FUNDAMENTALS OF EARTH SCIENCES (ESO 213A)

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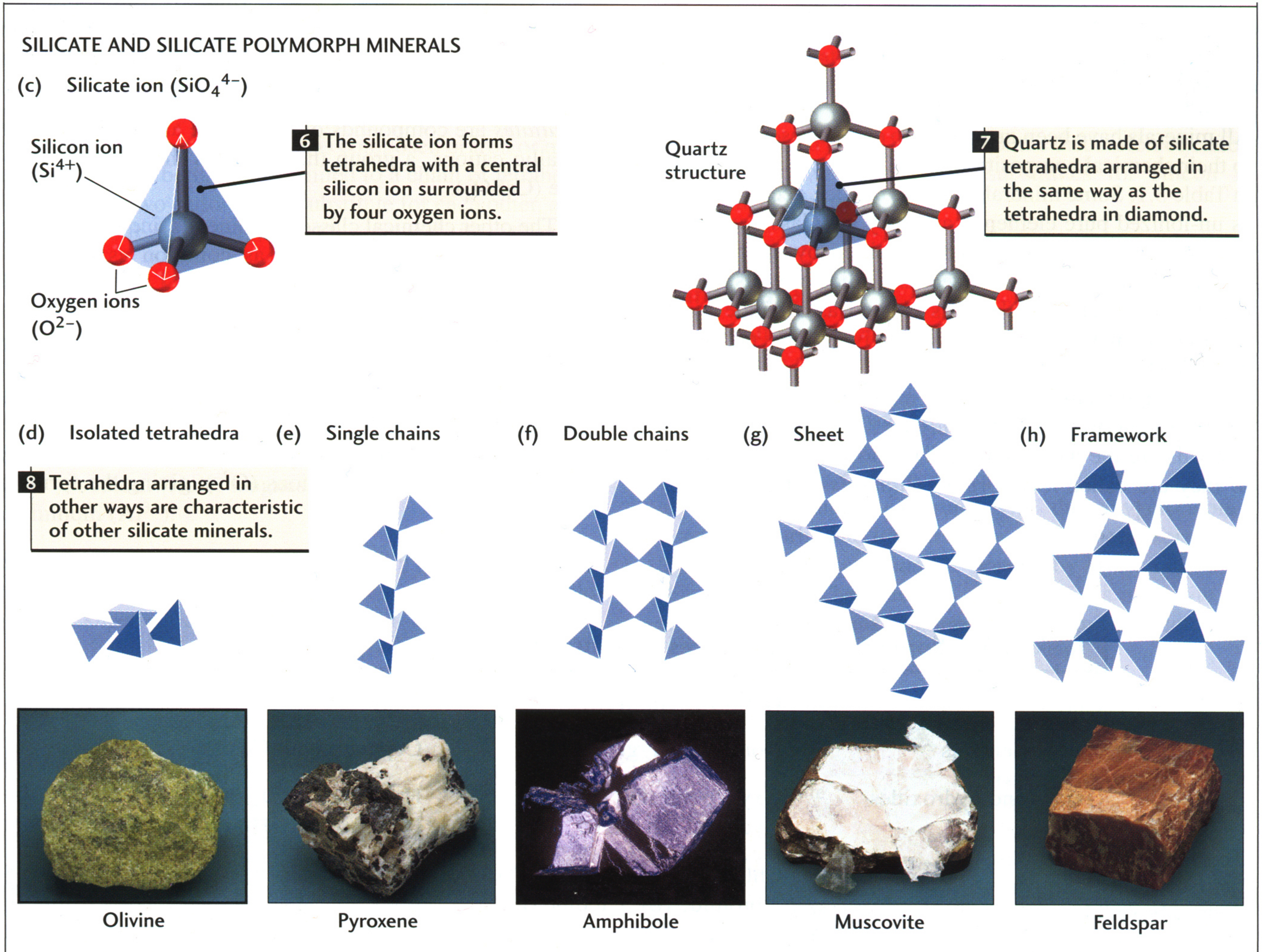
DEPARTMENT OF EARTH SCIENCES

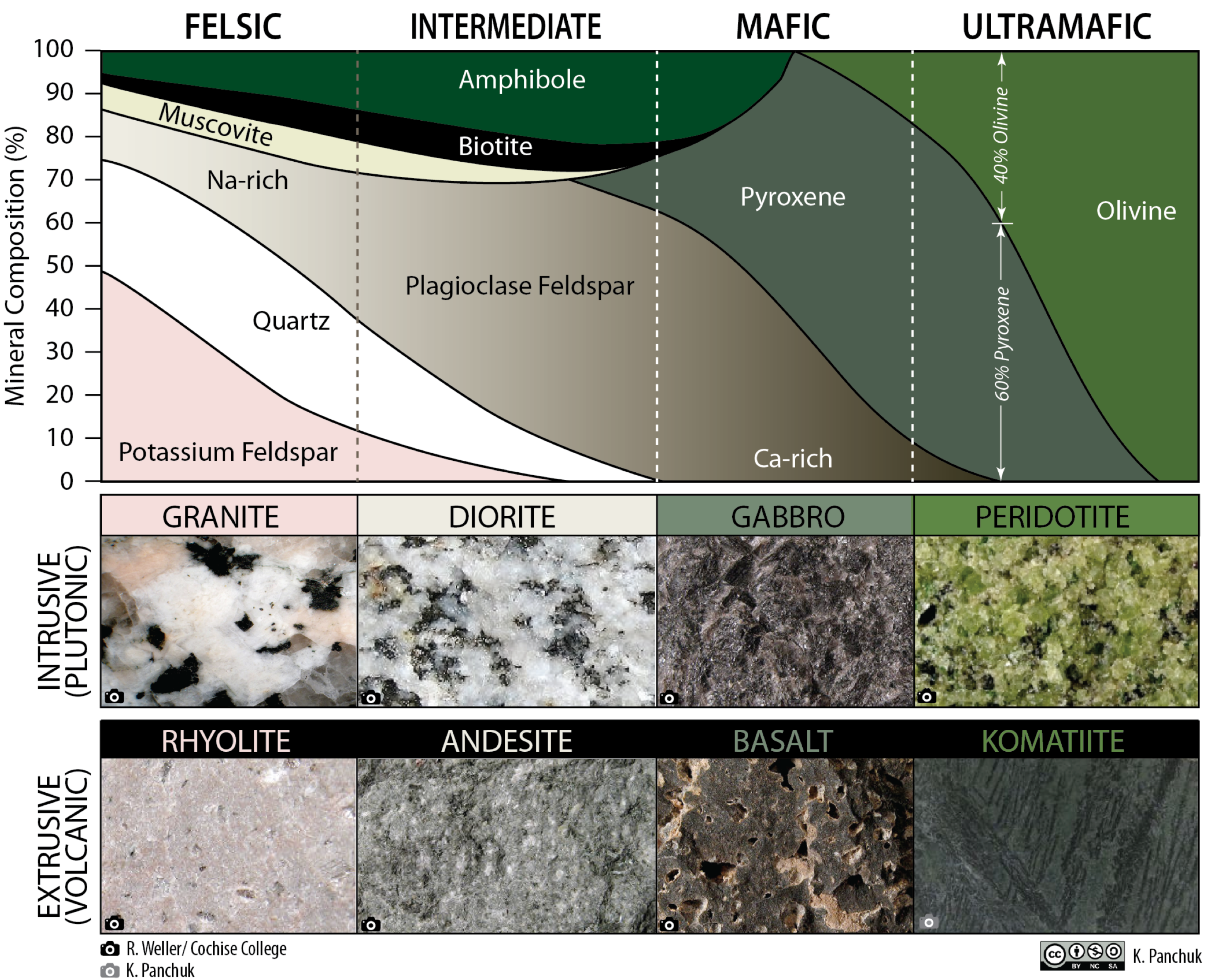
Topic: Magma and Igneous Rocks continued

Previous Class: Magma and Igneous Rocks “Granites”

Review: 1. Silicates



Review: 2. Mineralogy of common igneous rocks



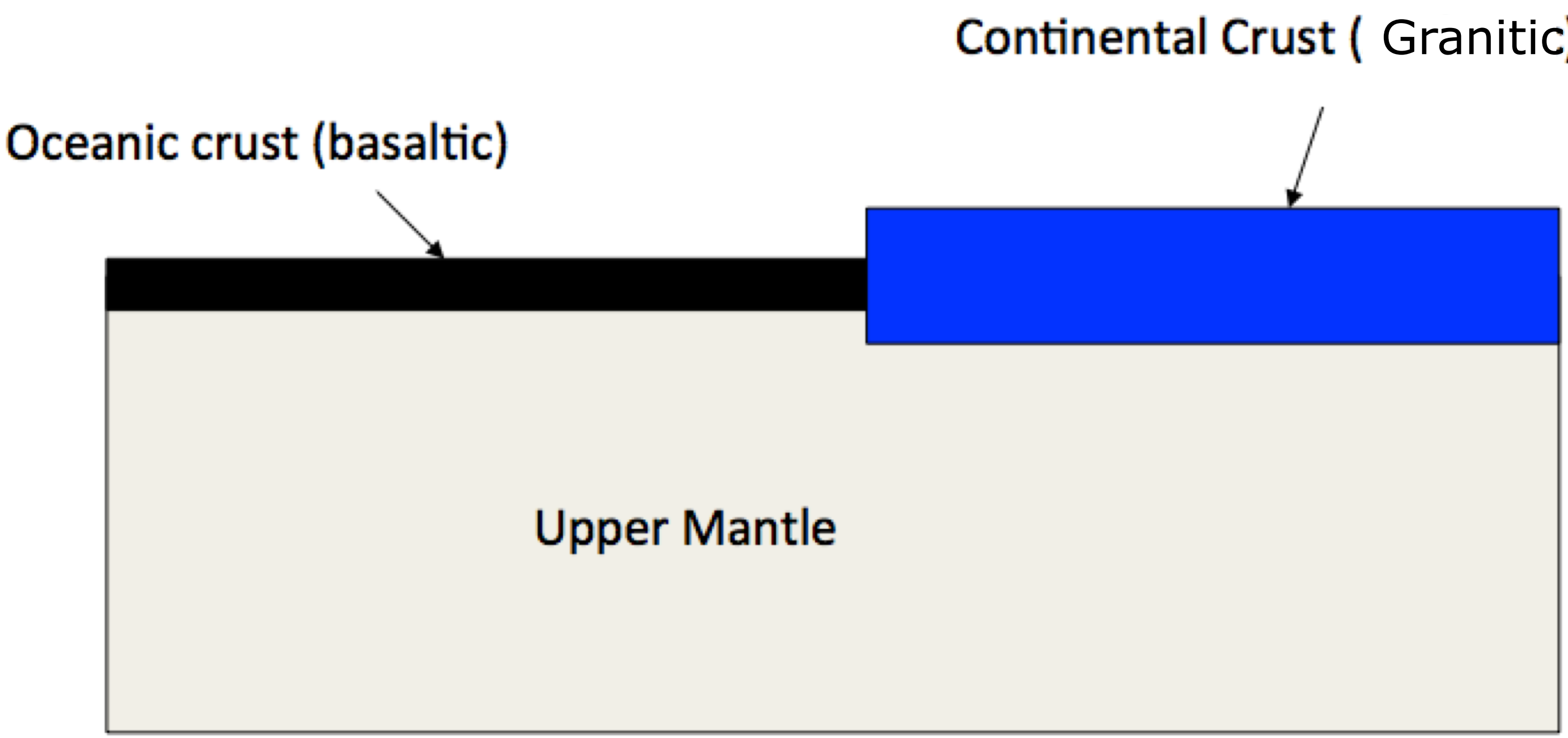
2. Rock nomenclature for mafic and ultramafic, Felsic and Volcanic rocks

Q: How does melt generate? How does magma ascend?

