IGNEOUS PETROLOGY I: MELTING THE MANTLE

Elemental Abundances in Earth's Mantle

- Most mantle minerals are silicates, rich in Mg, Fe
  - Olivine most common
  - Orthopyroxene 2nd most common
- Al, Ca, Na hosted by:
  - Clinopyroxene and/or
  - Plagioclase, spinel or garnet – depending on pressure, temperature and composition

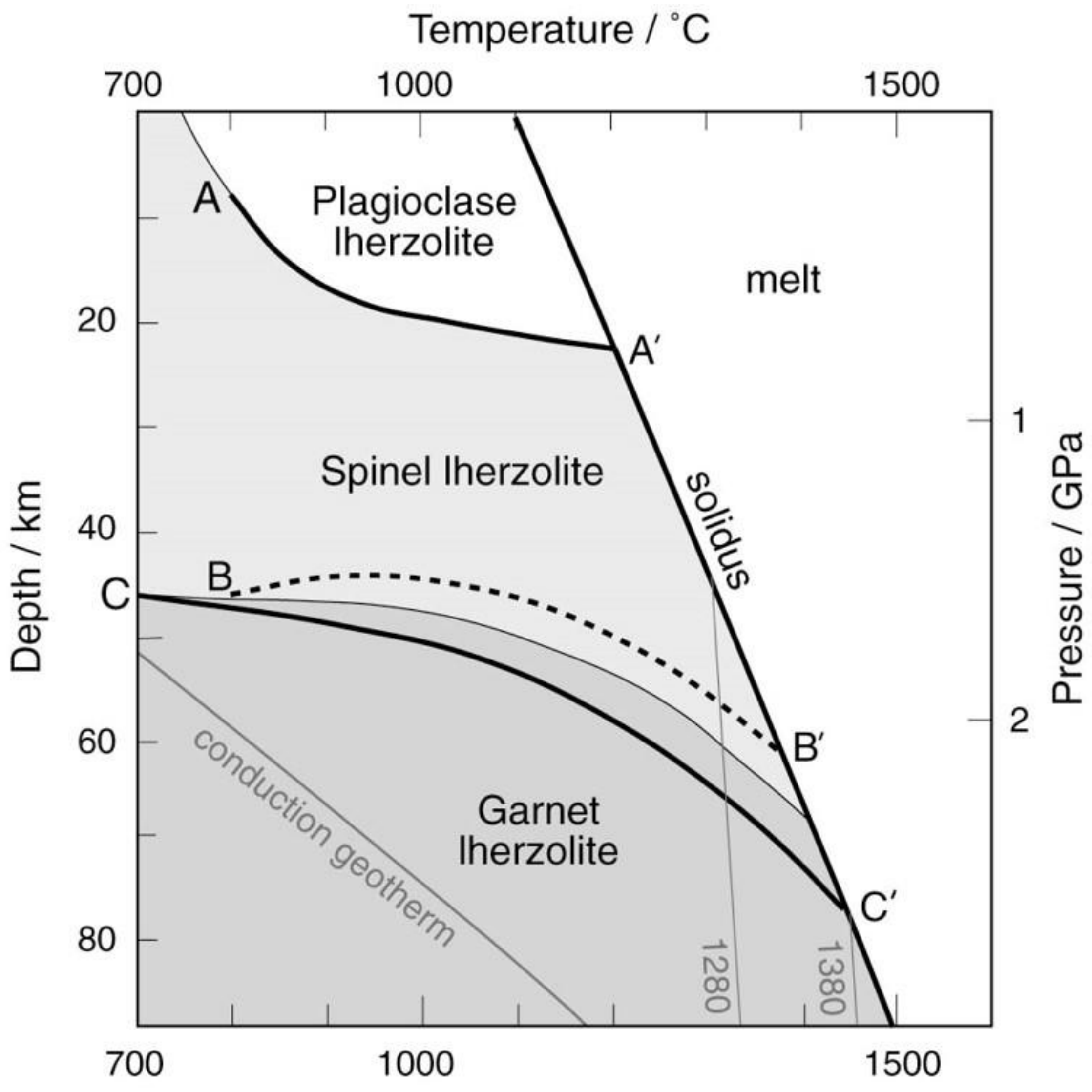
Z	Name (Z)	Symbol	Abundance in Mantle (atomic %)
8	Oxygen	O	44.8
12	Magnesium	Mg	22.8
14	Silicon	Si	21.5
26	Iron	Fe	5.8
13	Aluminium	Al	2.2
20	Calcium	Ca	2.3
11	Sodium	Na	0.3
19	Potassium	K	0.03

Minerals in Peridotite (and Pyroxenite)

Mineral name	Simplified chemical formula	Appearance in hand specimen
Olivine (Ol)	$(Mg,Fe)_2SiO_4$	Pale green, sometimes altered to brown, anhedral, no cleavage, glassy/vitreous luster
Orthopyroxene (Opx)	$(Mg,Fe)SiO_3$	Dark brown, 2 cleavages at 90°, often tabular crystals
Clinopyroxene (Cpx)	$CaMgSi_2O_6$	Bright green, 2 cleavages at 90°, often anhedral, sometimes prismatic
Spinel (Sp or Spl)	$(Mg,Fe)(Al,Cr,Fe^{3+})O_4$	Black or blown, opaque, usually anhedral
Garnet (Ga or Gt)	$(Ca,Mg,Fe)_3(Al,Cr)_2Si_3O_{12}$	Pink-purple, often euhedral, no cleavage, often altered at rim

Upper Mantle Minerals

- Al-bearing phase changes with depth
  - Plagioclase (Pl) (< ~1 GPa)
  - Spinel (1 – 3 GPa)
  - Garnet (>2 GPa)
- Presence of particular minerals gives an indication of pressure



Phase Changes

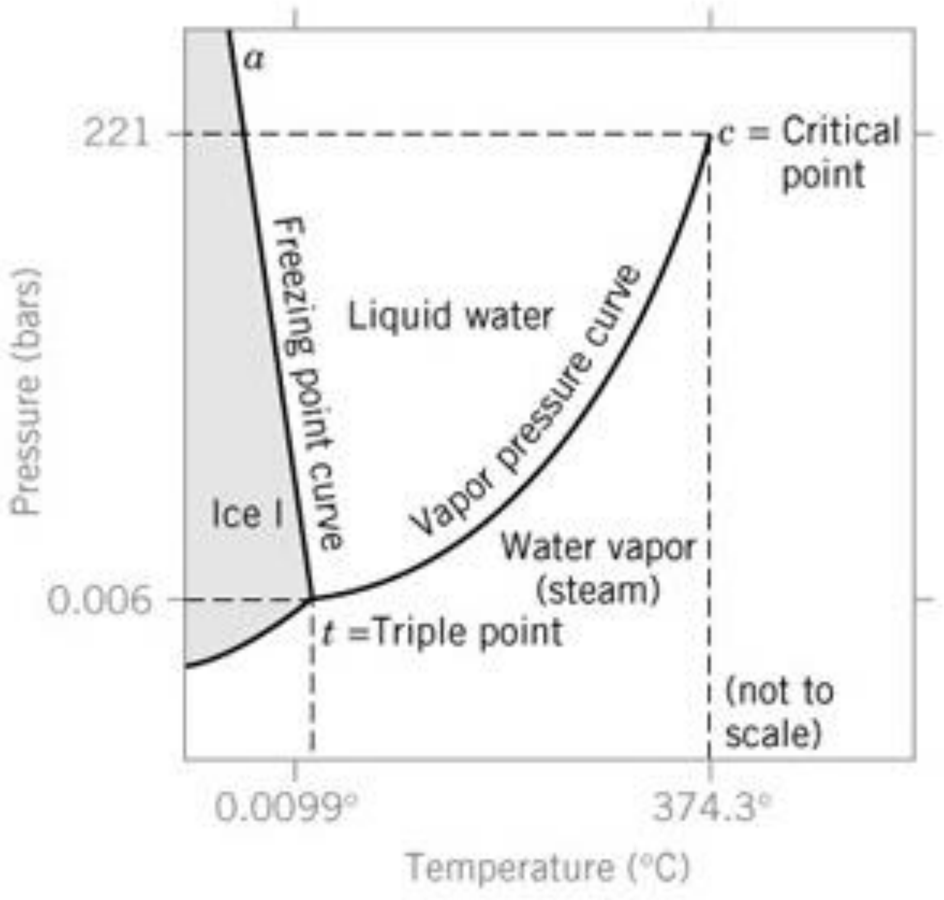
On a P-T diagram, phase boundaries occur when phases in equilibrium

- Get a phase change

Example: Water

What happens at:

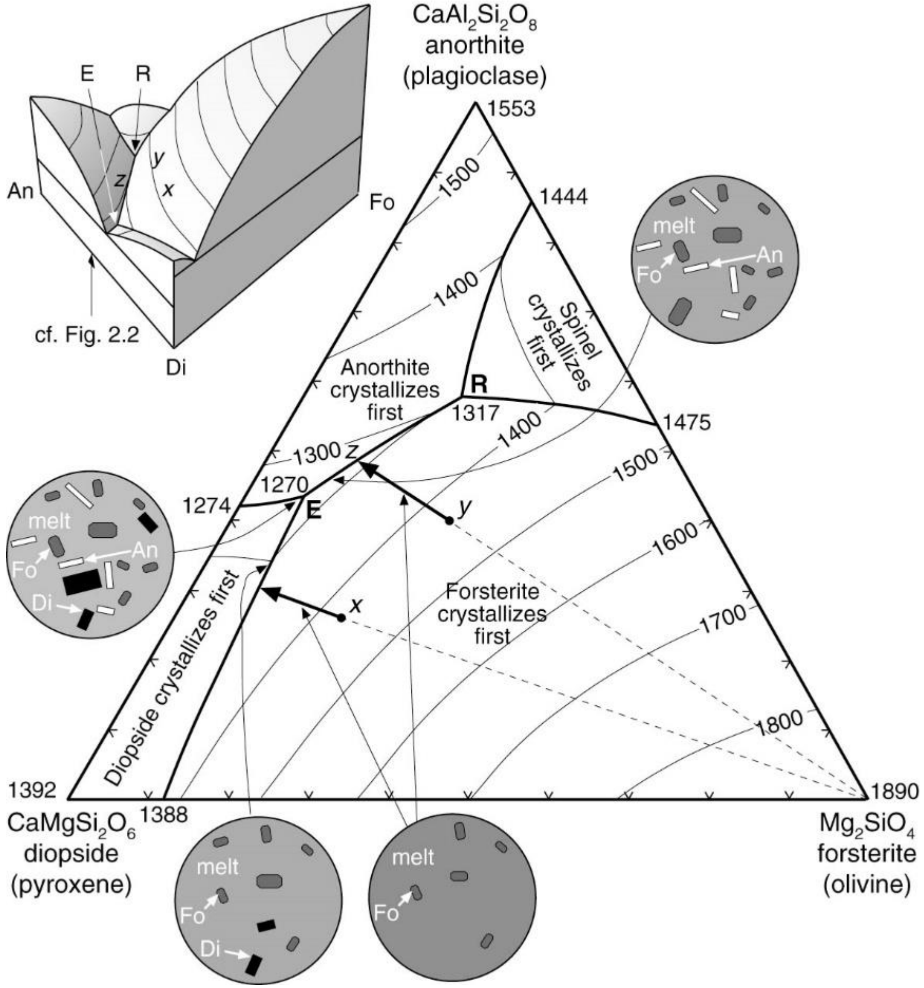
- Constant P, ↓T?
- Constant T, ↓P?
- Triple point?
- Critical point?



Klein & Dutrow Fig 11.3

Phase diagrams

- Display relationships between phases (components) in P-T-X space
  - May also show Eh-pH
- Used to determine mineral stability and reactions/processes
- Common types
  - P-T
  - T-X
  - X – ternary

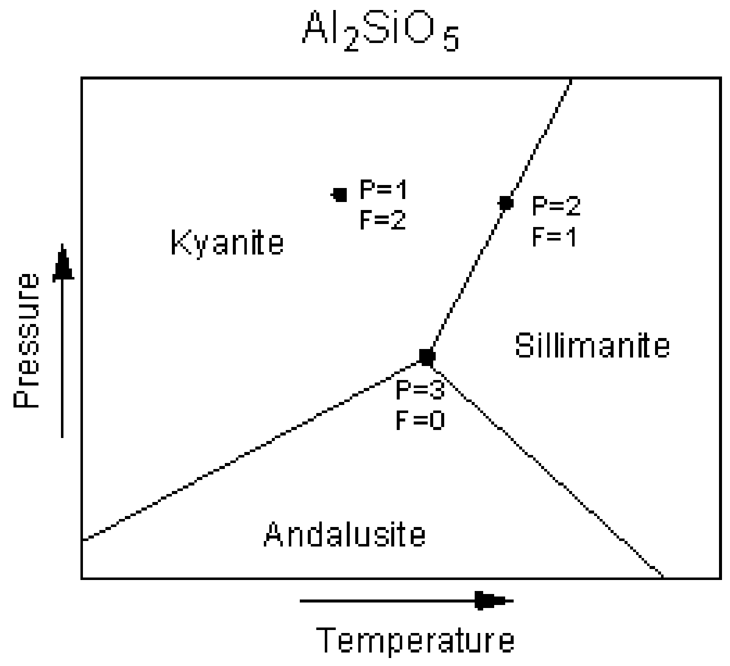


Gill: Igneous Rocks & Processes, 2010, Fig 3.3

Phase Rule

- System: part of the universe being considered
  - Isolated: no exchange of energy or mass
  - Closed: exchange of energy not mass
  - Open exchange of energy and mass
- Phase: physically separable part of system
  - Minerals, liquid, vapor, etc.
- Component: chemical species
  - Elements, molecules, ions, oxides, etc.
- Extensive Variables: properties which can vary
  - Pressure, temperature

- $F = C + 2 - P$
  - F = degrees of freedom
  - C = number of components
  - P = number of phases
  - 2 = number of extensive variables



[Stephen Nelson, Tulane University]

