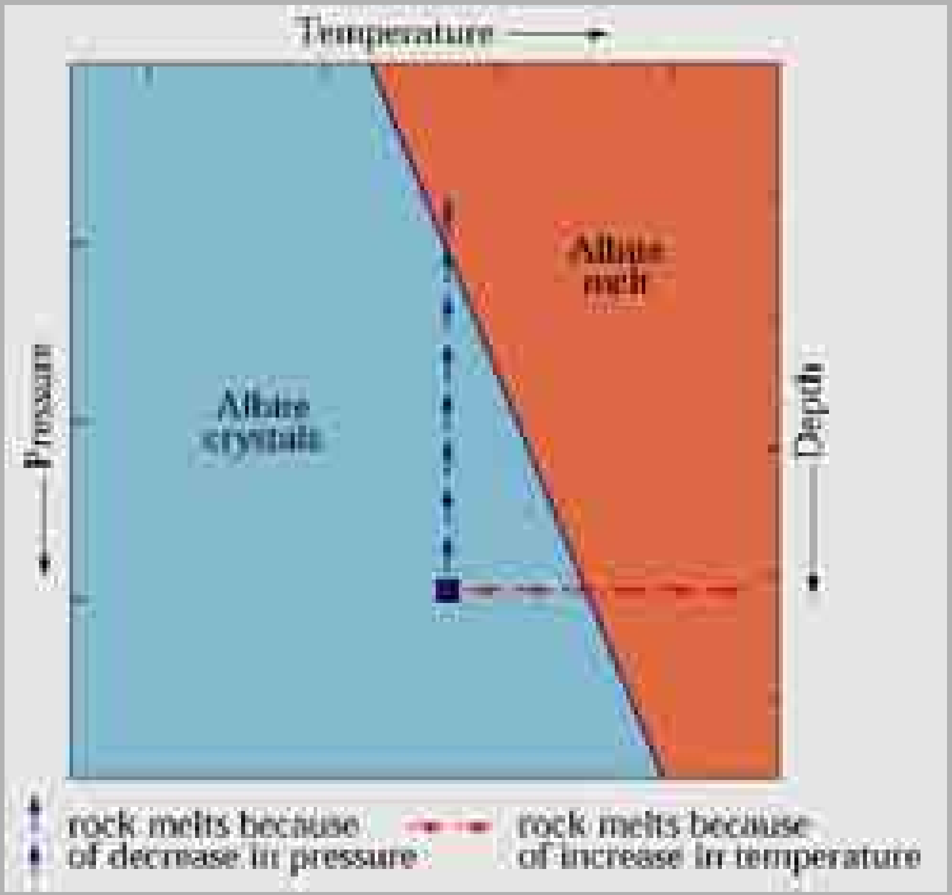
Earth's Internal Heat

- Most of Earth's internal heat derives from radioactive decay of uranium, thorium and potassium 40. Rock is a poor heat conductor, so it takes relatively little radioactive decay to build up significant heat.
- The temperature at the base of the crust is 800-1200°C whereas at the mantle-outer core boundary it is 3500-5000°C . Earth's center is estimated to be very near that of the Sun's surface, 6500°C .

Popocateptl, Mexico, December 2000

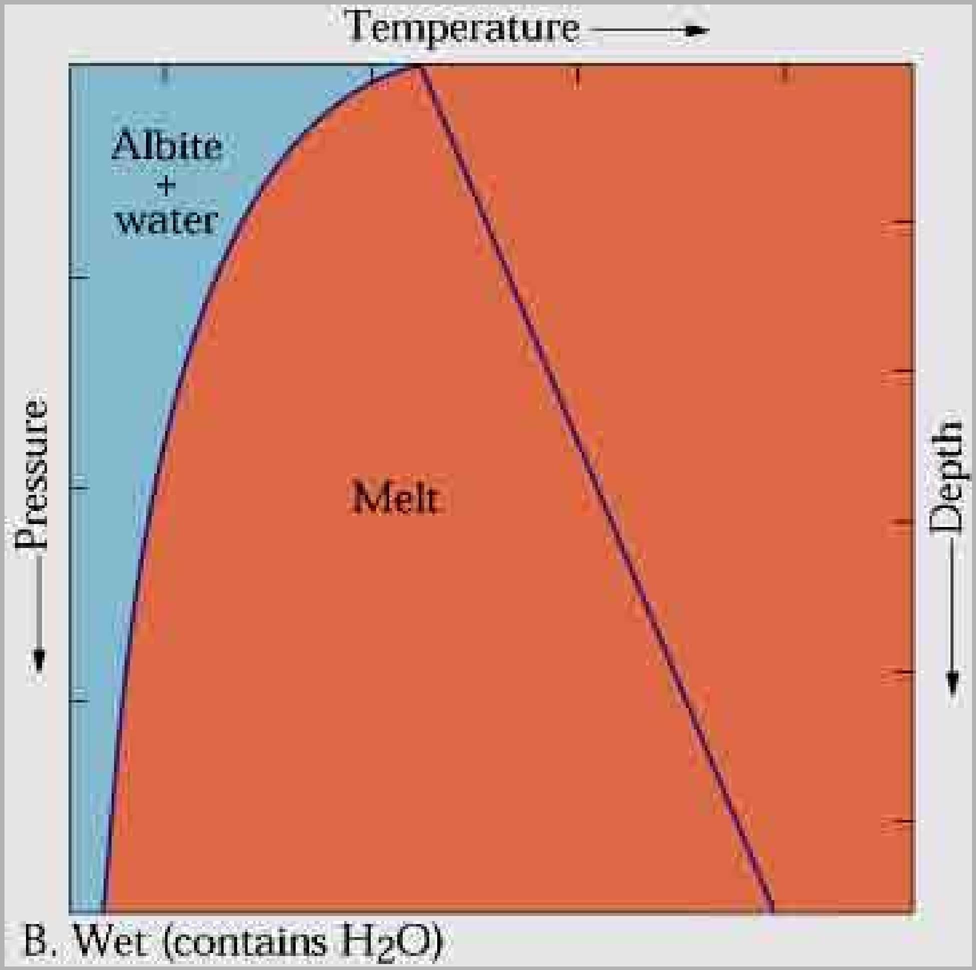
Effects of pressure

- Most lavas erupt at 1000°C & temps in the mantle are higher than this
- As P increases so does melting temp
- The reverse of this is decompression melting



Murck and Skinner (1999)

Effects of water

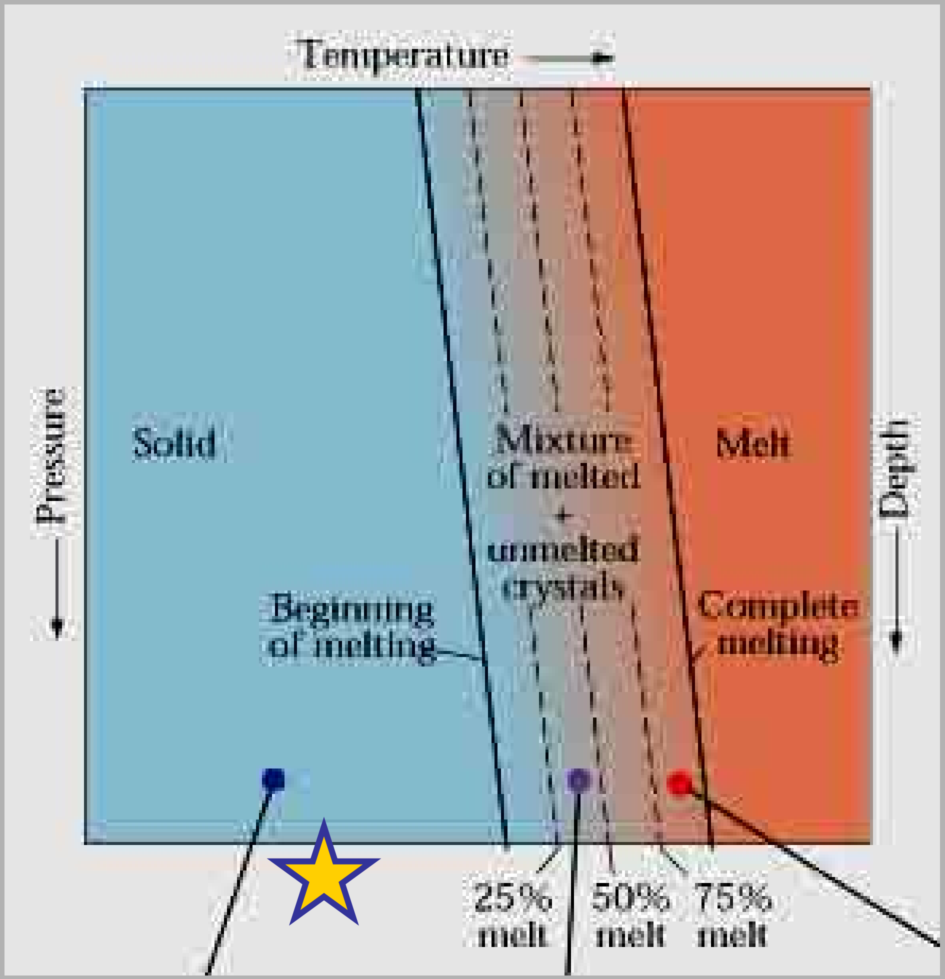


Murck and Skinner (1999)

- H_2O (or water vapour) will lower the melting temp
- Works the same way that salt does on ice
- Effect of water increases with pressure

Partial melting

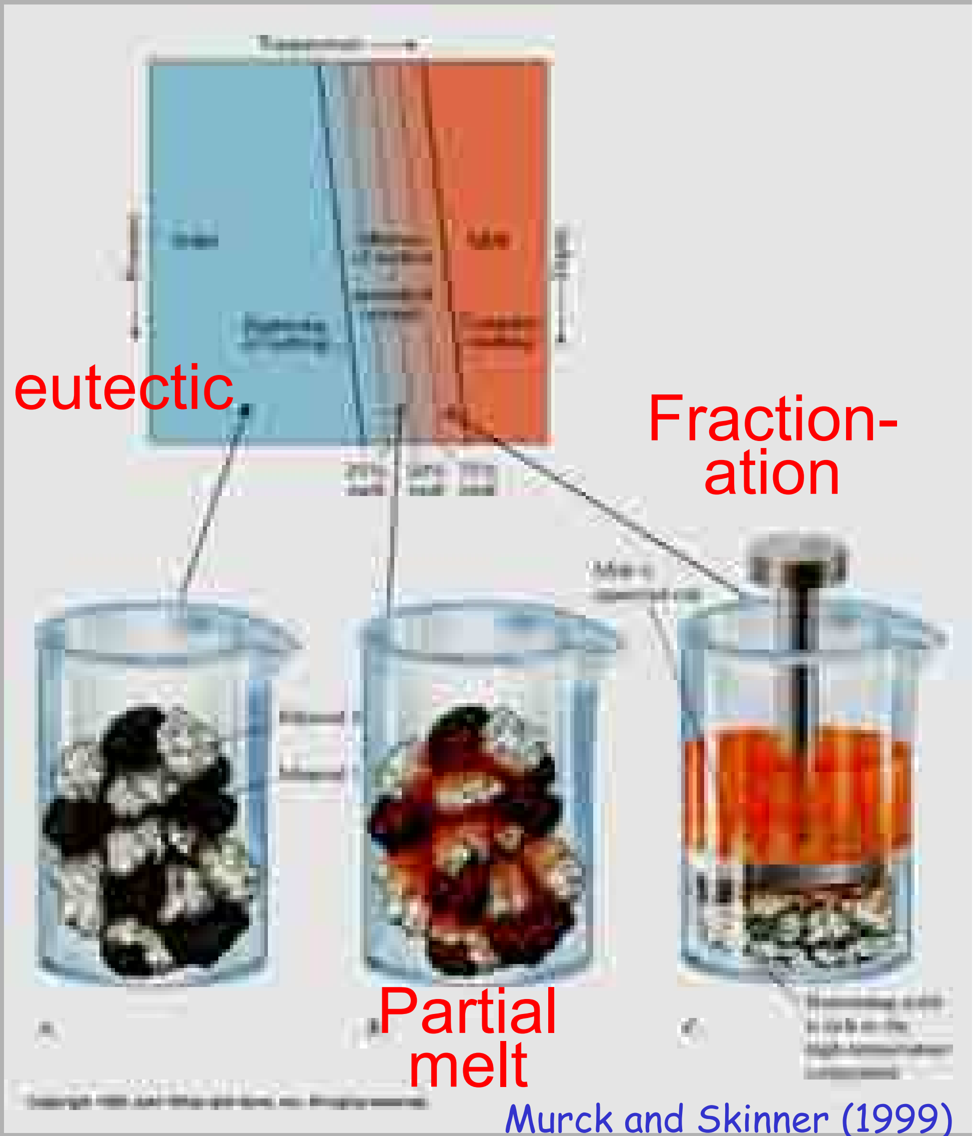
- Rocks melt over a range of temps
- The point at which melting begins is the eutectic
- This is generally lower than the melting temps of individual minerals



Murck and Skinner (1999)

Partial melting

- **Occurs when some components melt first**
- **Also called a fractional melt**
- **Fractionation occurs when the melt is separated from the residual solid**



Murck and Skinner (1999)

Igneous rocks

- Igneous rocks form by cooling and crystallization of molten rock
- Molten material residing below Earth's surface is known as magma, whereas the same material at the surface is called lava.
- Igneous rocks formed of cooled lava or volcanic ejecta are common, but most molten material cools below Earth's surface, producing bodies of igneous rock known as plutons.
- Intrusive and Extrusive

Puu'oo, Kilaeua, http://hvo.wr.usgs.gov

Properties of Magma and Lava

- All igneous rocks derive either directly or indirectly from magma. Lava is magma that has reached Earth's surface.
- Plutonic (intrusive) igneous rocks form as magma cools and crystallizes within Earth.
- Volcanic (extrusive) igneous rocks form by cooling and crystallization of lava or by consolidation of pyroclastic material, such as volcanic ash, ejected from volcanoes.