Magma Generation, Segregation, and Evolution

Under favorable thermal conditions, magma may form in the crust or upper mantle. Such magma must somehow segregate from the source rock, and form larger pools that will ascend toward the surface.

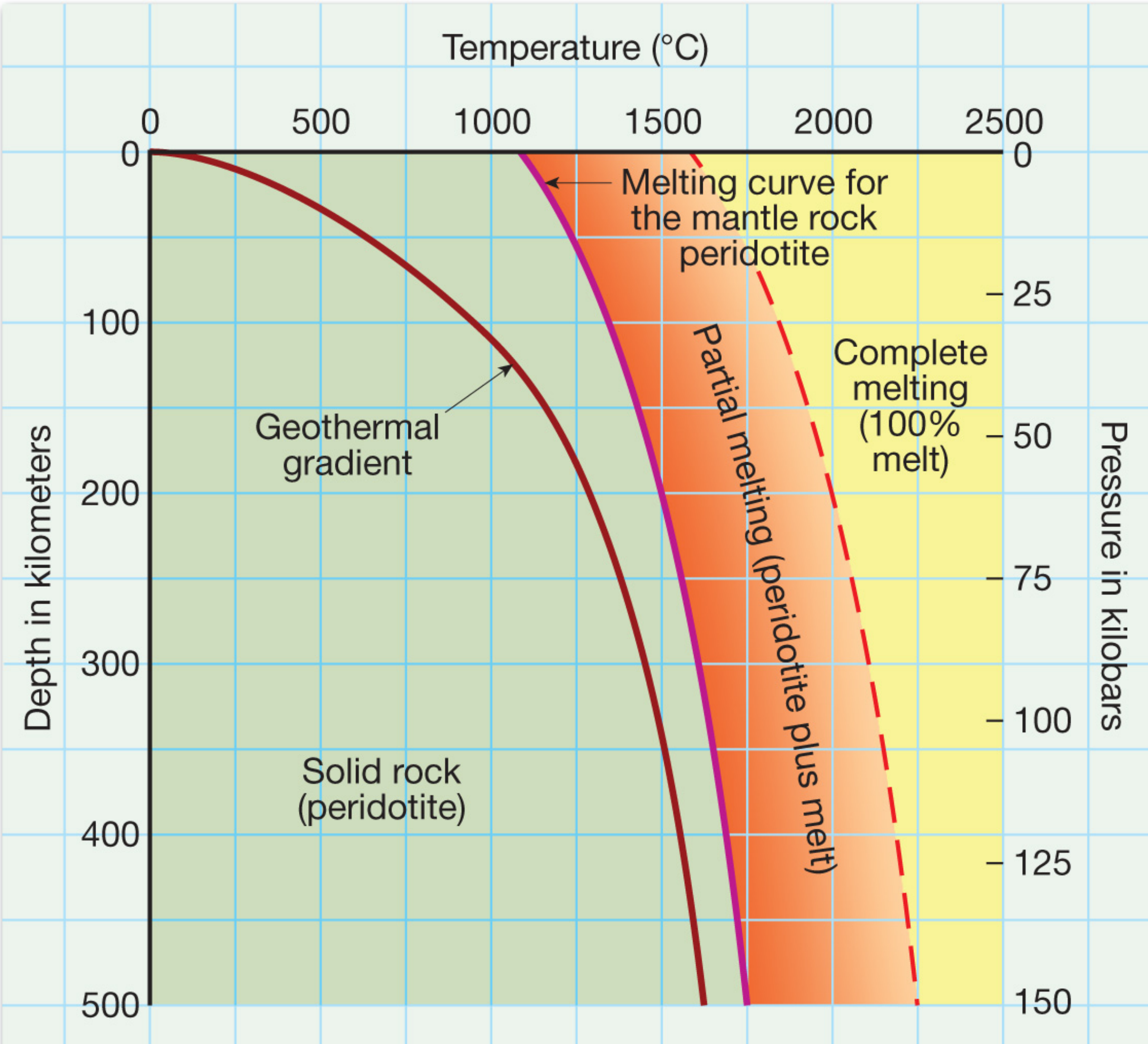
The Sources of Magmas



Origin of Magma

- • Highly debated topic
  • Generating magma from solid rock
- • Produced from partial melting of rocks in the crust and upper mantle
- – Consider the-
  • Role of temperature rise
  • Role of pressure
  • Role of volatiles

Origin of magma



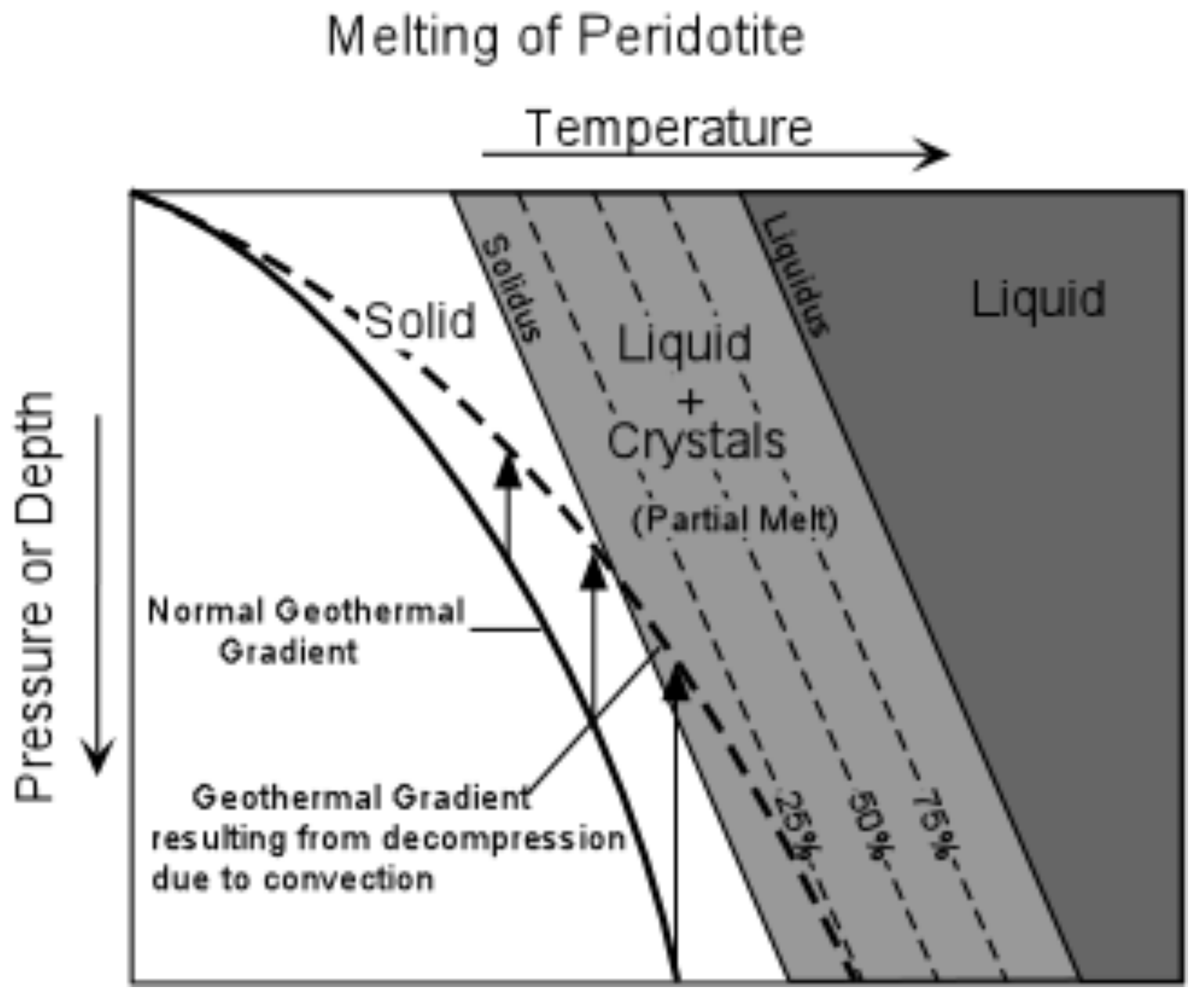
1. **Role of temperature**

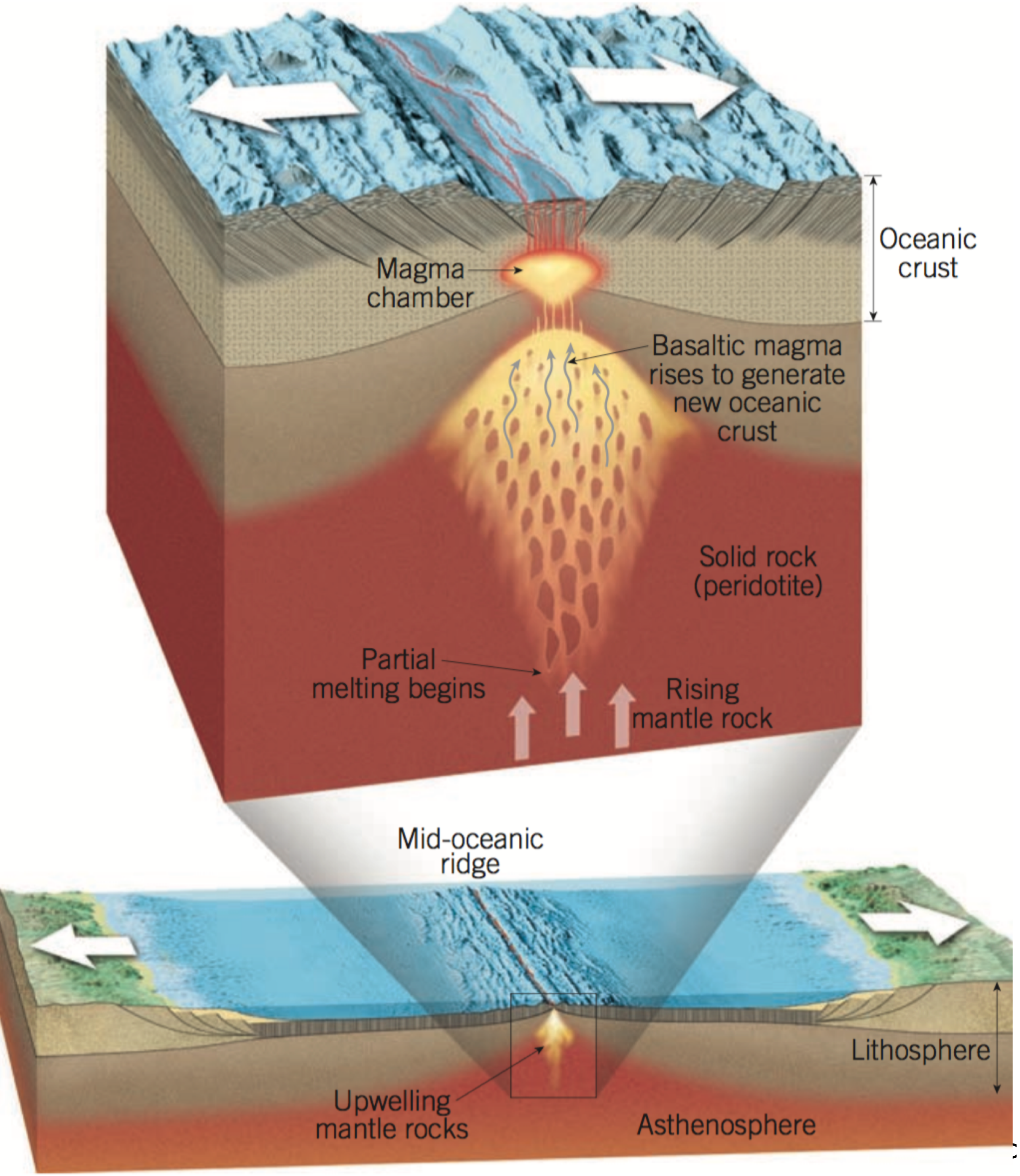
- Temperature increases within Earth's upper crust (called the geothermal gradient) average between 20°C to 30°C per kilometer
- Rocks in the lower crust and upper mantle are near their melting points. Any additional heat (from rocks descending into the mantle or rising heat from the mantle) may induce melting
- In continental settings, basaltic magma often "ponds" beneath crustal rocks, which have a lower density and are already near their melting temperature. The hot basaltic magma may heat the overlying crustal rocks sufficiently to generate a secondary, silica-rich magma.