Single Component Phase Diagrams

- P-T diagrams
- 1 component
- Multiple phases
- Phase boundaries
  - 1 degree of freedom
- Triple point
  - 0 degrees of freedom

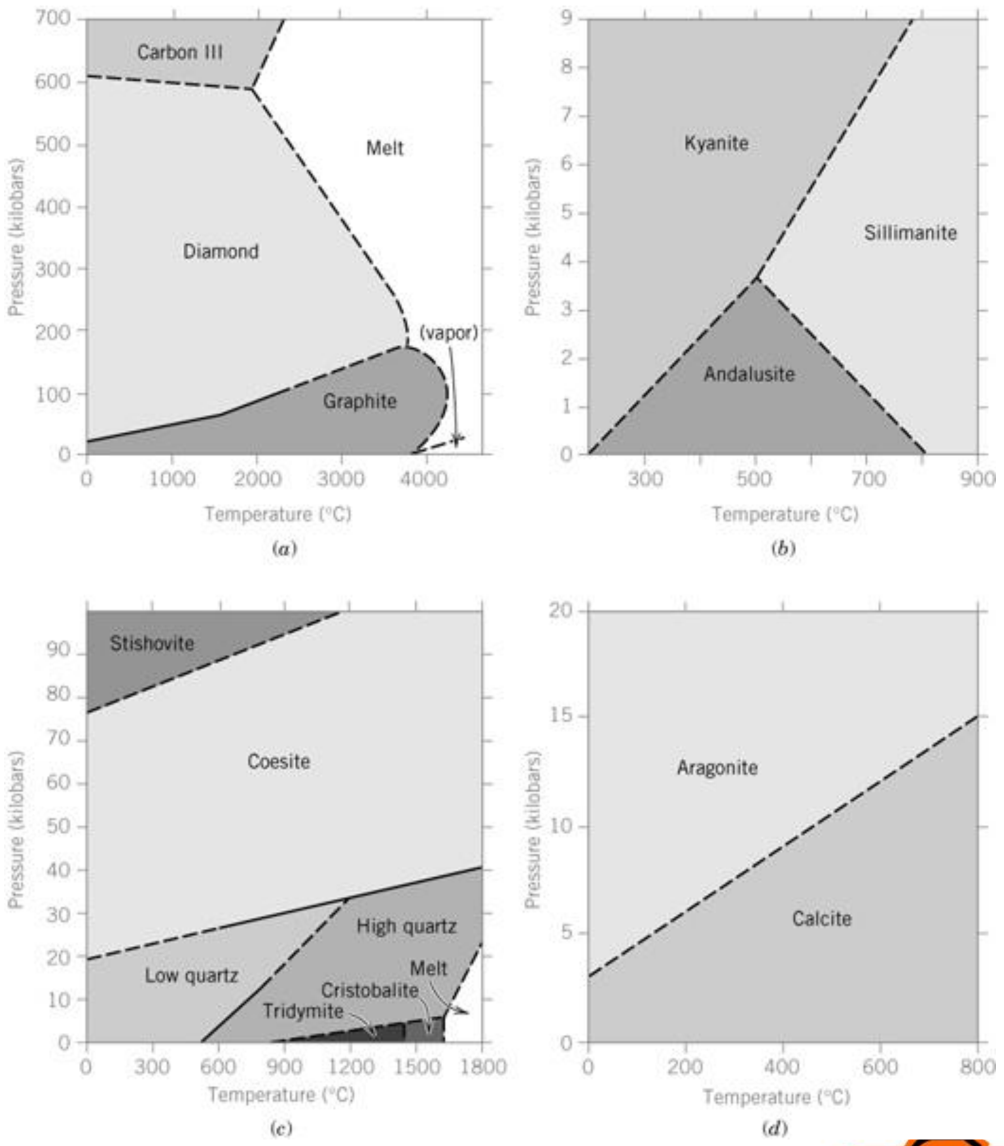


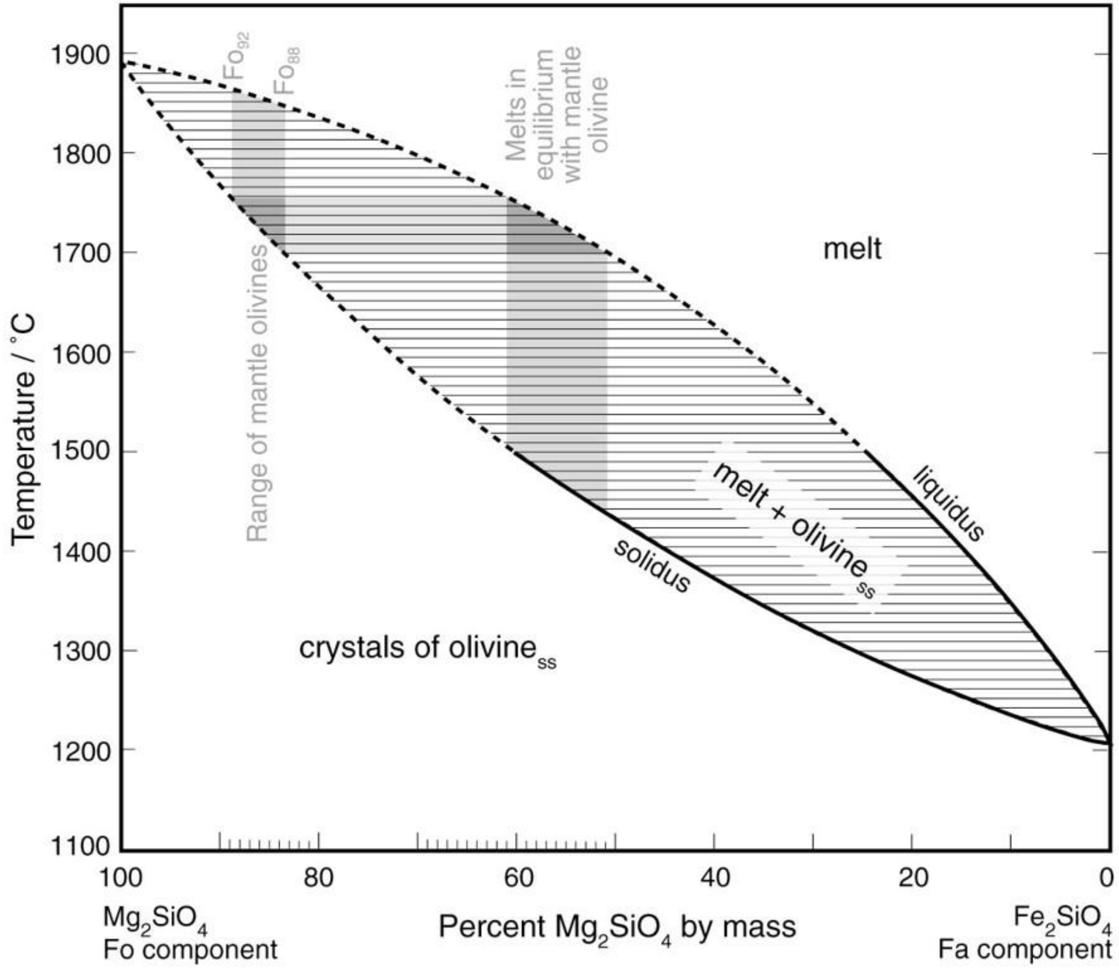
Fig 11.4, pg. 251

Compositional Variation

- Degree of solid solution is controlled by:
  - **Relative size** of the substituting atoms, ions, or ionic groups
    - Radius difference generally must be <~15%, each site has a limited space available
  - **Charges** on the substituting ions
    - Charge balance must be maintained, may involve another substitution (coupled substitution)
  - **Temperature and Pressure** at which substitution occurs
    - Ion sites expand at high T, compress at high P; at certain P, T there may be a greater tolerance
  - **Ion Availability**
    - Substitution requires ions to be abundant

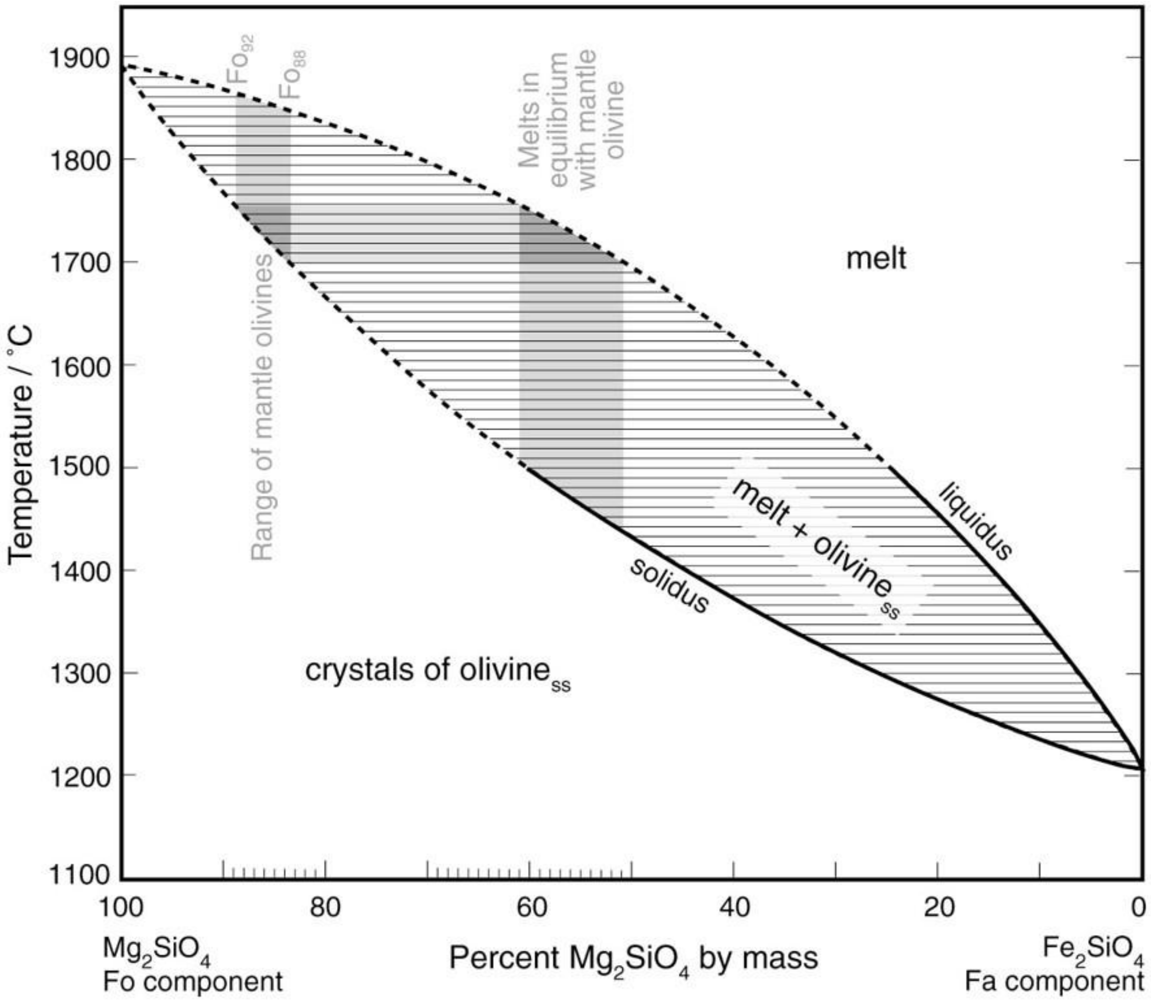
Olivine Phase Diagram

- Shows relationship between temperature (T) and composition (X)
  - Identifies regions of solid, melt, mixture
  - For a given pressure
  - Shows solid solutions
- Olivine is most abundant mineral in upper mantle
  - Provides simple model for mantle melting



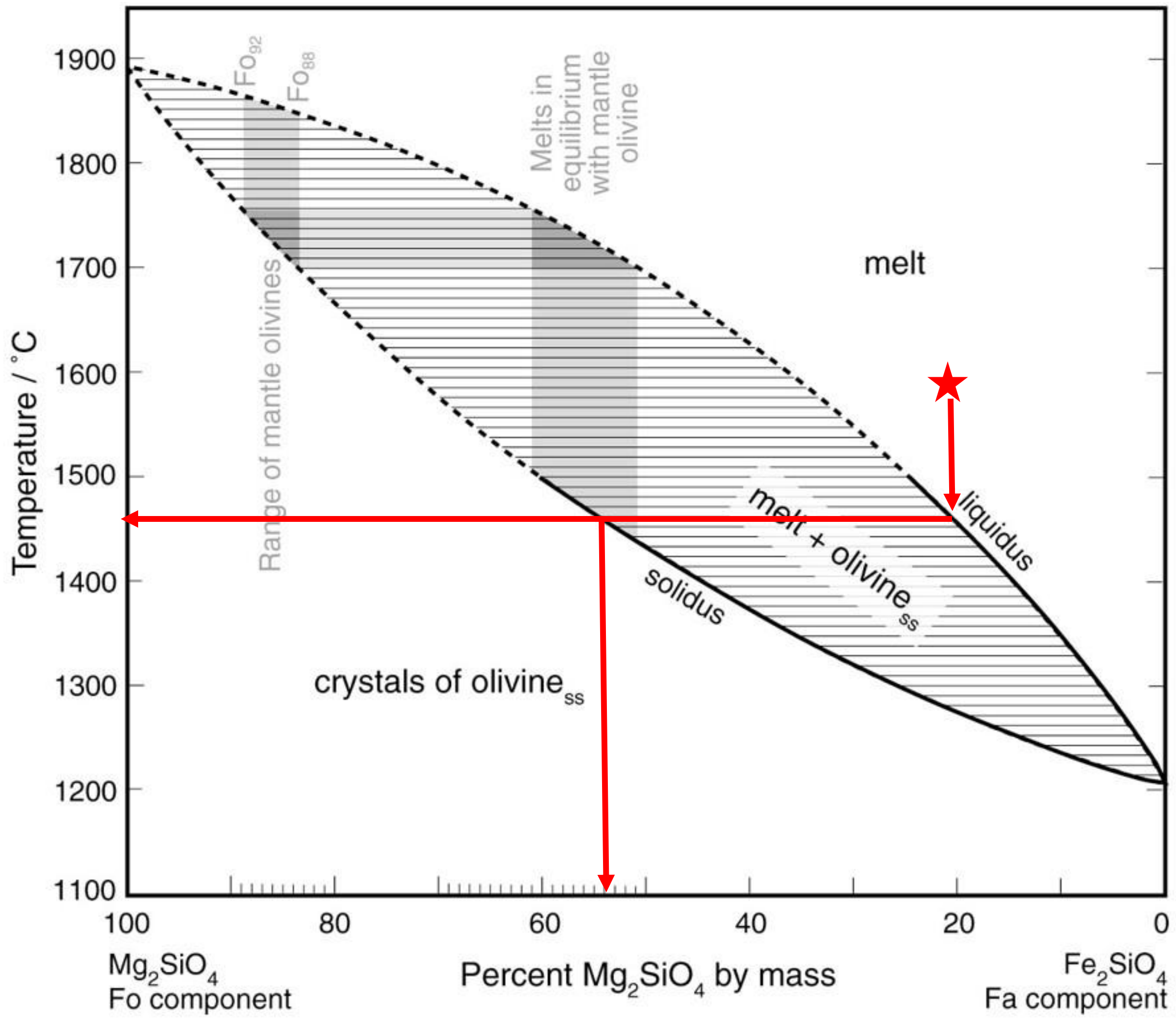
Olivine Phase Diagram

- Incongruent melting
  - Non uniform
  - Forms solid and liquid with different compositions
- Solidus (& liquidus) varies with composition
- Complete solid solution (ss) between Fo and Fa
- *Time to practice*