Murck and Skinner (1999)

Properties of magma

- It is not possible to study magma directly (can get very close in places like Hawaii)
- However, studying lavas can tell us a lot
  - Magmas have a range of compositions
  - Characterized by high temperatures
  - Have the ability to flow

Magma Composition

- Silicate minerals are by far the most abundant minerals in the crust and silica is the most abundant constituent of magma.
- The bulk chemical composition of magma is dominated by the most abundant minerals

  Si - Al - Fe - Ca - Mg - Na - K - H - O
- These major elements occur as oxides (SiO_2)
- SiO_2 = ~45 to 75% of rocks
- Water and CO_2 make up 0.2 - 3 %
- Minor and trace elements make up the remainder

How hot are magma and lava?

- Erupting lavas range in temperature from 1000° to 1200°C. Magma must be even hotter, but direct measurements are not possible.
- Rock is a poor heat conductor. Therefore, interiors of thick lava flows can remain hot for months or years, whereas plutons may take thousands to millions of years to cool completely.

Wicander and Monroe (2002)

Viscosity - Resistance to Flow

- A liquid's resistance to flow is referred to as viscosity
- Higher temperatures correlate to less resistance to flow
- Silica content exerts the greatest control on magma and lava viscosity. Mafic lava can flow 10s to 100s of kms, but felsic lava often flows only a few hundred ms

Magma Type	Silica Content	Na, K Al	Ca, Fe, Mg	Viscosity
Mafic	45 - 52%	↓	Increase	low
Intermed.	53 - 65	↓	↑	medium
Felsic	> 65	Increase	↑	high

Viscosity

More viscous

Wicander and Monroe (2002)

Less viscous

Murck and Skinner (1999)

Silica content & viscosity

- The SiO_4^{4-} anions that form the building blocks of most minerals are also present in magmas
- These anions polymerize in magmas
- That is they link by sharing oxygens
- As the polymerized groupings become larger the magma becomes more viscous
- So high silica contents = high viscosity

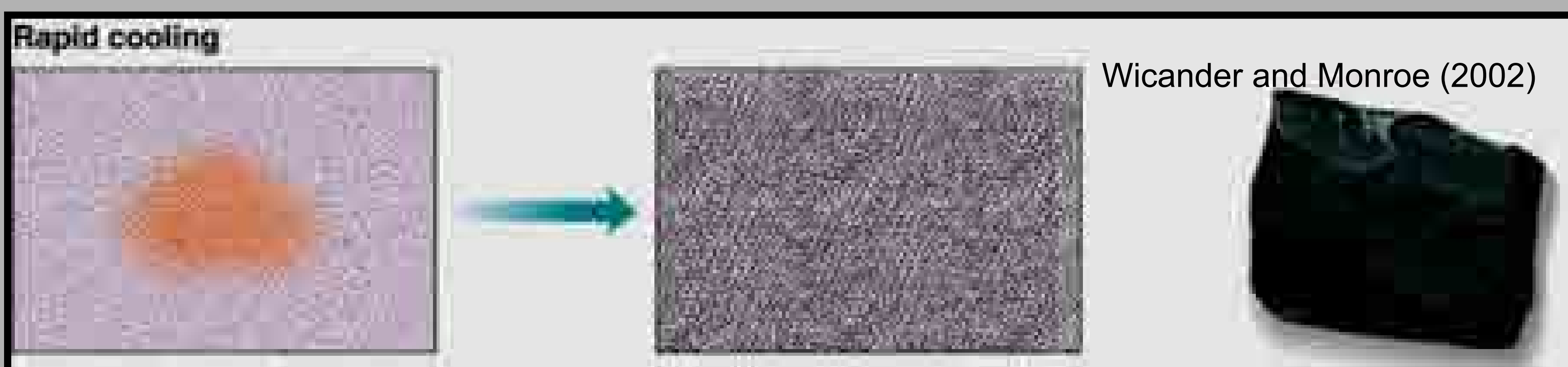
Cooling rates

- Intrusive (plutonic) rocks cool slowly while extrusive (volcanic) rocks cool quickly
- The cooling rate determines whether or not crystals form
- So cooling and crystallization determine the texture of the rock

- Lava tube in Big Red Cave, Hawaii. Photo by Dave Bunnell,
- NSS News v60, June 2002

Texture

- Texture refers to the size, shape and arrangement of minerals' grains and is an important characteristic of igneous rocks. Grain size records cooling history.
- An aphanitic texture consists of an aggregate of very small mineral grains, too small to be seen clearly with the naked eye. Aphanitic textures record rapid cooling at or very near Earth's surface and are characteristic of extrusive (volcanic) igneous rocks.



Wicander and Monroe (2002)

Volcanic textures: Quenching

- **Very rapid cooling of lava produces a "glassy texture". The lava cools so quickly that atoms do not have time to arrange in an ordered three-dimensional network typical of minerals. The result is natural glass, or obsidian**

Murck and Skinner (1999)

Wicander and Monroe (2002)

Volcanic textures: Vesicular

- **Gases trapped in cooling lava can result in numerous small cavities, vesicles, in the solidified rock.**

Wicander and Monroe (2002)

Vesicular texture

Murck and Skinner (1999)

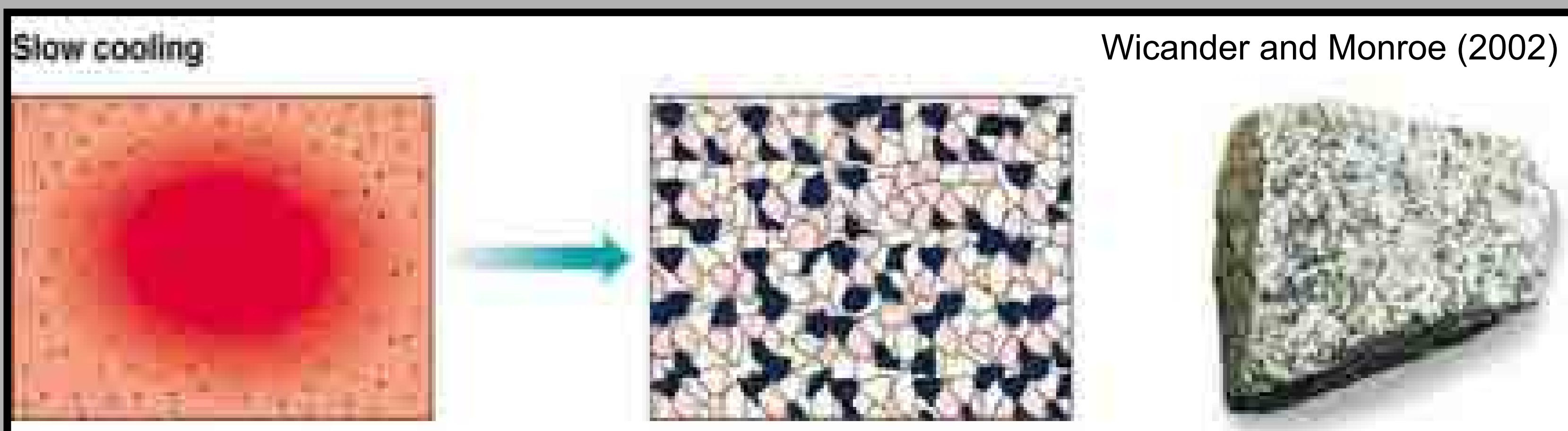
Volcanic textures: Pyroclastic

- Igneous rocks formed of mineral and rock fragments ejected from volcanoes by explosive eruptions have pyroclastic (fragmental) textures. The ejected ash and other debris eventually settles to the surface where it is consolidated to form a pyroclastic igneous rock.
- Much of this material consists of angular pieces of volcanic glass measuring up to 2mm

Wicander and Monroe (2002)

Plutonic textures: Phaneritic

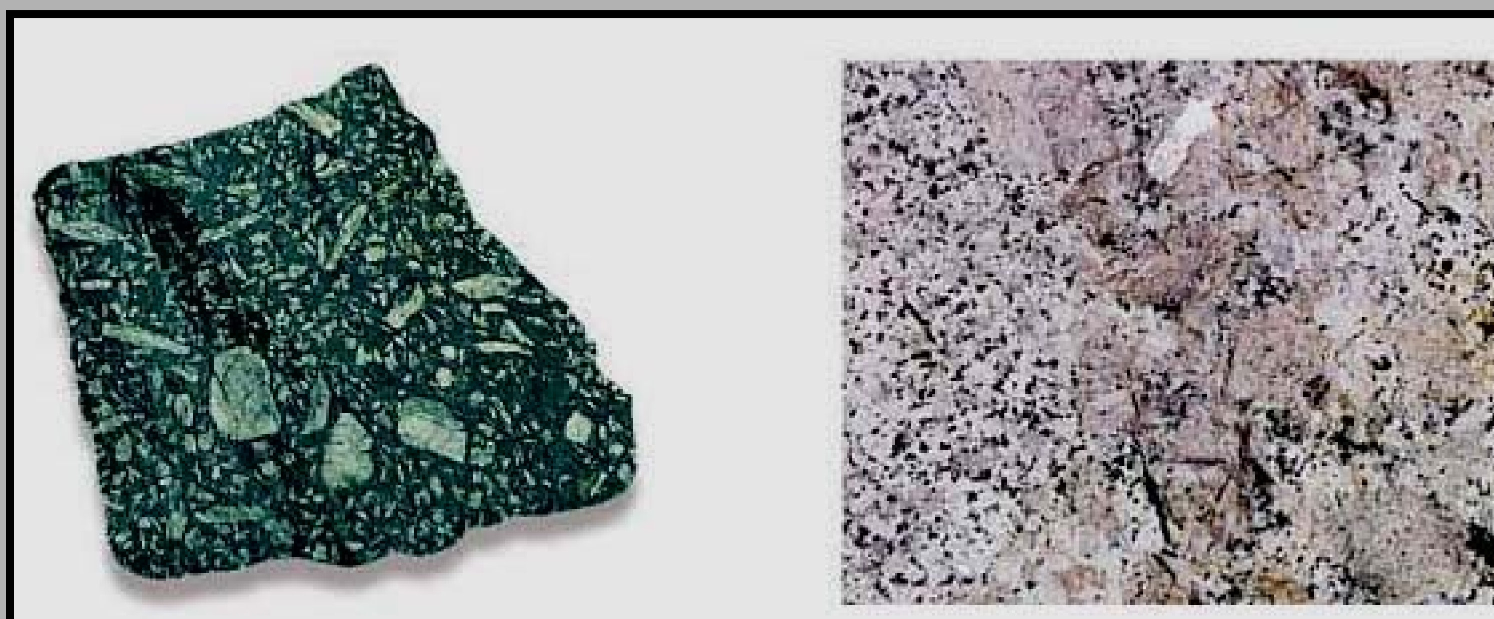
- A phaneritic texture consists of an aggregate of large mineral grains, easily visible without magnification. Phaneritic textures record slow cooling within Earth and are characteristic of intrusive (plutonic) igneous rocks.