Origin of Magma

2. Role of pressure (Decompression Melting)

- Increases in confining pressure increases a rock's melting temperature.
- When confining pressures drop, decompression melting occurs.





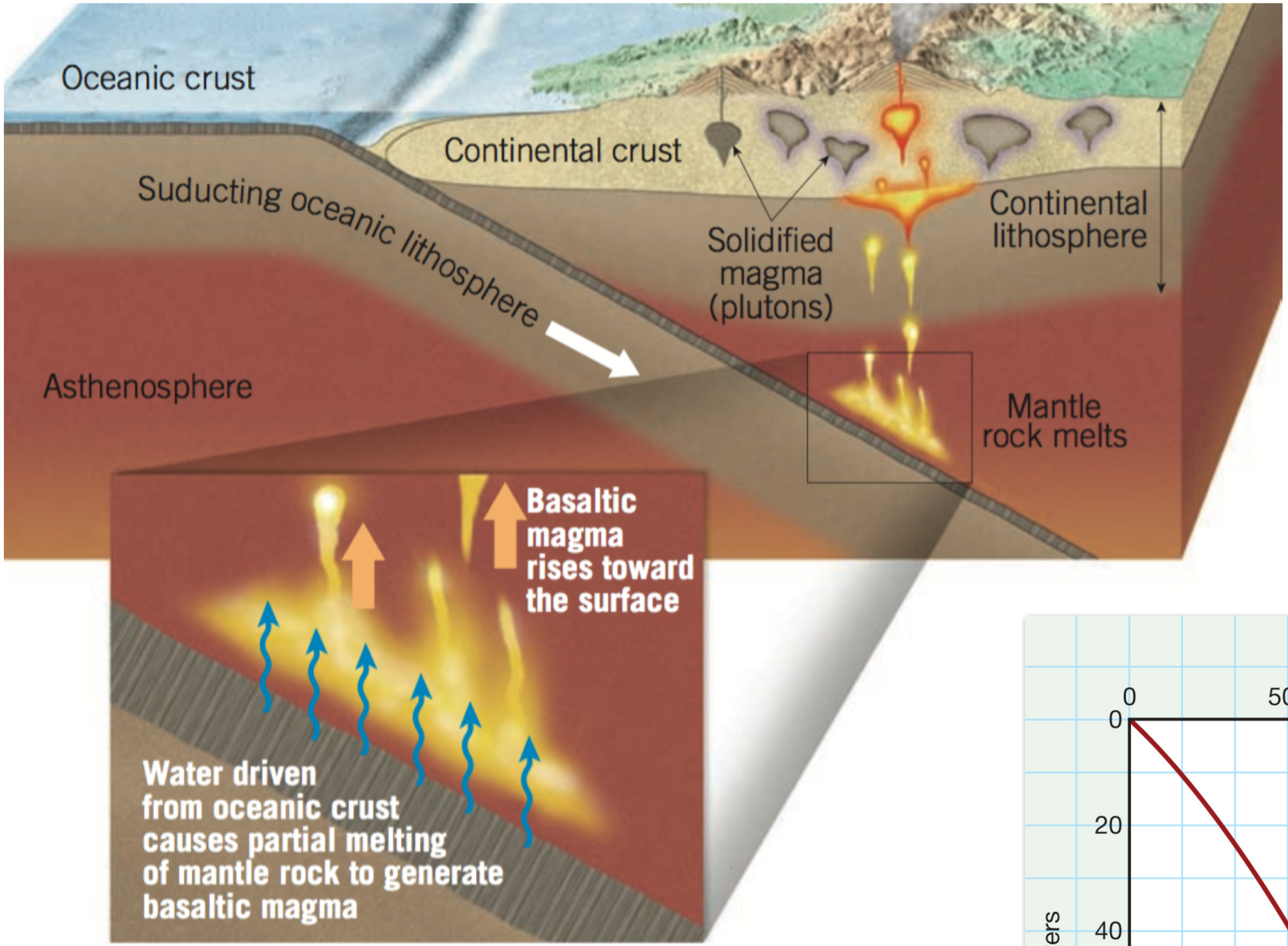
Decompression Melting

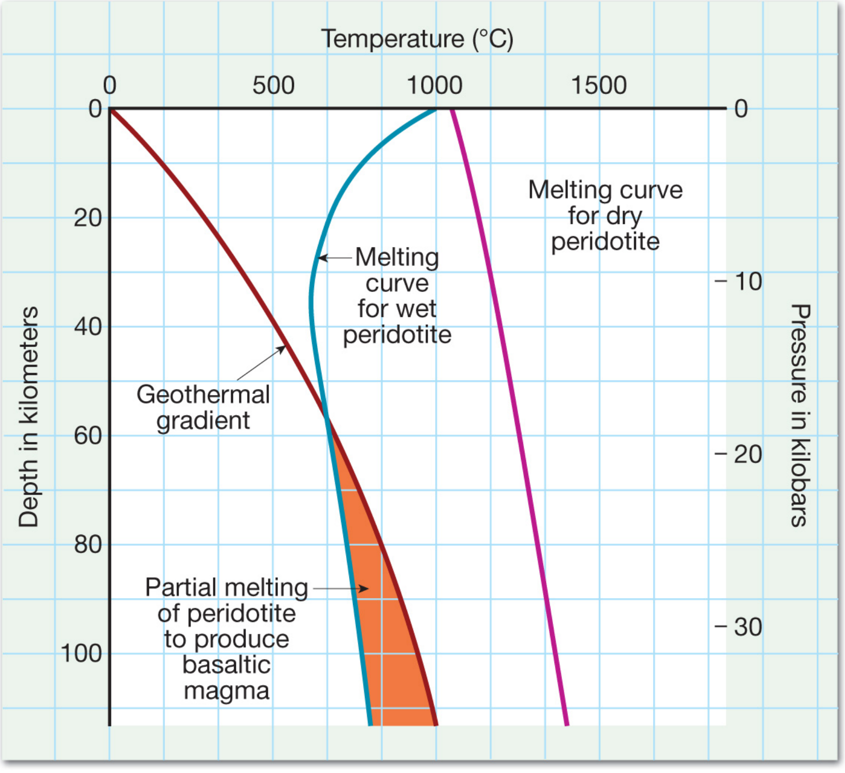
1. As hot mantle rock ascends through convective upwelling, it continually moves into zones of lower and lower pressure. This drop in confining pressure initiates *decompression melting*, in the upper mantle.

2. Decompression melting also occurs when ascending mantle plumes reach the uppermost mantle.

3. Role of volatiles

Volatiles (primarily water) cause melting at lower temperatures. Important factor where oceanic lithosphere descends into the mantle

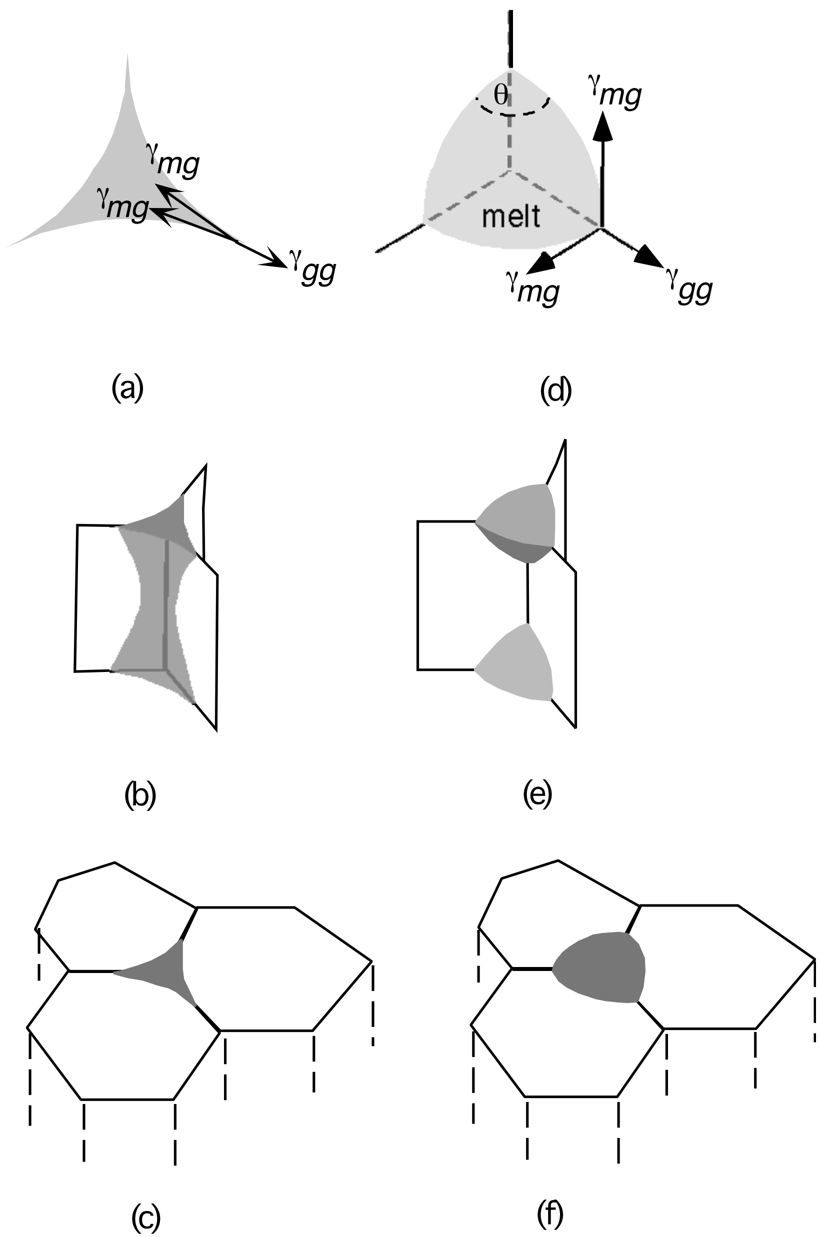




Water lowers the melting temperature of hot mantle rock to trigger partial melting

As an oceanic plate descends into the mantle, water and other volatiles are driven from the subducting crustal rocks into the mantle resulting partial melting of mantle rock and generate basaltic magma. At a depth of about 100 km the wedge of mantle rock is sufficiently hot that the addition of water leads to some melting. Partial melting of the mantle rock peridotite generates hot basaltic magma whose temperatures may exceed 1250° C.