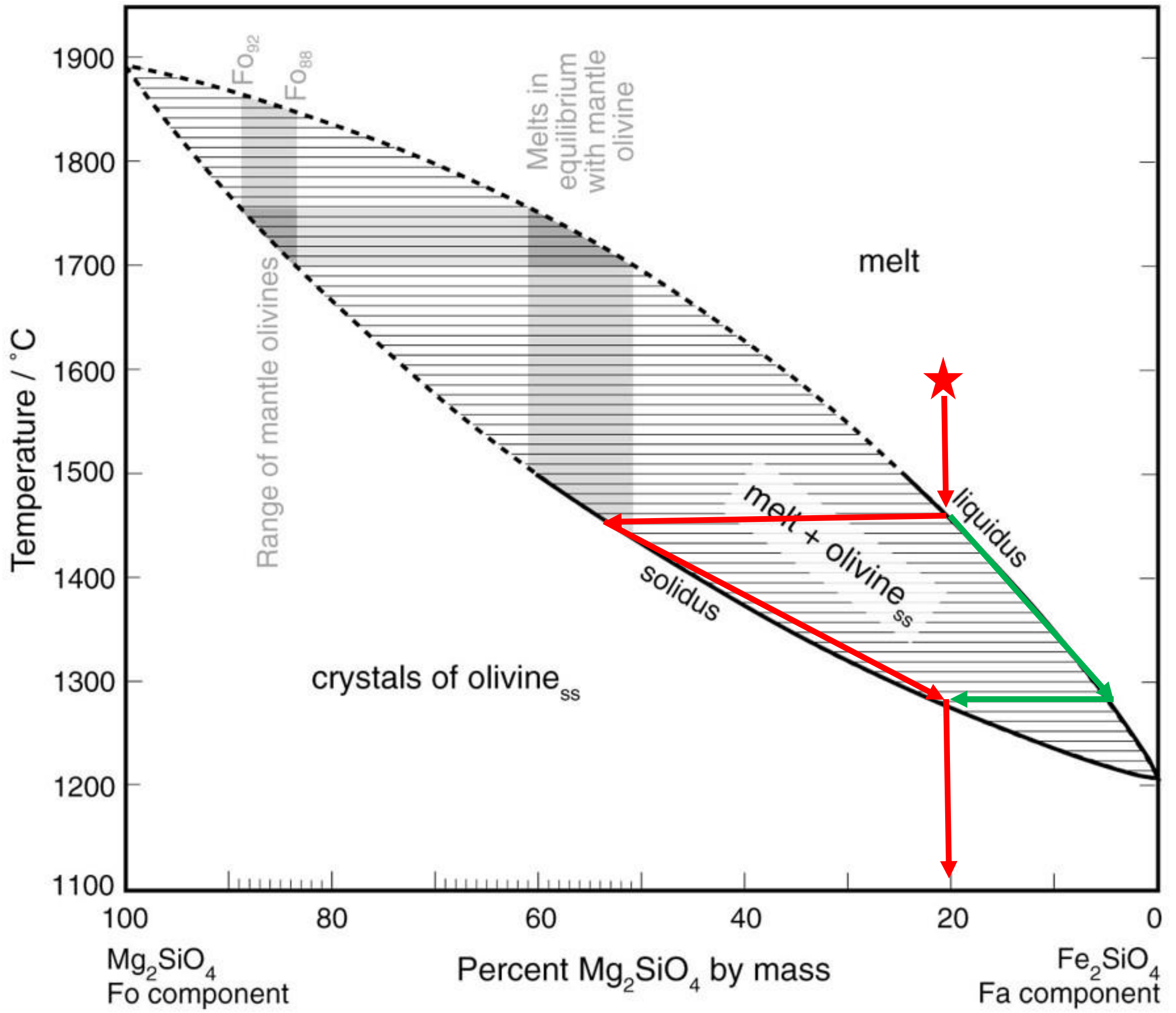
Olivine Phase Diagram

- 20 wt% Mg_2SiO_4 – cooling from 1600 °C
- What temperature does crystallization occur?
  - 1460 °C
- Forsterite content of initial olivine crystals?
  - 54% Fo



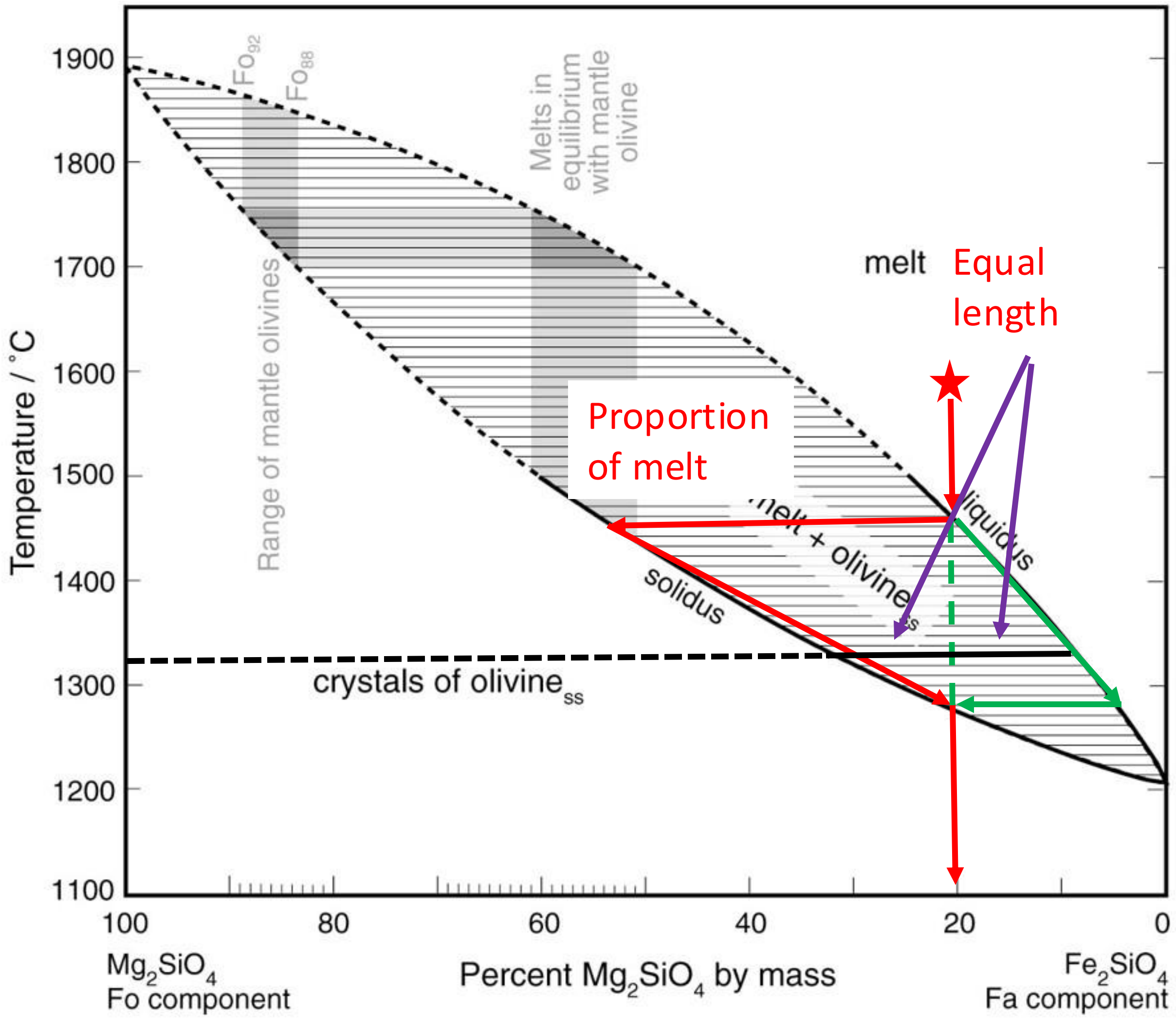
Olivine Phase Diagram

- 20 wt% Mg_2SiO_4 – cooling from 1600 °C
- What is the cooling/crystallization path followed by the melt and olivine until completely solidified
  - Melt – green
  - Olivine – red
  - Composition stays on solidus/liquidus until completely cooled
  - Final solid has same composition as initial melt (closed system)



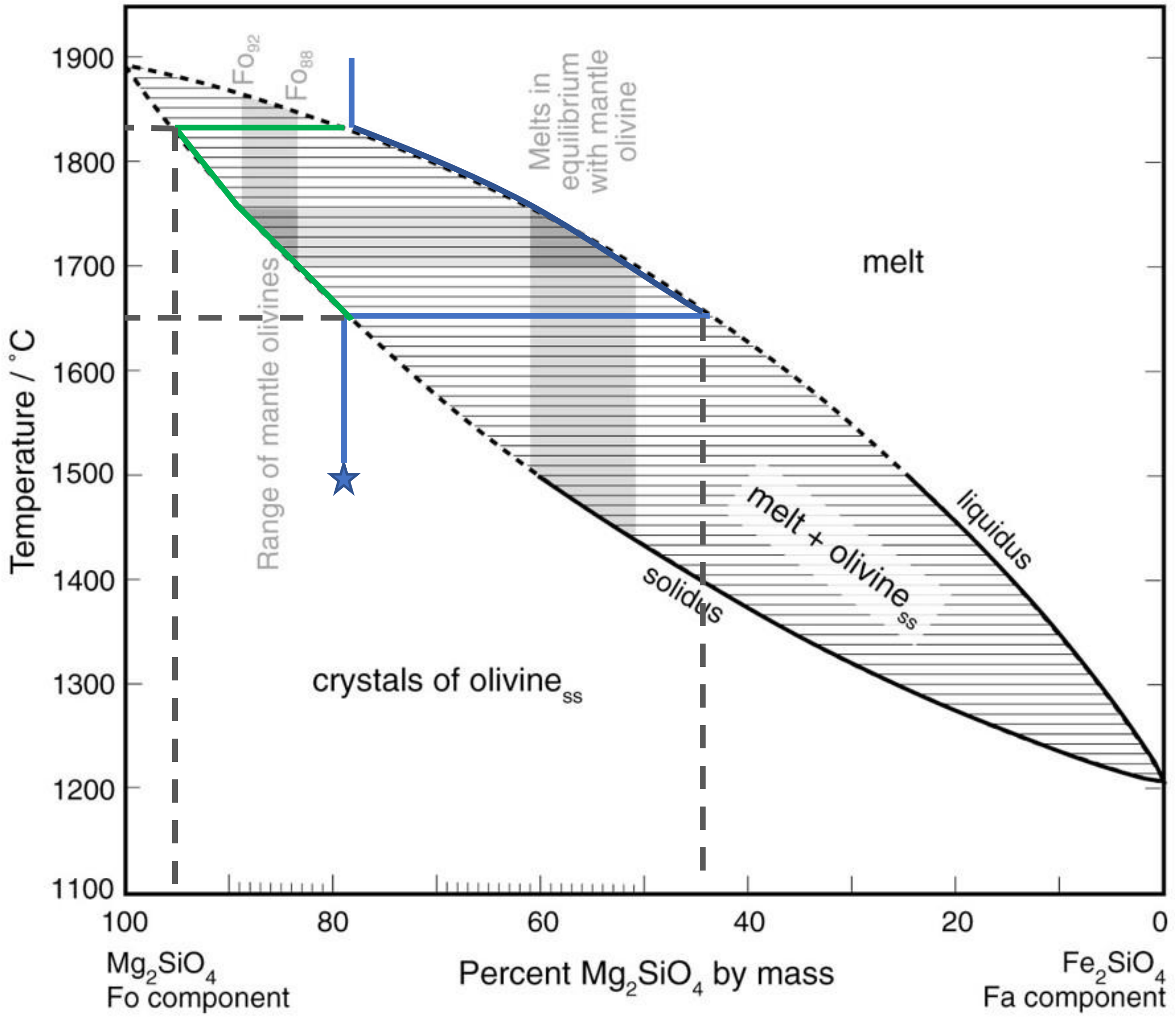
Olivine Phase Diagram

- 20 wt% Mg_2SiO_4 – cooling from 1600 °C
- At what temperature would this system contain equal weight proportions of olivine crystals and liquid?
  - Occurs when equal lengths of ss either side of initial composition
  - 1310 °C