Wicander and Monroe (2002)

Plutonic textures: Porphyritic

- Igneous rocks comprised of minerals of two or more markedly different grain sizes have a porphyritic texture. The coarser grains are called phenocrysts and the smaller grains groundmass. Porphyritic textures result from changes in cooling rate and include both aphanitic porphyrys and phaneritic porphyrys.



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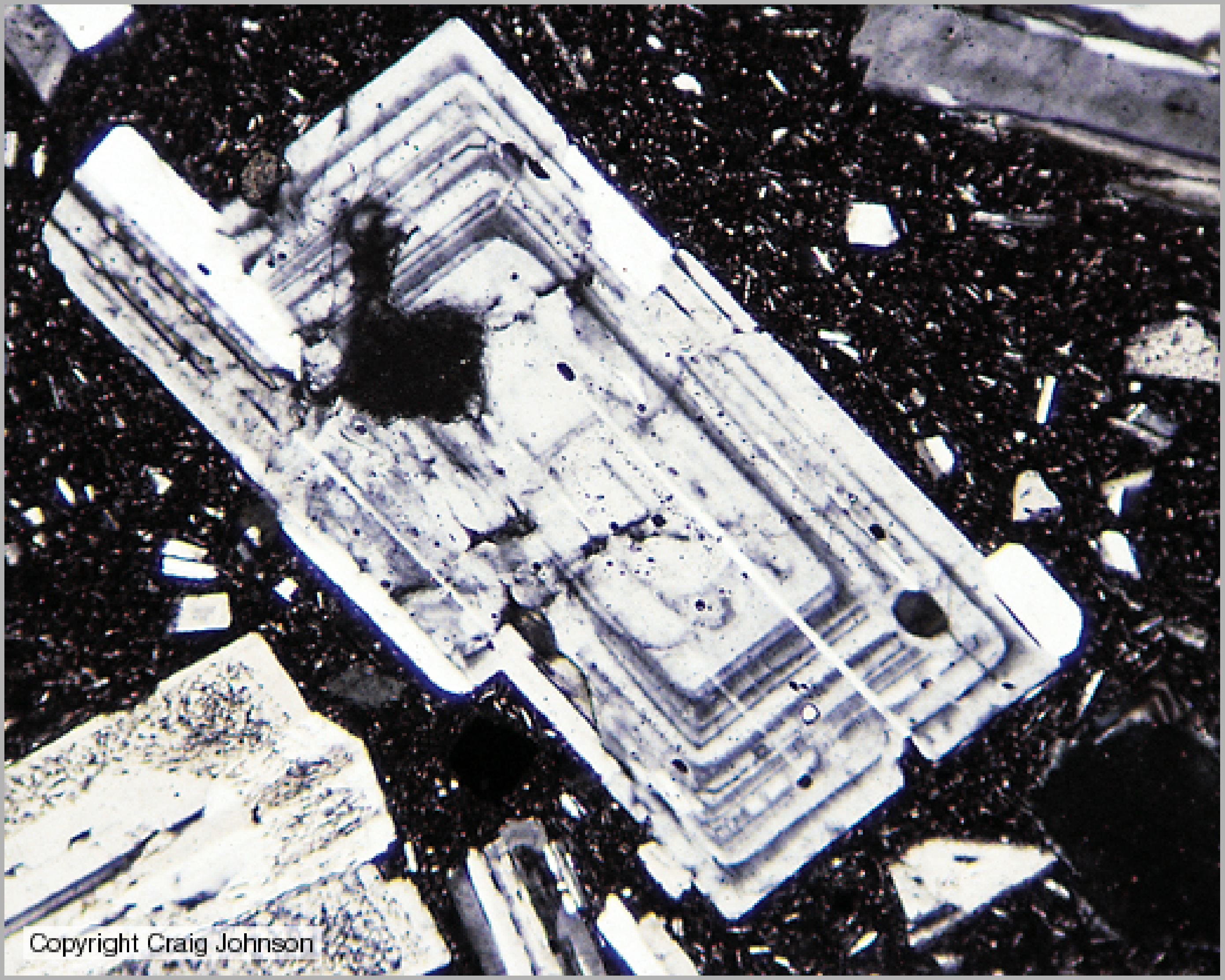
Feldspar phenocryst



Murck and Skinner (1999)

Tourmaline pegmatite

Tourmaline pegmatite, Montgomery (1998)

Chemical composition

- Chemical composition determines which minerals crystallize
- We use the mineral assemblage to classify igneous rocks
- The mineral assemblage is independent of cooling rate

Popocateptl, Mexico, December 2000

Mineral composition

- Common igneous rocks are composed of one or more of six minerals
  - Quartz, feldspar, mica, amphibole, pyroxene and olivine
- Quartz and feldspar are light coloured minerals
- Amphibole, pyroxene and olivine are dark ferromagnesian minerals
- Rocks dominated by qtz + fspar are felsic
- Rocks dominated by ferromagnesian minerals are mafic

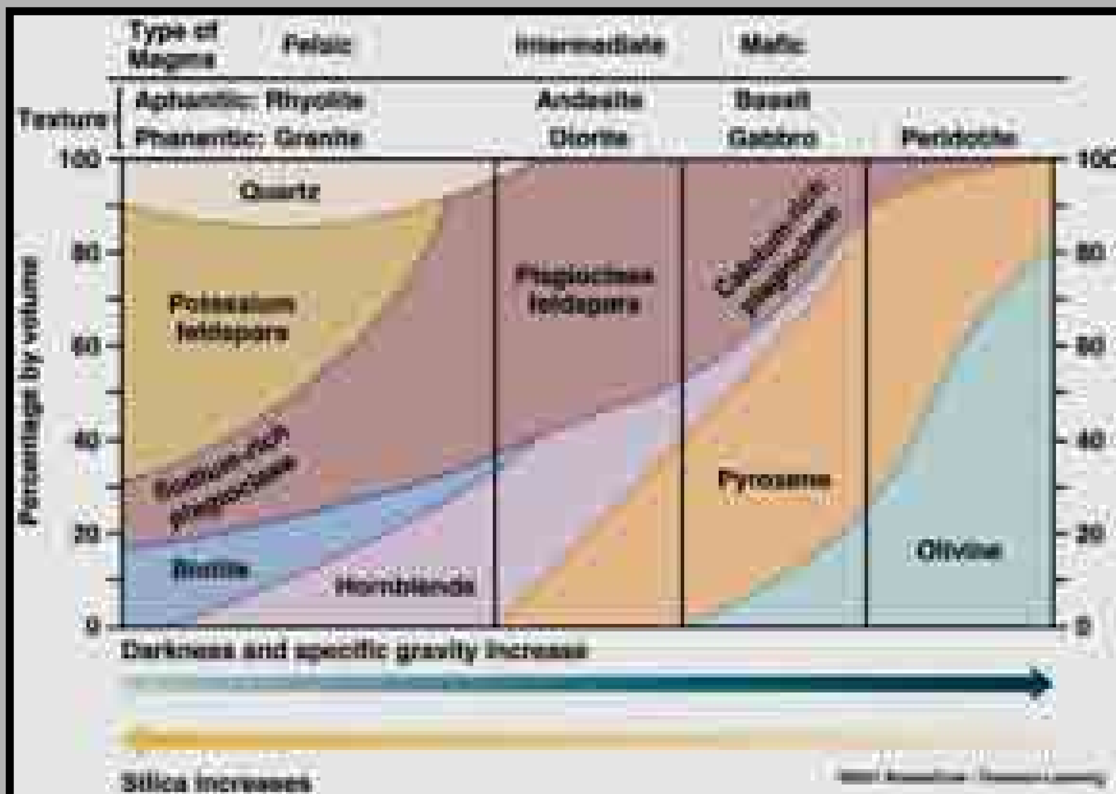
Magma Composition

- Felsic magma is formed of melted crustal rocks and is especially high in silica (>65%), but also contains considerable Al, Ca, Na, Fe, Mg, and K.
- Mafic magma is formed of melted rock of the upper mantle and contains comparatively less Si (45-52%) and significantly more Fe and Mg.
- Intermediate magma

Popocateptl, Mexico, December 2000

Classifying Igneous Rocks

- Most igneous rocks can be classified on the basis of texture and composition.
- Compositional equivalents



Wicander and Monroe (2002), and your lab manual!

Igneous Rock Classification Chart

Colour → / **Textures** ↓	Felsic	Intermediate	Mafic	**Ultramafic**
Phaneritic	Granite	Diorite	Gabbro	Peridotite
Aphanitic	Rhyolite	Andesite	Basalt	
Vesicular	Pumice		Scoria	
Glassy	Obsidian			

Composition of Igneous Rocks

- Magma composition controls the composition of the igneous rocks formed by cooling and crystallization.
- Due to crystal settling, assimilation, magma mixing and sequential mineral crystallization, a parent magma can yield igneous rocks of a variety of compositions.

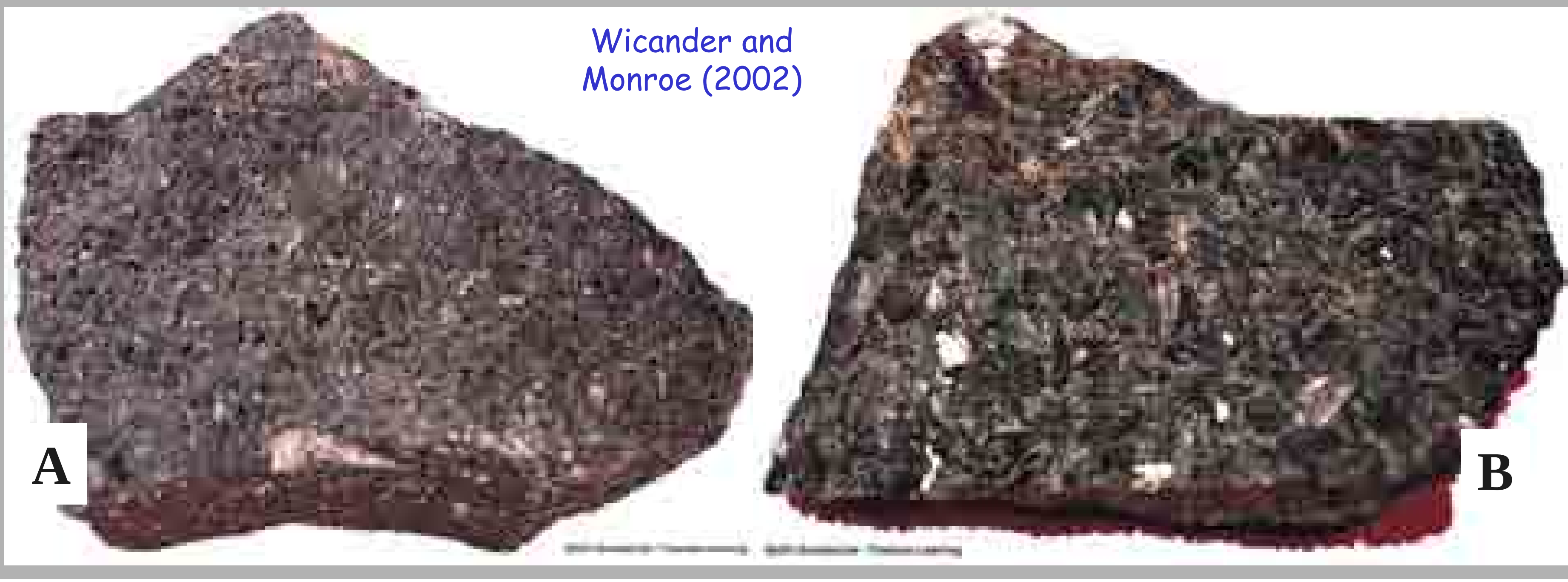
Classifying Igneous Rocks

- Ultramafic igneous rocks contain <45% Si and are composed of ferromagnesian (Fe- & Mg-rich) silicate minerals. These rocks are commonly dark colored because the minerals that comprise them, olivine, pyroxene, and Ca-plagioclase, are black to olive green. The ultramafic rock peridotite is composed almost entirely of olivine. Peridotite makes up the upper mantle, but like most ultramafic rocks, it is rare at the surface.

