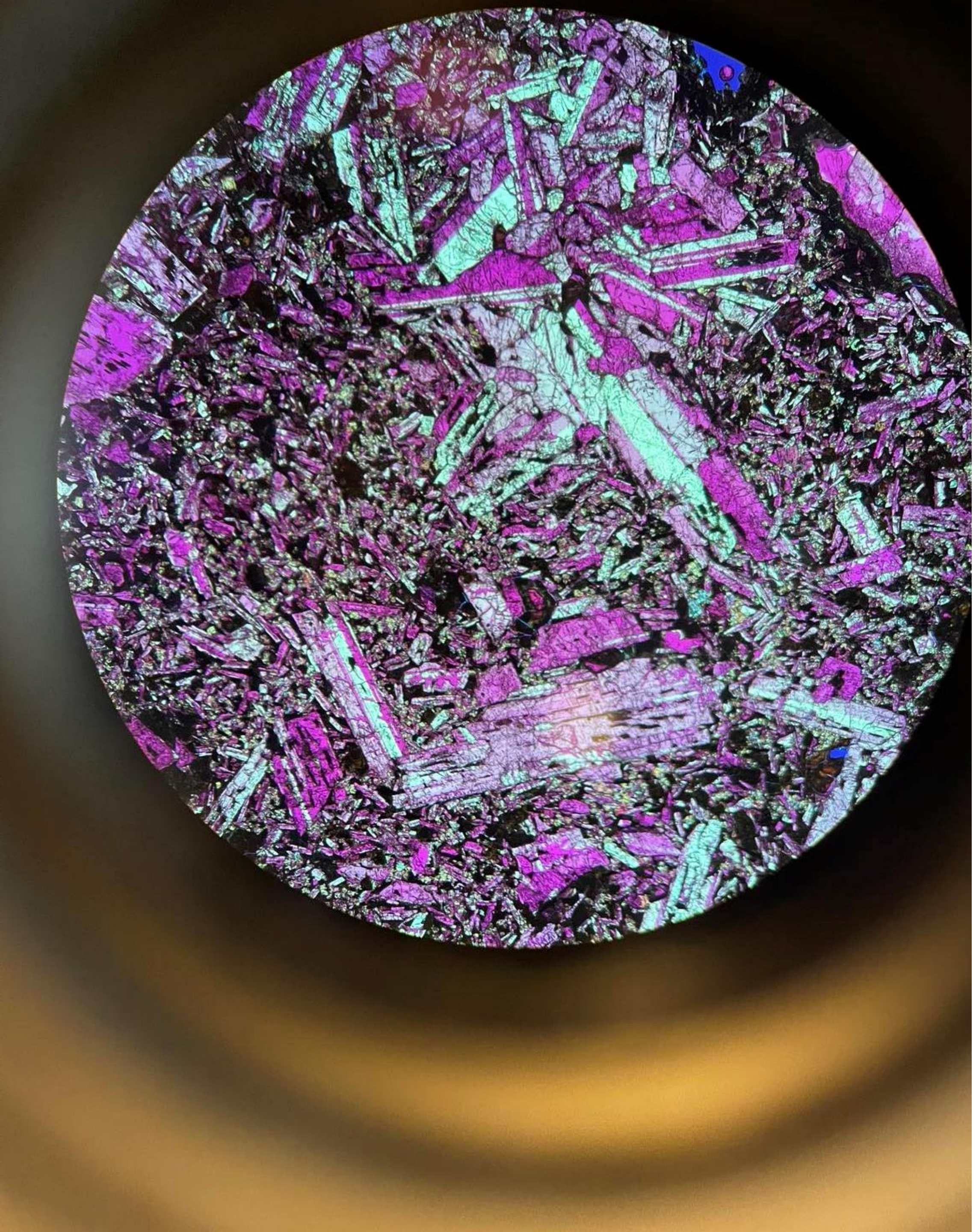


The Lithosphere and Asthenosphere

Mineralogical Constraints

Marija Plahter Rosenqvist

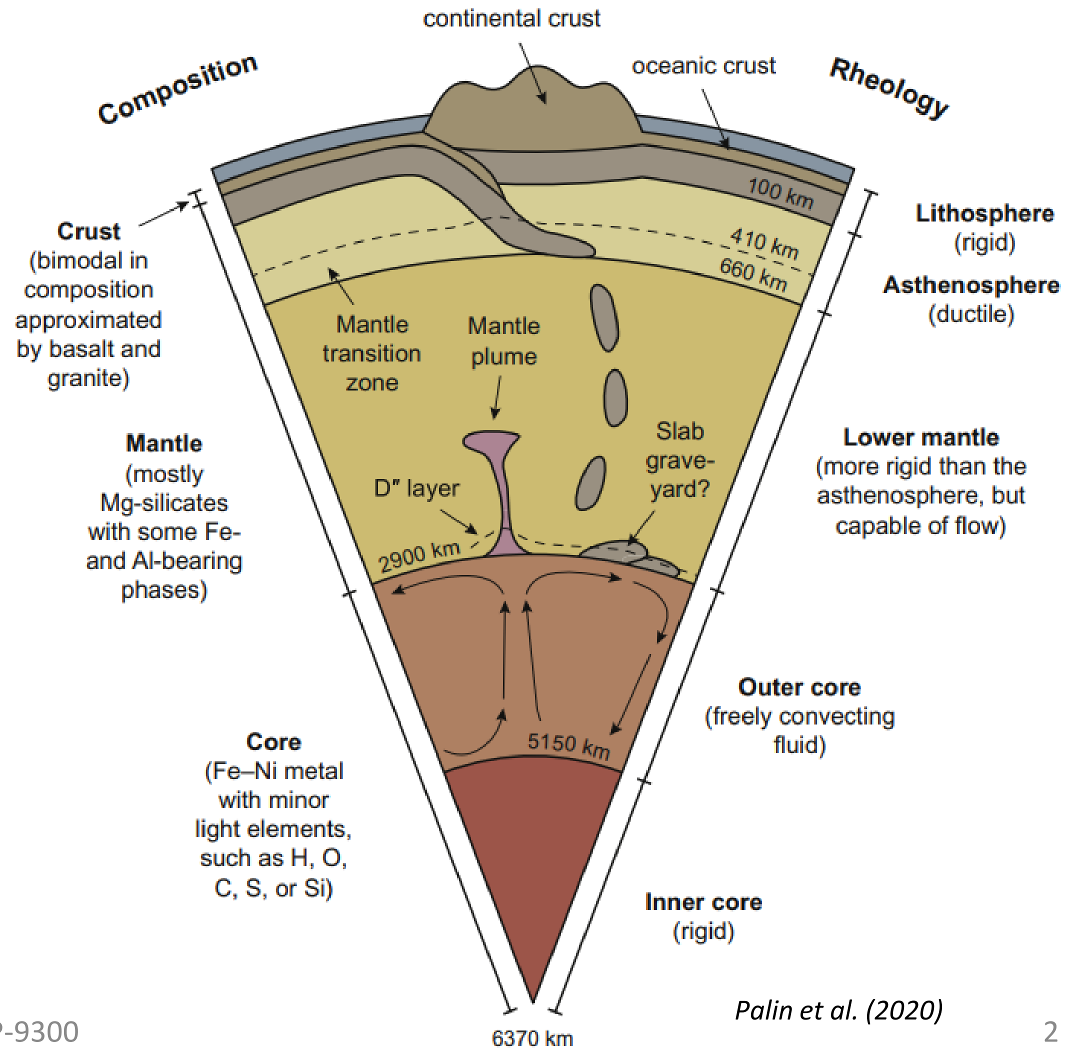
PhD Student, University of Oslo

GEO-DEEP-9300

16.01.2024, m.p.rosenqvist@mn.uio.no

The Lithosphere and Asthenosphere

- Changes in mineralogy explain many of the seismic and rheological boundaries observed in the earth, including in the lithosphere and asthenosphere.
- What are the mineralogical constraints that define these boundaries?
- What methods do we use to understand the mineralogy in the lithosphere and asthenosphere?