Olivine Phase Diagram

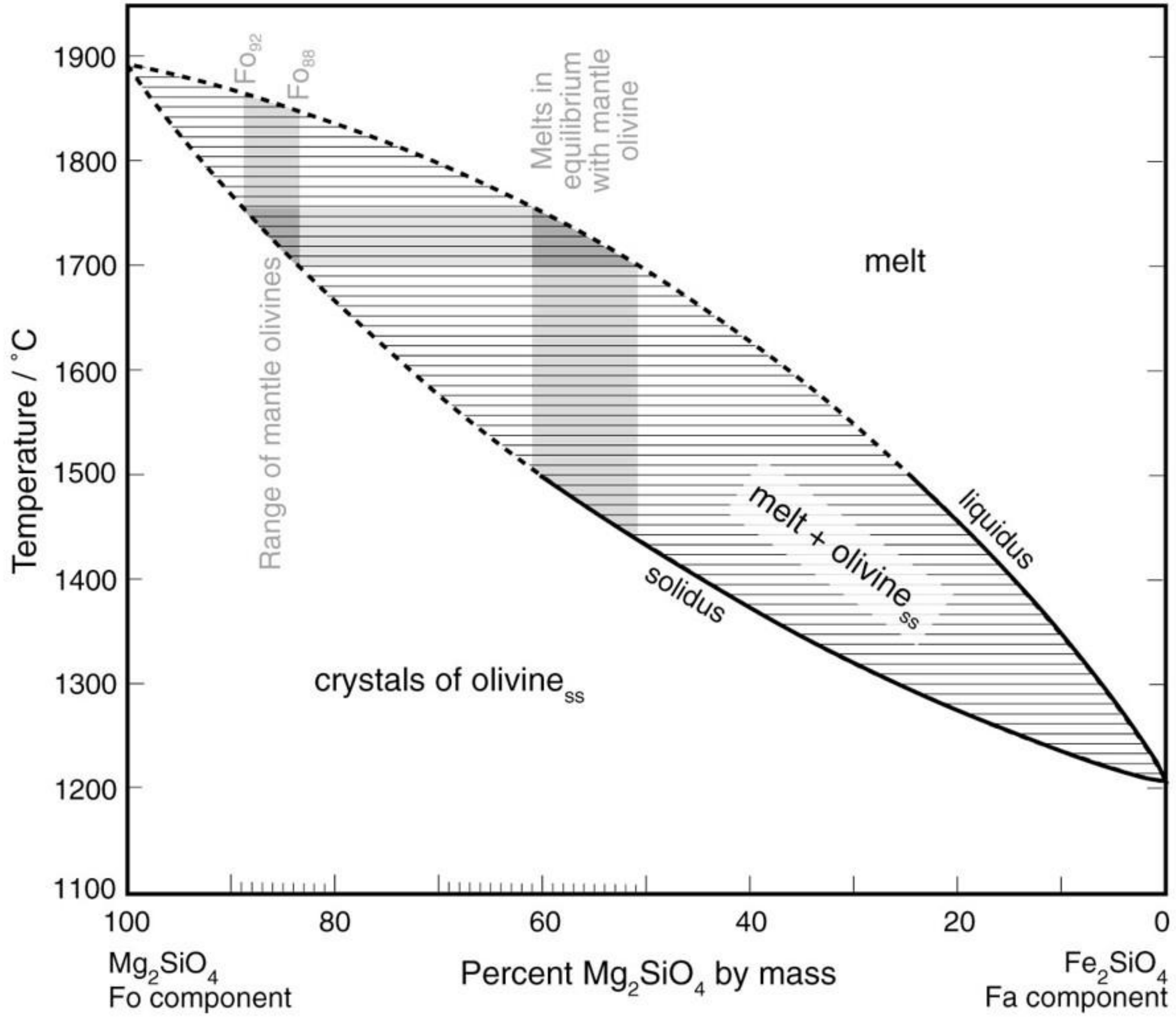
- 80 wt% Mg_2SiO_4 – heating from 1500 to 1900 °C
- Draw the path
  - Blue – melt
  - Green - olivine
- Initial melting temperature?
  - 1660 °C
- Composition of initial melt?
  - 45 wt% Fo



Olivine Phase Diagram

- What happens if olivine is removed as it crystallizes? (open system)
  - Mg rich Fo is removed
  - System becomes richer in Fa (Fe-rich) – melt higher in Fa
  - Later stages will produce more Fa

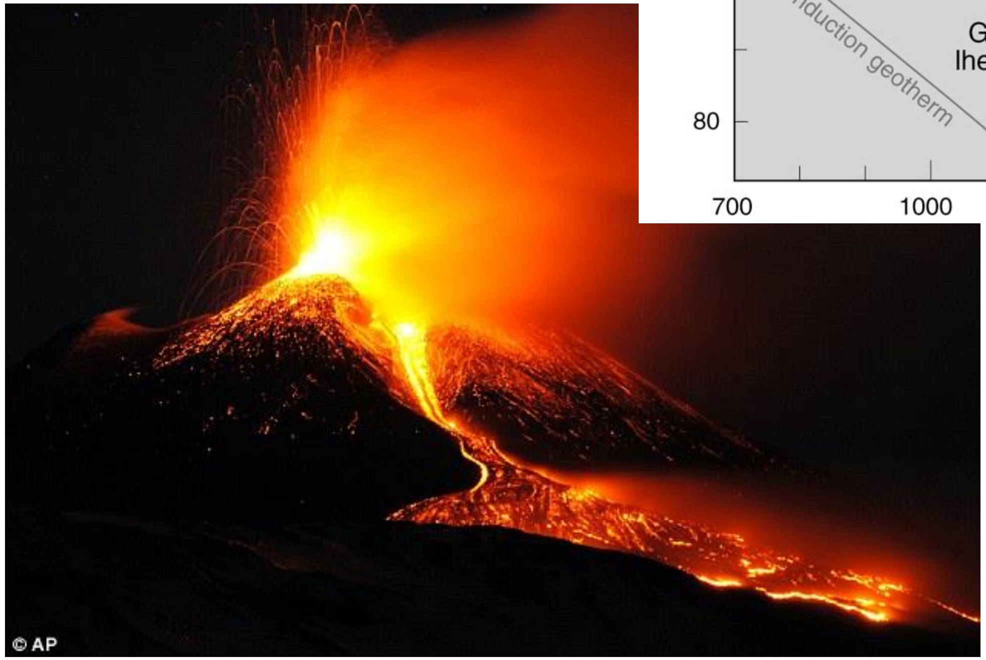
- This is what happens in magma chambers
  - Crystals sink
  - Fractional crystallization

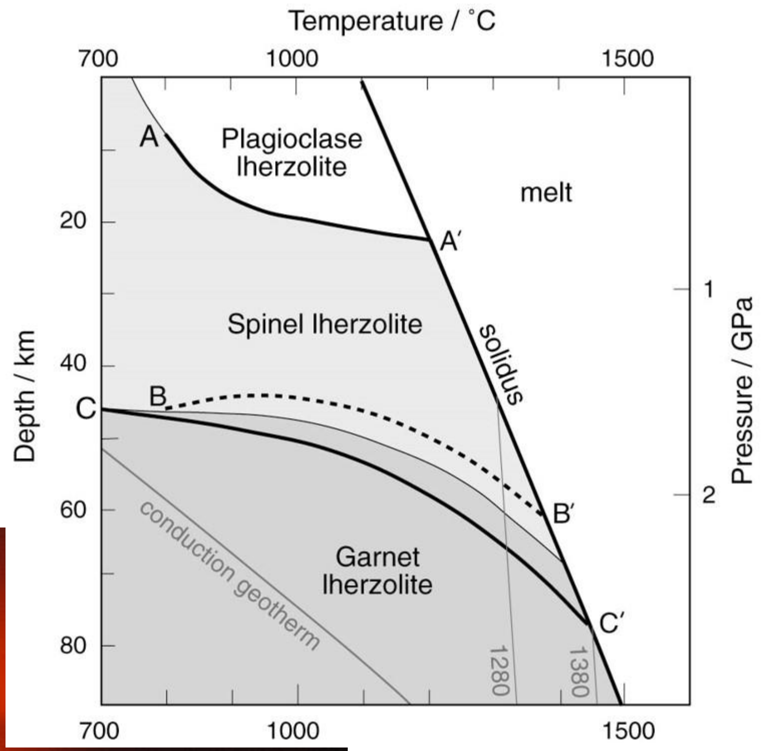


Melting in the Earth

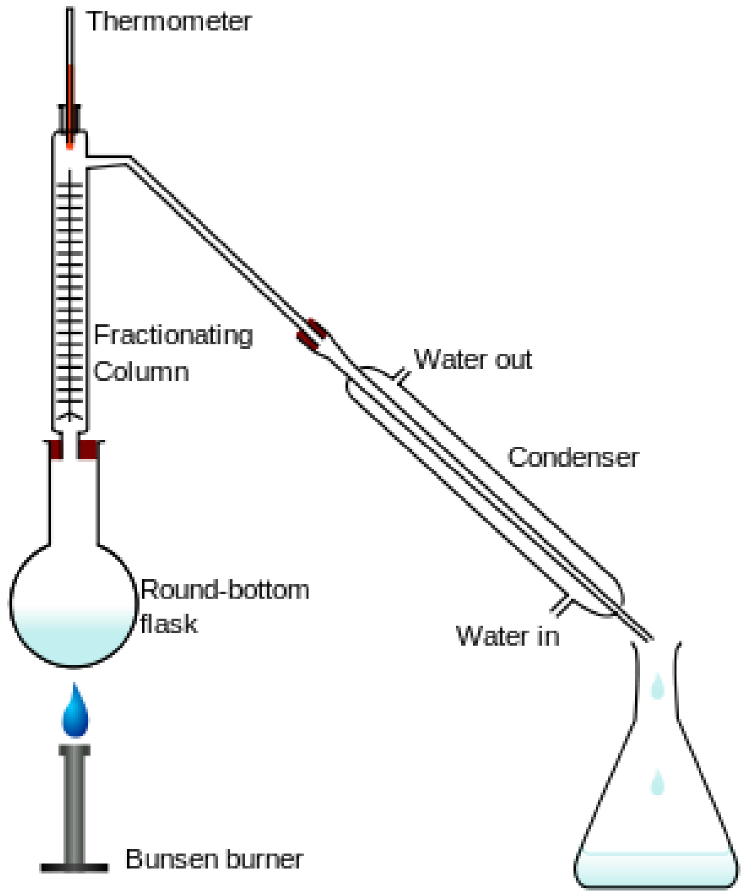
Single most important fractionation process of the Earth

- What type of liquids are produced?
- What is left behind?
- What is fractionation?
- Where does it occur on Earth?
- How does it occur?





Fractionation



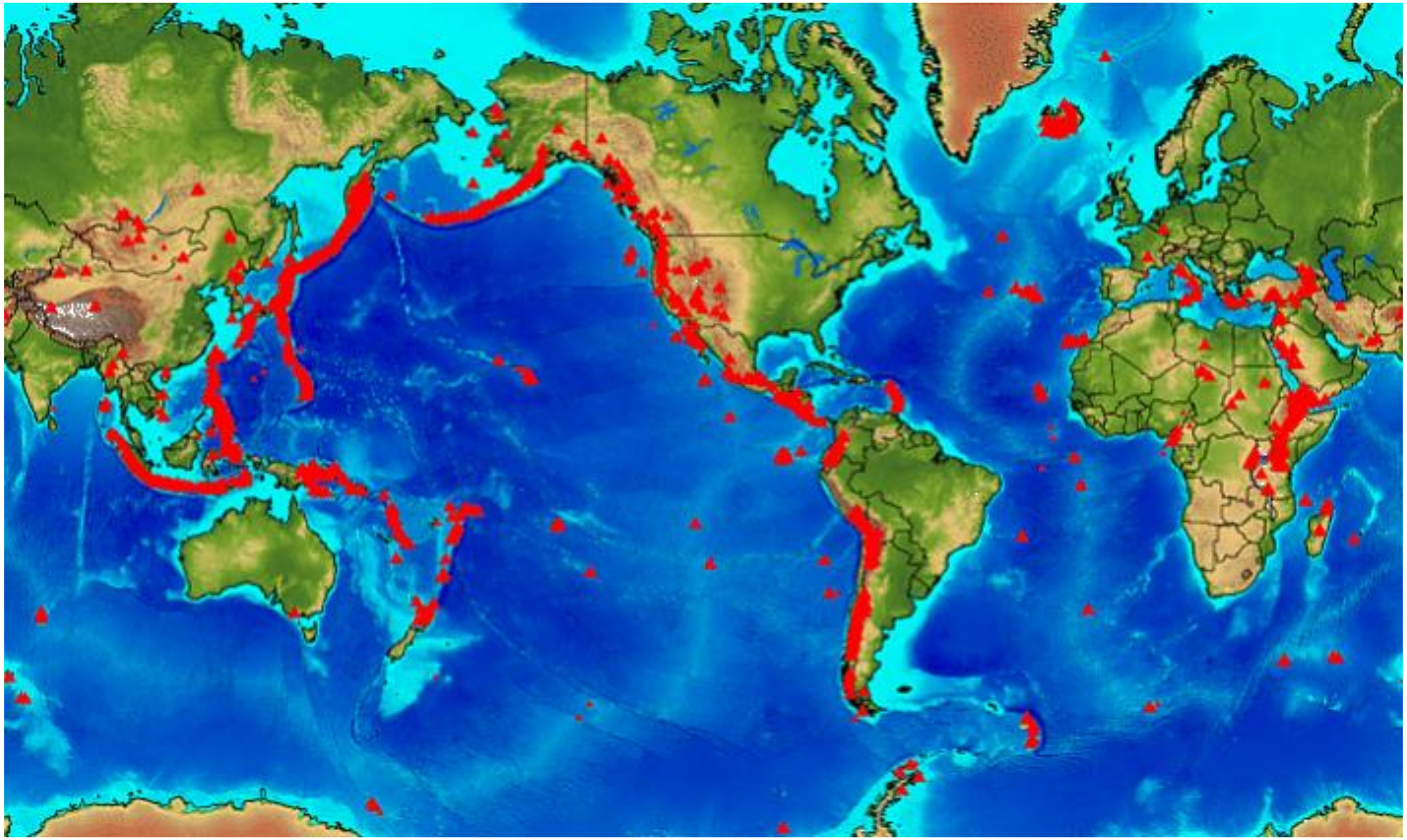
- What is fractionation?
  - Also known as differentiation
  - Separate a liquid into multiple components
  - Think fractional distillation of crude oil or distilling spirits
  - Produce a series of new products
  - Controls chemical evolution of the earth