Magma Segregation and Compaction



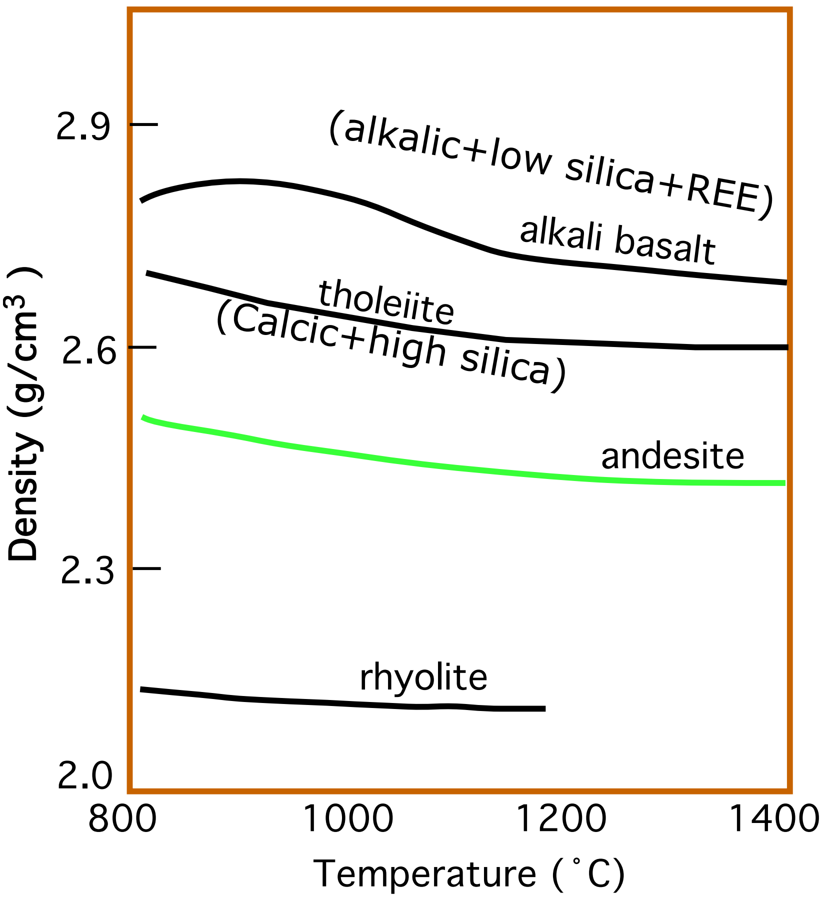
- Melting appears to begin at the intersections ("triple point junctions") of grains of different phases.
- The *dihedral angle* (*q*) between two adjacent solid grains and melt plays an important role in controlling melt distribution in the pore spaces of the rock. If $q < 60^{o}$, then melts in all corners will be interconnected, which allows the melt to escape along grain boundaries even when the melt fraction [i.e, mass of melt /(mass of melt + mass of rock)] is very small.
- Basaltic magmas exhibit this behavior, BUT NOT GRANITE

How magma flows?

Flow of magma through interconnected pores (i.e., porous flow) is governed by *D'Arcy's law:*

$$v = \frac{K}{\mu\phi} . \frac{dP}{dz}$$

where *v* is magma velocity, *K* is permeability, **Φ** is porosity and **μ** is viscosity of the magma. dP/dz is simply the pressure gradient caused largely by the density difference between a magma and the solid residue.



Densities of different magmas have been measured in the laboratory, mostly at atmospheric pressure, and they vary between 2.2 and 3.1 g/cm^3. Density of magma is directly related to the abundance of the mafic (i.e., Mg + Fe) component.

Consider a simple example of buoyant rise of a x magma from a depth of 60 km to the surface. We assume that the wall rock at ~60-40 km is y with a density of 3.3 g/cm^3. The magma's density is assumed to be constant at 2.9 g/cm^3.

$$P = \boldsymbol{\rho} g h$$

where P is pressure (in GPa), **ρ** is density, and g is acceleration due to gravity (assumed to be constant with a value of 980 cm/sec^2).

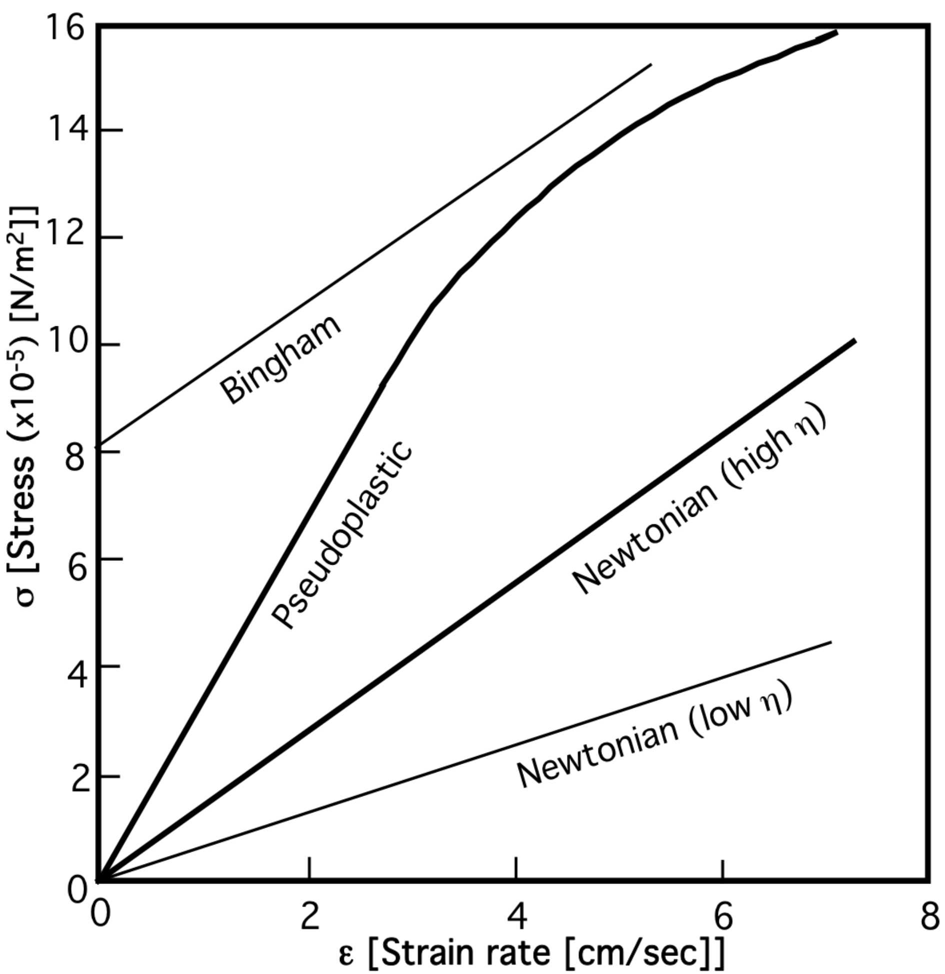
P_{rock} at 60 km = $(60{,}000{,}00 * 3.3 * 980)/10^{10} = 1.94$ GPa

P_{magma} at 60 km = $(60{,}000{,}00*2.9*980)/10^{10} = 1.70$ GPa

Therefore, the pressure difference of 0.24 GPa between the magma and wall rock makes the magma sufficiently buoyant to rise to the surface.

Magma Flow

Viscosity and Density are important factors that determine how fast magma will rise.



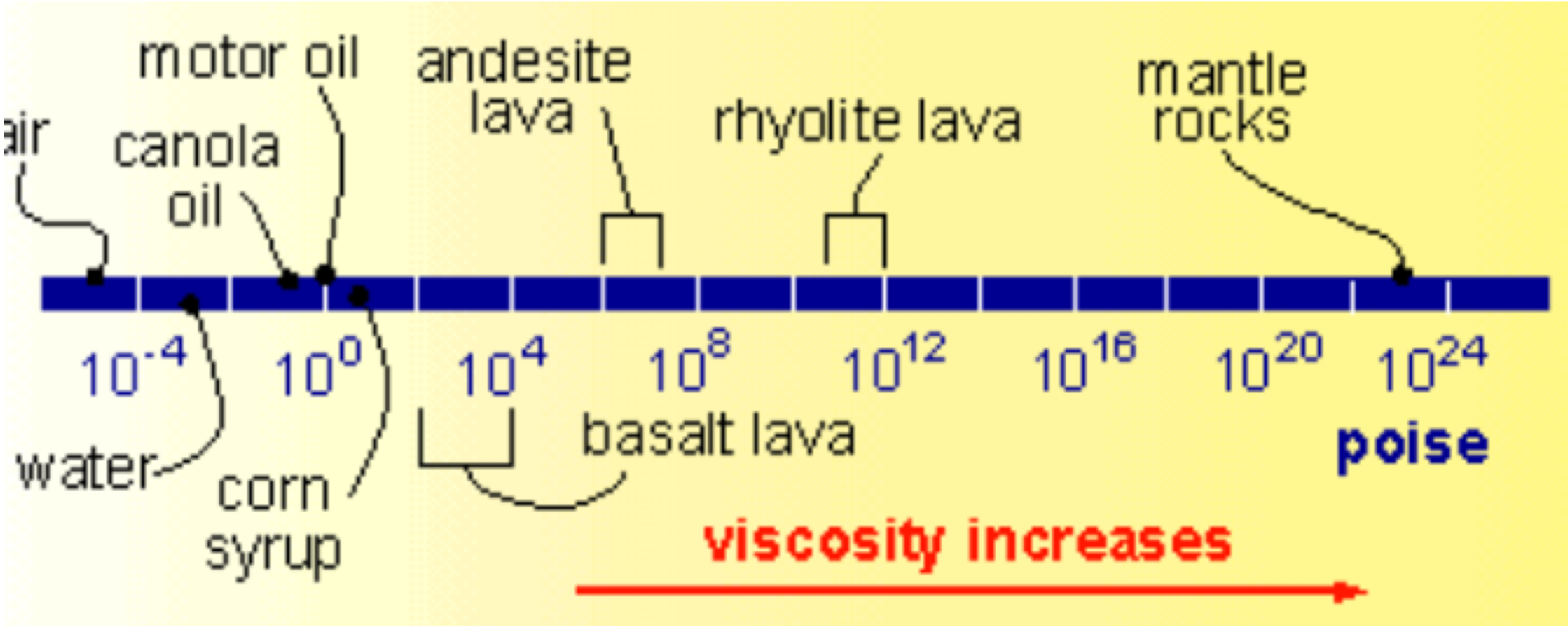
Viscosity (**η**) of a magma is simply defined as its <u>internal resistance to flow</u> and is given as:

$$\eta = \sigma / \varepsilon$$

σ=Shear Stress

ε=Shear Strain rate

- <u>Crystal-free basalt magmas show Newtonian behavior</u>.
- <u>Andesitic magma</u> containing abundant crystals may behave like a <u>*Bingham plastic*</u> - that is, they may possess some finite yield strength and thus flow only when a certain threshold value of stress has been exceeded.
- <u>Rhyolitic magmas exhibit *pseudoplastic* behavior</u> in that it shows a non-linear relationship between stress and strain rate.