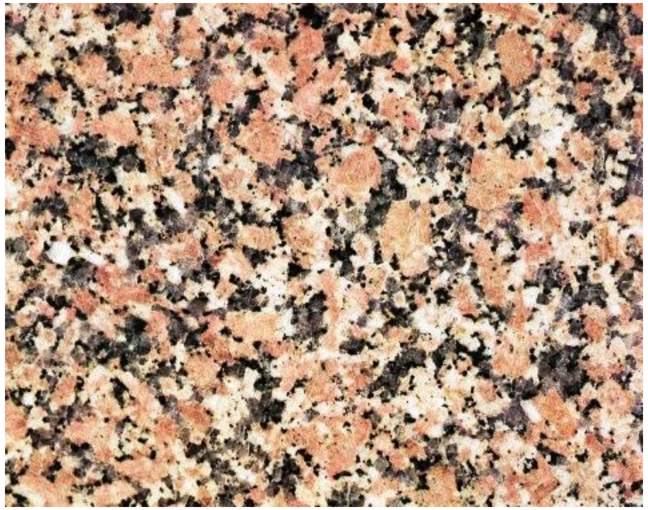
Palin et al. (2020)

The Lithosphere:

- The Crust
  - Continental → **felsic/intermediate**
  - Oceanic → **mafic**
- The lithospheric mantle → **ultramafic**
- The crust is very heterogeneous
- The mineral evolution depends on:
  - Volcanism and degassing, fractional crystallization, crystal settling, assimilation reactions, regional and contact metamorphism, plate tectonics, associated large-scale fluid-rock interactions and biochemical processes

Felsic: *fel*dspar + *si*lica

- **Light minerals rich in Si and Al**



Mafic: *Ma*gnesium + *f*errum (iron)

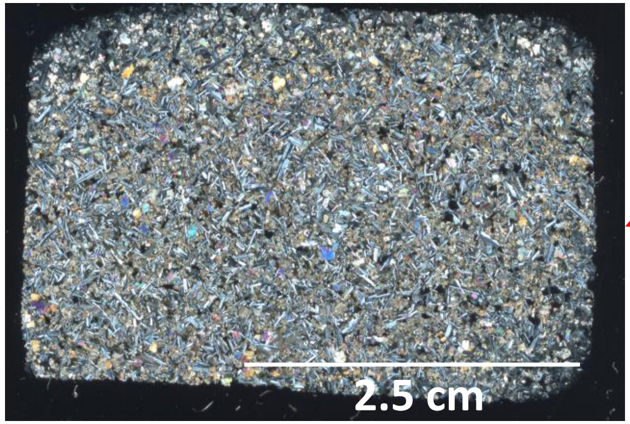
- **Dark minerals rich in Mg and Fe**

Mineral Evolution of the Earth’s Lithosphere

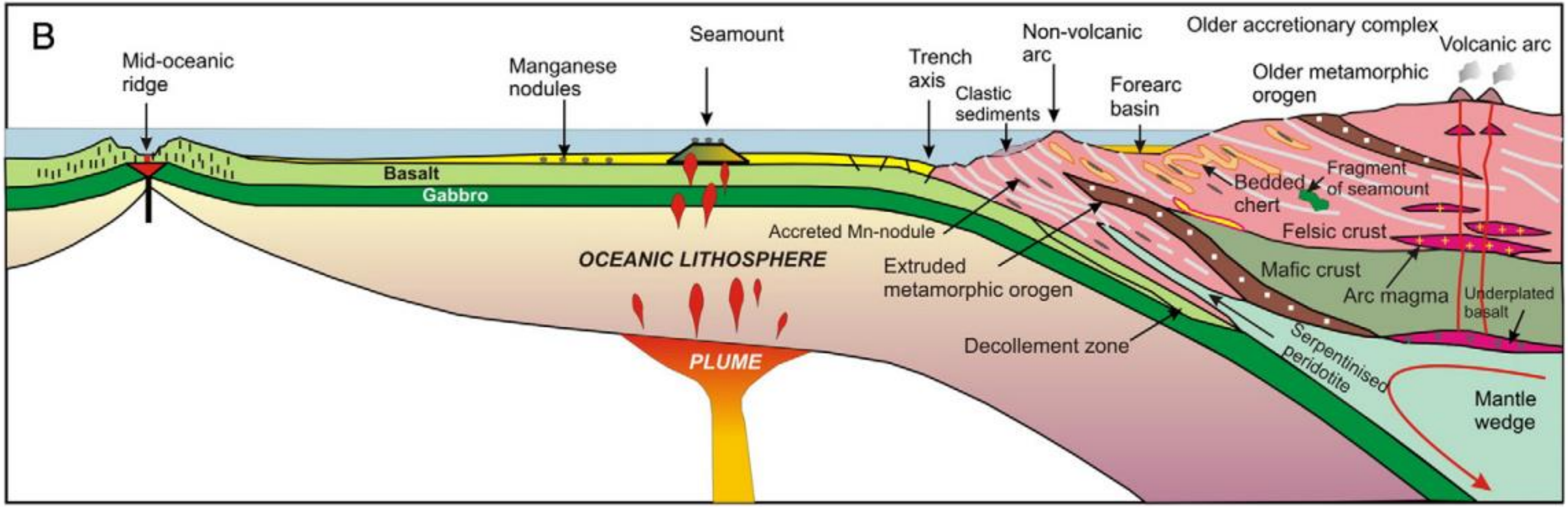
- Today we know of more than 5000 minerals but were there always this many?

Mineral Evolution of the Earth's Lithosphere

- Difficult to find rocks older than 2.8 Ga
- Early stage: crystallization of igneous rocks and bombardment of asteroids etc. (4.55 to 2.5 Ga)
- Igneous rock activity dominating (4.55 to 4.0 Ga)



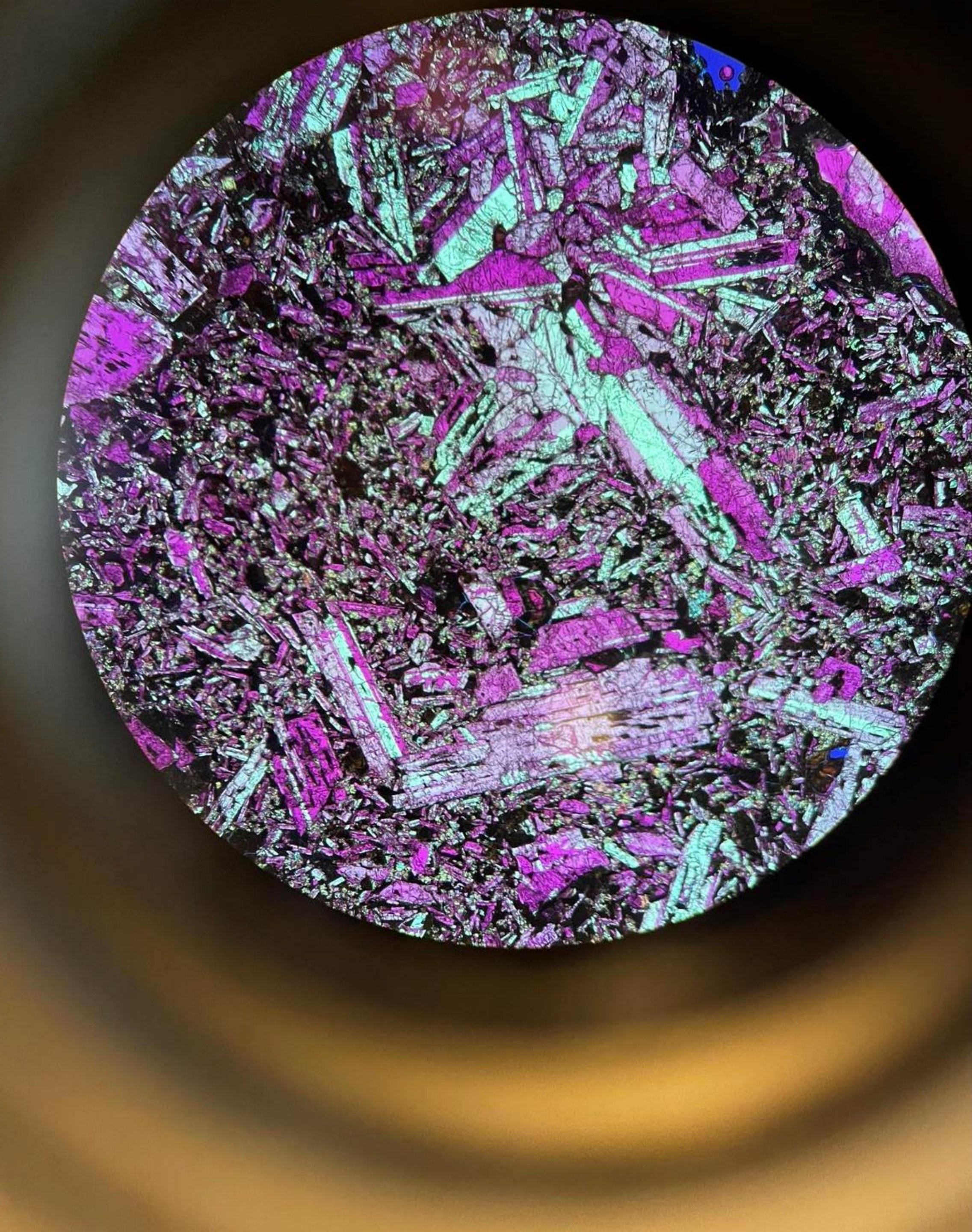
USGS.gov



Safonova et al. (2024)

