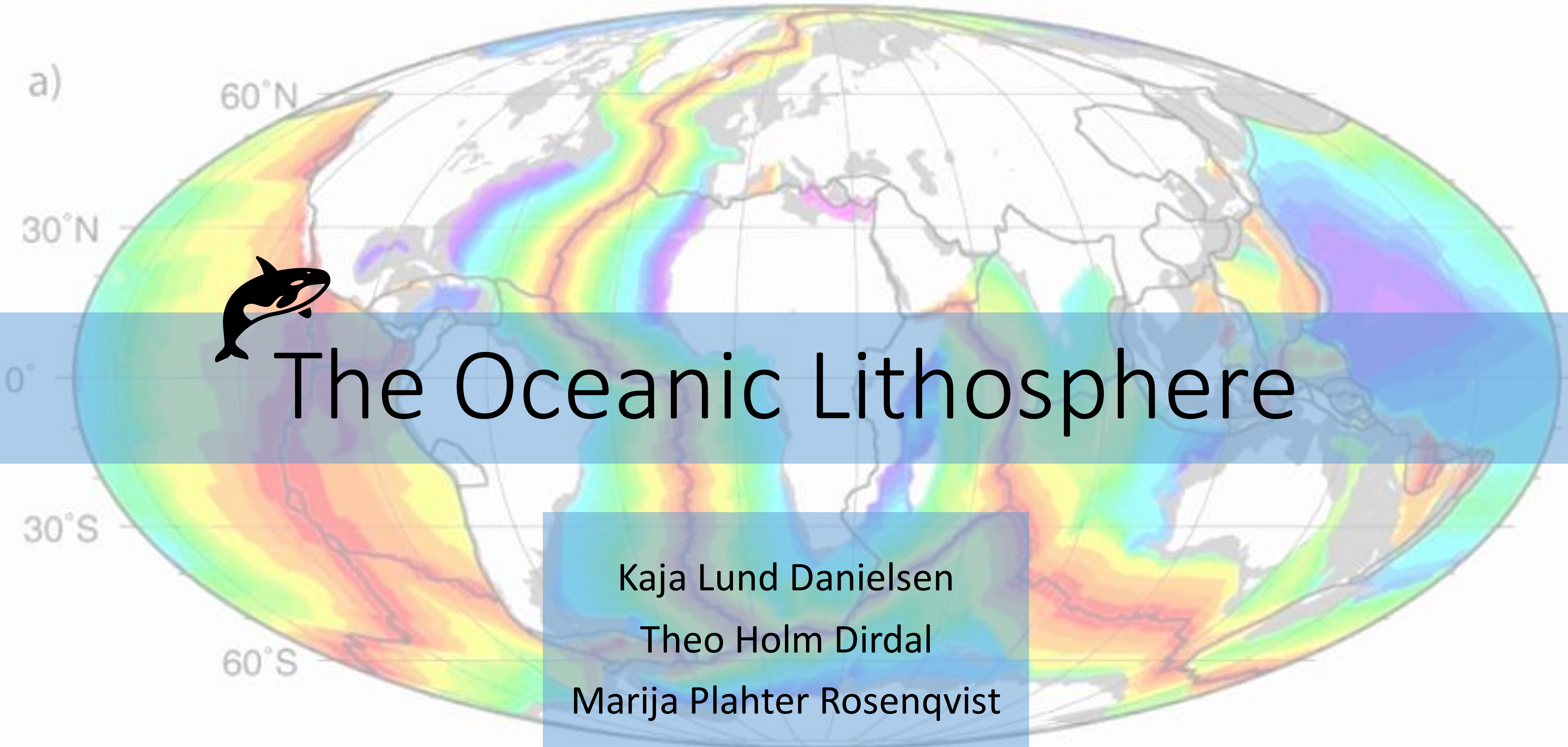

The Oceanic Lithosphere

Kaja Lund Danielsen
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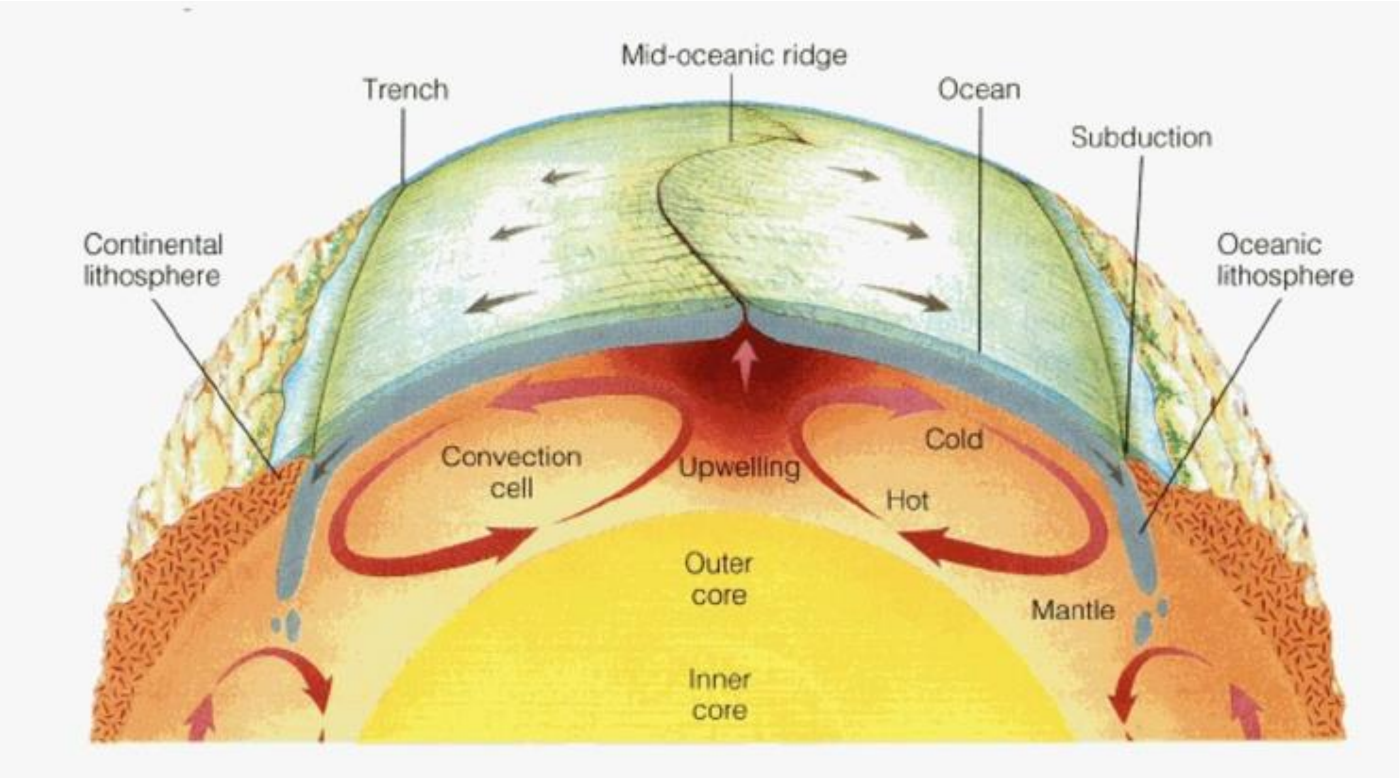
18.01.2024

GEO-DEEP-9300

The oceanic lithosphere

- Consists of the crust and upper mantle under the earth
- Primarily composed of basaltic rock
  - Rich in Iron and magnesium
- Thinner and denser than continental lithosphere → slabs
- Forms at mid ocean ridges by volcanic activity
- Oldest near subduction zones