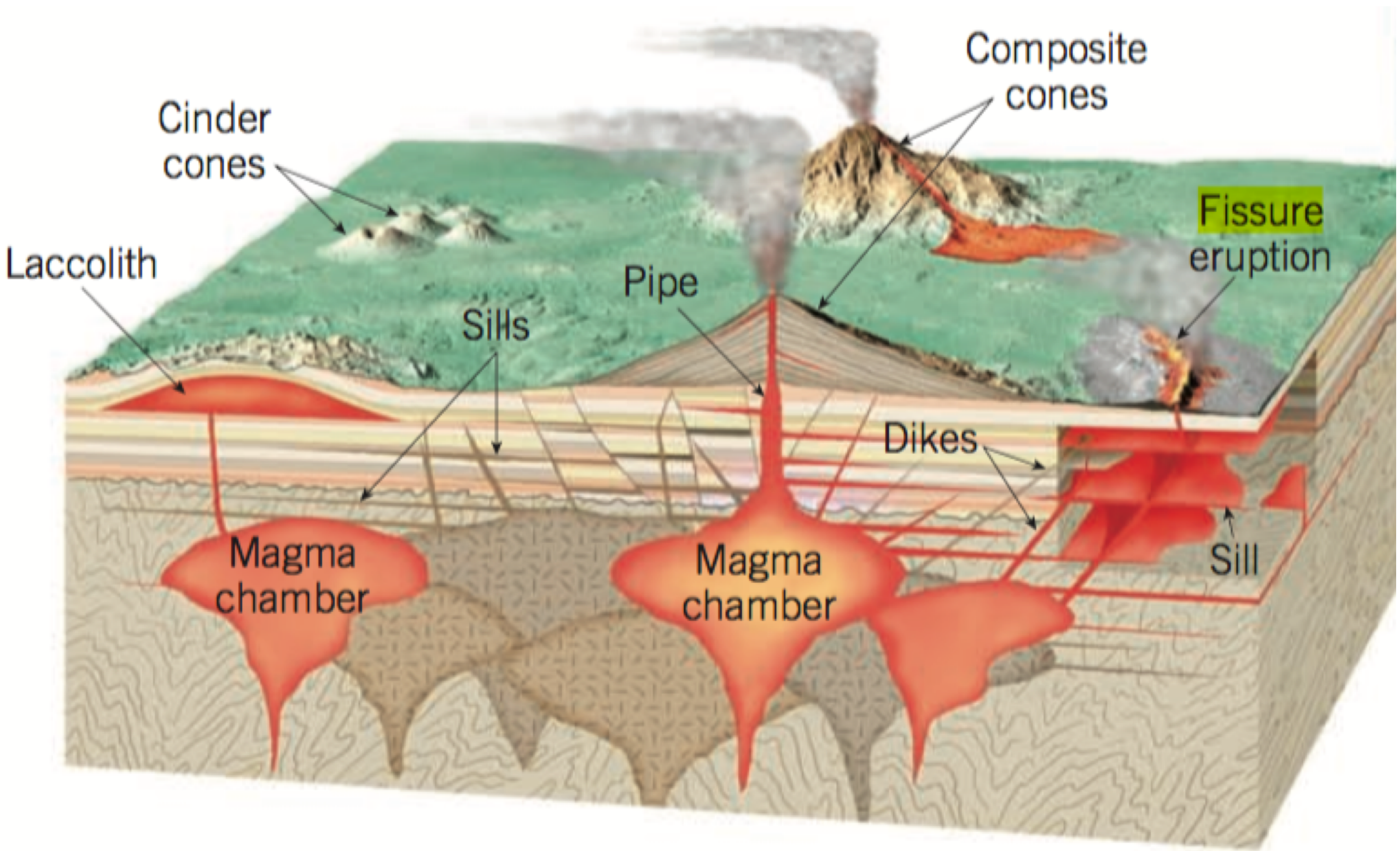
(University of British Columbia)

Factors affecting viscosity

- **Temperature—Hotter magmas are less viscous.**
- **Composition—silica (SiO_2) content**
  - **– Higher silica content = higher viscosity (e.g., felsic lava such as rhyolite).**
- **Dissolved gases**
  - **Gases expand within a magma as it nears Earth's surface due to decreasing pressure.**
  - **The violence of an eruption is related to how easily gases escape from magma.**

The Nature of Volcanic Eruptions

- In summary, factors affecting viscosity:
  - Fluid basaltic lavas generally produce quiet eruptions.
  - Highly viscous lavas (rhyolite or andesite) produce more explosive eruptions.



Why?

Q1: How come oceanic crust is composed of basalt although upper mantle is of peridotite?

Q2: Why do we observe andesitic volcanism at the Subduction zones when the subducting oceanic plates are made up of basalts??

Q3: Why continents are of granitic compositions?

Q4: How come a single volcano extrudes lavas of very different compositions?

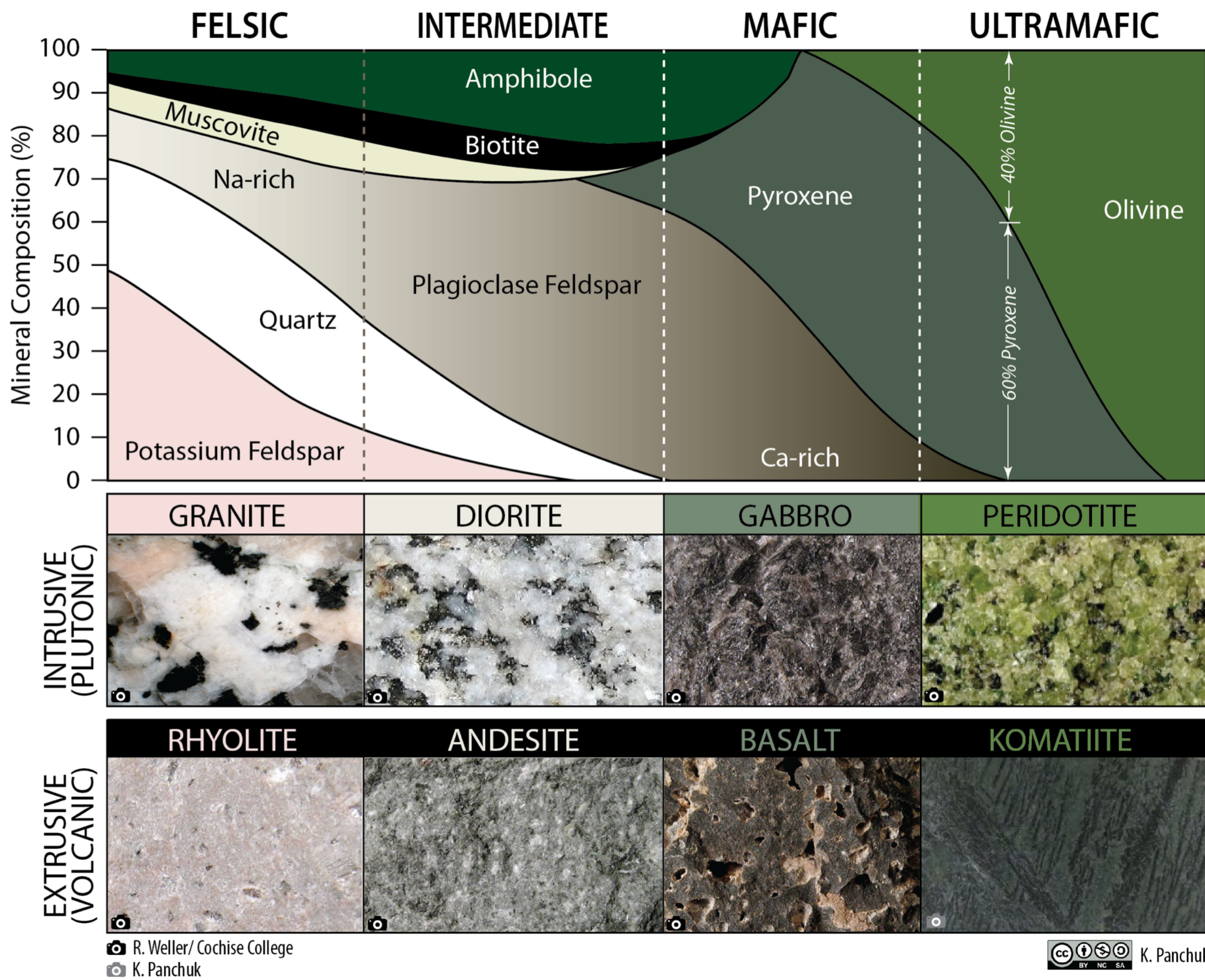
Evolution of Magmas

- A single volcano may extrude lavas of very different compositions.

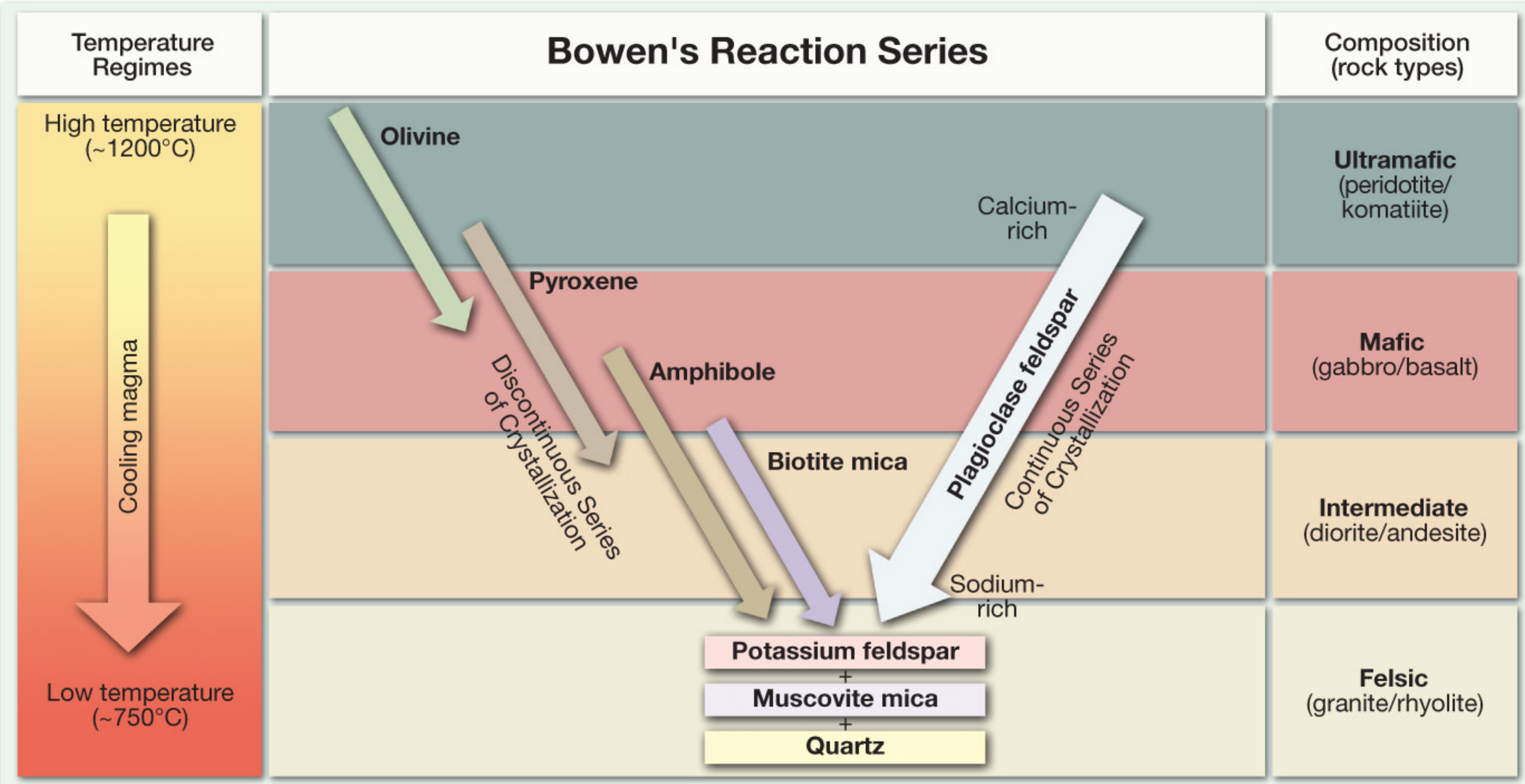
Bowen's reaction series

- Minerals crystallize in a systematic fashion based on their melting points.