Melting in the Earth

- What type of liquids are produced?
  - Magma
  - Lava
  - Variable compositions – basalt is first to form
- What is left behind?
  - Residue (called restite in the crust)
  - Often Fe rich

Dee Wright Observatory, McKenzie Pass, Oregon

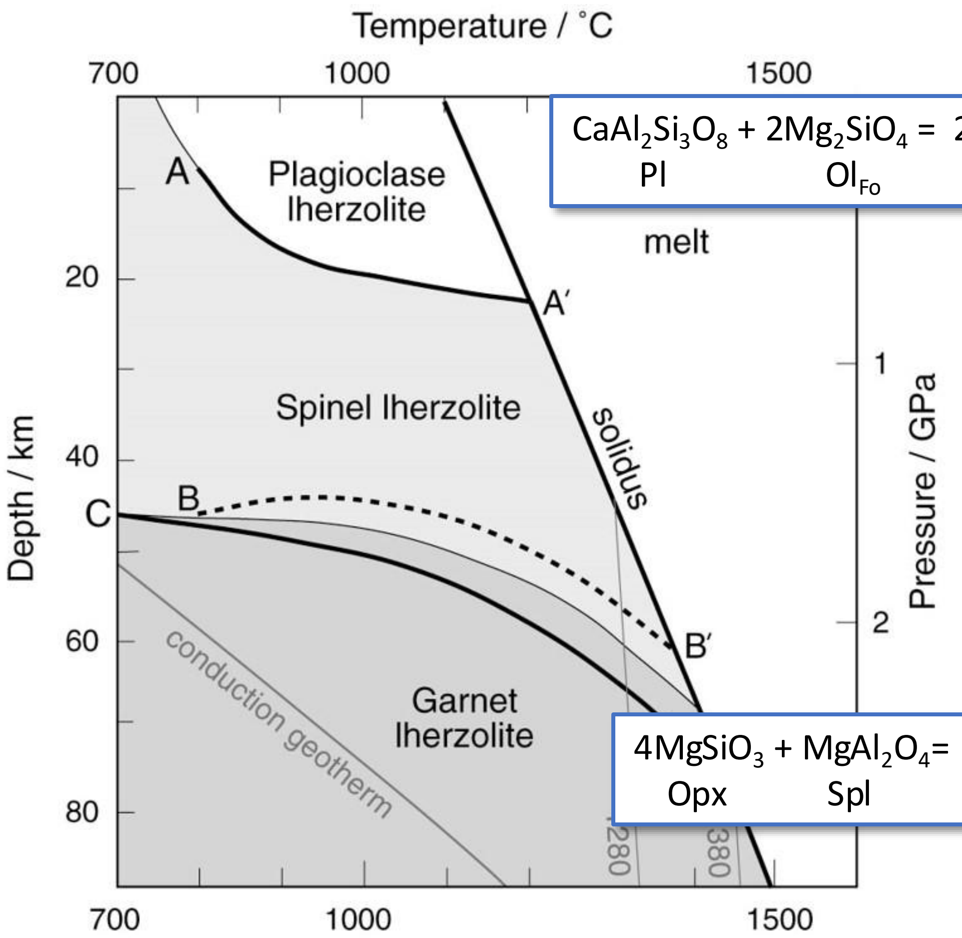
Where does melting occur?



▲ Active volcano

- Convergent Boundaries
  - Subduction zones
- Divergent Boundaries
  - Mid-Ocean ridges
- Intraplate settings
  - Mantle plumes
  - Hotspots

Melting Peridotite



$$\underset{Pl}{CaAl_2Si_3O_8} + \underset{Ol_{Fo}}{2Mg_2SiO_4} = \underset{Opx}{2MgSiO_3} + \underset{Cpx}{CaMgSi_2O_6} + \underset{Spl}{MgAl_2O_4}$$

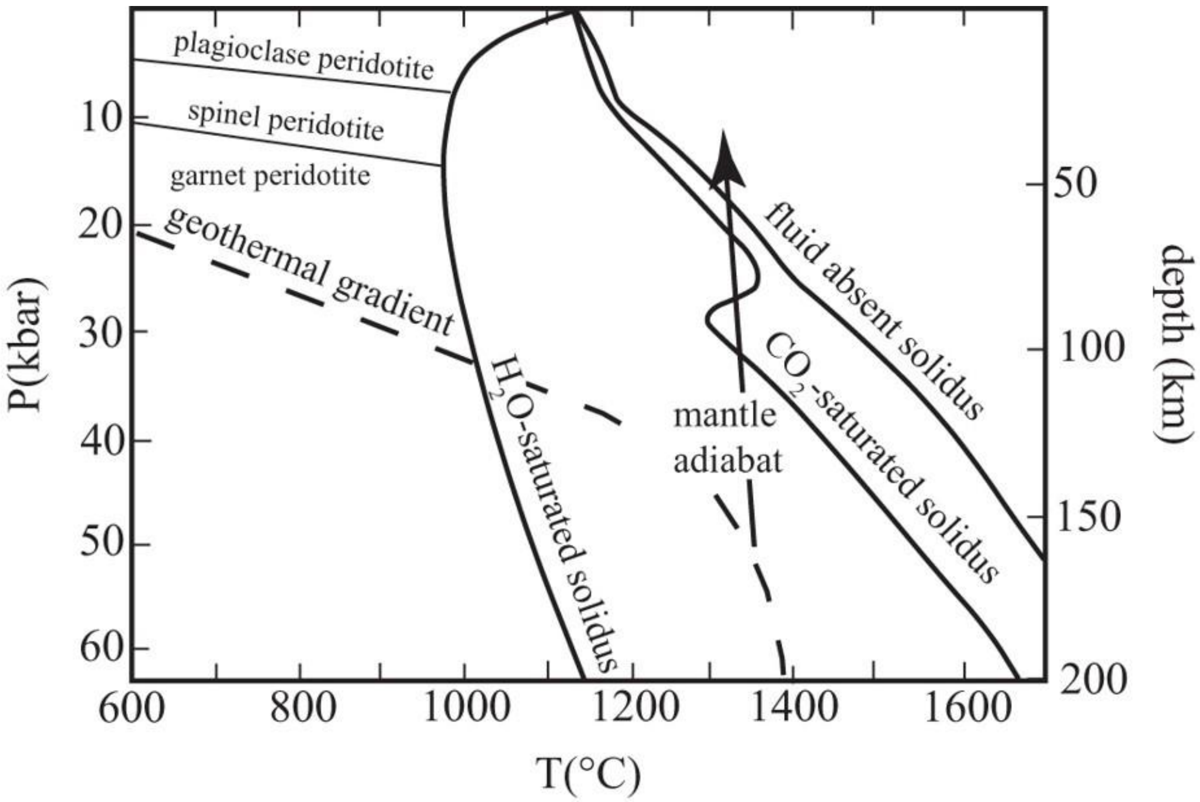
$$\underset{Opx}{4MgSiO_3} + \underset{Spl}{MgAl_2O_4} = \underset{Ol_{Fo}}{Mg_2SiO_4} + \underset{Gt_{Py}}{Mg_3Al_2Si_3O_{12}}$$

- **Solidus:** the temperature below which a substance is completely solid, at a given pressure
    - **High P =** higher solidus temperature

- *How does peridotite in the mantle cross the solidus?*

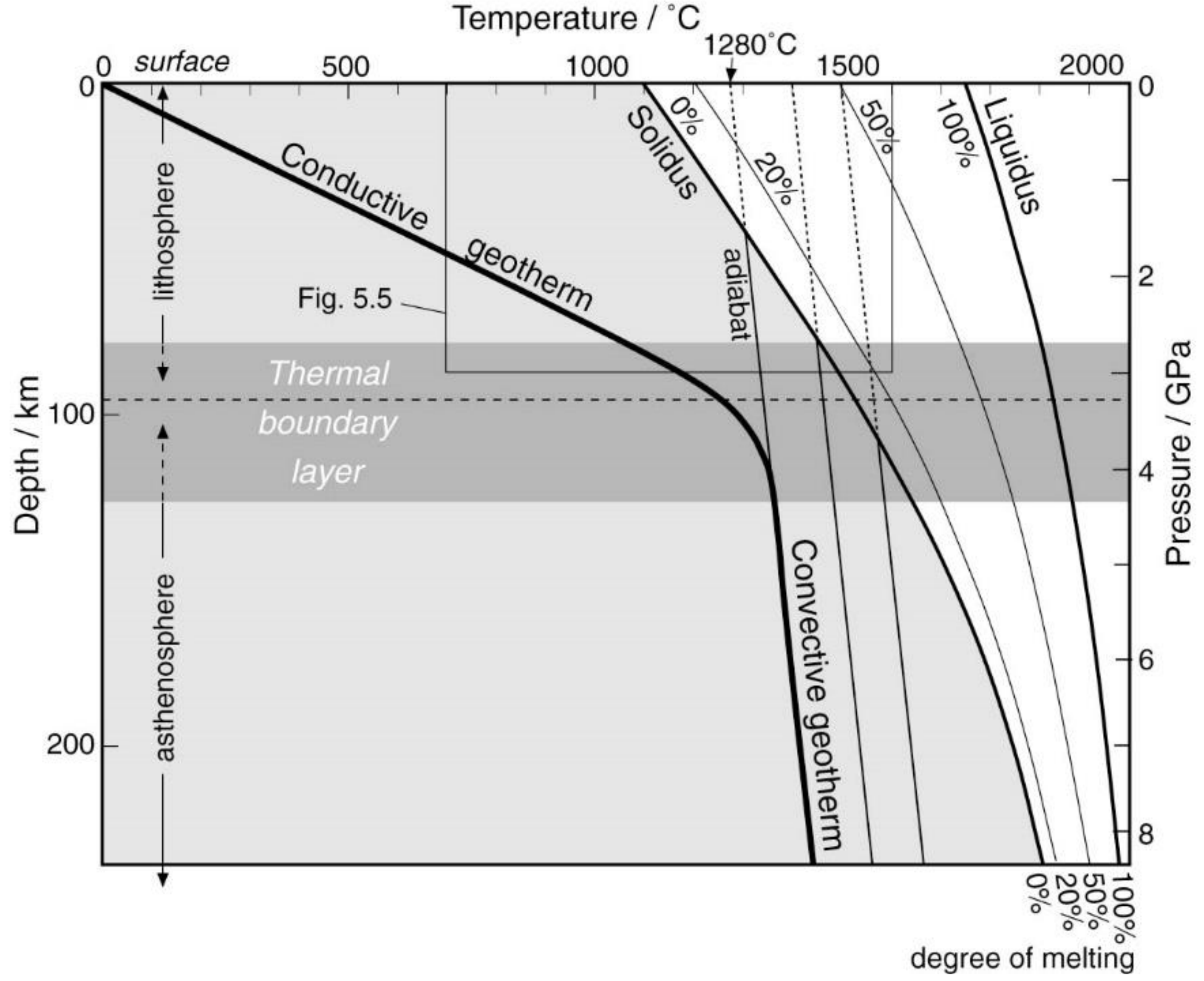
How do we melt the Earth?

- Three main methods
  - Increase the temperature
  - Reduce the pressure
  - Add water (or other volatiles)
- Need to cross the solidus
  - Varies with composition
- How does the melt move?
- How does it behave during cooling?



Geothermal Gradient (Geotherm)

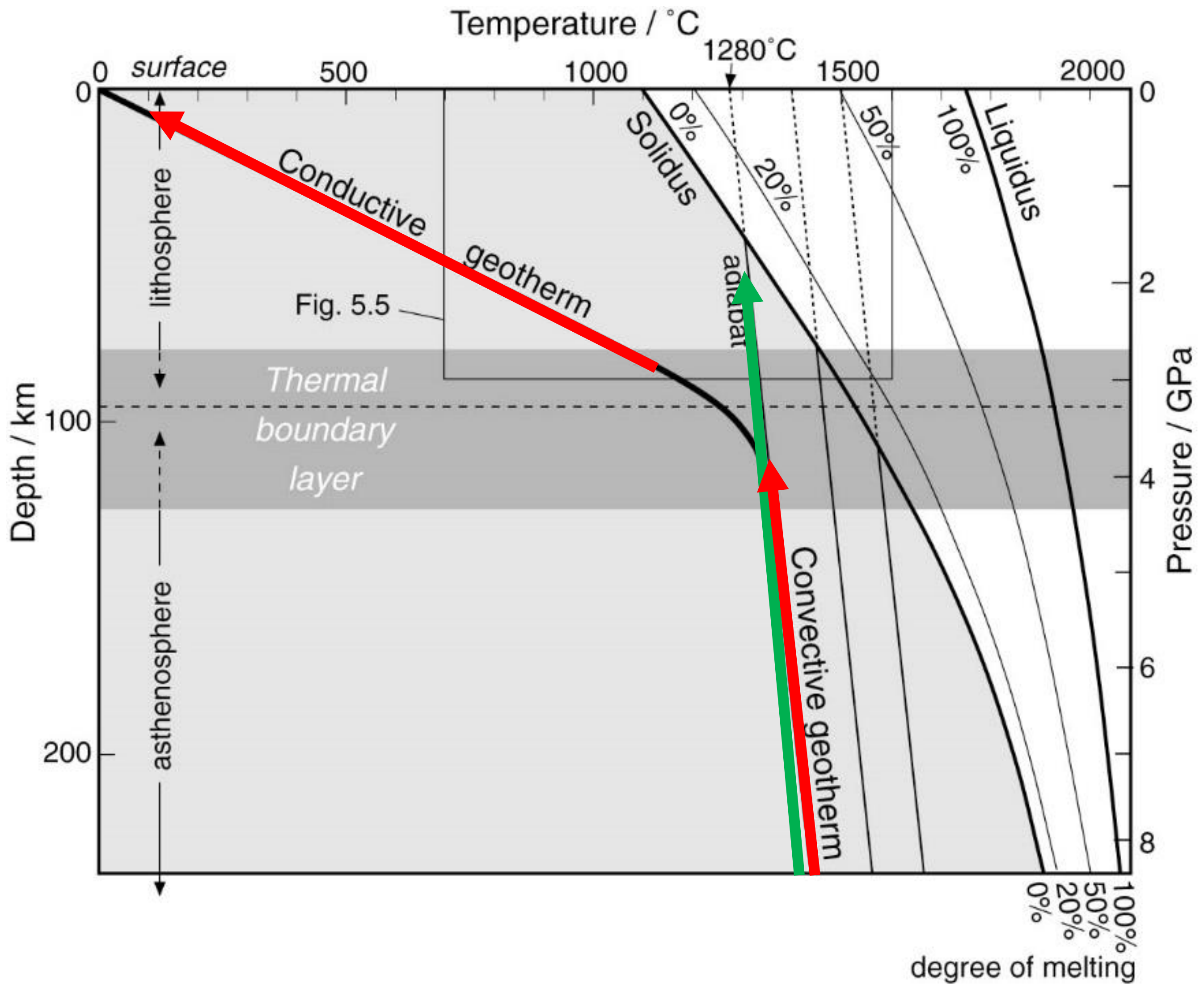
- Geothermal gradient – rate at which pressure and temperature change in the Earth
- Heat sources in Earth's interior
    - Primordial heat – trapped during earth formation
    - Decay of radioactive isotopes (K, Th, U,…)
- **Liquidus** – temperature above which a substance is completely molten (liquid), at a given pressure