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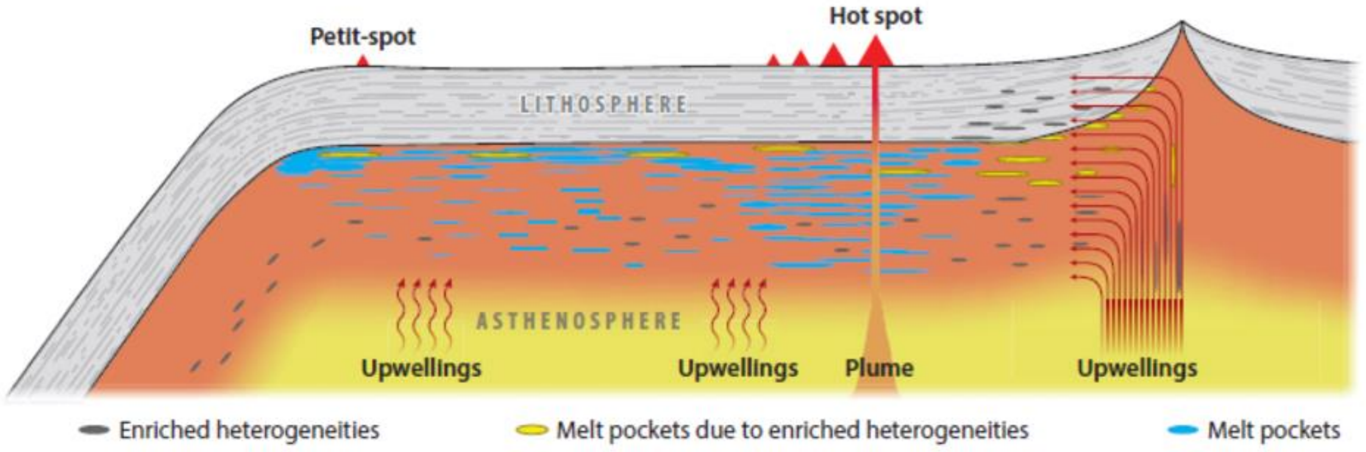


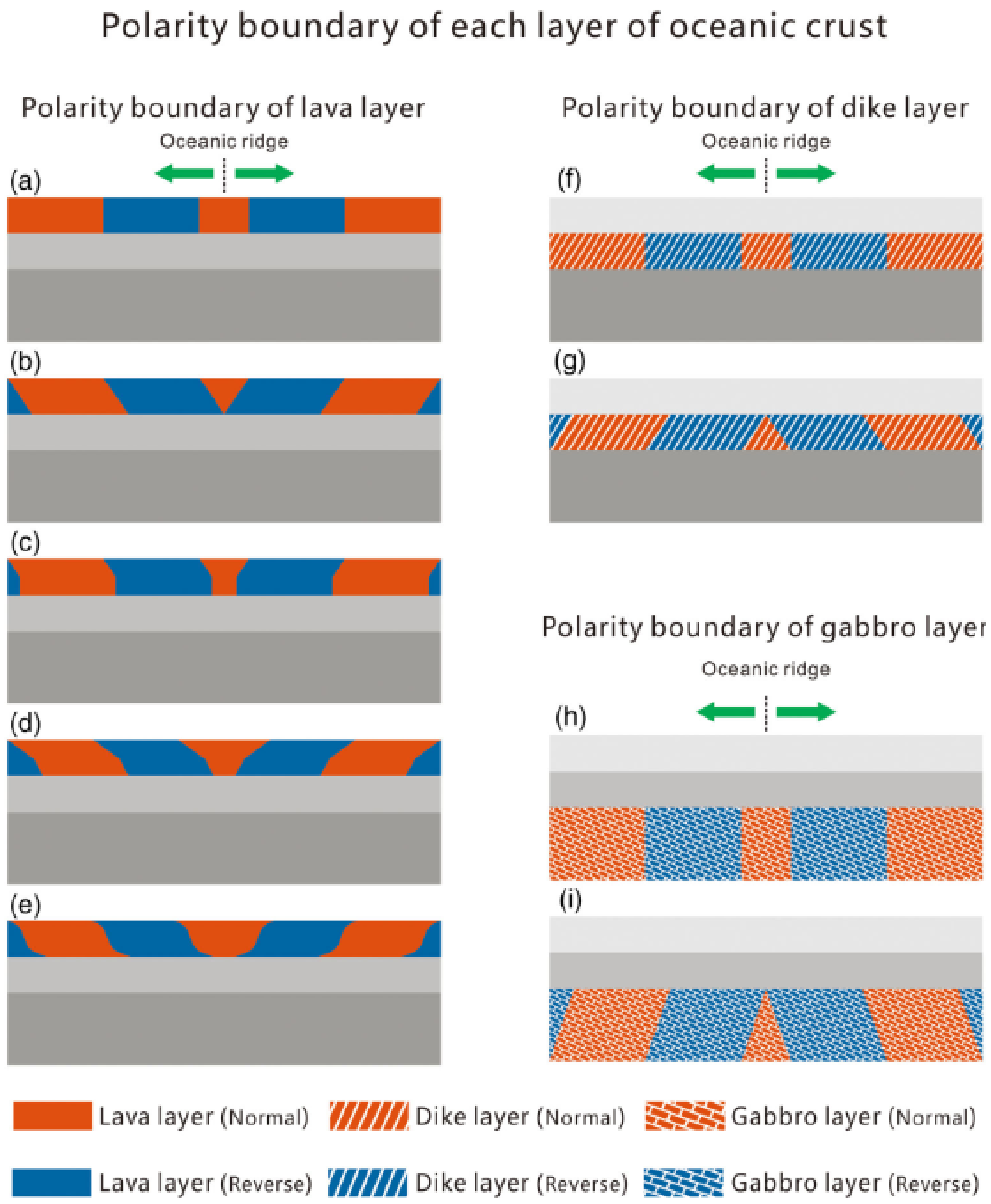
Kawakatsu and Utada (2017)