Creation of Continental and Oceanic Crust

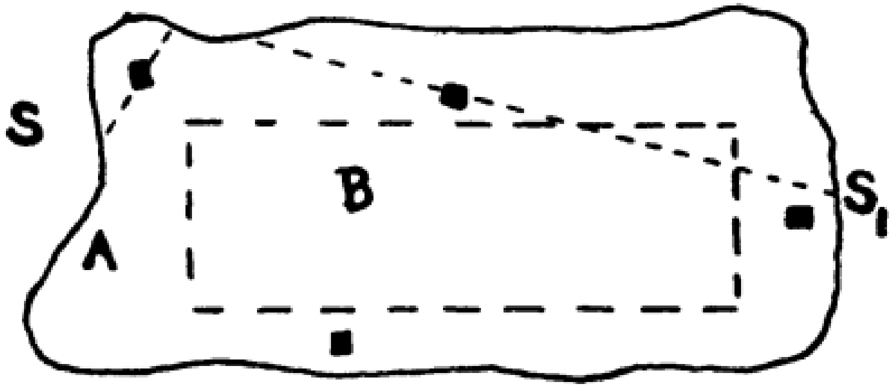
- Growth of buoyant lithosphere and initiation of craton formation (4.0 to 3.5 Ga)
- Plate tectonics and large-scale hydrothermal reworking of the crust (>3.0 Ga) → Estimated 1500 different mineral species
  - **Creation of continental and oceanic crust**
- Era of biologically mediated mineralogy (2.5 Ga→) → More than 5000 mineral species



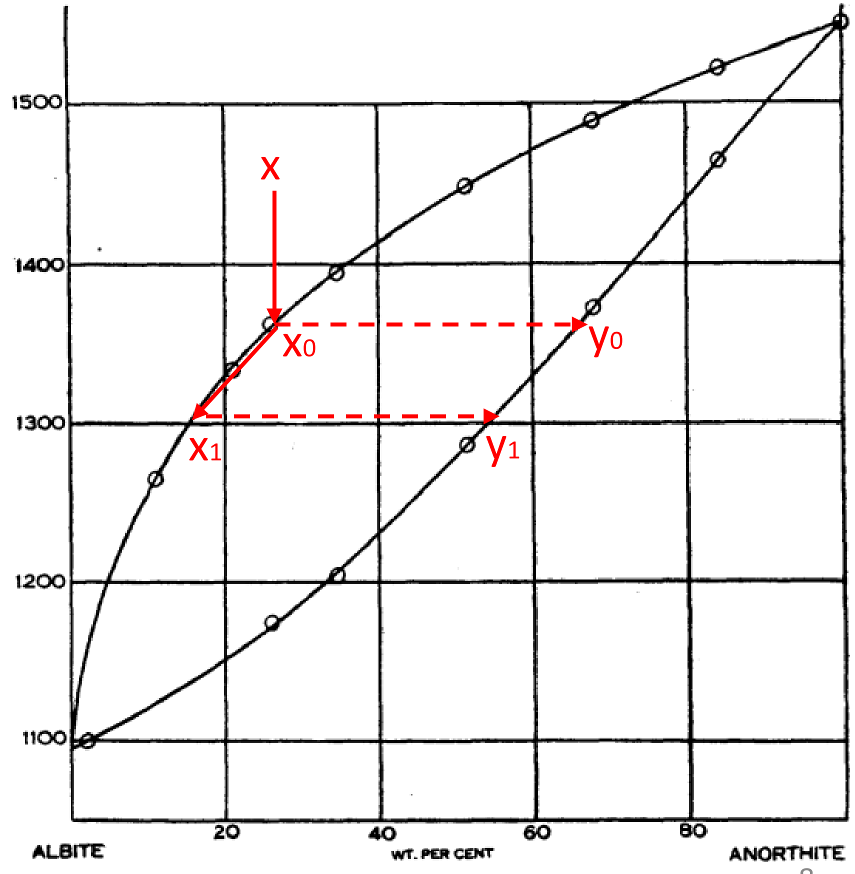
Methods

Petrography

- Detailed descriptions of mineral assemblages, microstructures and textures
- Microscopy and chemical analyses
- Describe the order of crystallization from a melt or a solution
  - Zoning
  - Cross-cutting, indentations or enclosing
- Use to create phase/equilibrium diagrams
- Describe the reaction series
- Needs to be backed up by experiments



Bowen (1912)

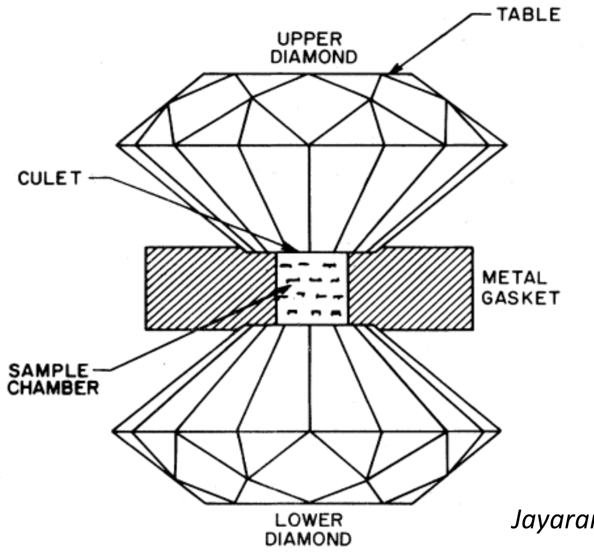


Bowen (1922)

Experiments

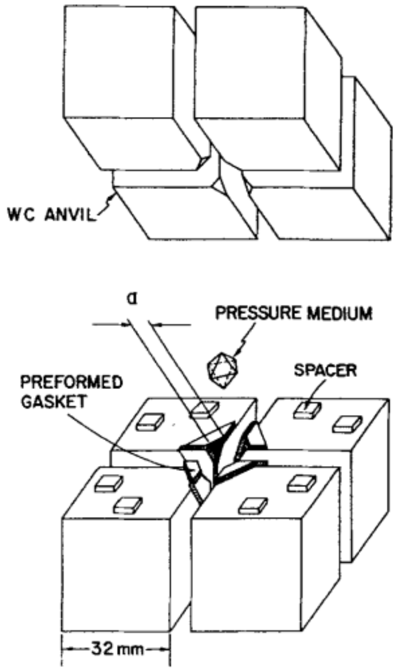
- High-pressure experiments
- High-temperature experiments
- High PT experiments combined with chemical analyses: Raman spectroscopy or electron microscopy
- Diamond anvil cell
- Multi-Anvil Press
- Uniaxial stress to synthesize minerals
- Can get mineralogical and petrophysical properties as experiments progress

Diamond anvil cell:



Jayaraman (1983)