Geothermal Gradient (geotherm)

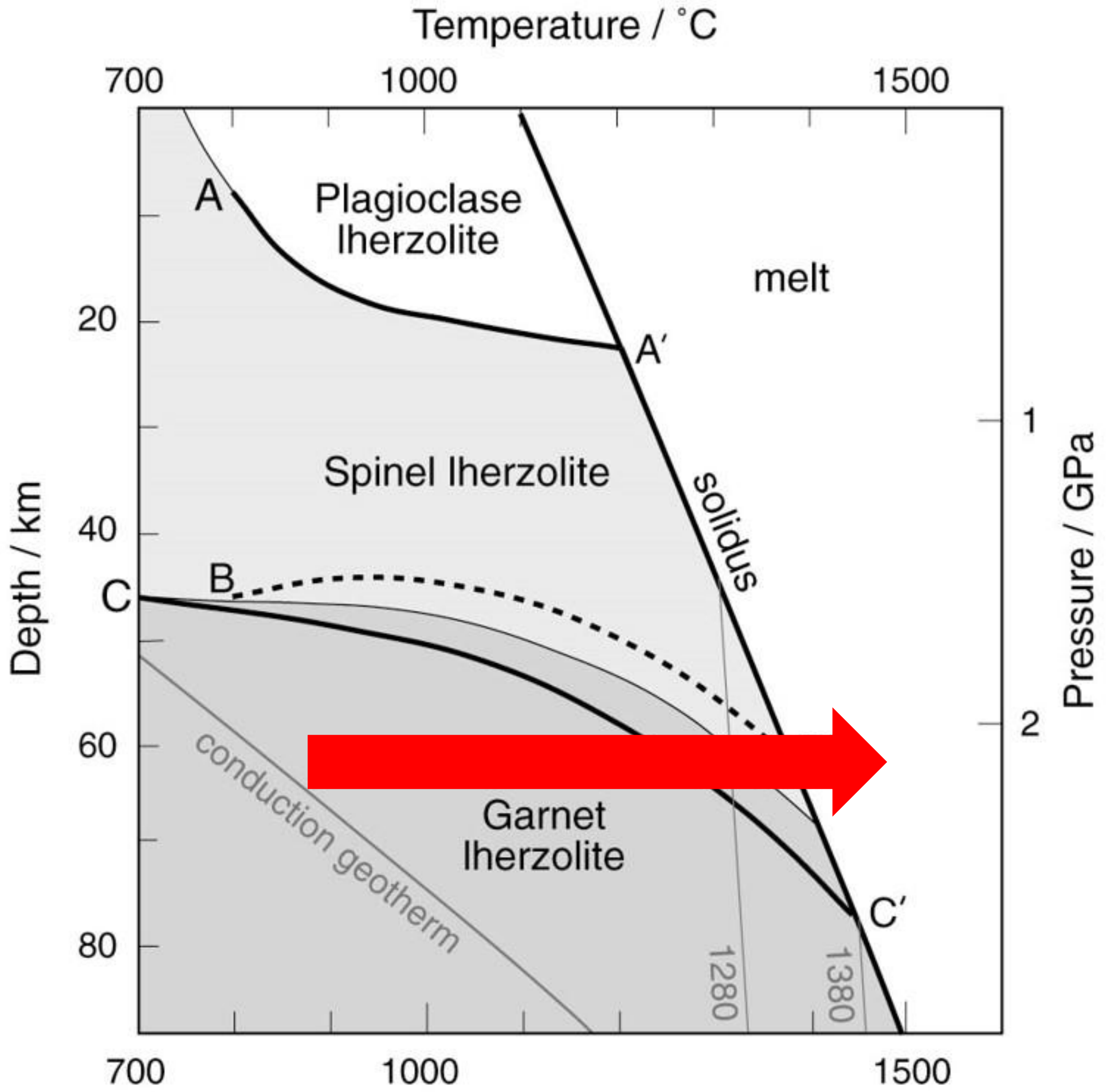
- Geothermal gradient types
  - Convective
  - Conductive

- Adiabatic Upwelling
  - Net heat transfer during uplift is zero (0), but cooling is caused by work done on surrounding peridotite
  - Mantle adiabat



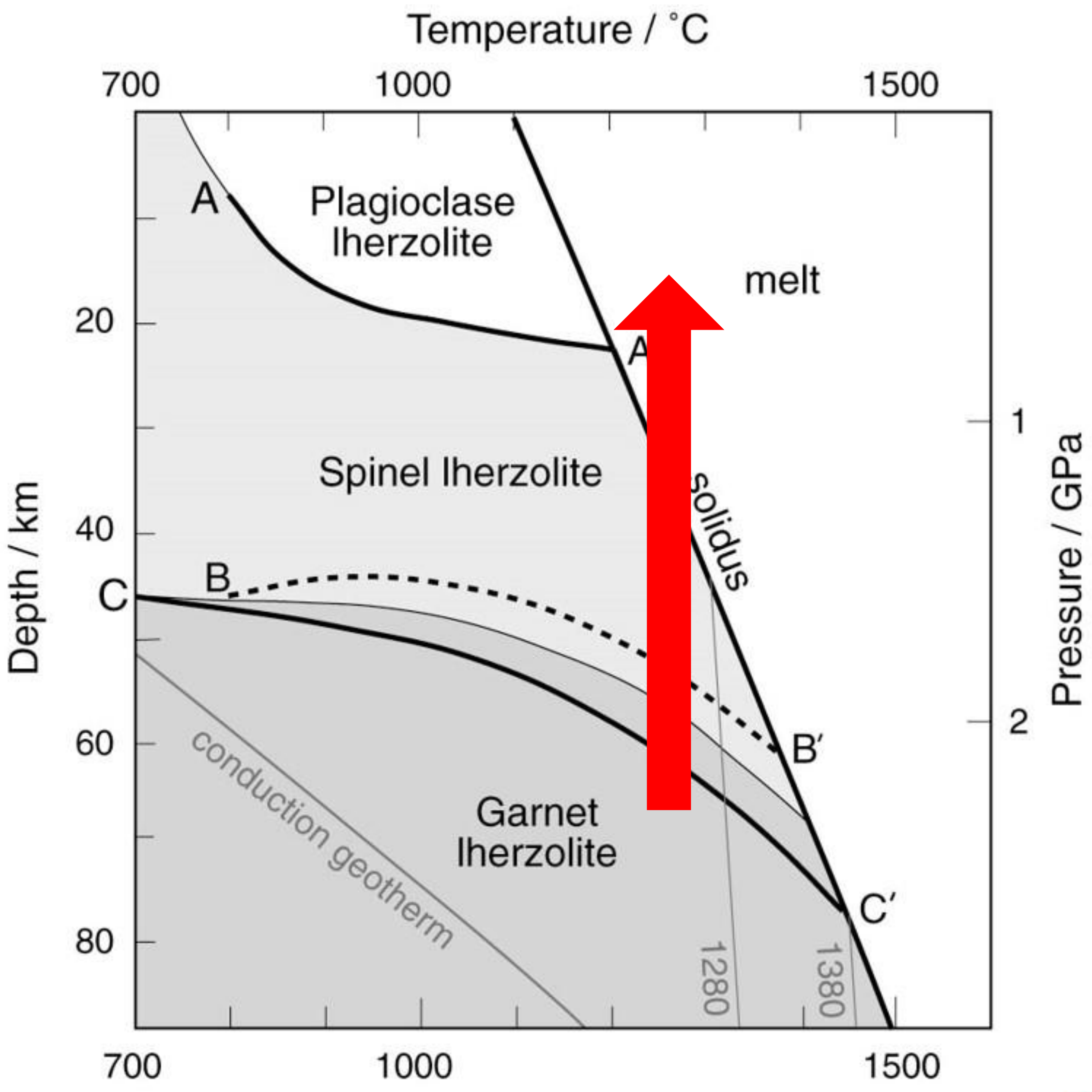
Melting Peridotite

- Add Heat
- Heat Sources
  - Convecting mantle
  - Upwelling mantle plumes



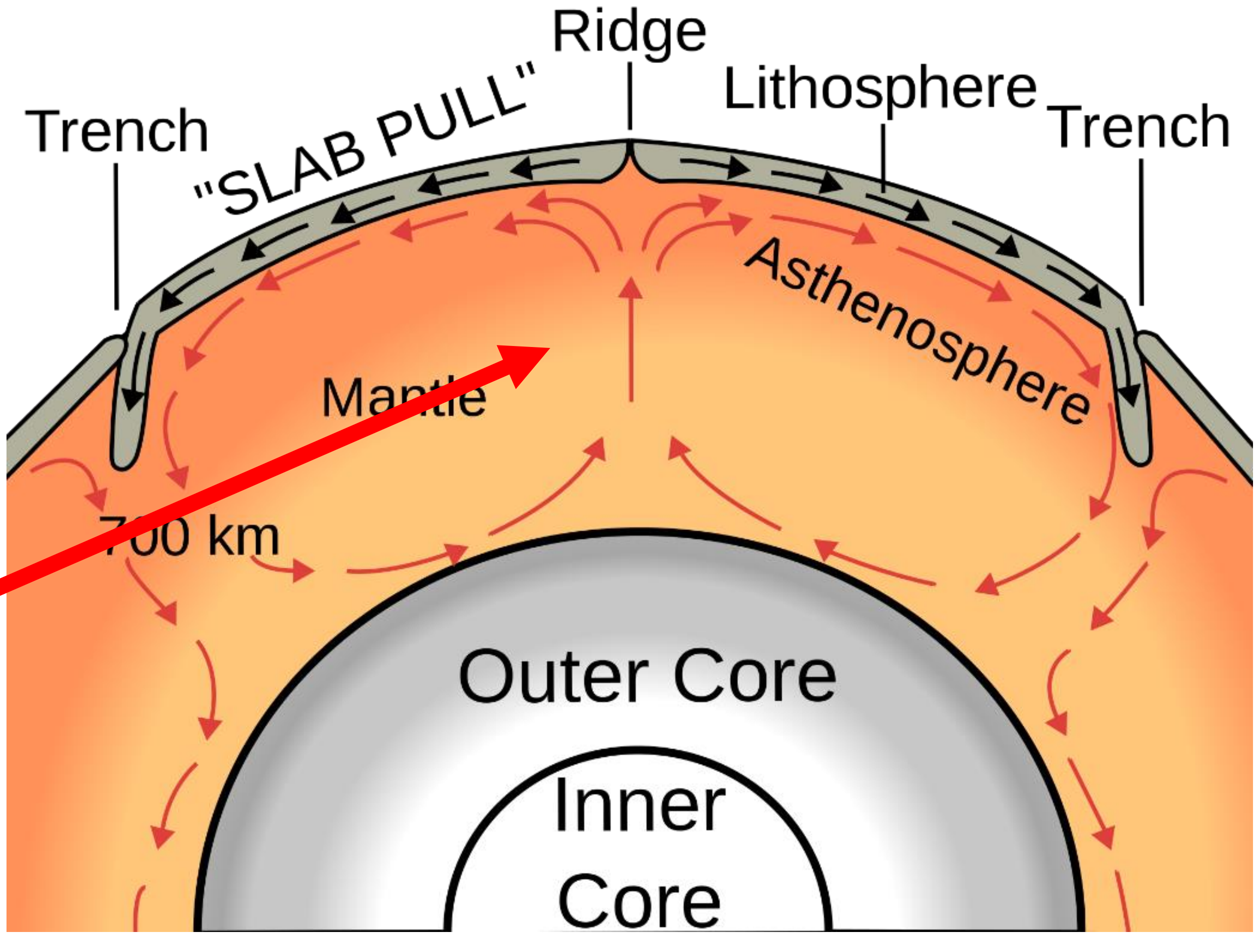
Melting Peridotite

- Reduce Pressure
  - Decompression melting
- How to do this?
  - Remove material above
  - Mid-Ocean ridges
  - Continental rifts
  - Redistribution of ice, etc.