Mid-Ocean-Ridge

- Production of oceanic crust
- Further away from MOR, the age increase as well as thickness

- Magnetic anomaly strips
  - Lava layer contribute 70-90%
  - Dike layer
  - Gabbro layer

- Polarity boundary based on observation
  - Lava → Eruption and solidification
  - Dike → Intrusion mode
  - Gabbro → Isotherms



Hu et al. (2022)

Mid-Ocean-Ridge initiation

- Convection currents
- Plate tectonic movements
- Magma upwelling

Sim et al. (2020)

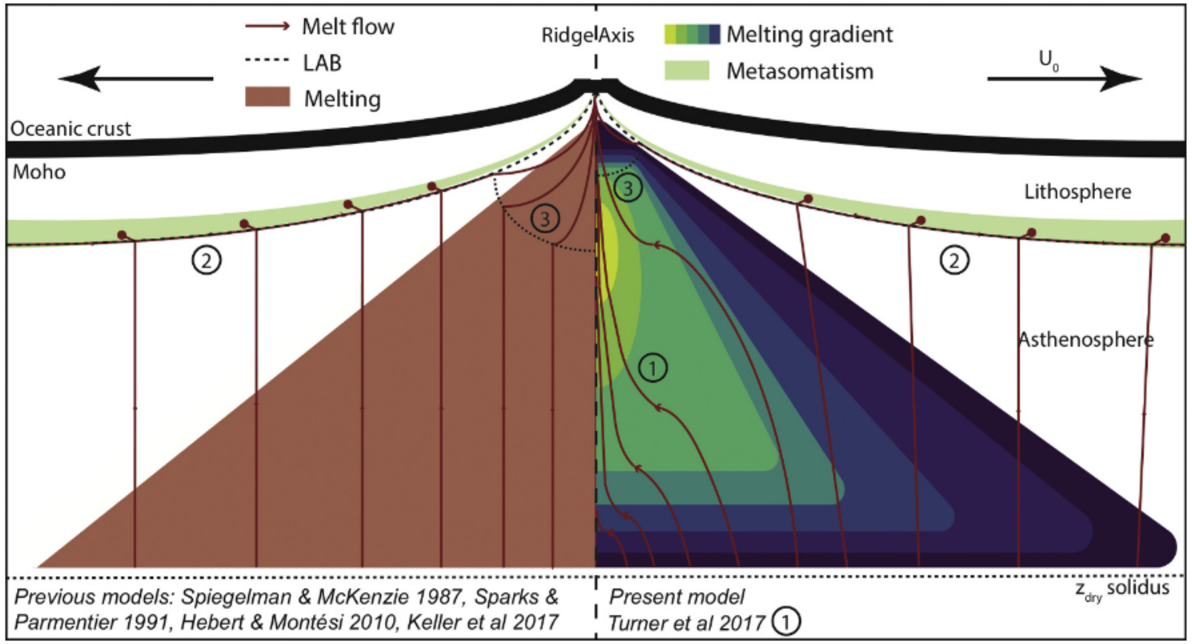
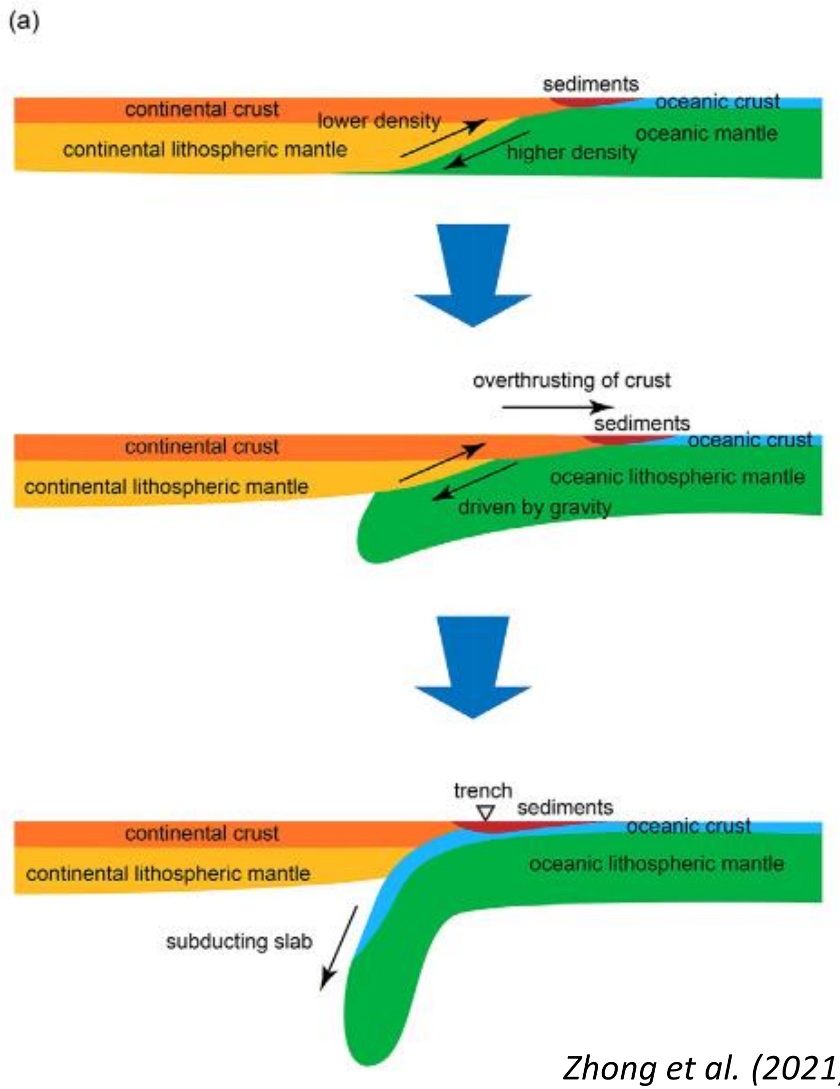