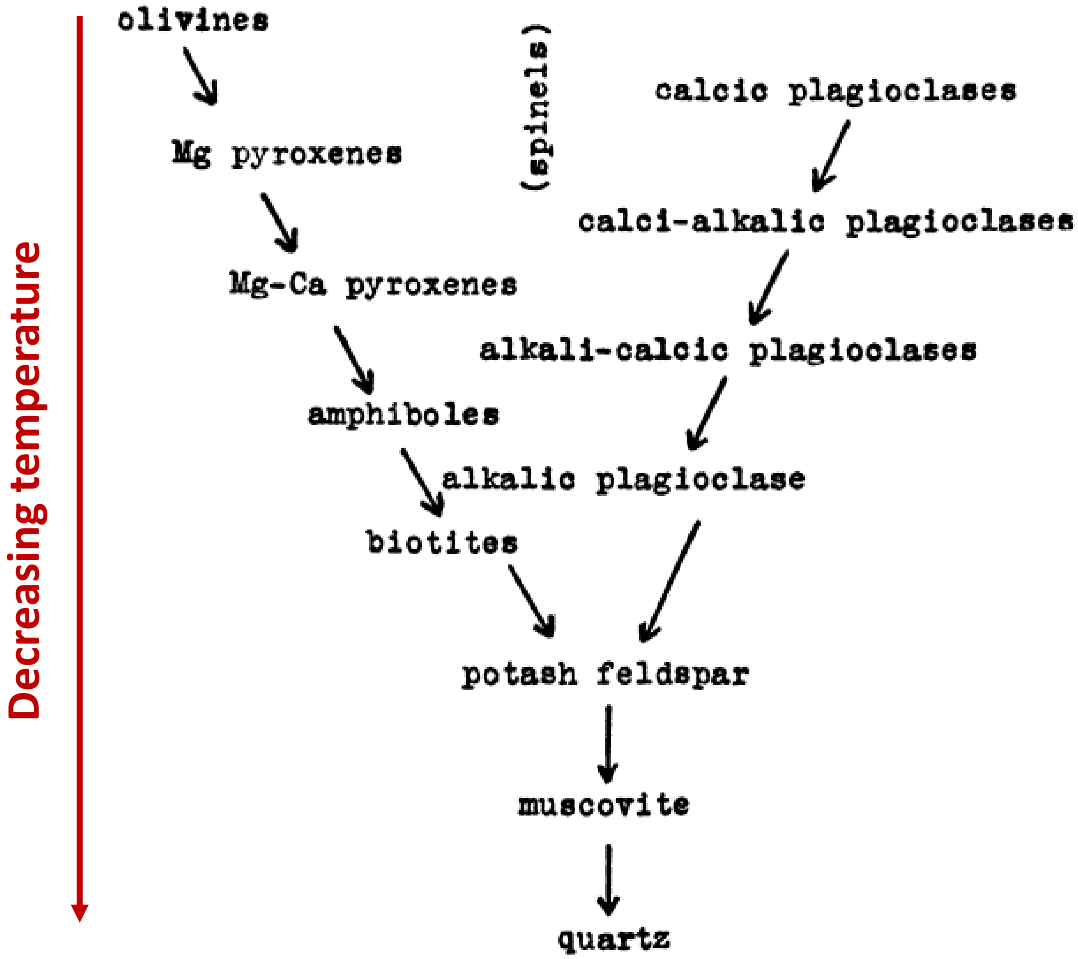
Multi-Anvil Press:



Gwanmesia et al. (1994)

Bowen's Reaction Series: Petrography and Experiments

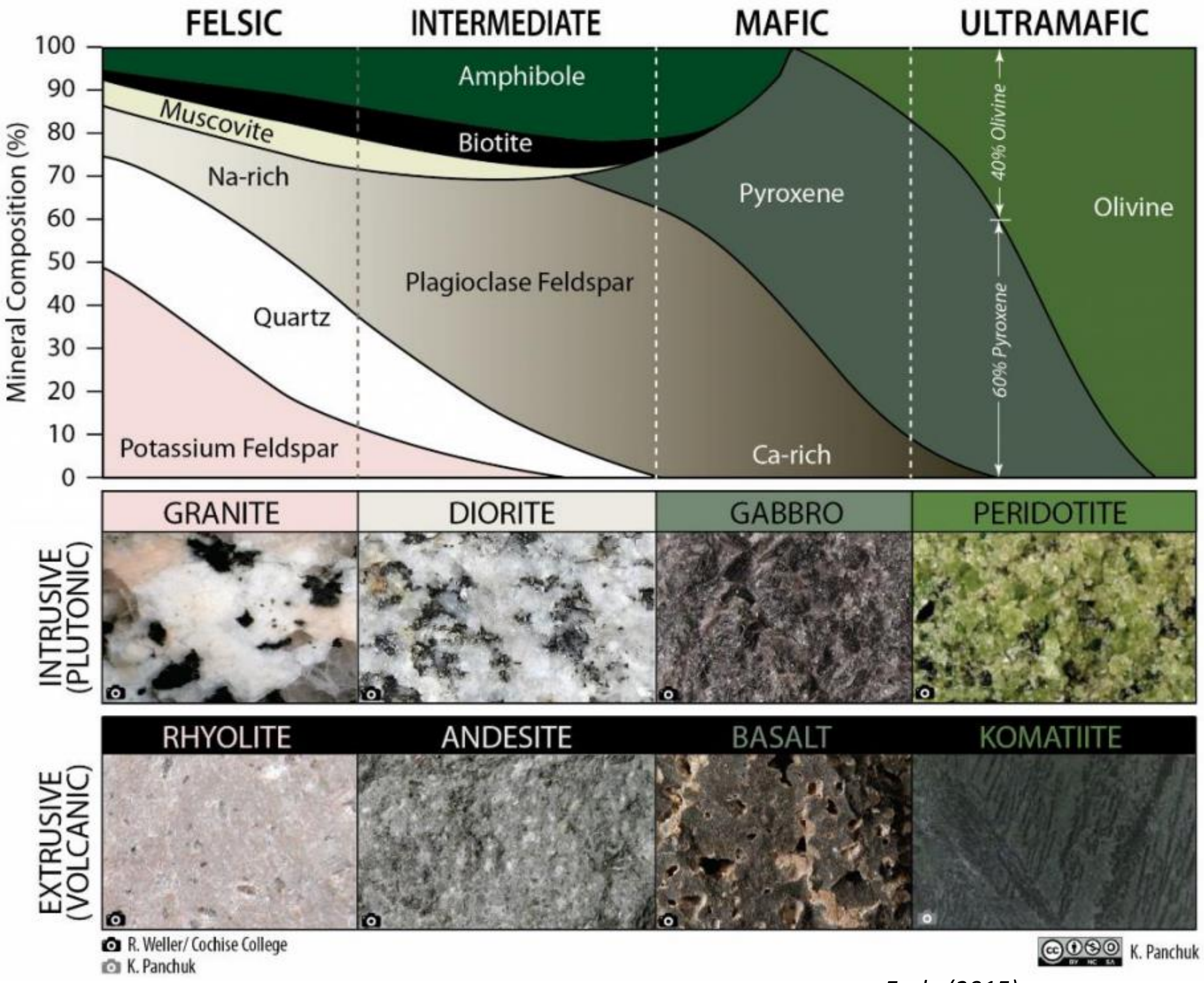
- Igneous rock activity
- Leads to a repeated cycle of fractional melting
- Bowen's reaction series
- Separation of ultramafic, mafic and felsic rocks



Bowen (1922)

Felsic, Mafic and Ultramafic Rocks

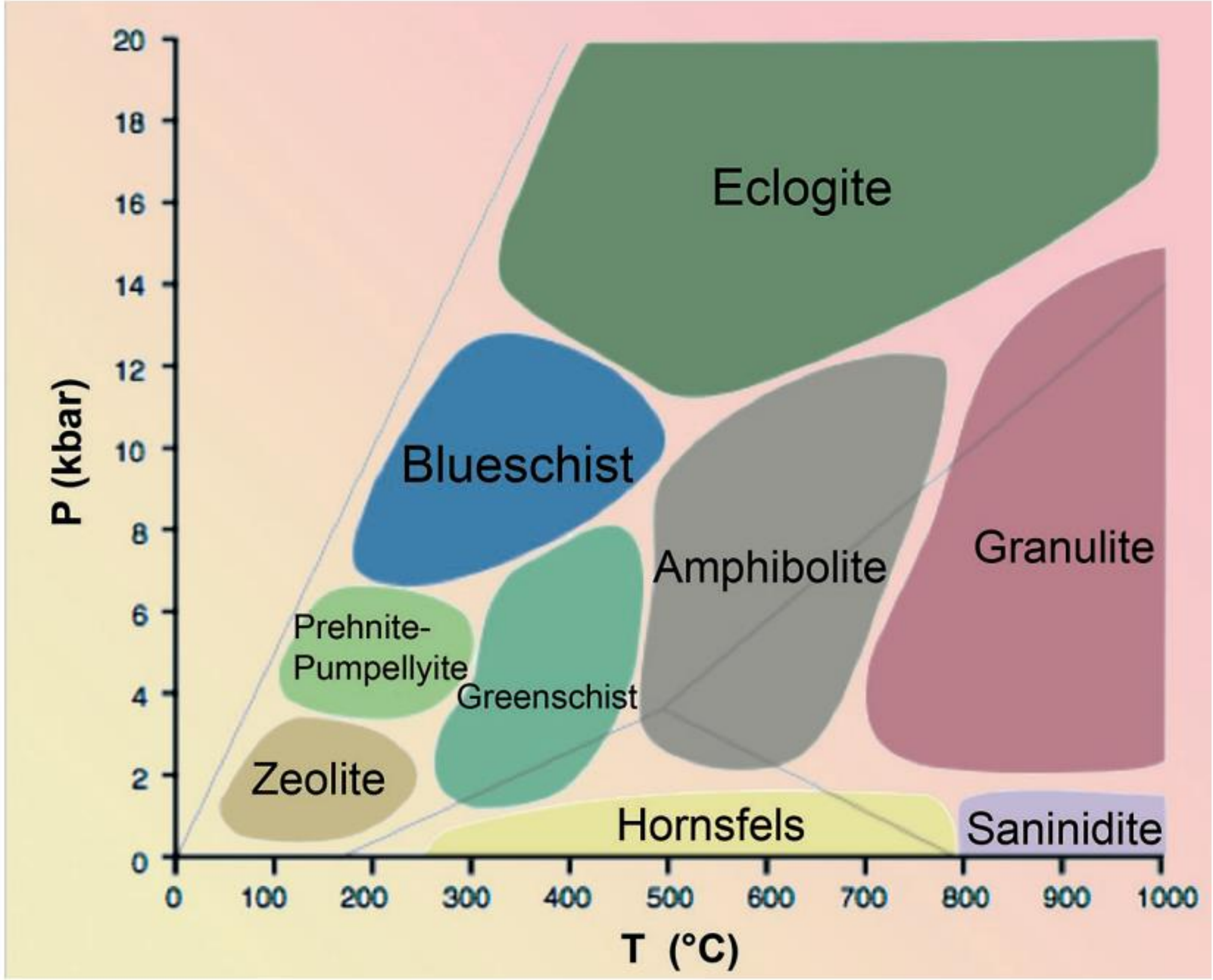
- Mantle = ultramafic rocks
- Get mafic rocks by partial fractional melting of ultramafic mantle rocks
- Get felsic/intermediate rocks by remelting the crust
  - Not by differentiation of a mafic melt from the mantle
  - The most Si-, Al-, Na-, K- and H_2O-rich components crystallize last → amphibole, mica, K-feldspar, silica
  - Understanding this means that we can understand how the crust develops and where the melt comes from