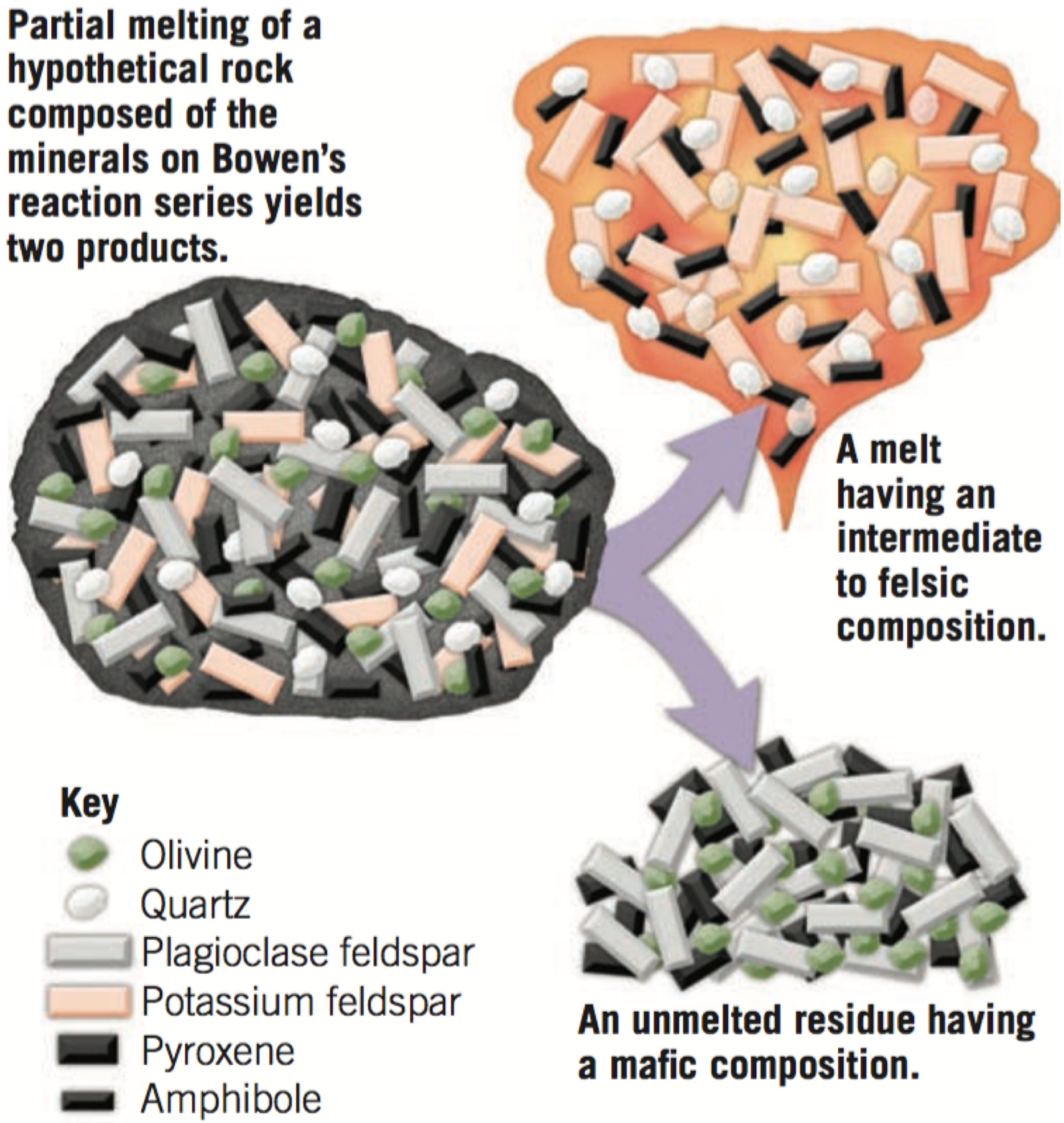
- During crystallization, the composition of the liquid portion of the magma continually changes.



Bowen's Reaction Series



This diagram shows the sequence in which minerals crystallize from a mafic magma.

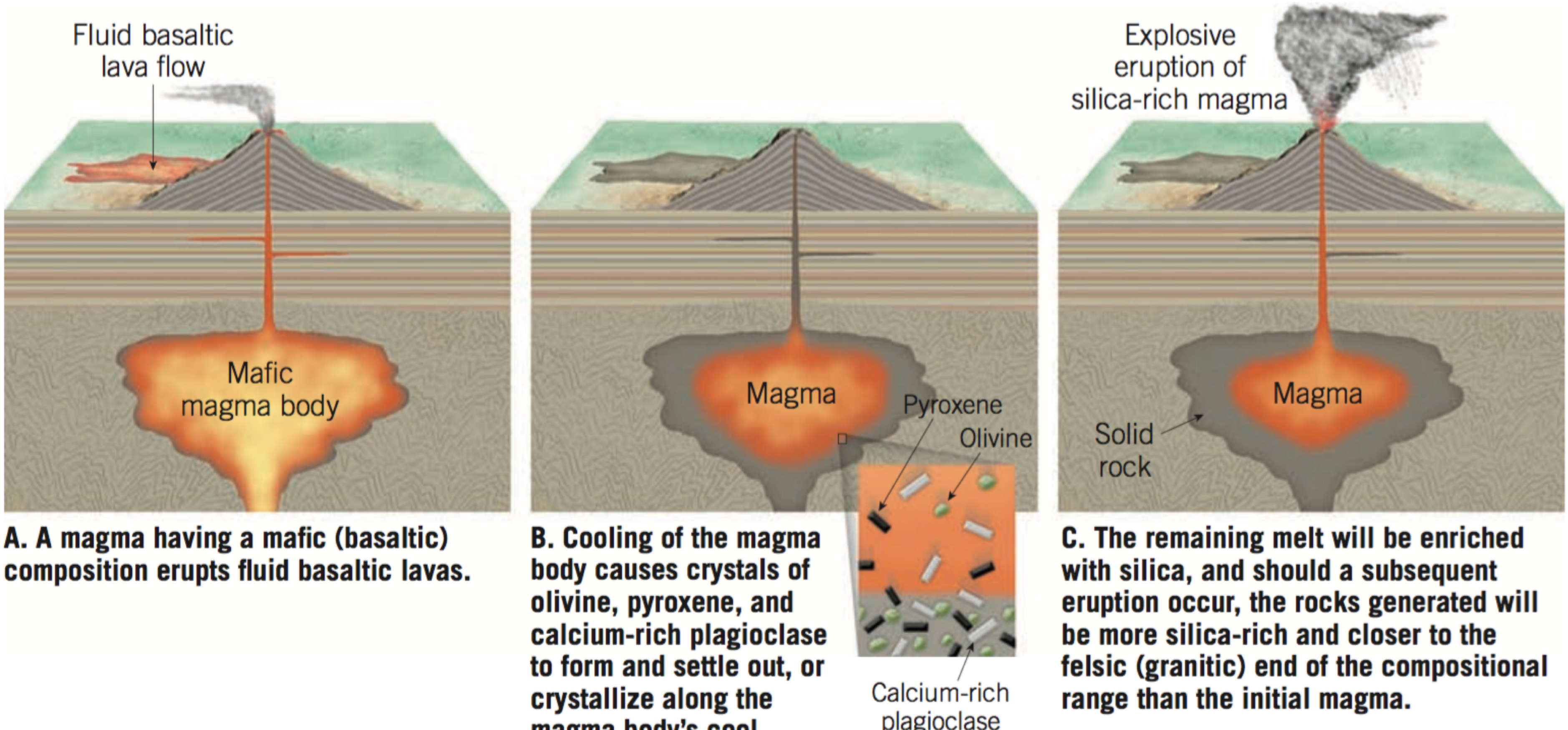


Partial melting generates a magma that is nearer the felsic (granitic) end of the compositional spectrum than the parent rock from which it was derived.

- Partial melting of *ultramafic* rocks yields *mafic (basaltic) magmas*,
- partial melting of *mafic* rocks yields *intermediate (andesitic) magmas*,
- partial melting of *intermediate* rocks yields *felsic (granitic) magmas.*

Magmatic Differentiation and Crystal Settling

The formation of one or more secondary magmas from a single parent magma is called **magmatic differentiation**.