Wicander and Monroe (2002)

Classifying Igneous Rocks

Mafic (45-52% silica) igneous rocks are dark colored because they are largely composed of Ca-plagioclase and pyroxene. Basalt is fine-grained, whereas gabbro is coarse-grained. Basalt is the most common extrusive (volcanic) igneous rock. The lower part of oceanic crust is comprised of gabbro.



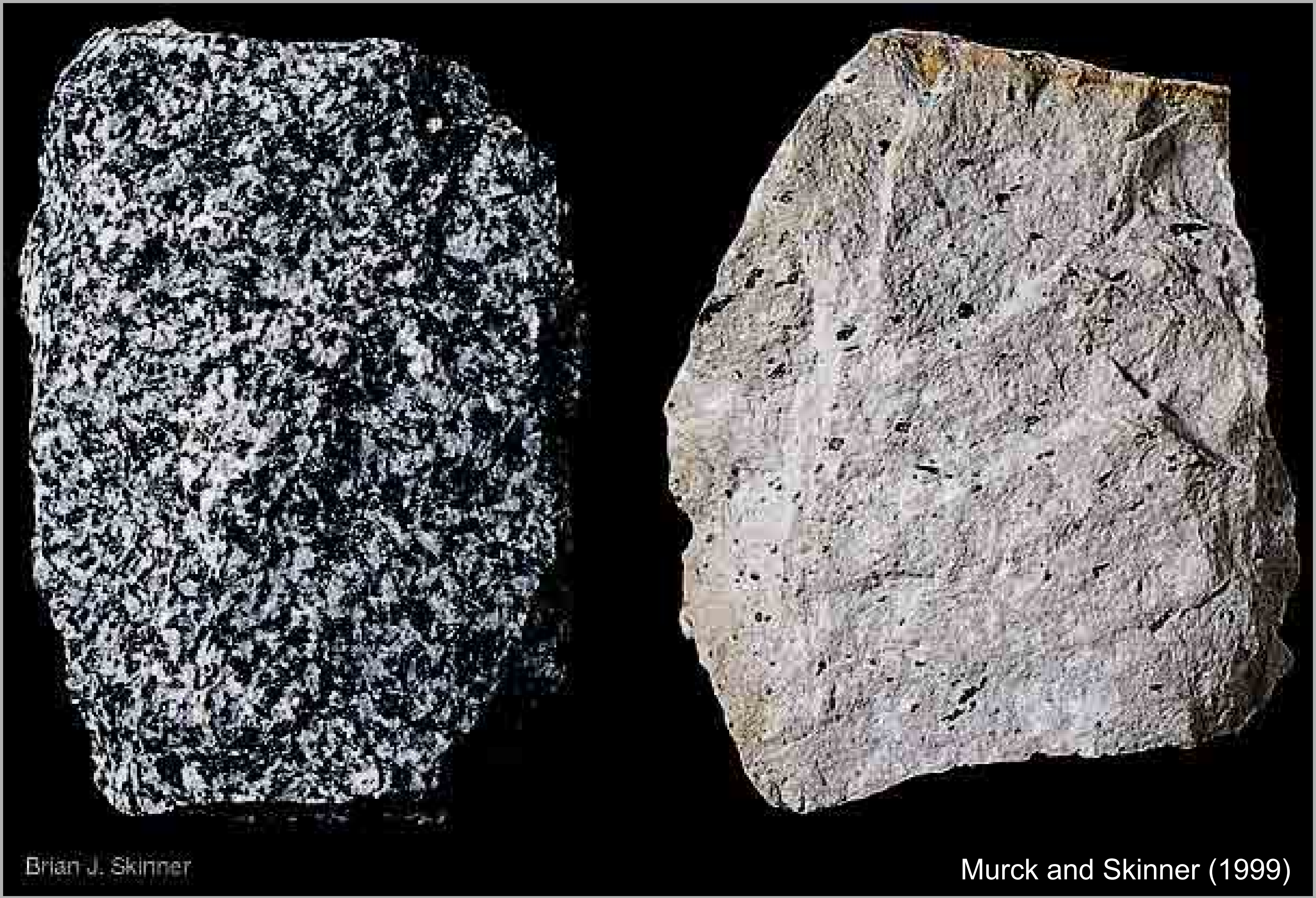
Gabbro and basalt

Classifying Igneous Rocks

Intermediate (53-65% silica) igneous rocks contain nearly equal amounts of dark colored ferromagnesian silicate minerals such as amphibole and biotite and light colored plagioclase feldspar. Andesite is fine-grained, whereas diorite is coarse-grained. Andesite is formed of lava erupted from volcanic island arcs. Diorite is fairly common in continental crust.

Wicander and Monroe (2002)

Diorite and Andesite



KCRs (Kimberlite Clan Rocks)

Igneous Rock Classification Chart (again ☺)

Colour / **Textures**	Felsic	Intermediate	Mafic	**Ultramafic**
Phaneritic	Granite	Diorite	Gabbro	Peridotite
Aphanitic	Rhyolite	Andesite	Basalt	
Vesicular	Pumice		Scoria	
Glassy	Obsidian			

KCRs

Classifying Igneous Rocks

- Felsic (>65% silica) igneous rocks are light colored because they are largely composed of orthoclase, Na-plagioclase, and quartz. Rhyolite is fine-grained, whereas granite is coarse-grained. Granite is the most common intrusive (plutonic) igneous rock. Continental crust is granitic in composition.

Wicander and Monroe (2002)

Granite and rhyolite

Classifying Igneous Rocks

Some igneous rocks are identified by their distinctive textures: vesicular, glassy, and pyroclastic or fragmental.

	COMPOSITION	Felsic ⟷ Mafic	
TEXTURE	Vesicular	Pumice	Scoria
	Glassy	Obsidian	
	Pyrocalstic or Fragmental	← Volcanic Breccia → Tuff/welded tuff	

Wicander and Monroe (2002)

Classifying Igneous Rocks

Obsidian and pumice are varieties of volcanic glass. Both are high in silica and compositionally similar to rhyolite. Small amounts of impurities color obsidian black, dark gray, red, or brown. Pumice contains abundant vesicles formed when trapped gas bubbles form a froth.

Wicander and Monroe (2002)

Classifying Igneous Rocks

Tuff is a pyroclastic igneous rock formed of ash (<2mm diameter) erupted from volcanoes. Most of the ash consists of tiny shards of volcanic glass.

Wicander and Monroe (2002)

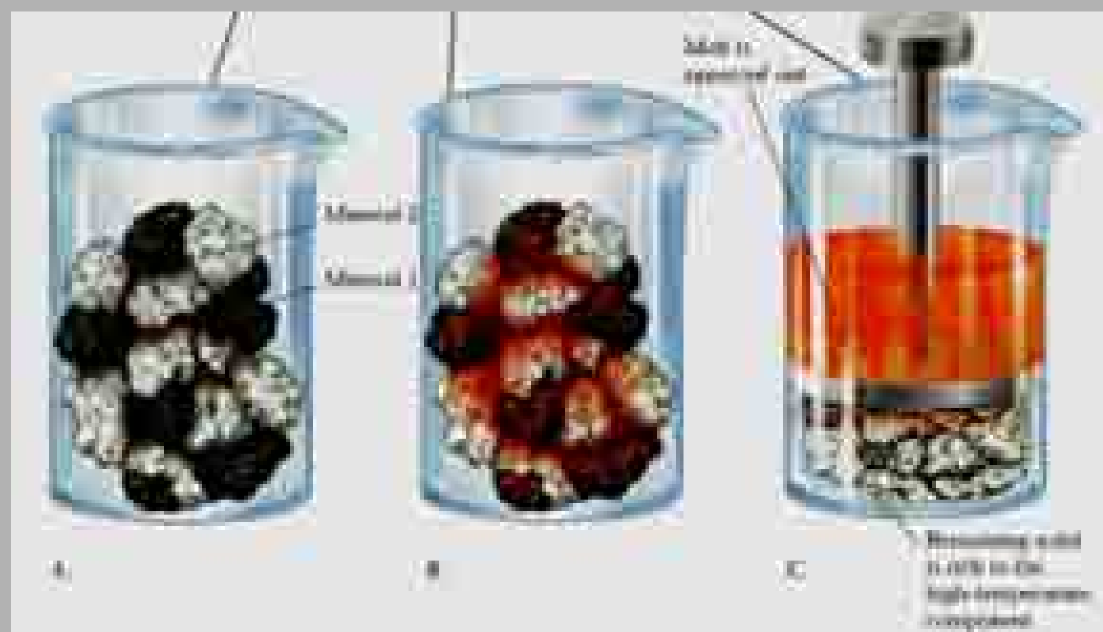
Classifying Intrustive Igneous Rocks

Pegmatites are very coarse-grained (grains >1 cm in diameter) igneous rocks. Most pegmatites are similar to granite, mineralogically. The mineral grains comprising pegmatites crystallized from the fluid and vapor phases left over from the cooling and solidification of magma to form granite. Pegmatites can contain very large mineral grains, several meters long in some cases.

Wicander and Monroe (2002)

Fractional crystallization

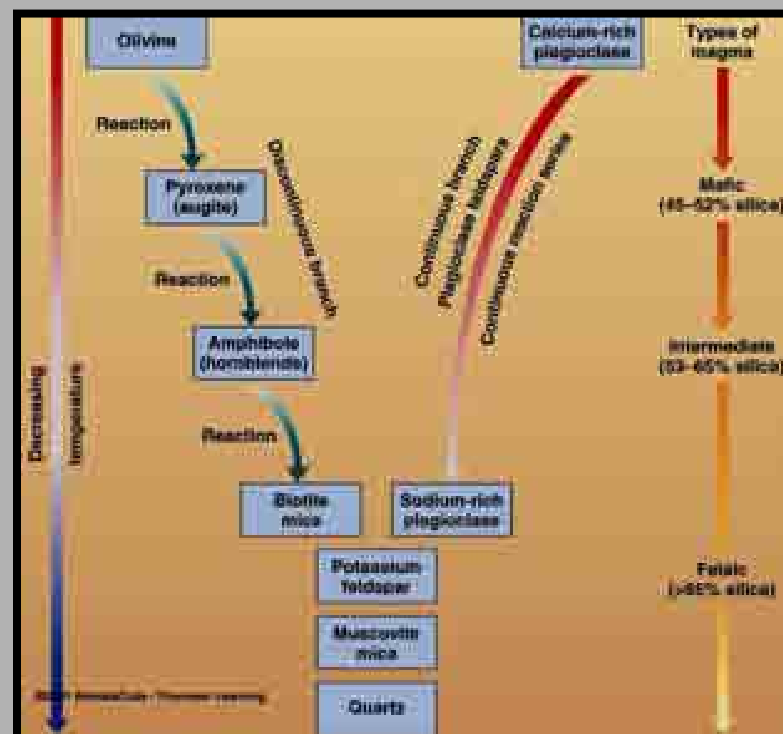
- As discussed earlier a single magma can crystallize into a variety of igneous rocks - magmatic differentiation
- One way of doing this is by fractional crystallization



Murck and Skinner (1999)

Fractional crystallization

- As a magma cools different minerals will crystallize at different temperatures
- If these crystals are separated from the magma then they will leave a residual magma with a slightly different composition