Earle (2015)

Metamorphic Facies:

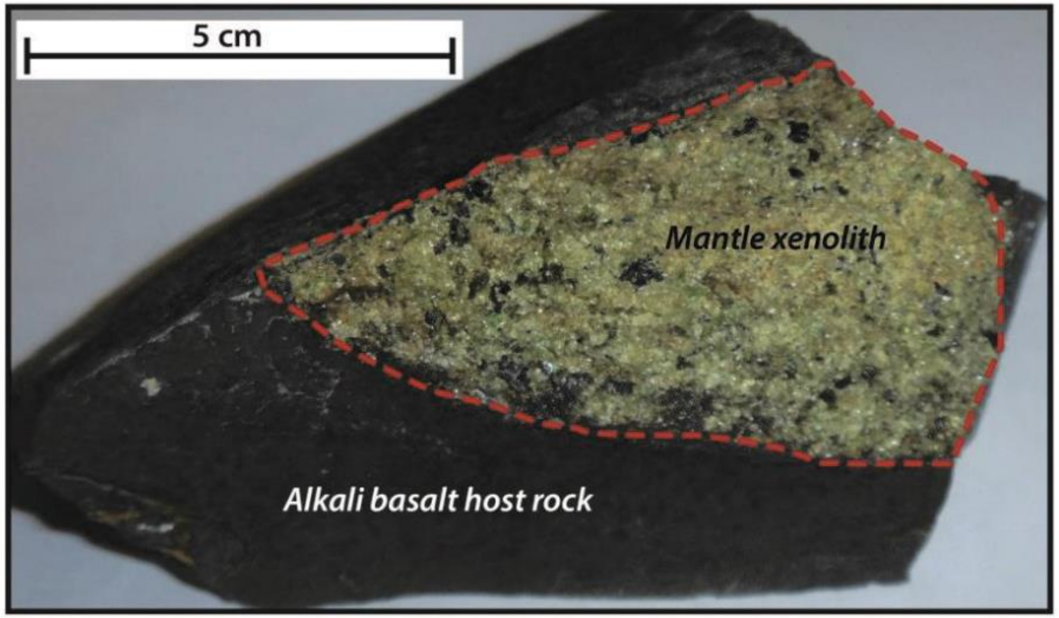
- Different metamorphic facies can record P and T and presence of fluids in the deep crust
- Determined by mineral assemblages and textures
- E.g., garnet, epidote, coesite etc.



Arndt (2013)

Xenoliths

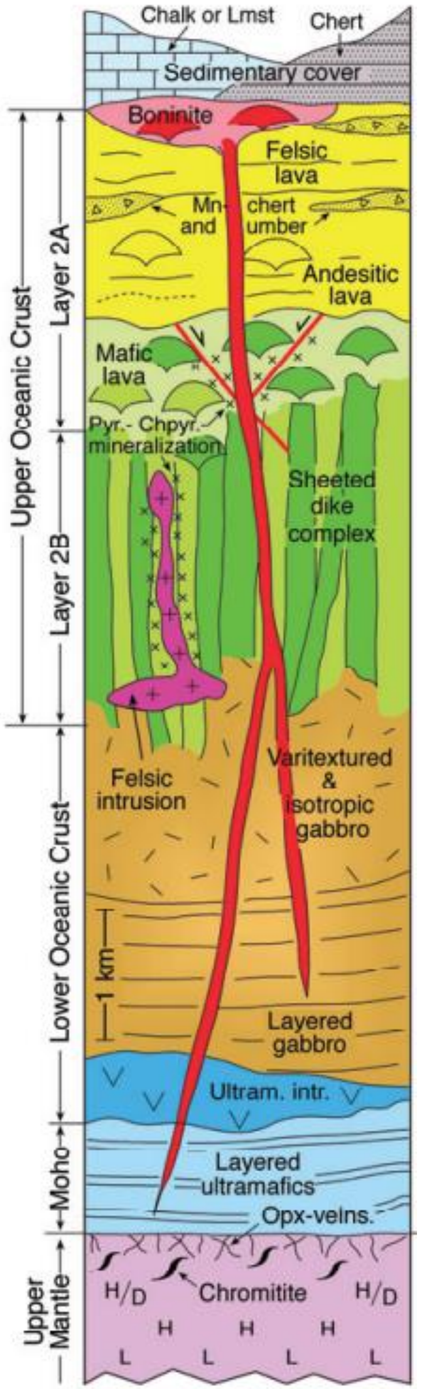
- Piece of rock trapped in another rock
- Sampling of the lower crust and upper mantle
- Can bring up rocks from deeper down
- Most often related to melt movement
- Record pressures and temperatures based on mineralogy
    - Microstructures (e.g., recrystallization)
    - Zoning (equilibration during ascent?)
    - Mineral assemblages and geochemistry (garnet+orthopyroxene+clinopyroxene)
    - Dating (isotopes)



Dalton and Scott (2014)

Ophiolites

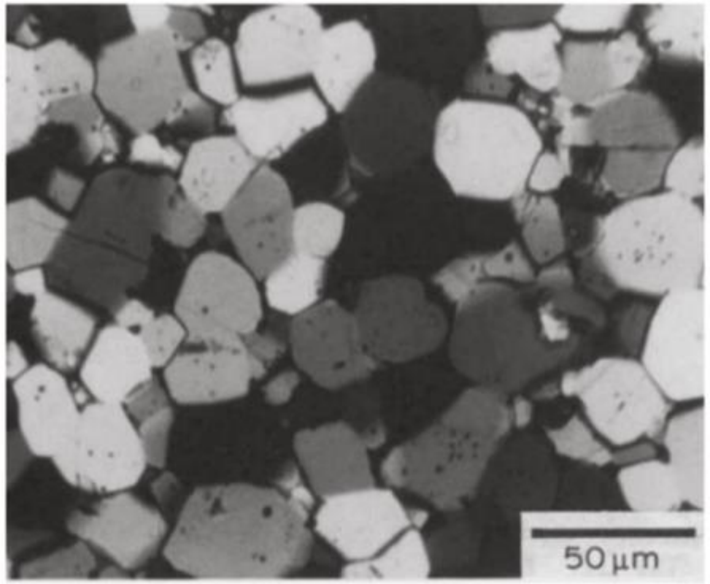
- Way to study the crust-mantle boundary mineralogy in the field
- More complete picture
- Part of the oceanic crust and upper mantle that has been moved up:
  - Tectonically emplaced
  - Most related to subduction zones
  - May be altered: metamorphism or intrusions