Fig. 6. Illustration of melt focusing mechanisms from past and present work based on Keller et al. (2017). The three melt focusing mechanisms are numbered: 1) Melting pressure focusing 2) Decompaction layers and 3) Ridge suction. The dashed black line down the center represents the ridge axis. The thick black curved lines that connect at the highest point at the ridge axis represent the oceanic crust. The Moho is the bottom of the oceanic crust. Modeled or hypothesized melting is represented as the half triangle on the left for previous work while it is represented by a lime green to dark violet melting triangle on the right for these models presented. Red lines and arrows indicate melt flow and direction. Red circles indicate where melt freezes into the lithosphere in the green region of metasomatism above the black dashed line for the lithosphere-asthenosphere boundary (LAB). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Subduction

- Mature subduction driven by negative buoyancy of the cold oceanic lithosphere relative to the mantle below

- Driving forces into two groups
  1. Local forces: Gravitational instabilities, loading sediments, density contrast
  2. External forces: Far-field convergent, neighbouring slab-pull, convection



Zhong et al. (2021)

Induced Subduction

- Initiated subduction through transform fault

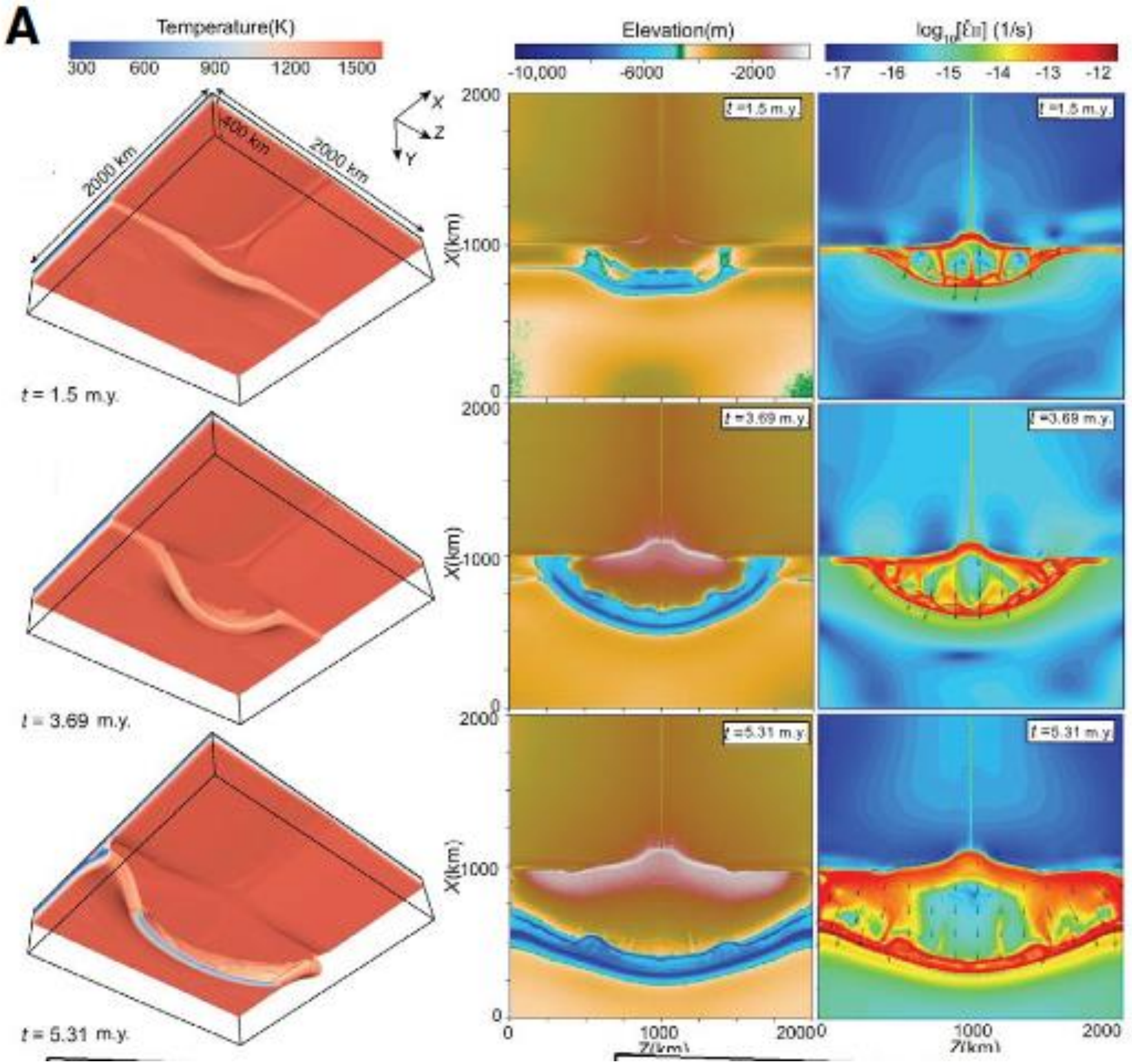


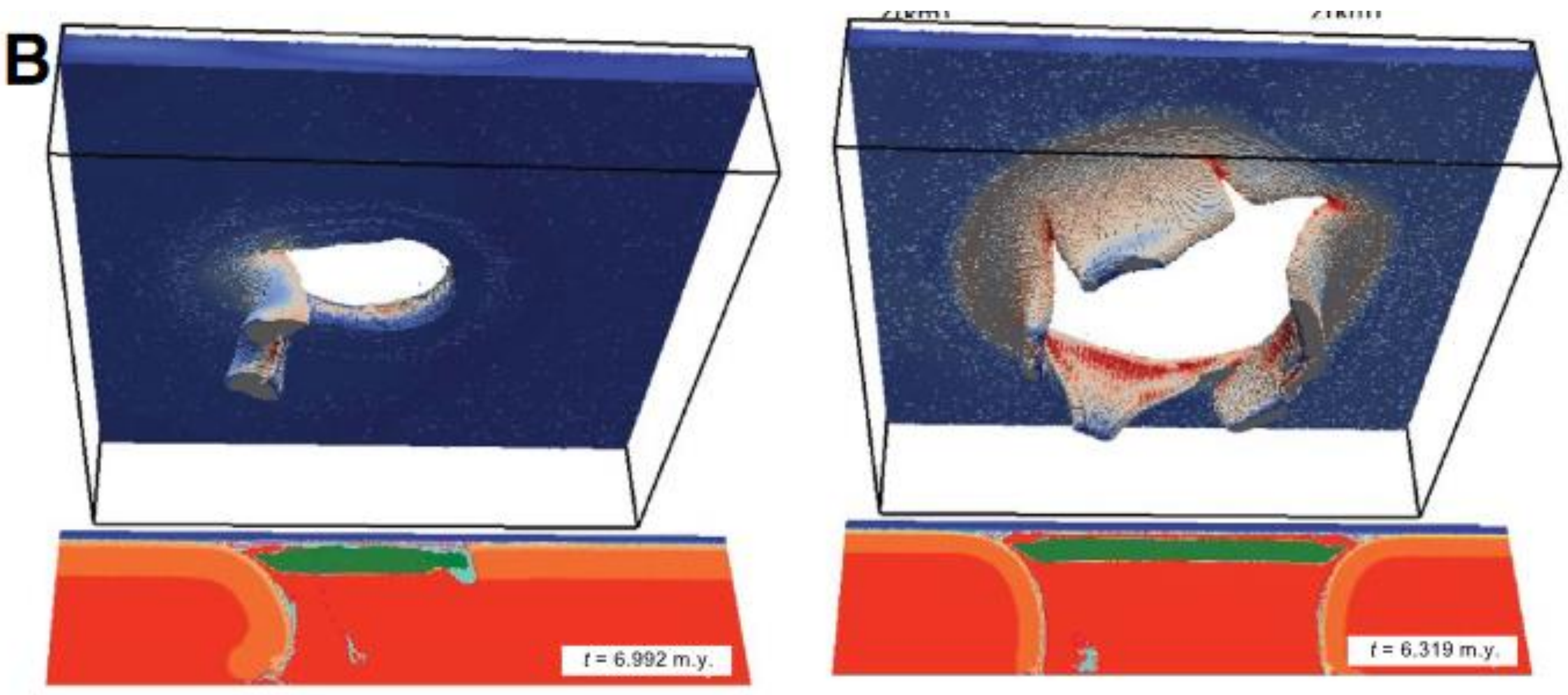
Figure 2. 3D models of subduction initiation (SI). (A) SI propagation along transform fault (Zhou et al., 2018). First column shows bottom view of subducting and overriding plates. Second