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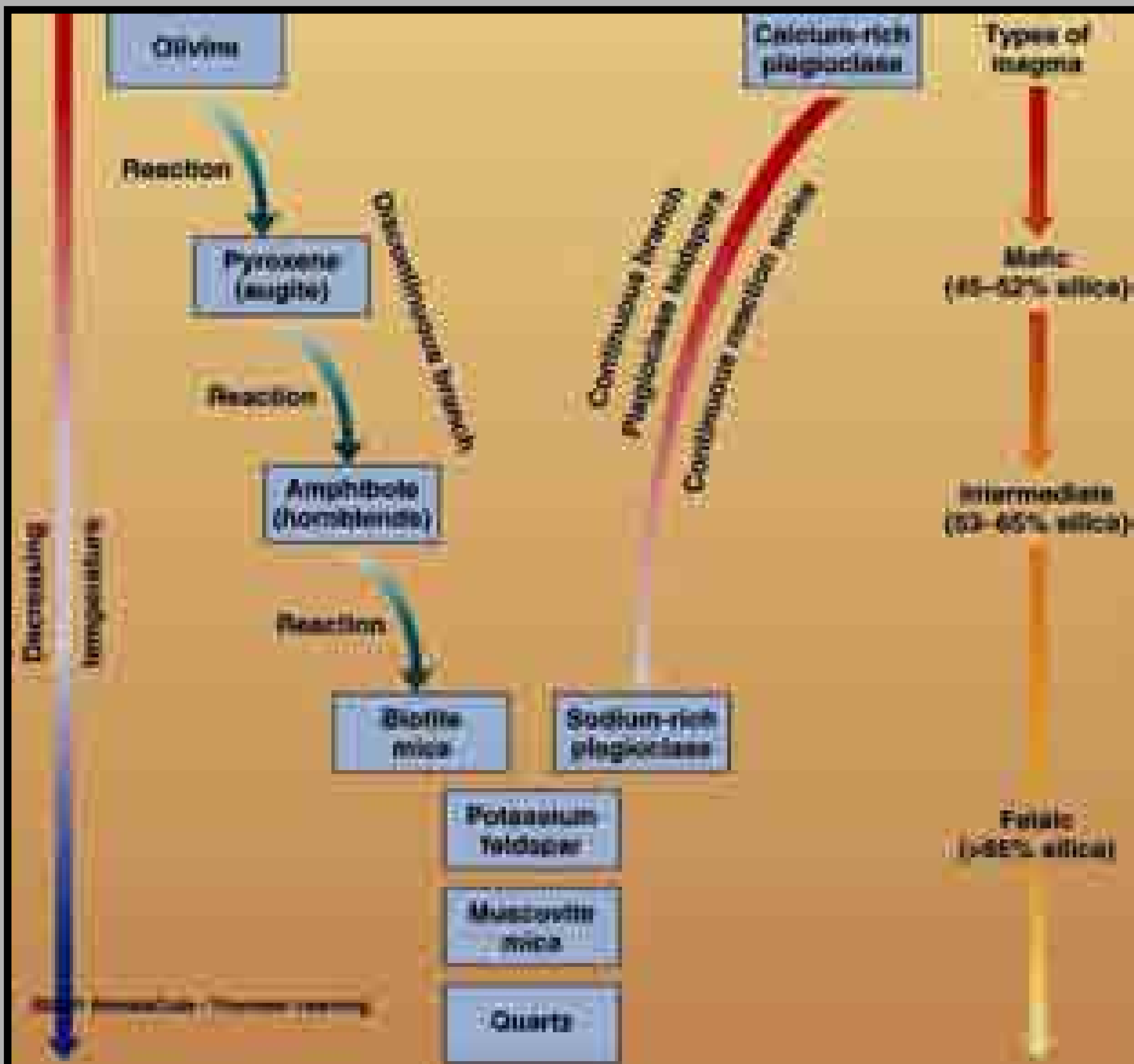
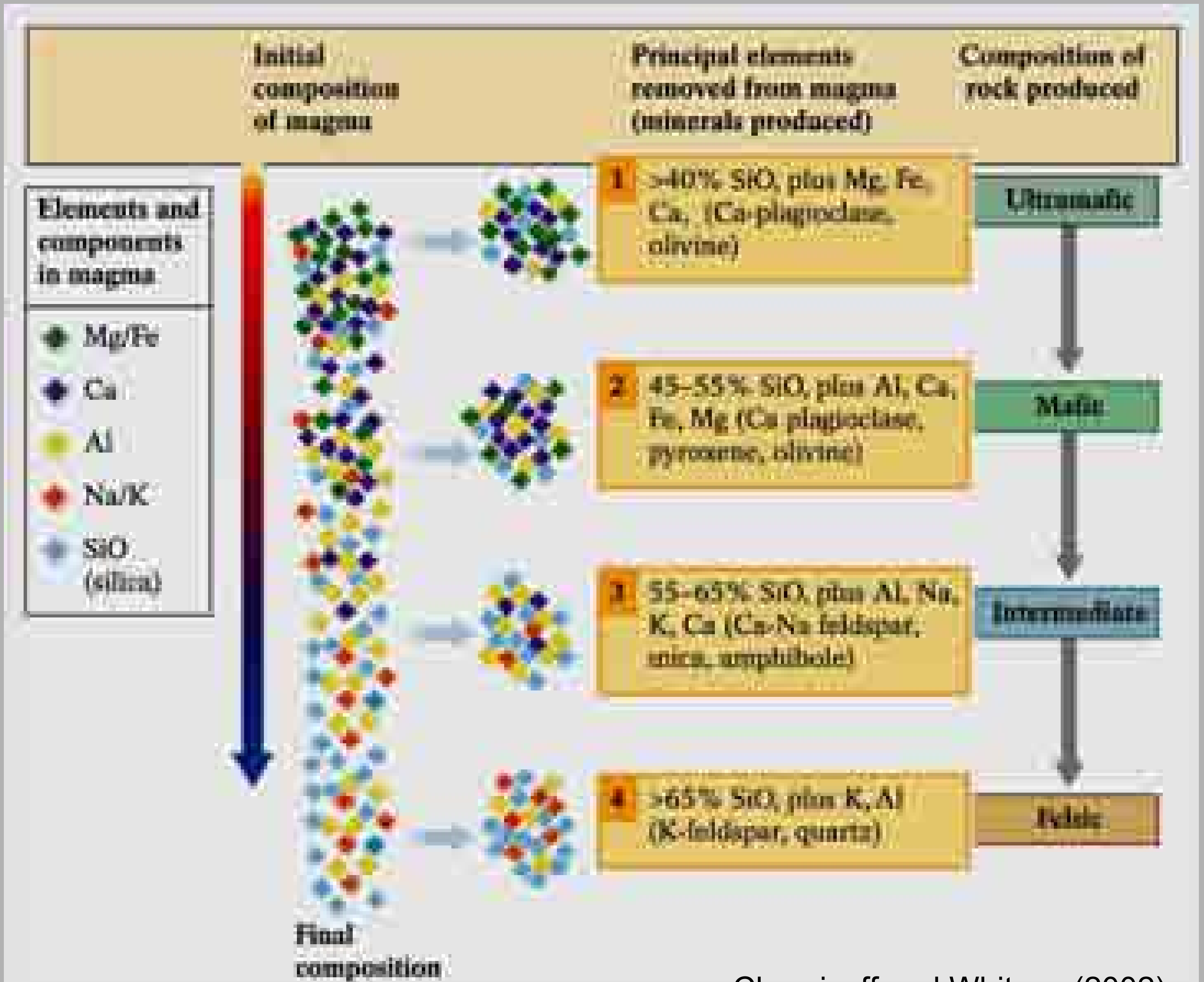
Bowen's Reaction Series



N.L. Bowen tracked the sequence of crystallization of minerals in cooling mafic magma. As mafic magma cools, iron-, magnesium-, and calcium-rich minerals crystallize first, leaving magma enriched in silica, aluminum, and potassium.

Wicander and Monroe (2002)

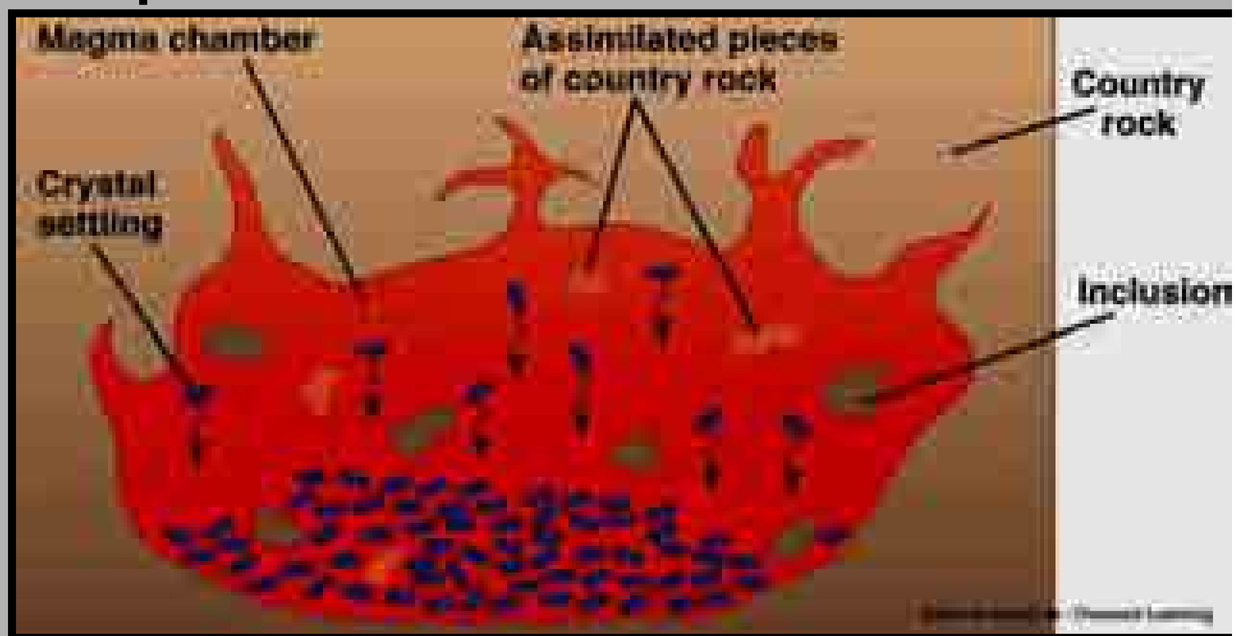
Crystallization



Chernicoff and Whitney (2002)

Crystal settling

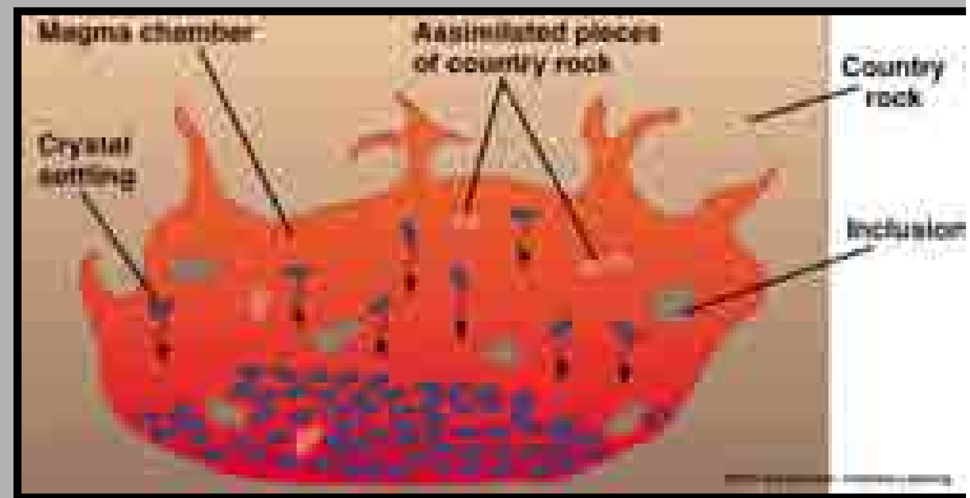
Crystal settling involves physical separation of dense minerals by gravitational settling. Dense iron and magnesium silicate minerals such as olivine crystallize first and settle downward through the remaining less dense, silica-enriched magma. Evidence of crystal settling is preserved in some thick, sheetlike, intrusive bodies called sills, but volumetrically this process has limited influence on magma composition.