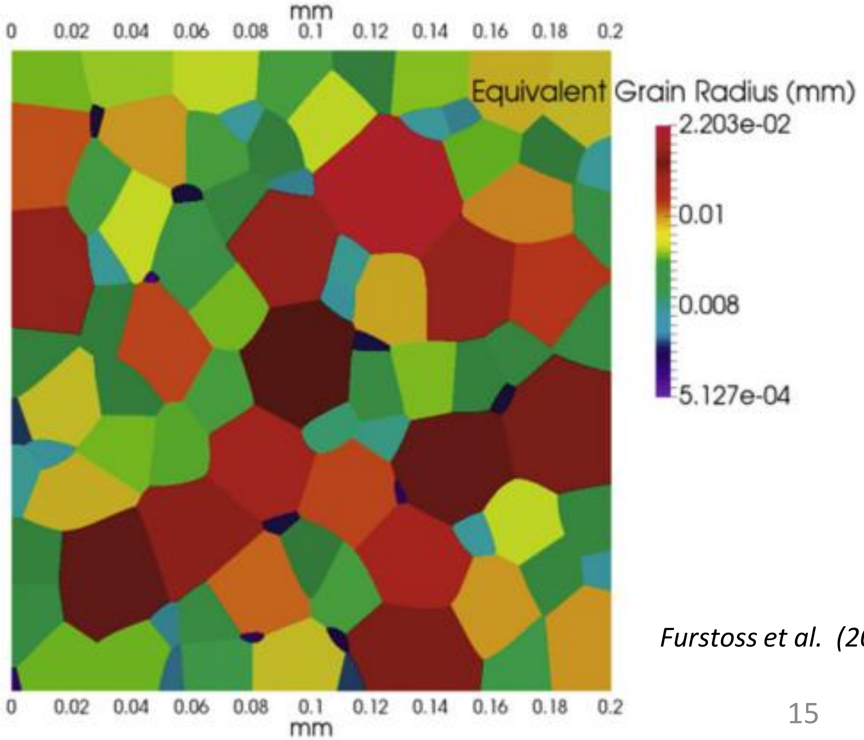


Dilek and Furnes (2014)

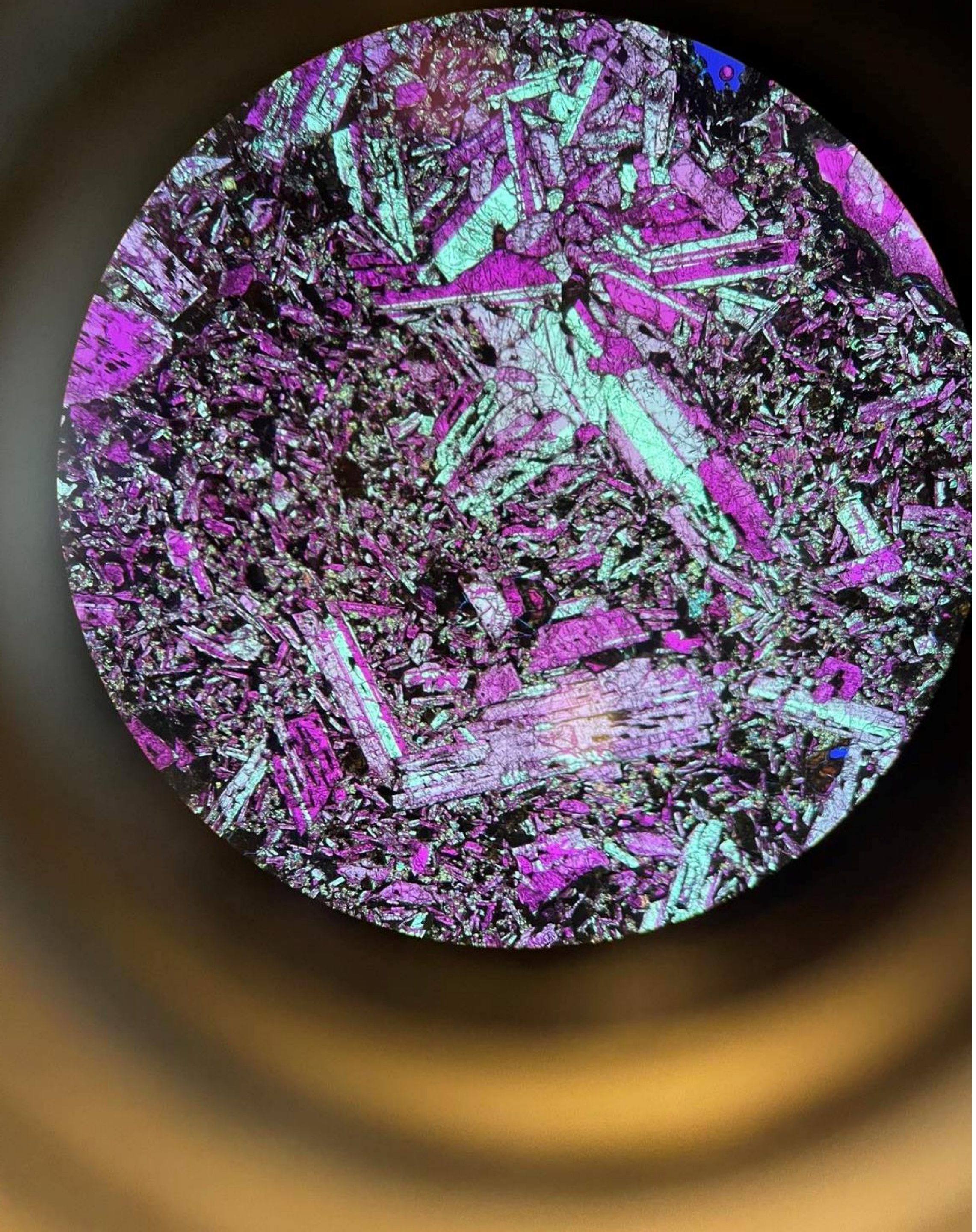
Modelling

- Numerical simulations of crystal growth
- Models for pressure and temperature distributions in the crust and upper mantle
  - Where will different minerals be stable?
  - Where will we start to have melting?
  - How will the mineralogy affect seismic velocities?





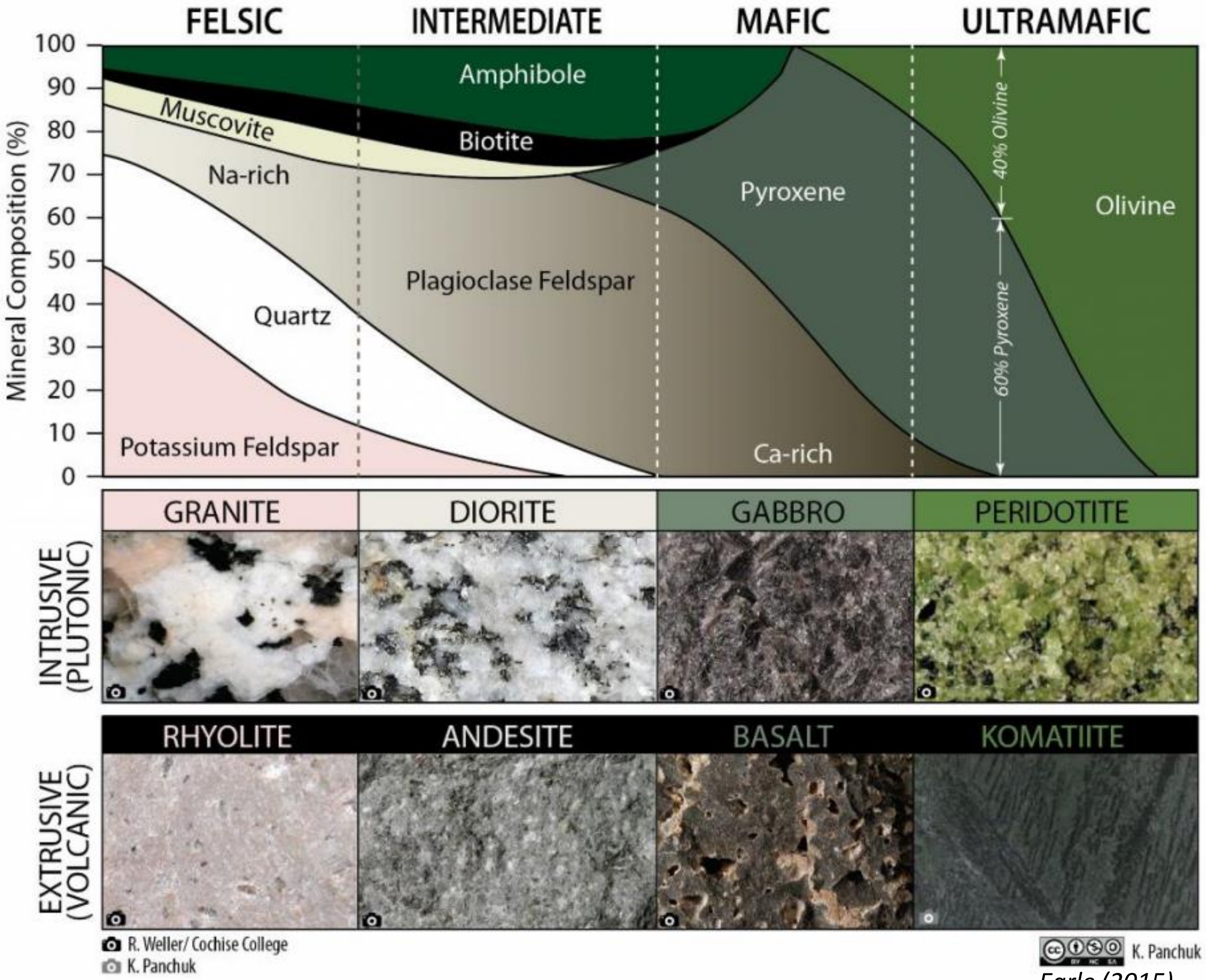
Furstoss et al. (2018)