column shows top view of topography evolution. Third column shows second invariant of strain rate at a constant depth of 25 km. (B) Plume-induced SI producing single slab (left) or multi-slab (right) subduction (Baes et al., 2020b).

Geray (2022)

Induced Subduction

- Initiated subduction through transform fault
- Plume induced subduction

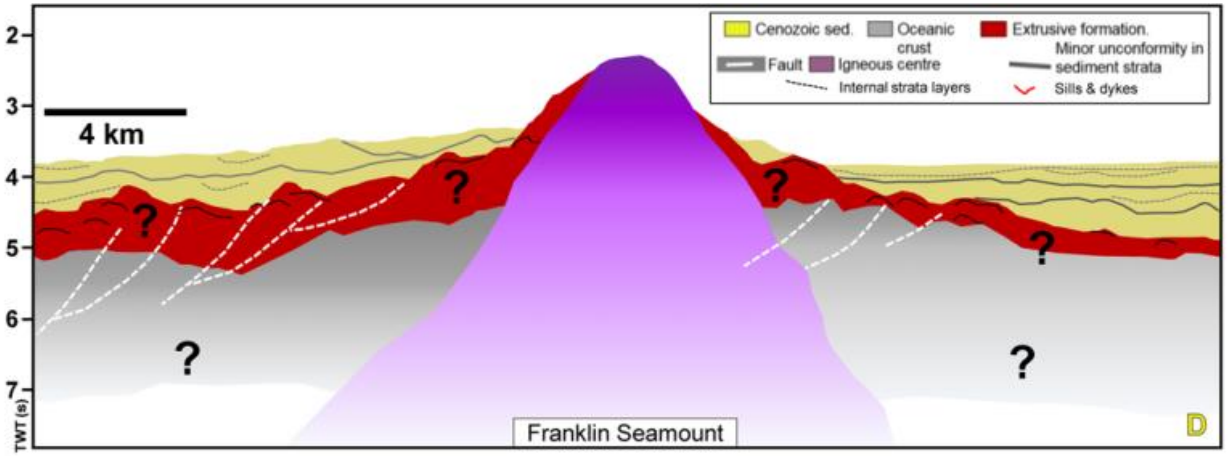
Figure 2. 3D models of subduction initiation (SI). (A) SI propagation along transform fault (Zhou et al., 2018). First column shows bottom view of subducting and overriding plates. Second column shows top view of topography evolution. Third column shows second invariant of strain rate at a constant depth of 25 km. (B) Plume-induced SI producing single slab (left) or multi-slab (right) subduction (Baes et al., 2020b).