Wicander and Monroe (2002)

Assimilation

- **Assimilation: the melting of country rock that has fallen into or surrounds a magma chamber.**
- **Country rock seldom has the same composition as magma, so assimilation can change the composition of magma.**
- **Inclusions of country rock in plutonic igneous bodies records incomplete melting. (A limited amount of rock can be assimilated, thus this process does not result in major changes in magma composition)**



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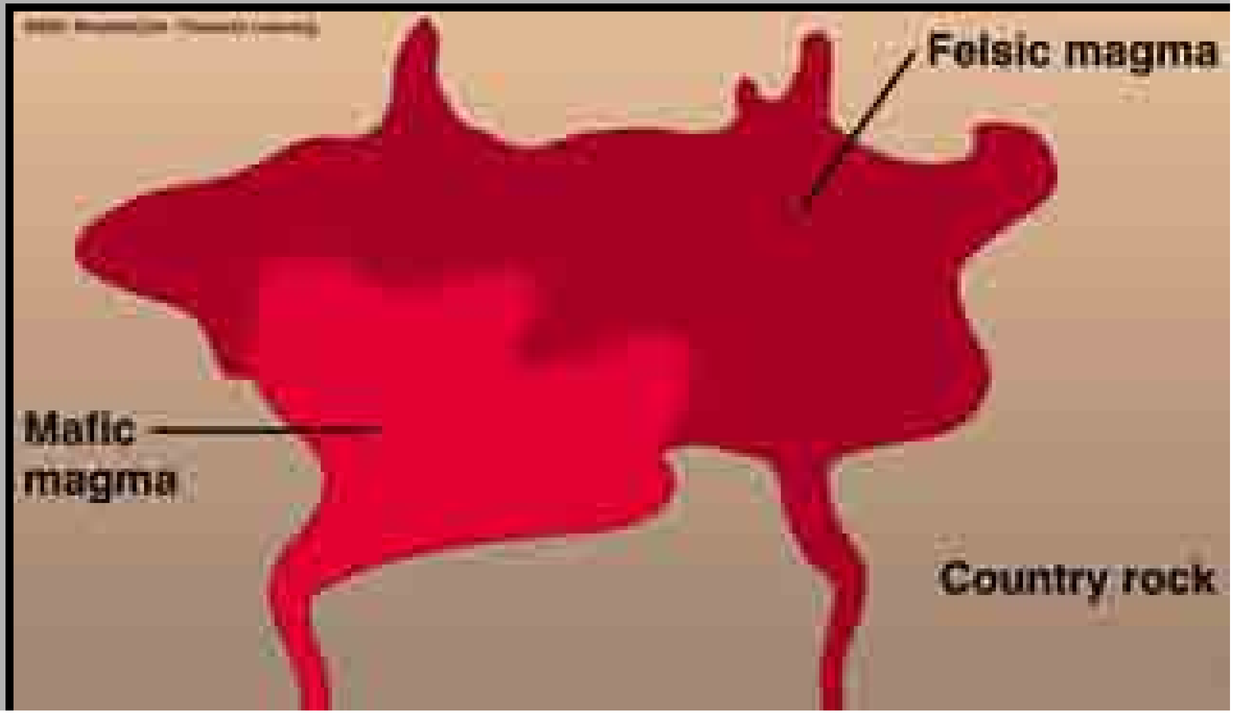
Magma mixing

Magma mixing occurs when bodies of magma of different composition come in contact and mix to produce a third magma with a composition intermediate between the two parent magmas.

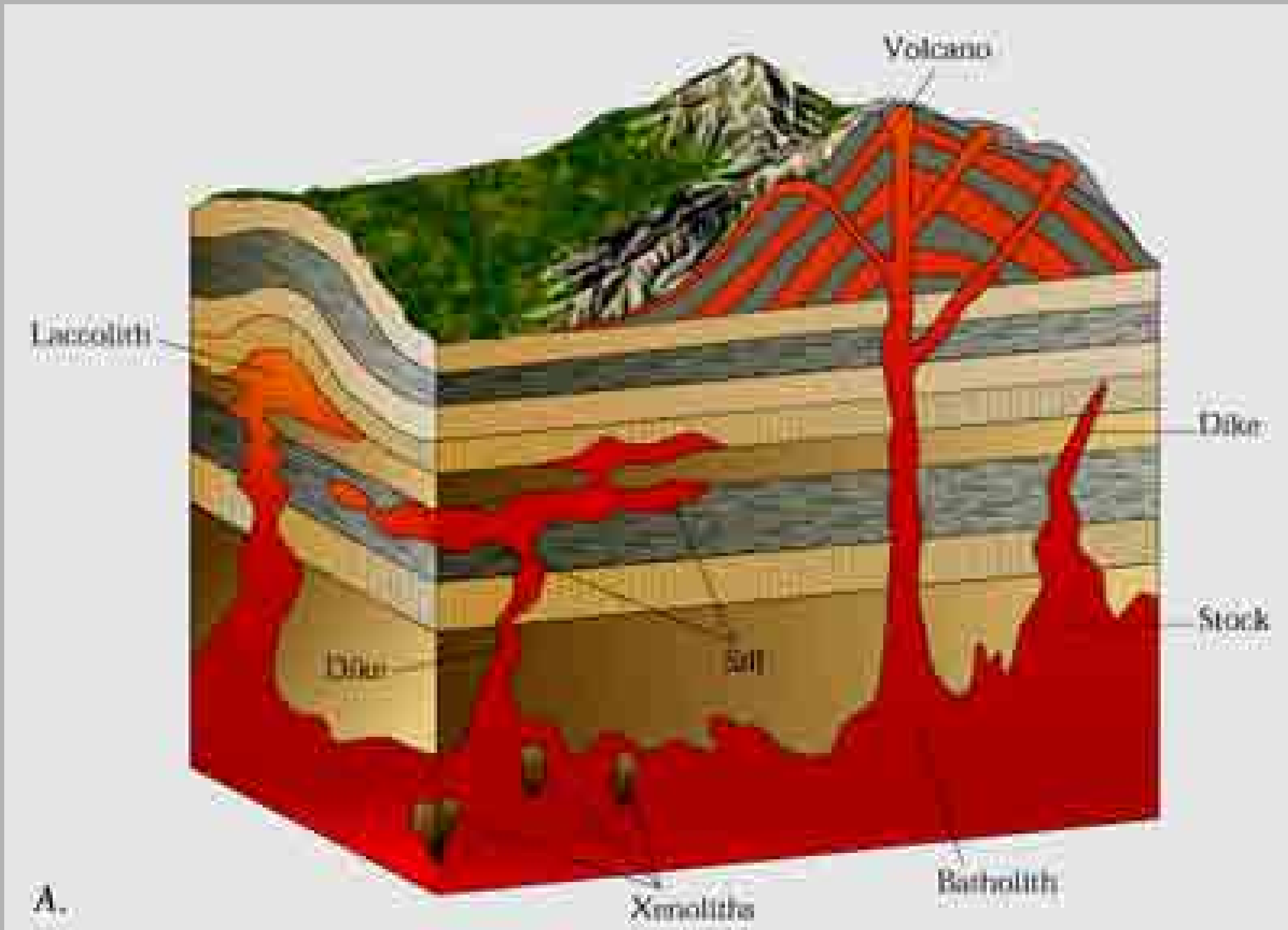


Wicander and Monroe (2002)

Plutons and plutonism

- **Although volcanoes are the more spectacular aspect of igneous rocks the majority of igneous rocks are intrusive**
- **The generic term for an intrusive body is pluton**
- **But geologists like to complicate things so we have come up with a bunch of names for plutons of different sizes and shapes**

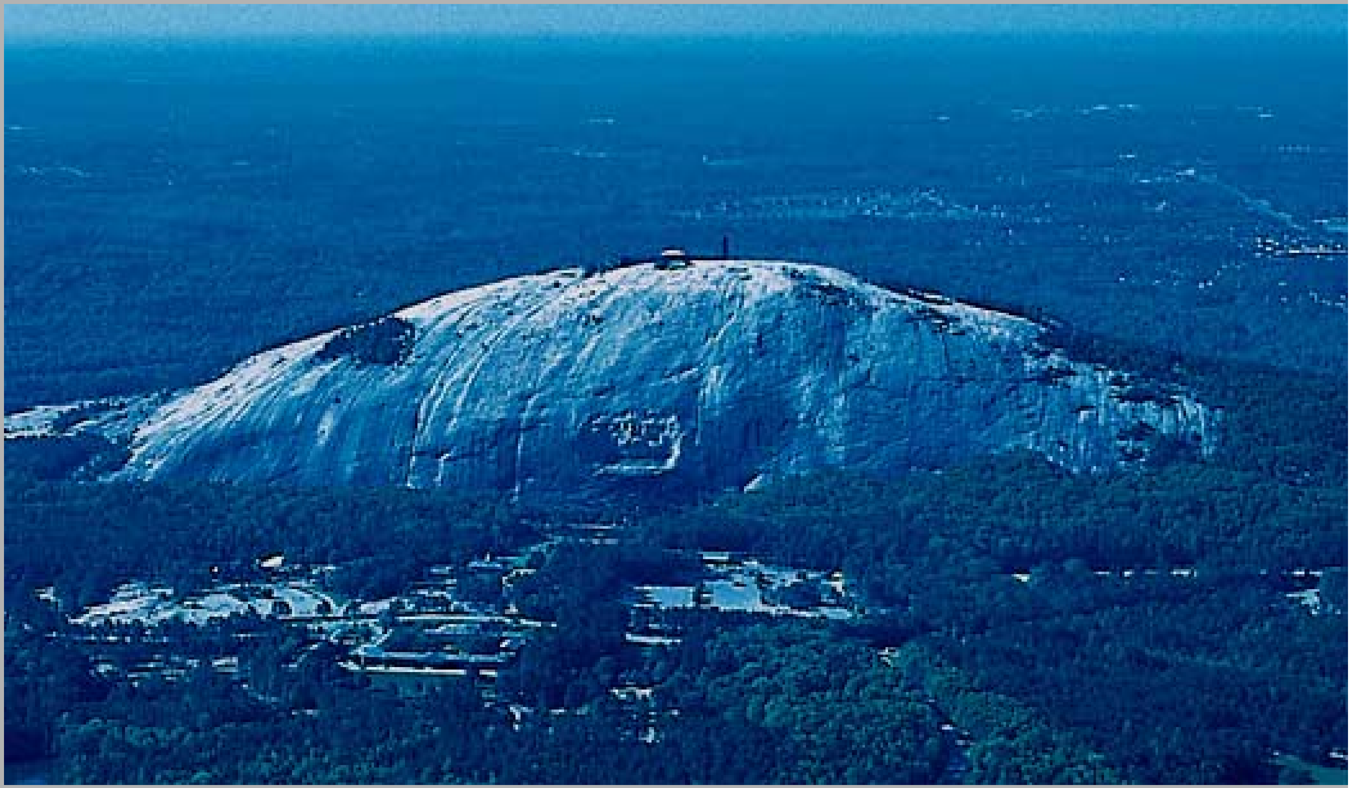
Plutons & plutonism



Murck and Skinner (1999)

Batholith

- Largest form of pluton
- Coast Range batholith is 1000km x 250km
- $>100km^2$



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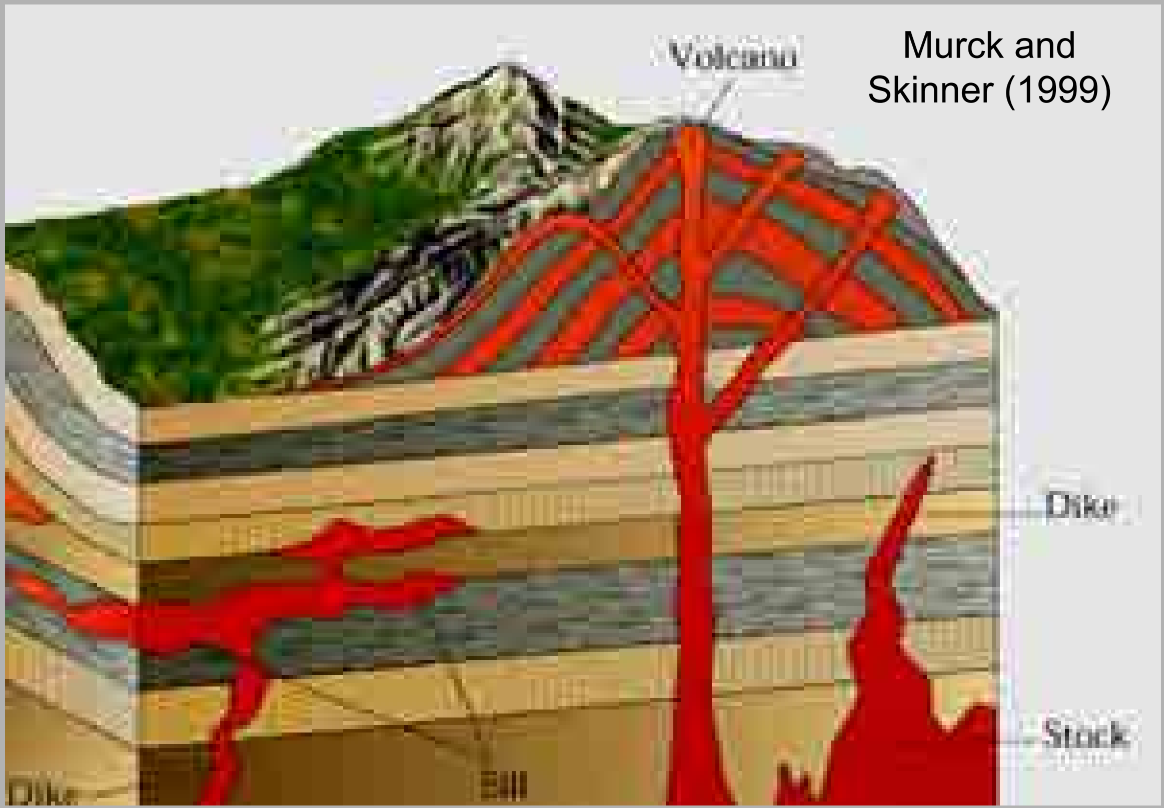
Intrusive Igneous Bodies