A. A magma having a mafic (basaltic) composition erupts fluid basaltic lavas.

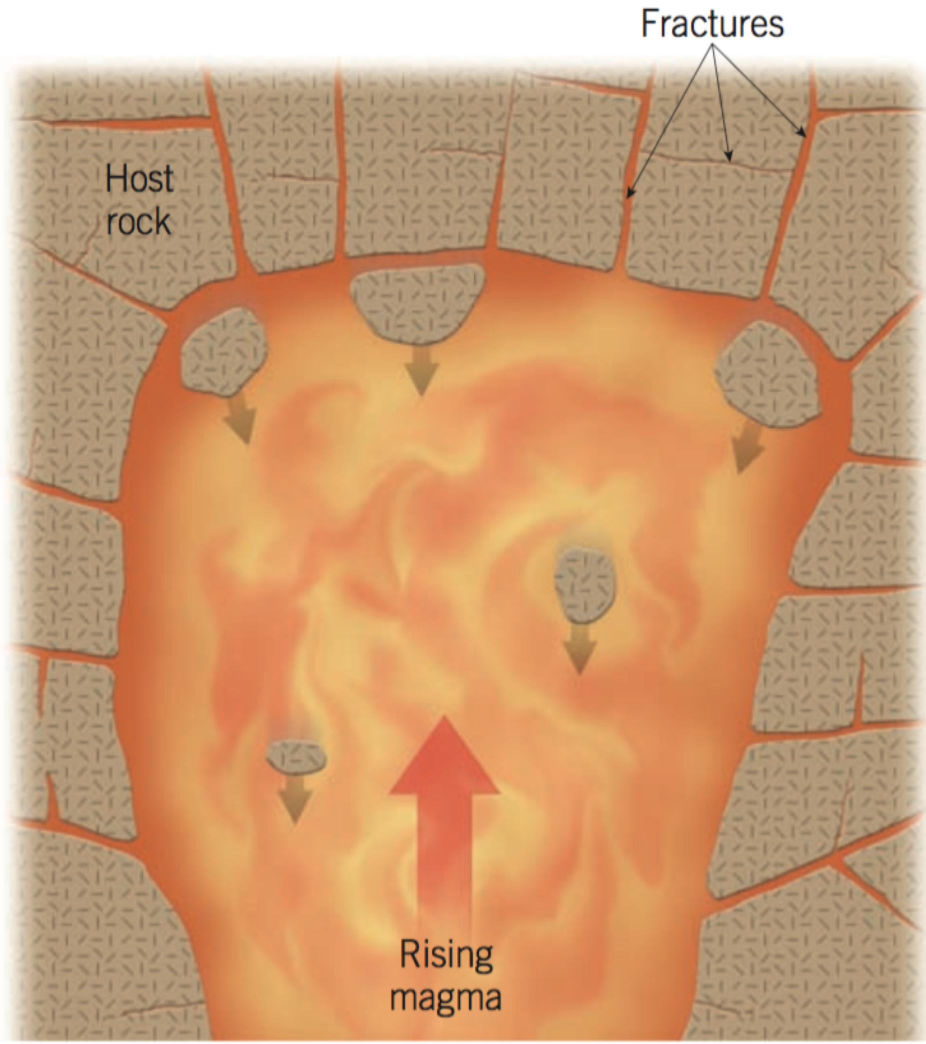
B. Cooling of the magma body causes crystals of olivine, pyroxene, and calcium-rich plagioclase to form and settle out, or crystallize along the magma body's cool margins.

C. The remaining melt will be enriched with silica, and should a subsequent eruption occur, the rocks generated will be more silica-rich and closer to the felsic (granitic) end of the compositional range than the initial magma.

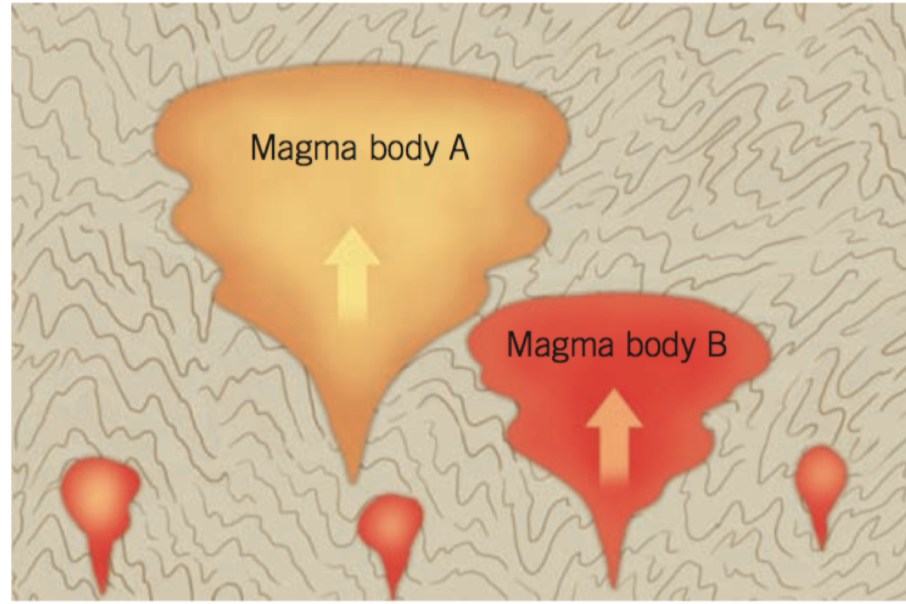
Crystal settling results in a change in the composition of the remaining melt

Illustration of how a magma evolves as the earliest- formed minerals (those richer in iron, magnesium, and calcium) crystallize and settle to the bottom of the magma chamber, leaving the remaining melt richer in sodium, potassium, and silica (SiO_2)

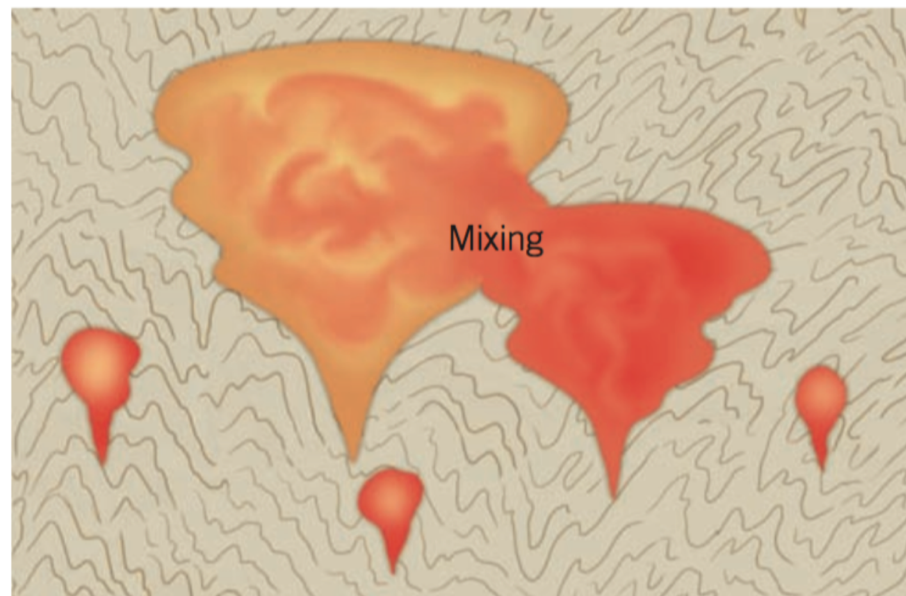
Assimilation and Magma Mixing



As magma rises through Earth's brittle upper crust, it may dislodge and incorporate the surrounding host rocks. Melting of these blocks, a process called *assimilation*, changes the overall composition of the rising magma body.