Applications

The Continental Crust: Exposures/Cores and Xenoliths

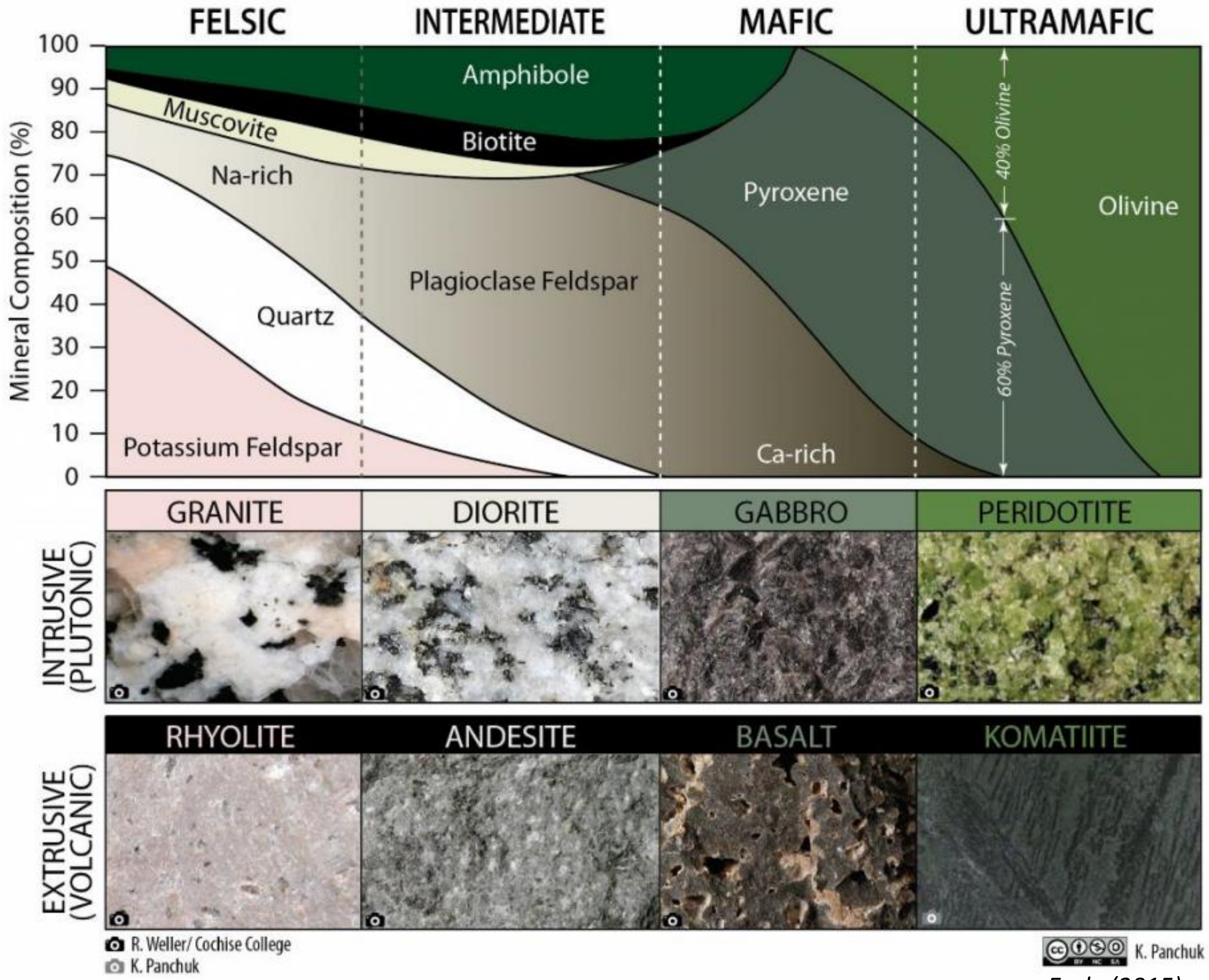
- Mostly felsic to intermediate composition
- Because of differential melting we get a grading (seen in seismic refraction data):
  - Upper crust: more felsic dominated
  - Middle crust: intermediate bulk composition
  - Lower crust: average composition is mafic



Earle (2015)

The Oceanic Crust: Cores, Ophiolites and Xenoliths

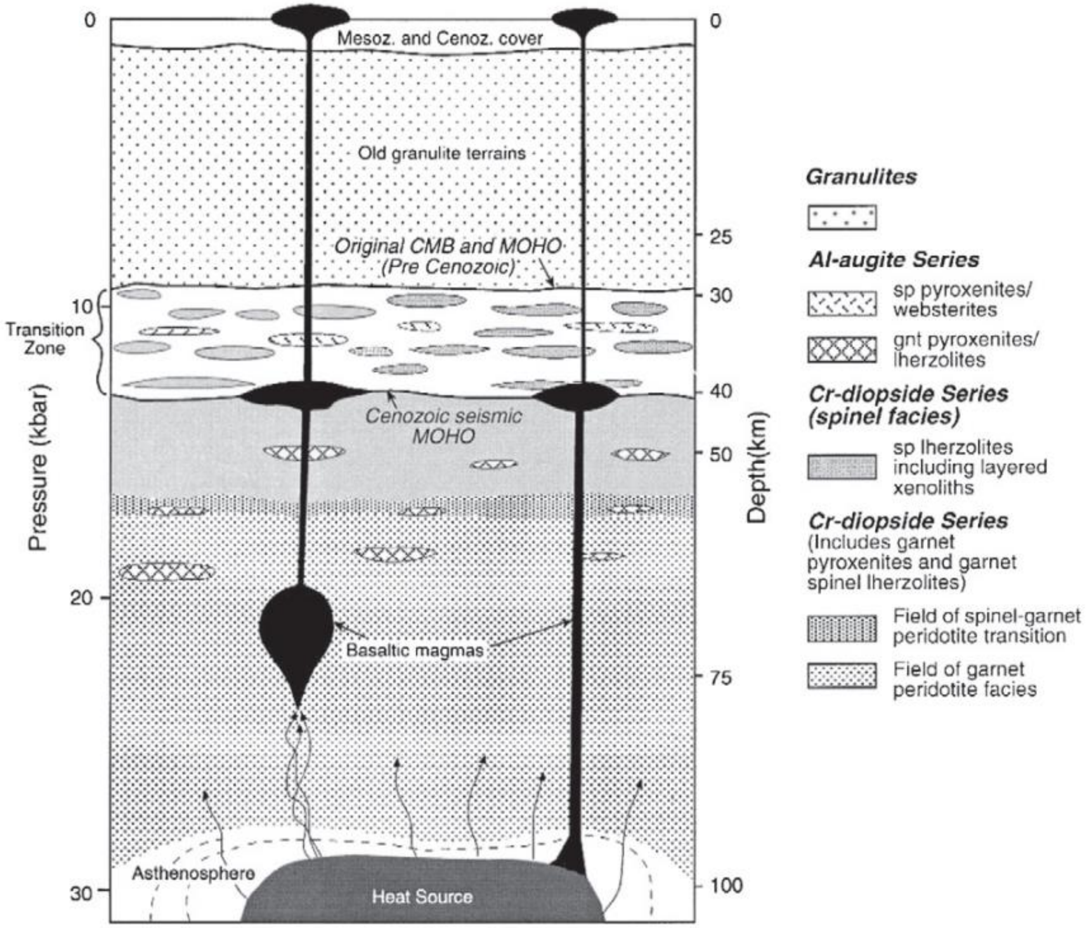
- Composed of mafic rocks created by partial melting of mantle peridotite
  - More Mg- and Fe-rich minerals
- Tholeiitic basalt (extrusive)
- Amphibolite and hornblende gabbro (intrusive or plutonic)
  - Often crystallization under hydrous conditions and metamorphism