- Concordant plutons, parallel and discordant plutons cross-cut the layering of the intruded country rock.
- Dikes are discordant and sills concordant tabular plutons



Murck and Skinner (1999)

Dyke

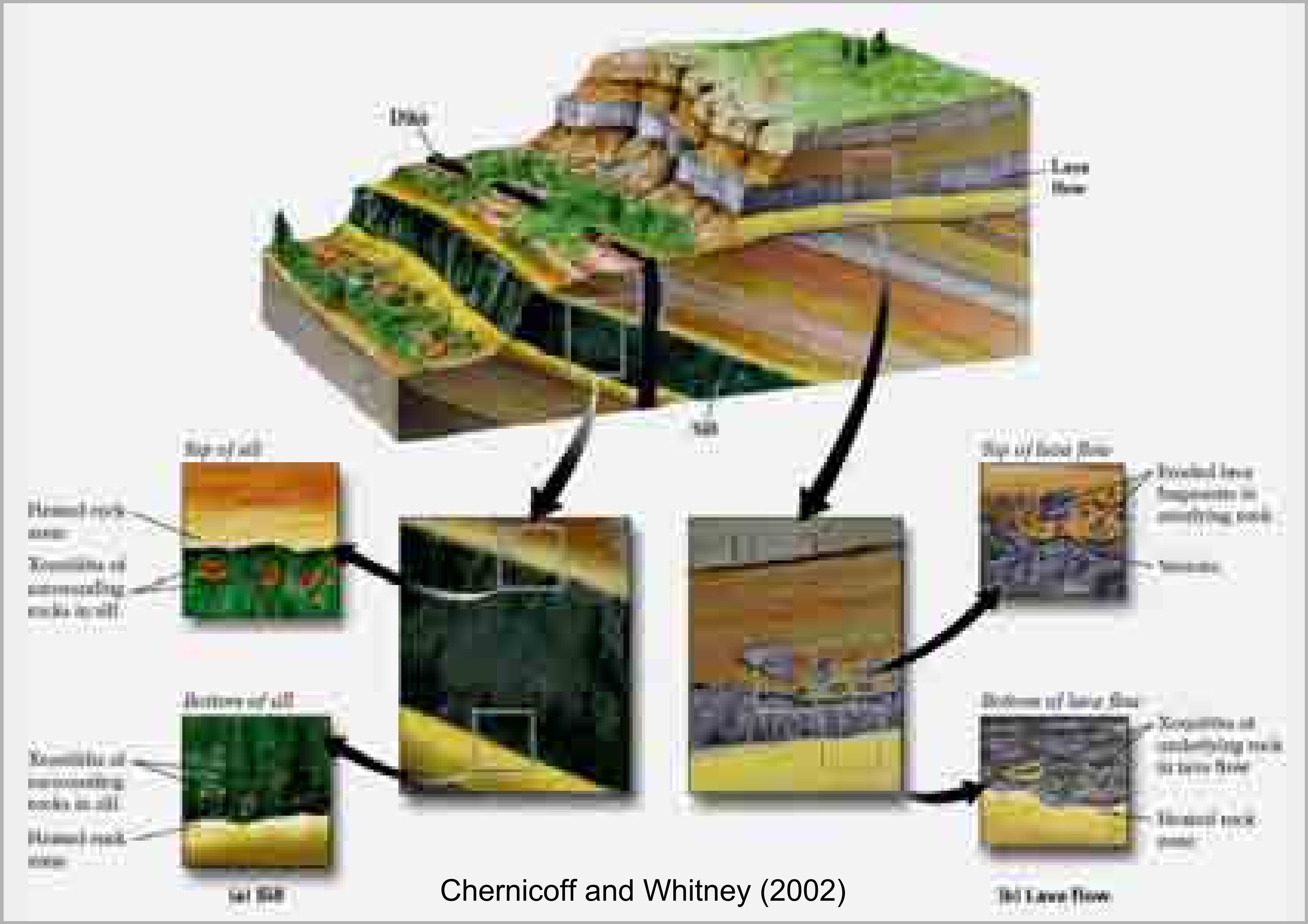
- The great dyke in Zimbabwe is 500km long and 8 km wide but most are smaller

Sill

- A lot of the hills around Thunder Bay are gabbroic sills

Murck and Skinner (1999)

Sills and lava flows

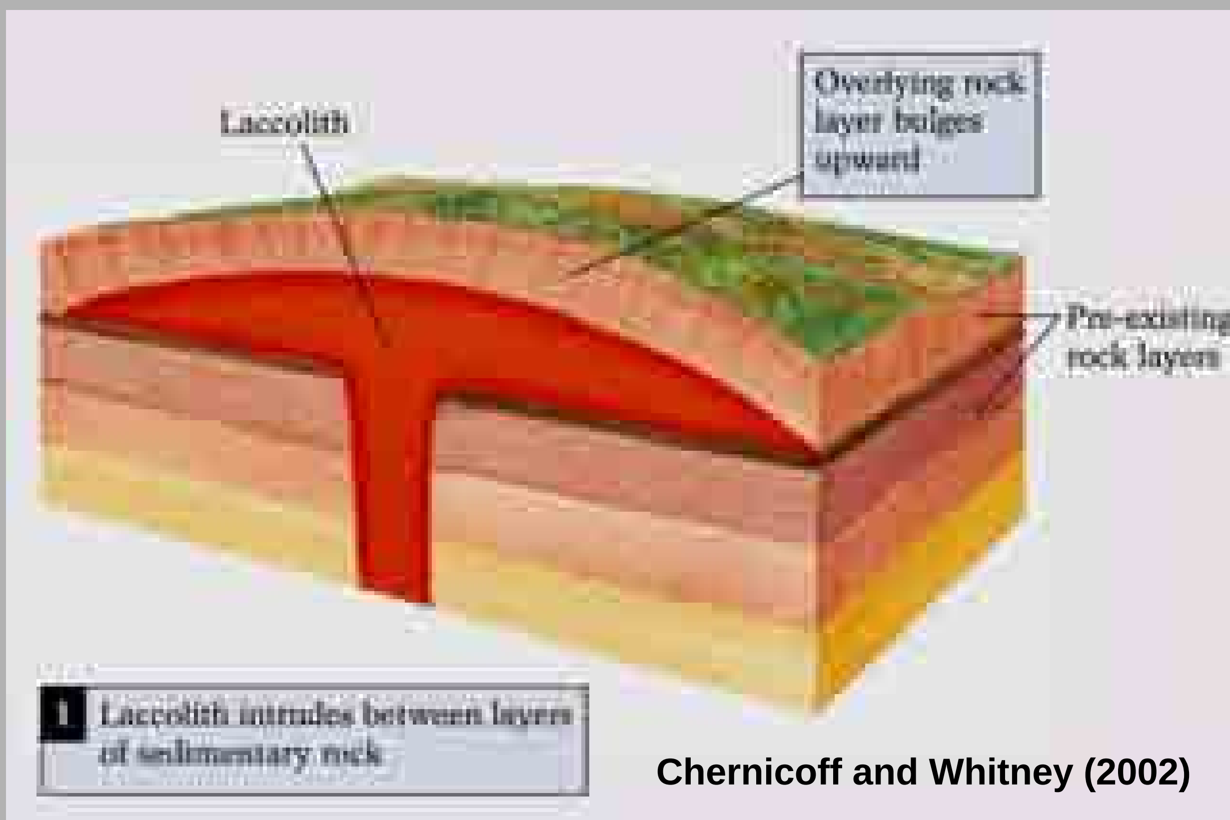


Chernicoff and Whitney (2002)

Dykes and sills

Intrusive Igneous Bodies

- Laccoliths are mushroom-shaped sills.



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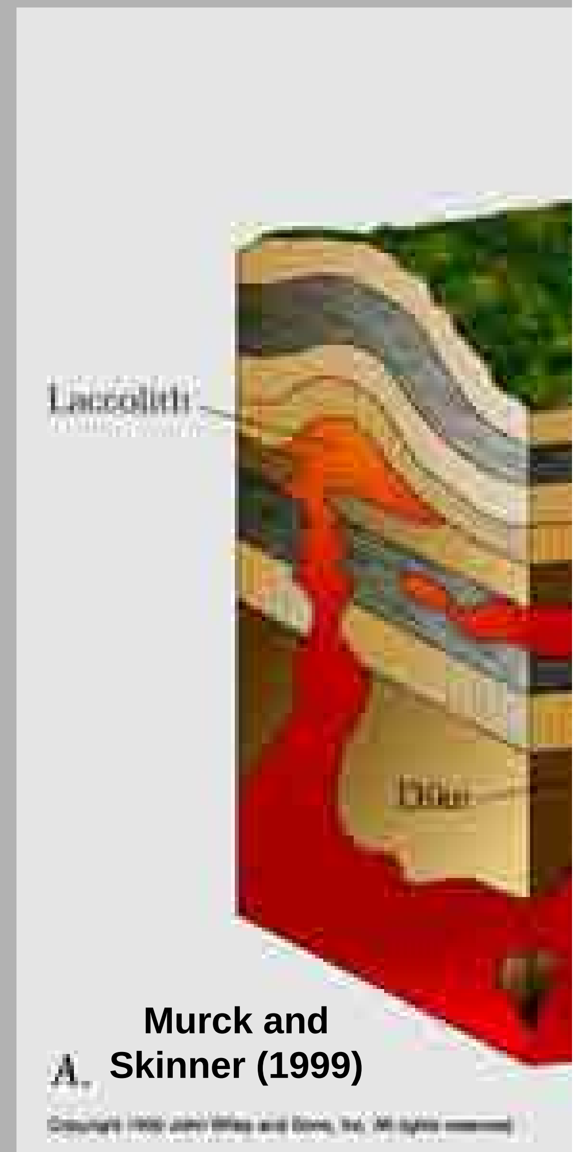
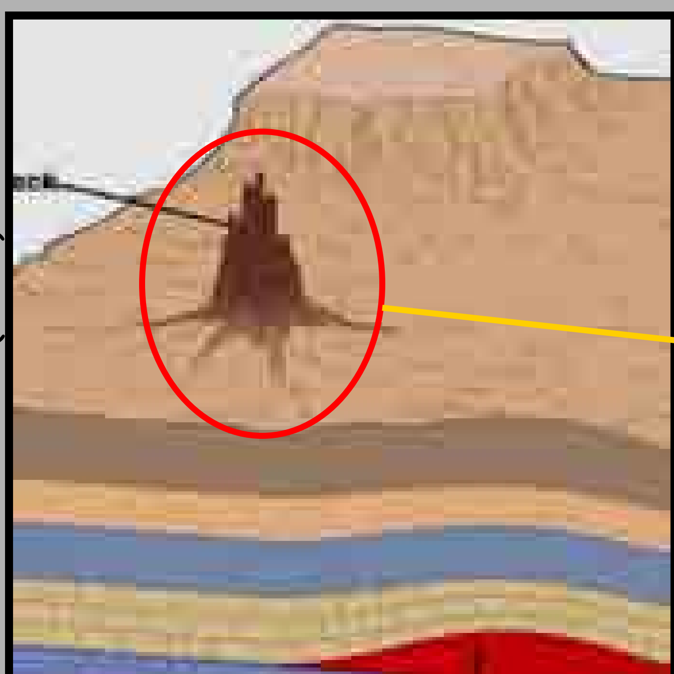


Murck and Skinner (1999)

Intrusive Igneous Bodies

A volcanic pipe is a conduit connecting a crater to an underlying magma chamber and forms a volcanic neck when a volcano is eroded.