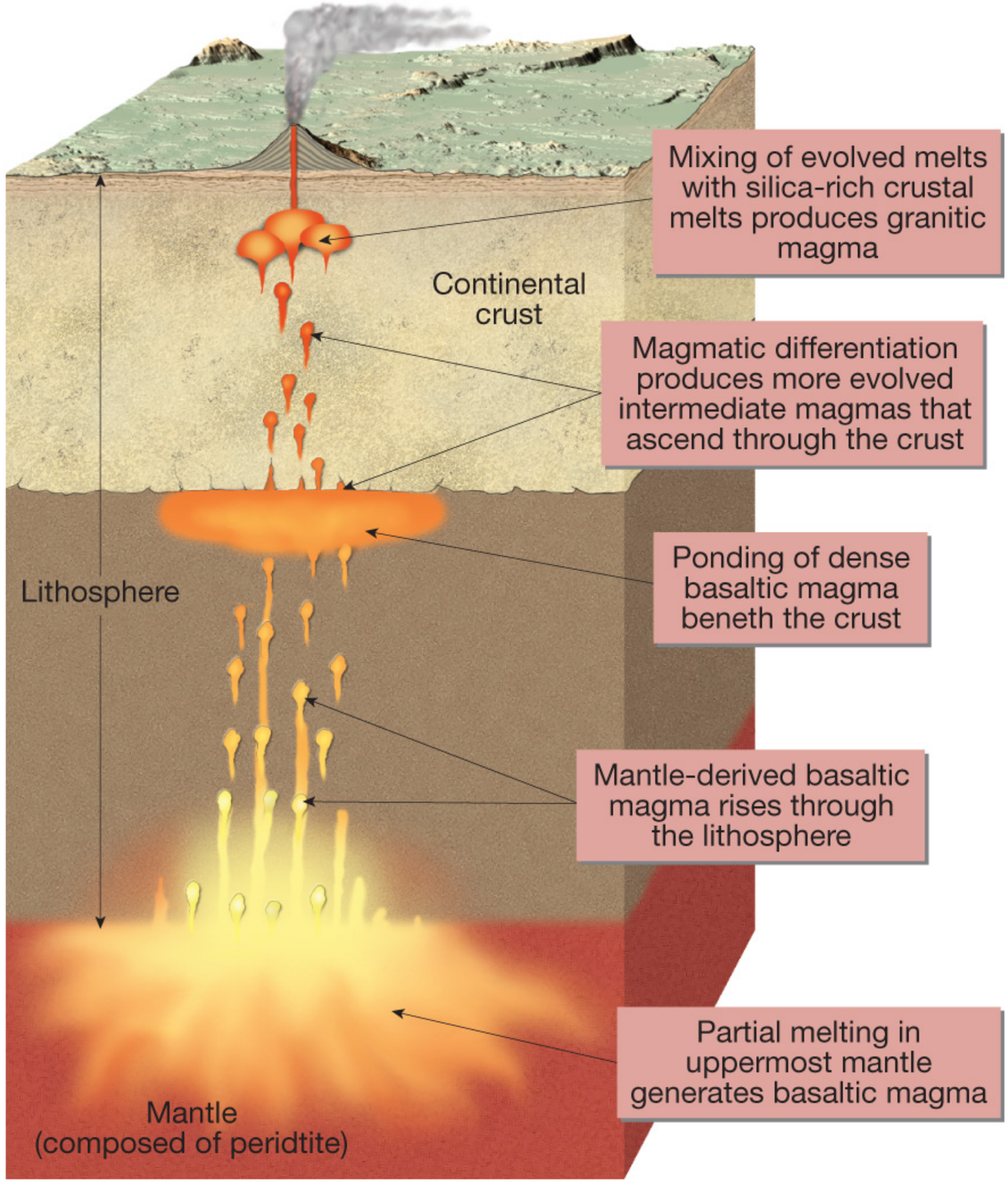


A. During the ascent of two chemically distinct magma bodies, the more buoyant mass may overtake the slower rising body.

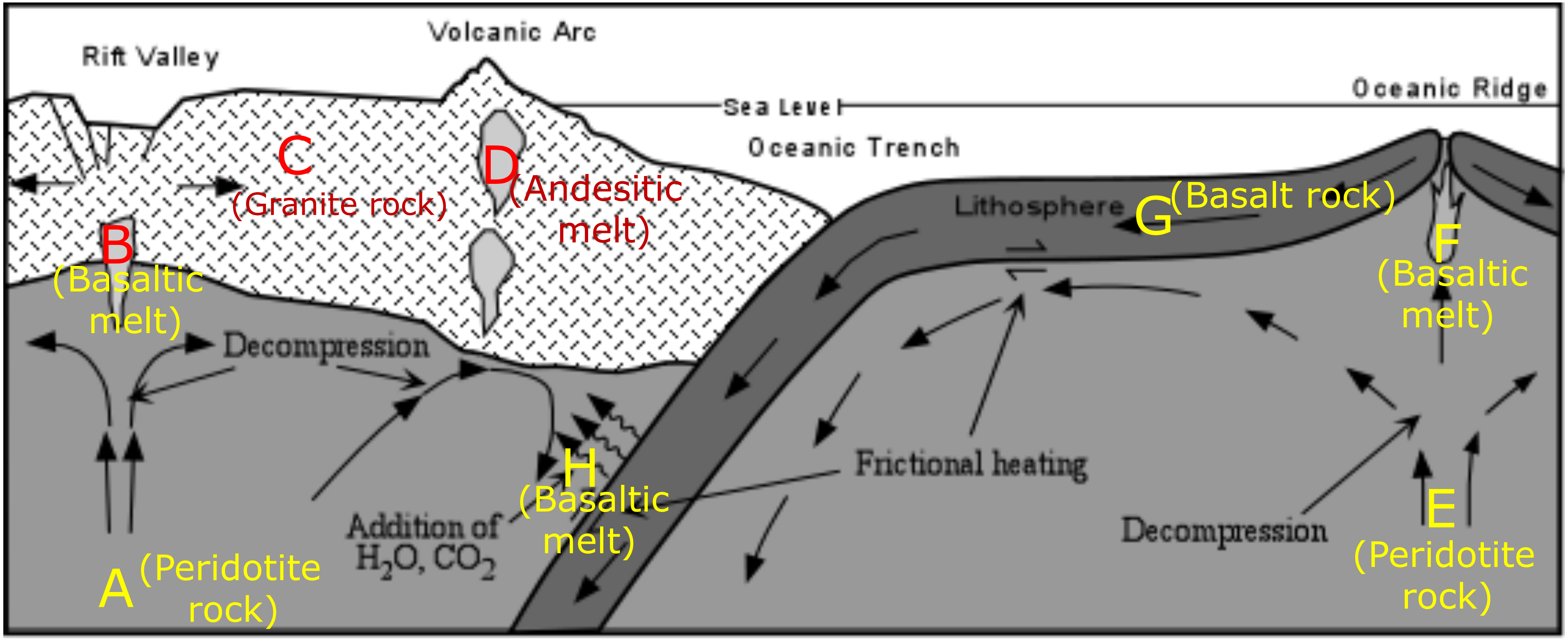


B. Once joined, convective flow will mix the two magmas, generating a mass that is a blend of the two magma bodies.

Granitic magmas are generated by partial melting of continental crust

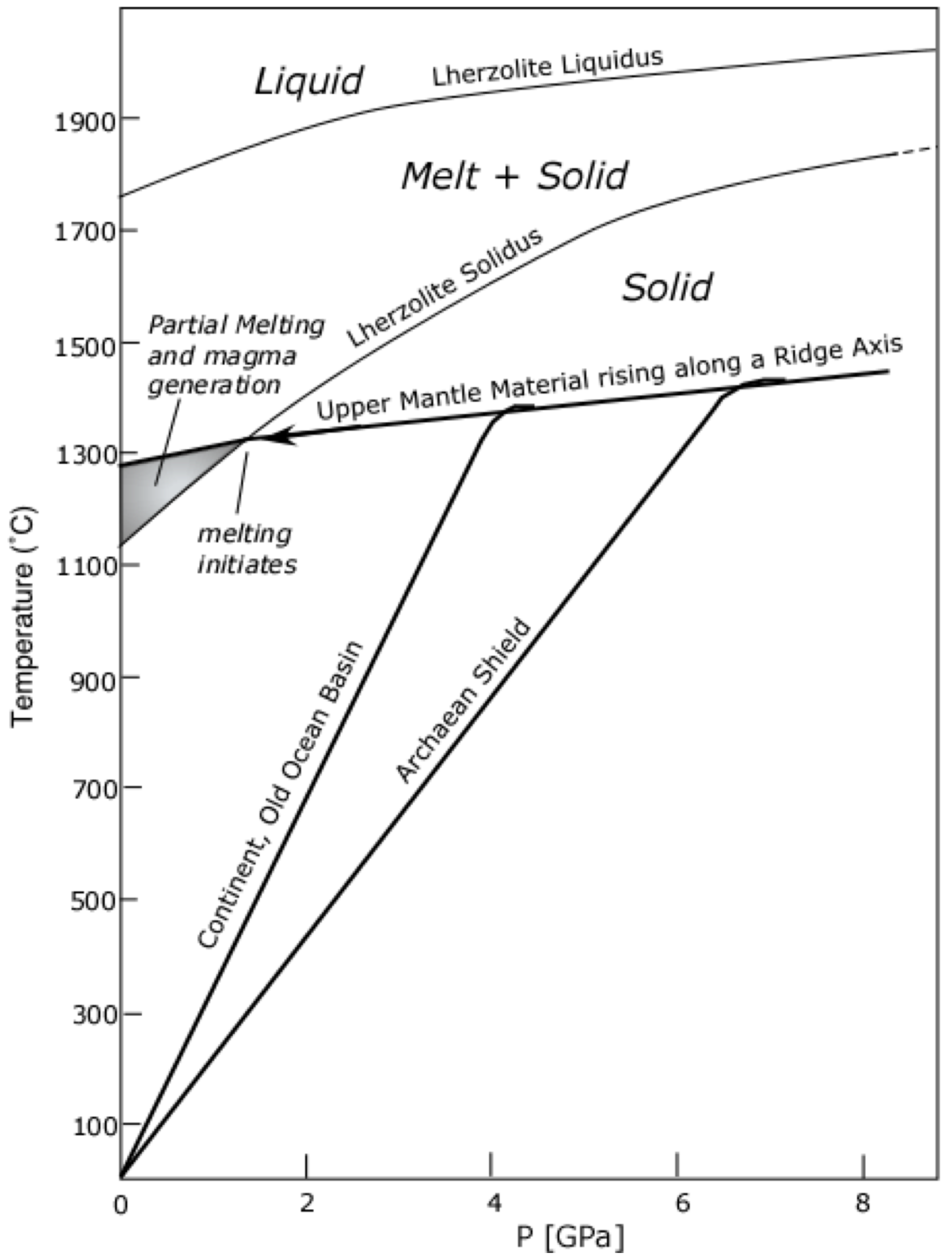


Questions

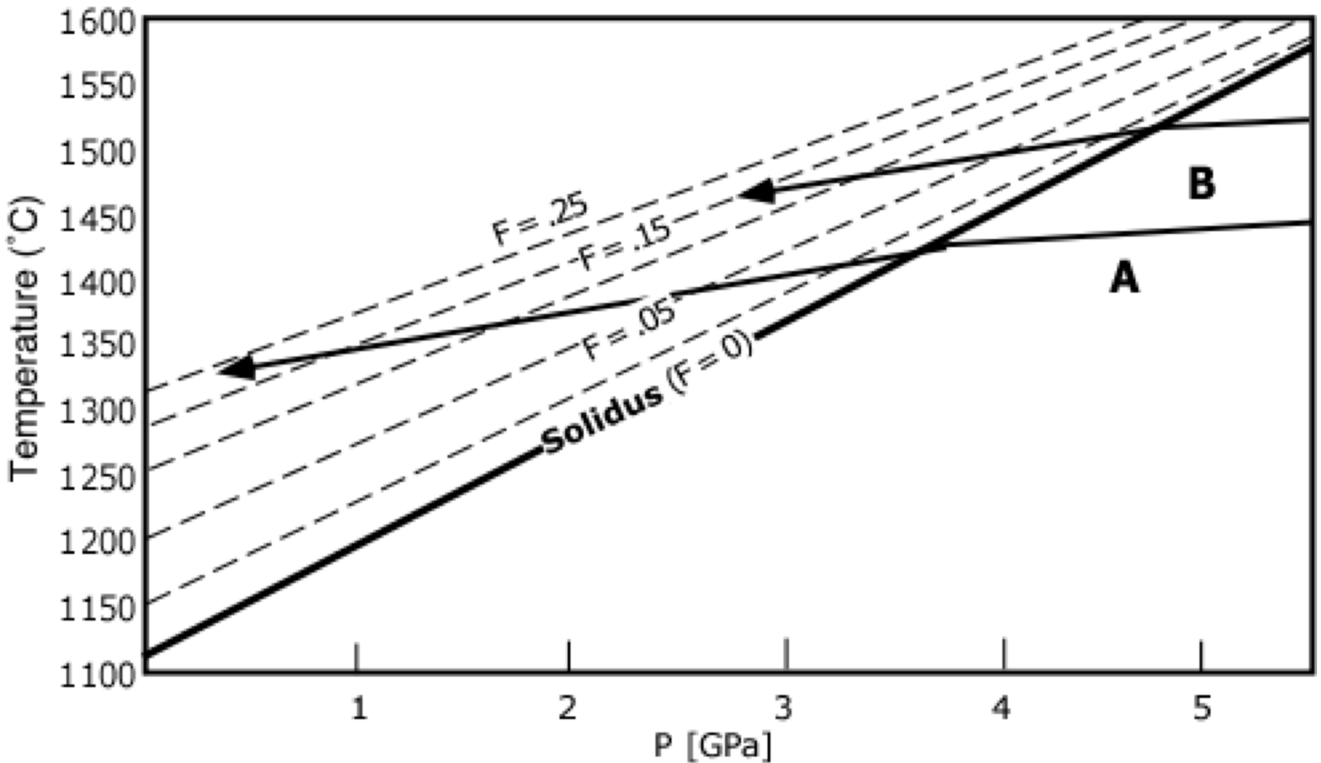


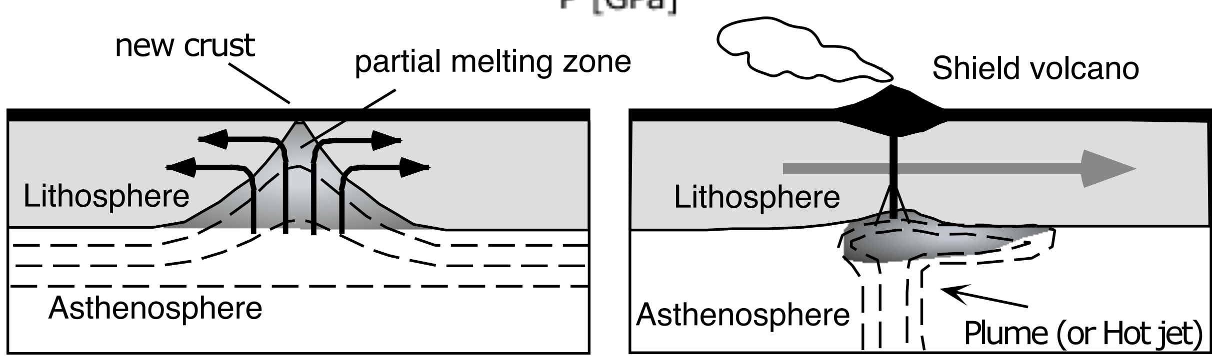
1. Which kind of rocks/melt you expect at A, B, C, D, E, F, G, H?
2. Which one is older: Oceanic/Continental crust?

Evolution of Magmas



This diagram shows the solidus and liquidus of upper mantle lherzolite, adiabatic ascent path of mantle rock beneath a mid-oceanic ridge (MOR), and geothermal gradients in Archaean shield areas, stable continental platform areas and old (far away from ridge axis) ocean basin (redrawn after McKenzie and Bickle 1988). In this model, the Mid-ocean ridge adiabat represents the path taken by a parcel of mantle rock (asthenosphere) that rises and crosses lherzolite solidus at about 1.8 GPa, at which point it begins to melt. It continues to melt all the way up to the base of the crust. This partially molten region is depicted as the gray area here.





Passive Upwelling of Asthenosphere

Hot Plume impact on a moving Lithosphere

Formation of different kind of Magma