Earle (2015)

Crust-Mantle Boundary: Ophiolites, Xenoliths and Modelling

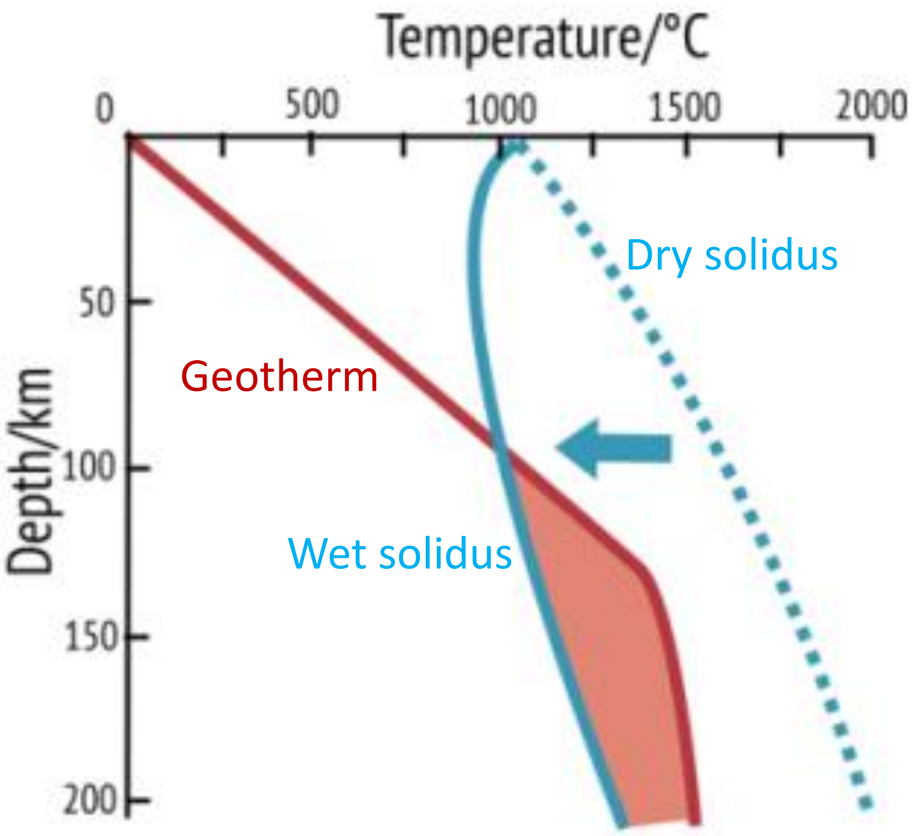
- Moho vs crust-mantle boundary
- Definition base of crust: the depth at which ultramafic rocks become significant (<10-20%)
  - Lithospheric mantle: ultramafic → dunite (>90% Olivine) to lherzolite (>40% Olivine)
  - Lithospheric mantle: Olivine>>Orthopyroxene>Clinopyroxene
- There is a transition zone between the crust and upper mantle: mafic and ultramafic rocks interlayered
  - Depth of the Crust-Mantle Boundary varies through time → magmatic underplating, tectonics



O'Reilly and Griffin (2013)

The Asthenosphere: Experiments and Models

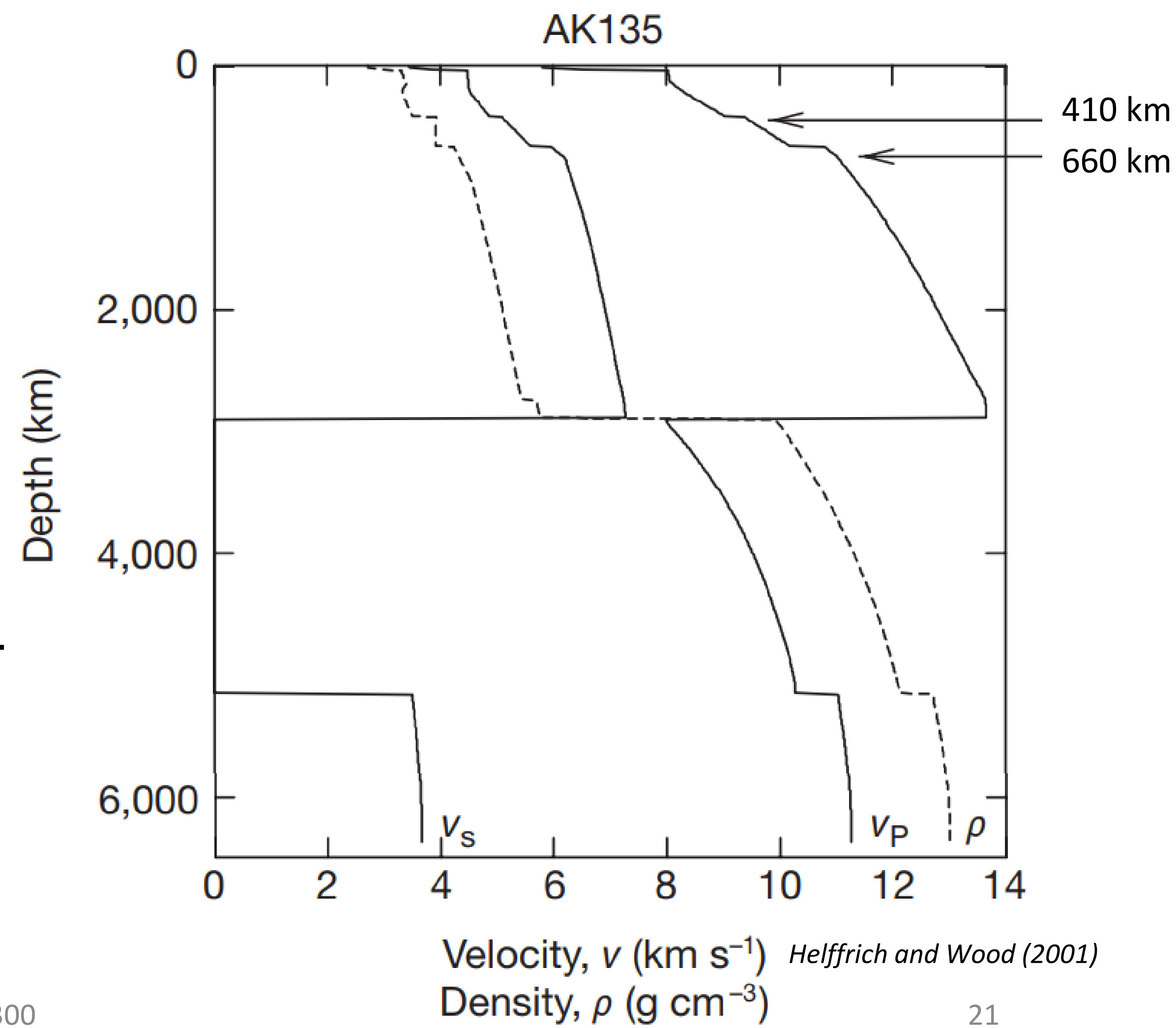
- Lithosphere – Asthenosphere boundary (LAB):
  - Sharp velocity reduction → Brittle to ductile
- What causes the rheology change? Theories:
  - Peridote stops behaving elastically close to solidus temperatures (NO MELTING)
  - Presence of water to reduce the solidus (PARTIAL MELTING) for Ca- Al- minerals
  - Amphibole (Pargasite) in lherzolite contains water
  - $NaCa_2(Mg_4Al)(Si_6Al_2)O_{22}(OH)_2$



The Geological Society of London

Transition to lower mantle: Experiments and Models

- 410 km discontinuity → transition to 660 km discontinuity and lower mantle
- Phase transitions and reactions:
  - α → β → γ → Pv + Mw
  - α, β, γ polymorphs of $(Mg, Fe)_2SiO_4$
  - Olivine → Wadsleyite → Ringwoodite: 410-discontinuity
  - Olivine → Wadsleyite: 410-discontinuity
  - Ringwoodite → Periclase (MgO) and Bridgemanite ($MgSiO_3$): 660-discontinuity



Helffrich and Wood (2001)

Summary

- Changes in mineralogy explain many of the observed seismic and rheological boundaries in the earth, including in the lithosphere and asthenosphere.
- Most of what we know about the mineralogy and petrology of the lithosphere and asthenosphere comes from:
    - Petrography and geochemistry studies
    - Experiments
    - Modelling
- The data to study the petrological variations in the lithosphere and asthenosphere may come from, e.g., outcrops, cores, xenoliths, ophiolites and seismic velocity data.