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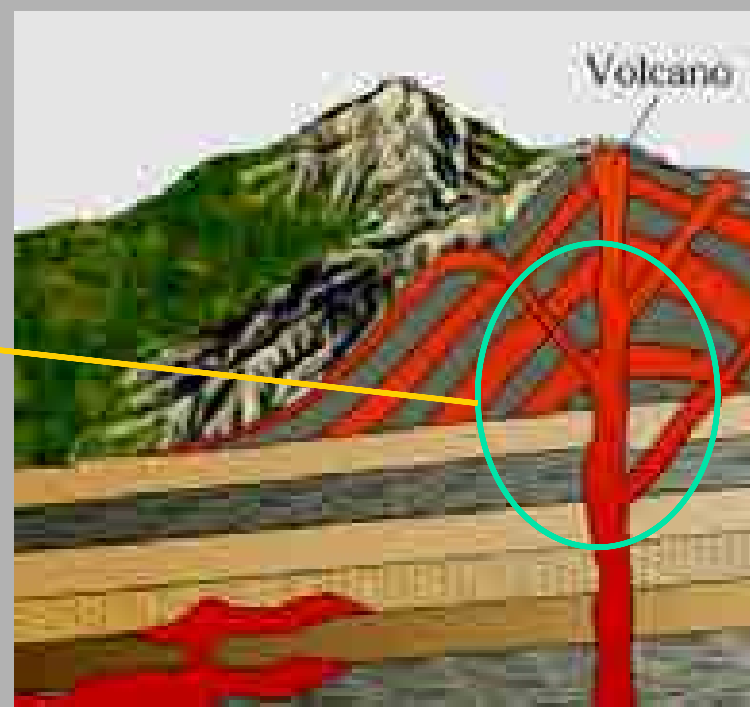

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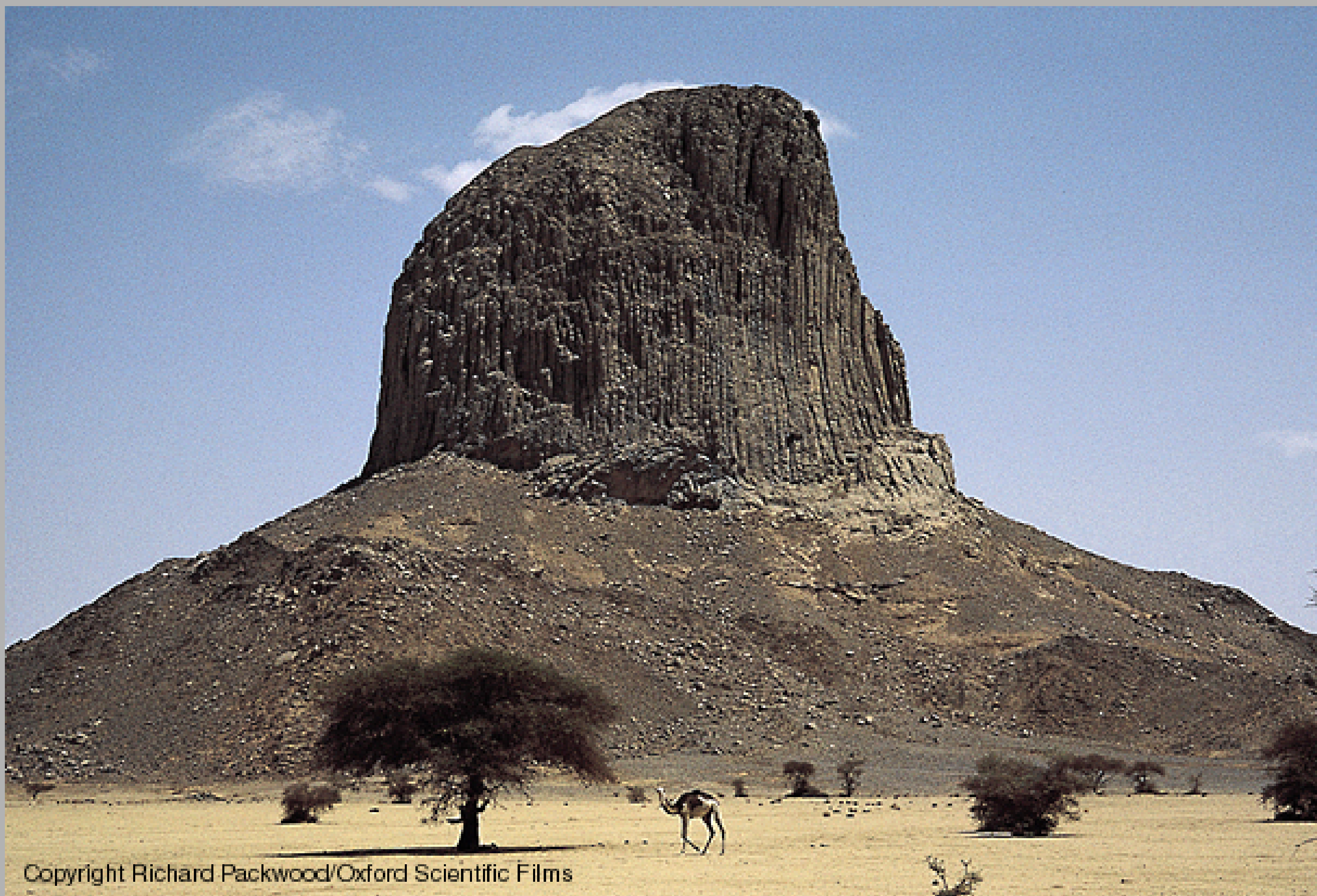
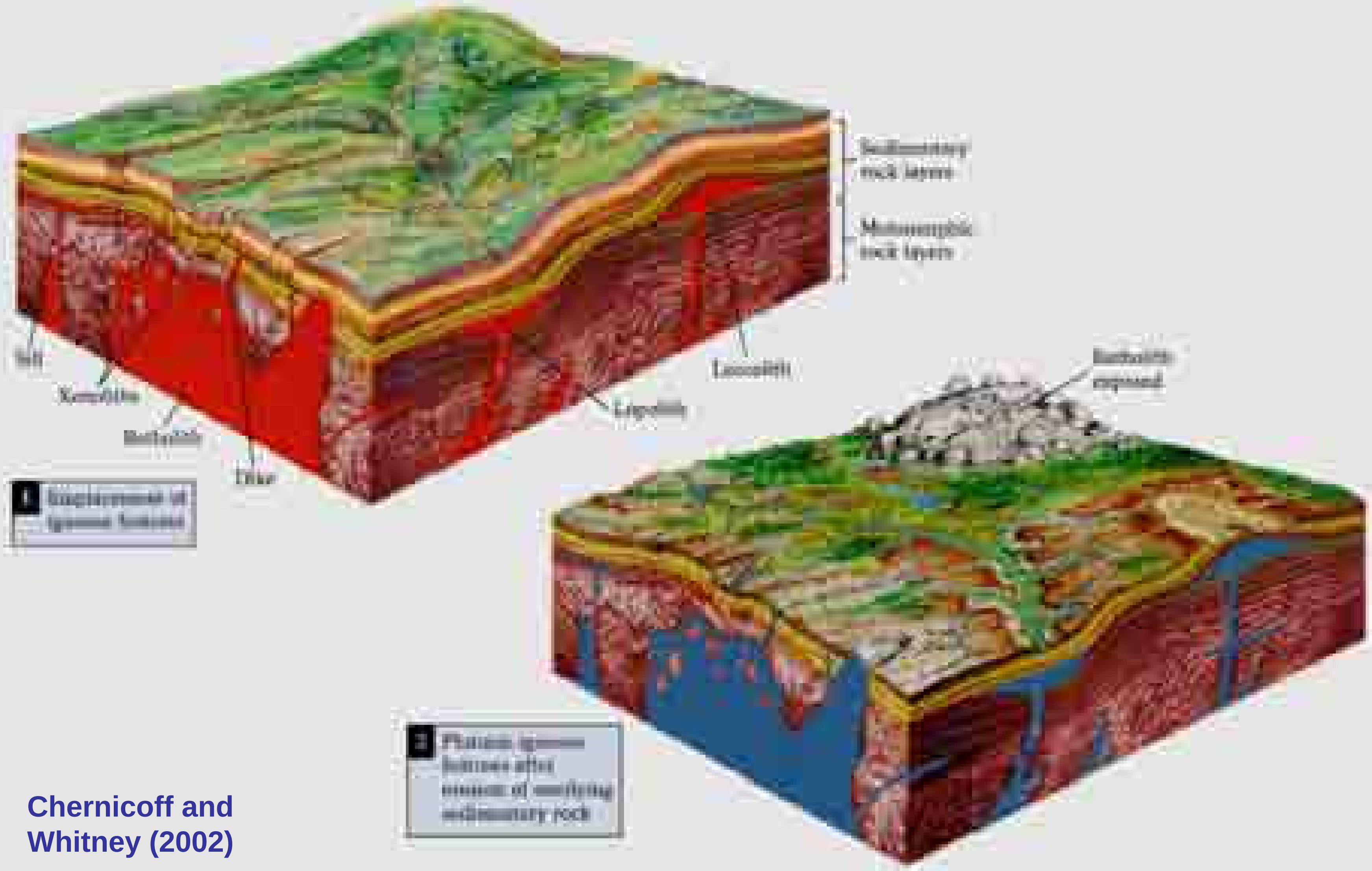
Volcanic neck, Algeria



Murck and Skinner (1999)

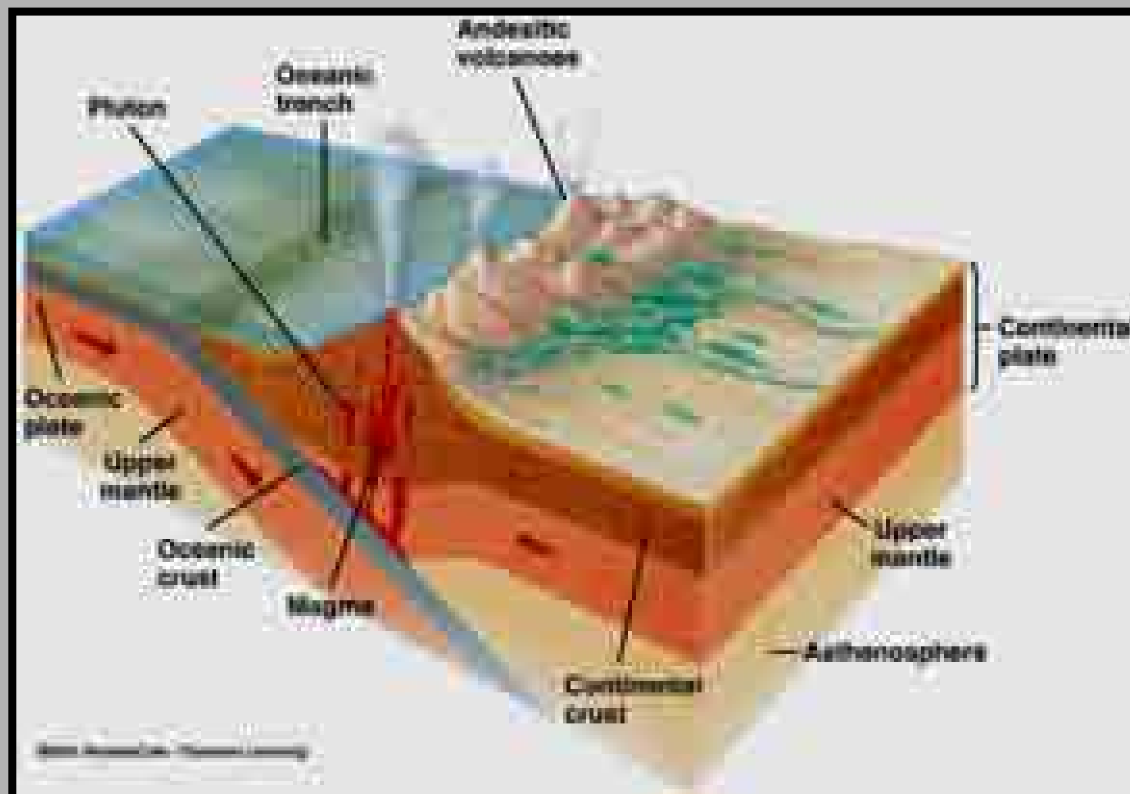
Plutonic igneous features



Chernicoff and Whitney (2002)

Subduction Zones

- **Magma generated at convergent plate boundaries is intermediate (53-65% silica) or felsic (>65% silica) in composition. Magmas of these compositions are formed by partial melting of subducted mafic oceanic crust.**



Wicander and Monroe (2002)