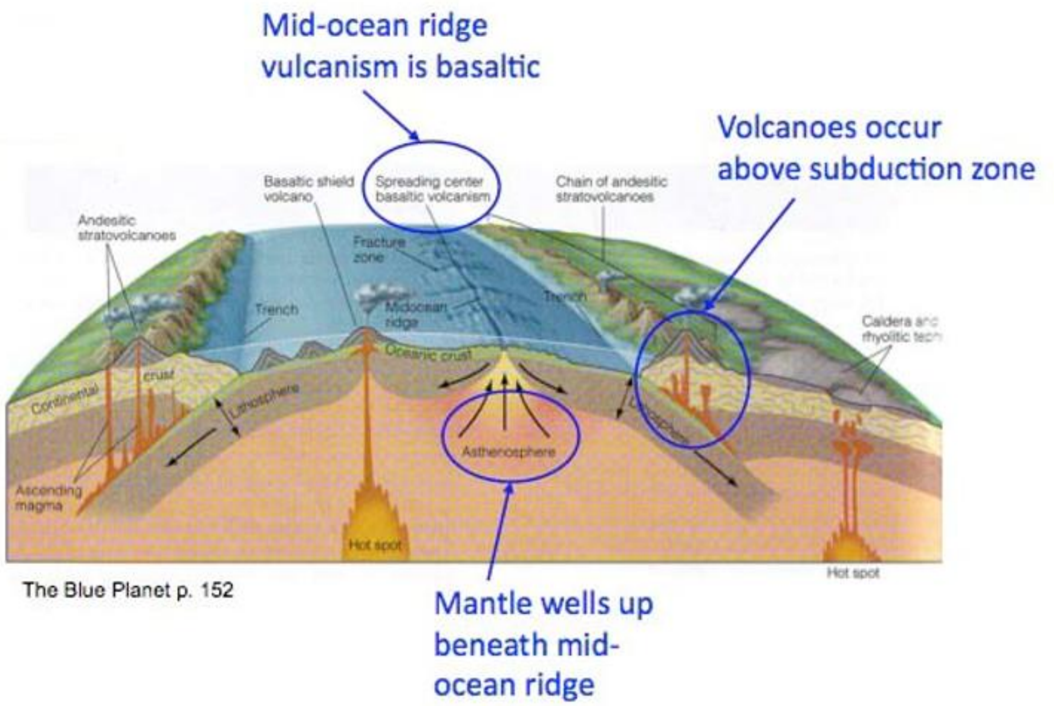
Melting processes

- Dynamic Earth
  - Rigid, brittle, cold lithosphere – conductive geotherm
  - Soft, plastic, flowing asthenosphere – convective geotherm
- Adiabatic upwelling
  - Net heat transfer during uplift is zero, but cooling caused by work done on surrounding peridotite

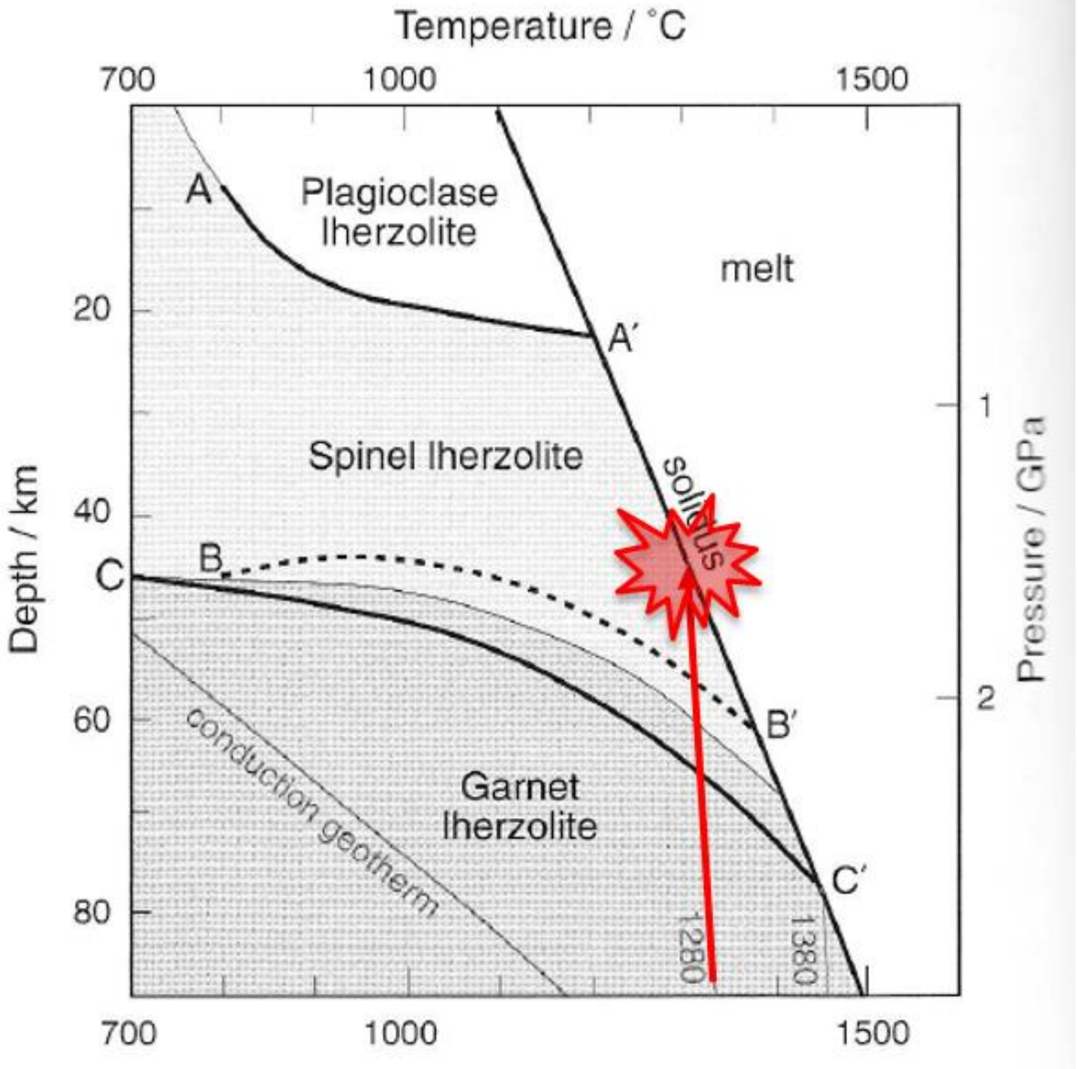


Mid-Ocean Ridge Melting

- Adiabatic upwelling
  - Melting due to decrease in pressure

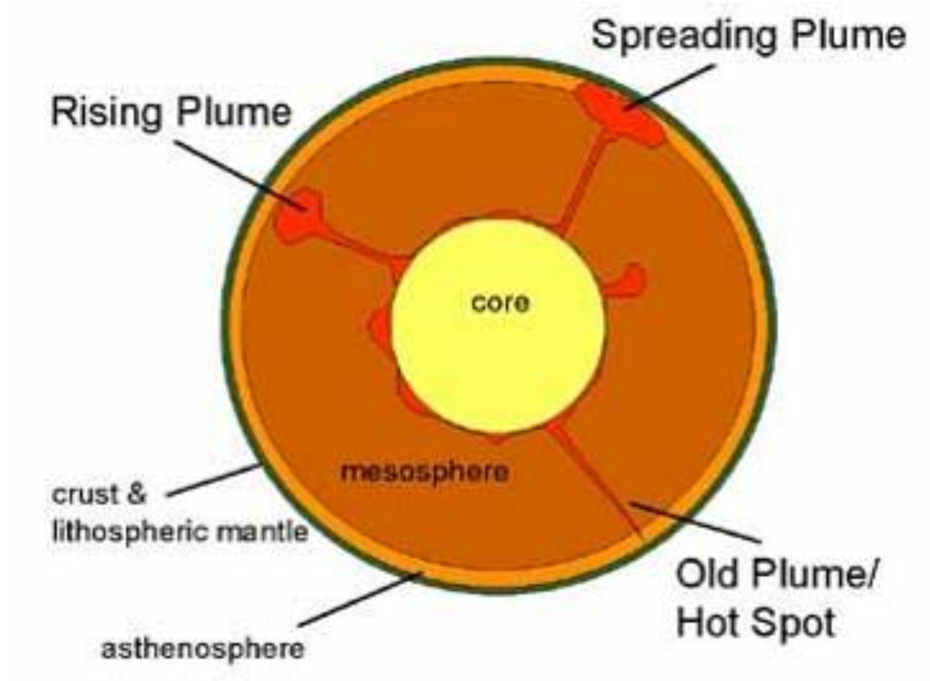


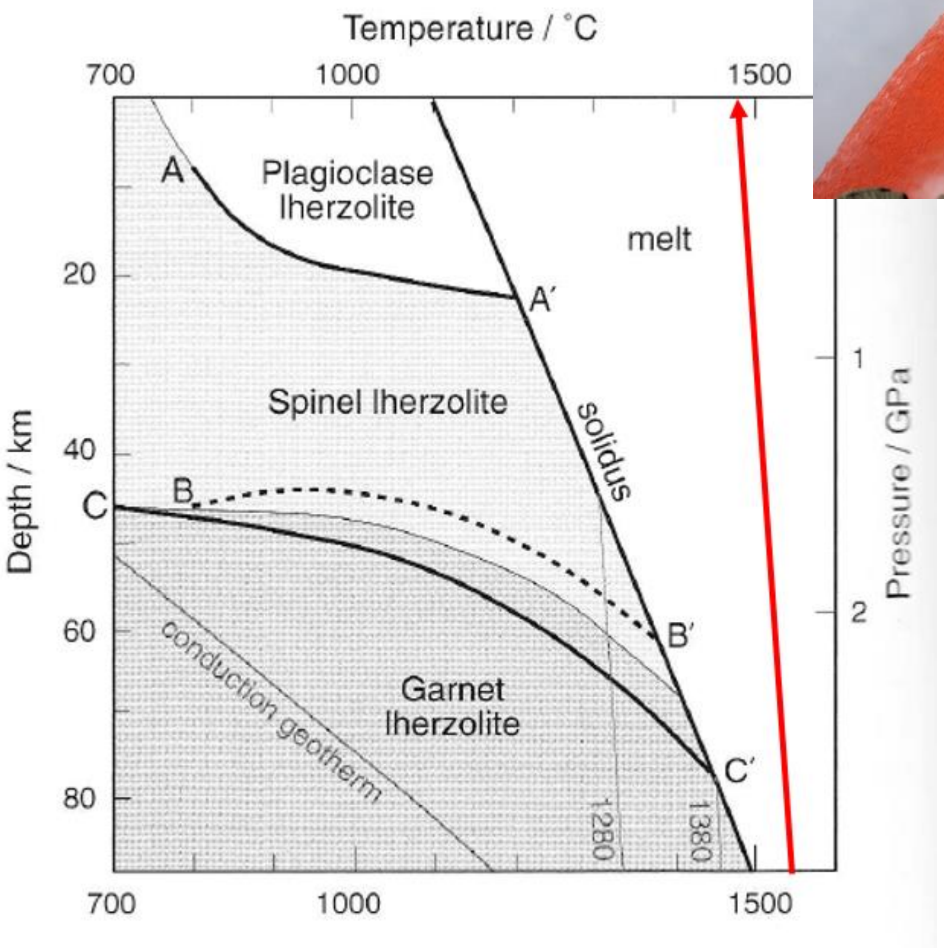
The Blue Planet p. 152



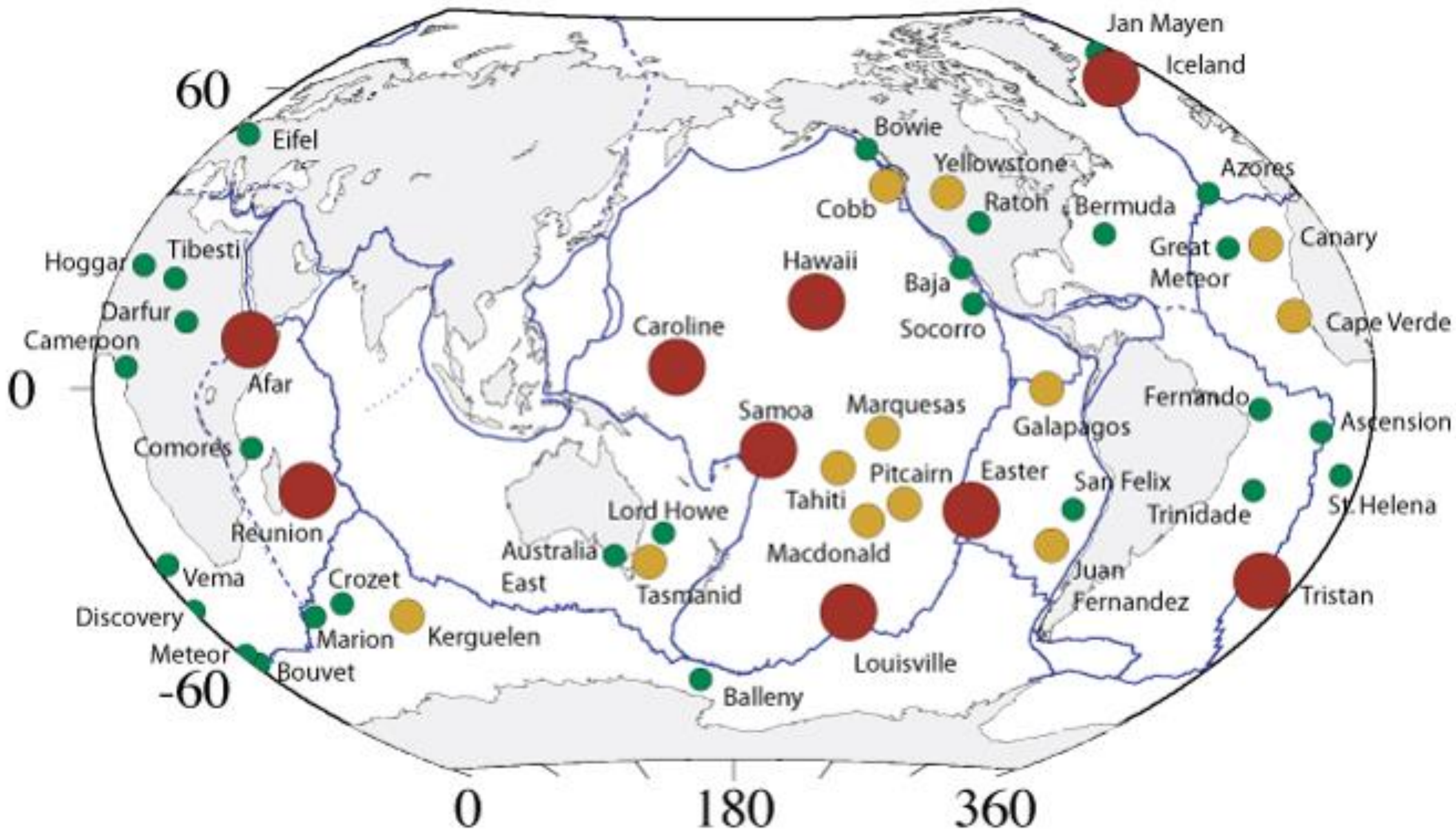
Plumes/Hotspots

- Adiabatic upwelling
  - Anomalously hot mantle
  - Melting due to pressure decrease



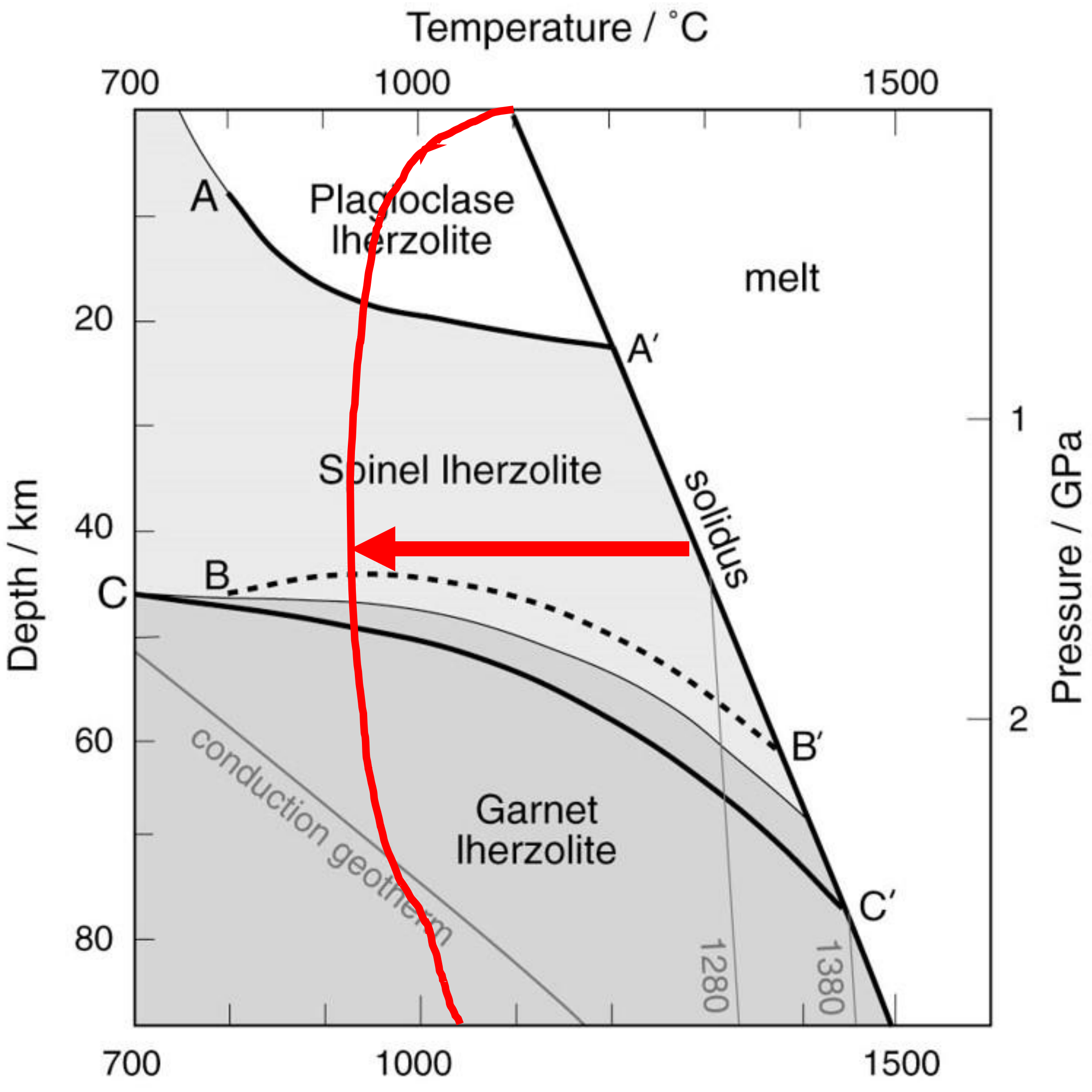


Hotspot Locations



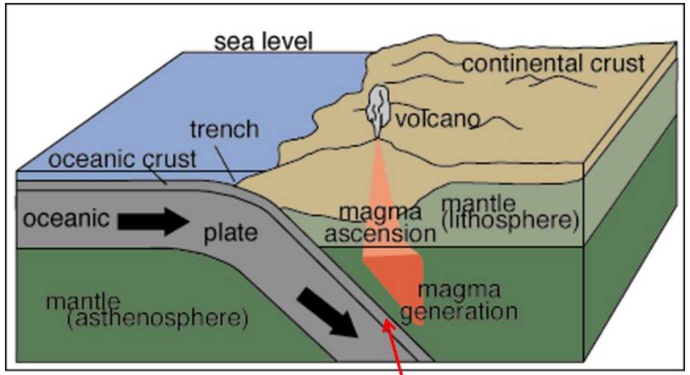
Melting Peridotite

- Reduce the Solidus
- How to do this?
  - Add Water (H_2O)
  - Add other volatiles – CO_2, etc.

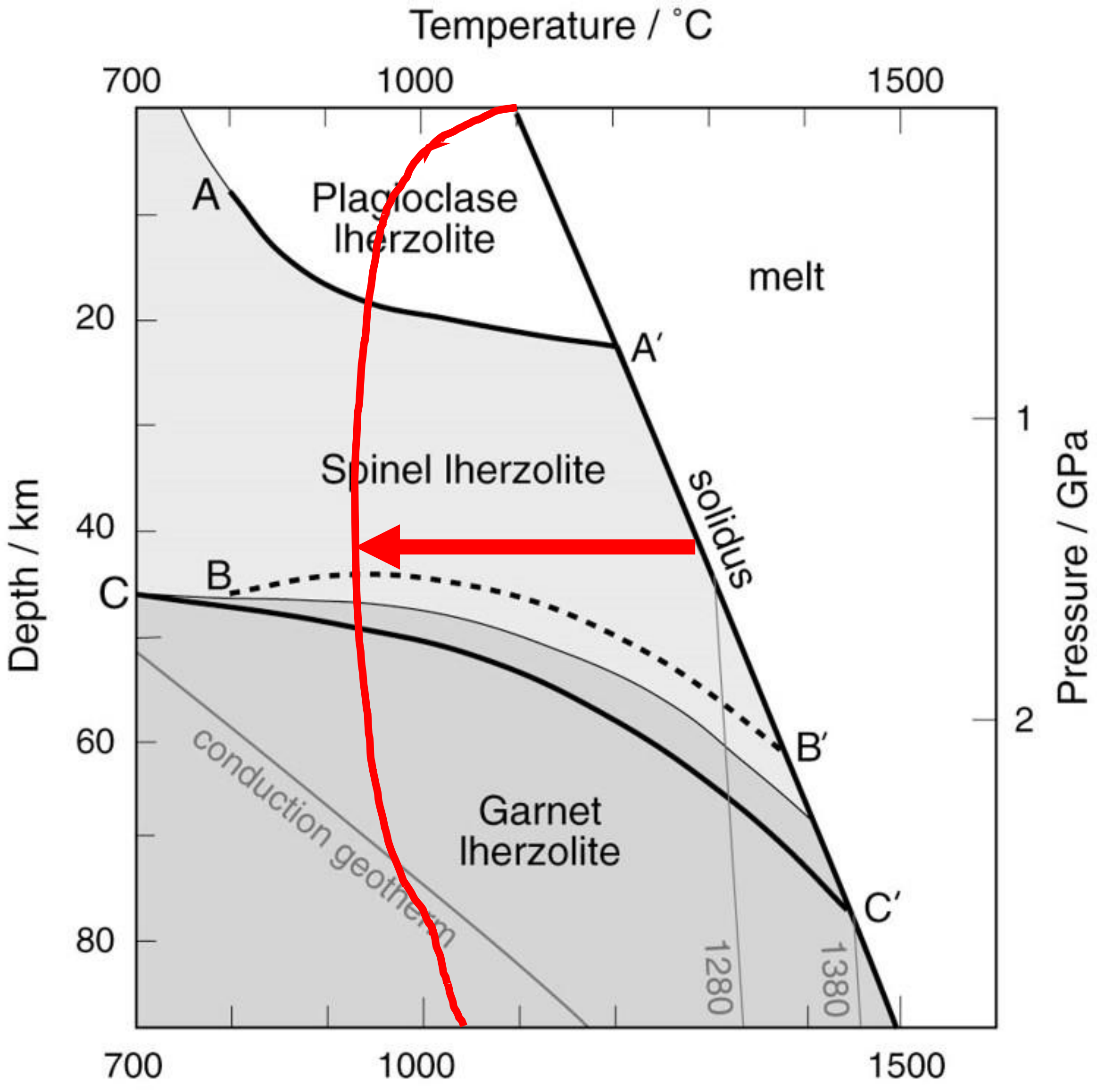


Subduction Zones

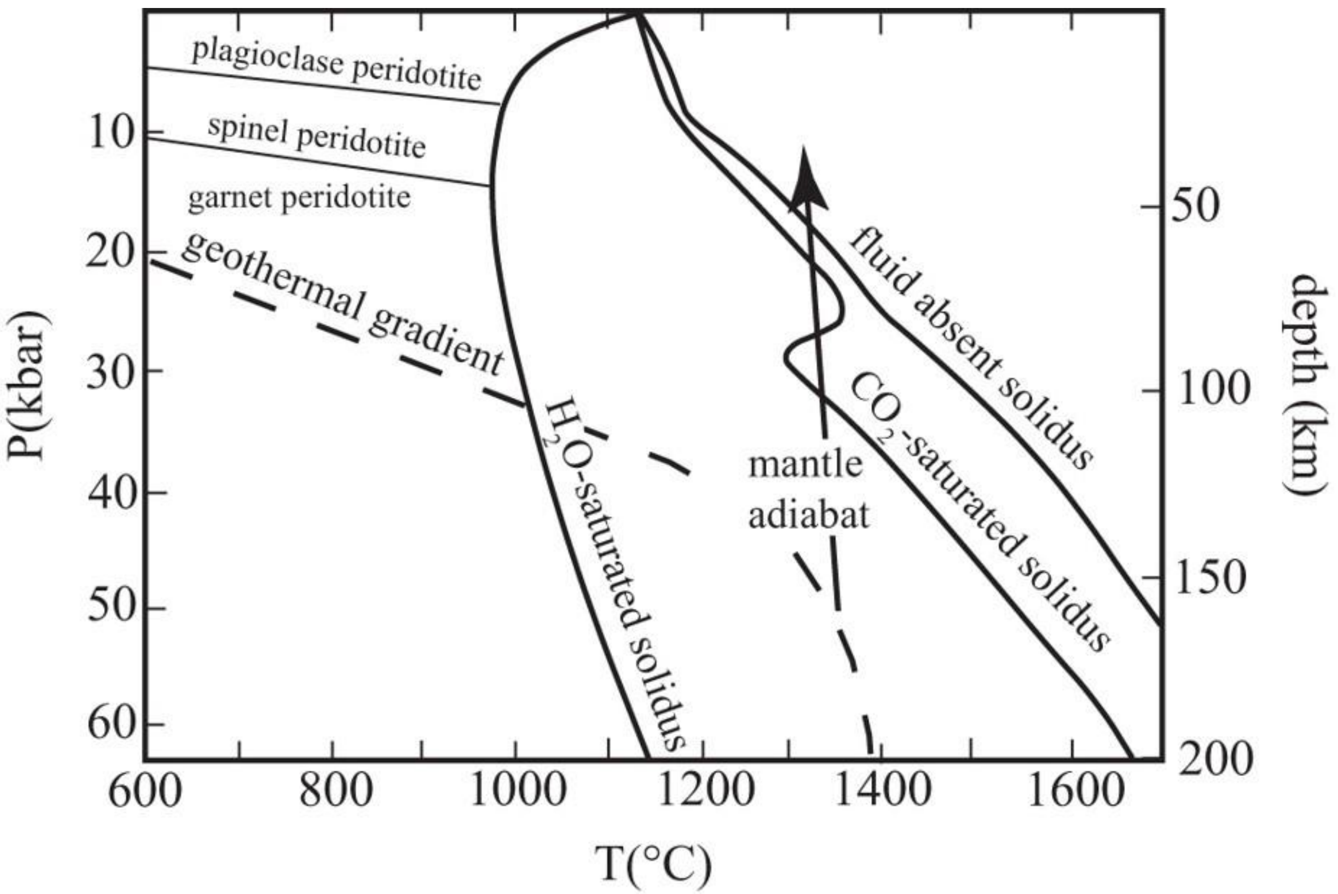
- Subducting minerals contain water
  - Heating releases water (hydrous fluids)
  - Water lowers solidus
  - Hydrous fluids provide flux for melting of peridotite



Dehydration of minerals in slab



Summary of Melting



- Three ways to melt
  - Increase temperature
  - Decrease pressure
  - Lower the solidus

- Which mineral controls melting of peridotite?
  - Olivine – highest volume