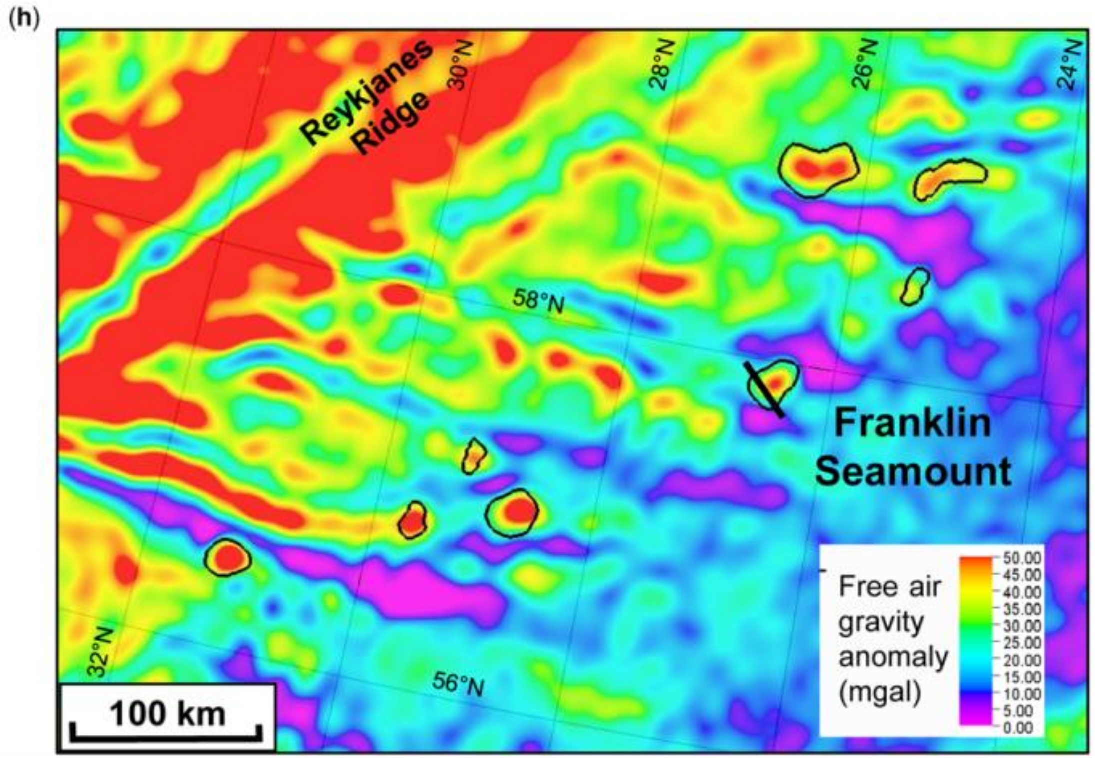


Geray (2022)

Intra plate volcanism

- Seamounts
- Connected to the formation of new oceanic crust
- Intra-plate volcanism:
  - Lithosphere cracking
  - Melt extraction from a heterogeneous mantle
  - Small-scale sublithospheric subduction
  - Shear-induced melting of low-viscosity pockets of asthenospheric mantle along the LAB





Gaina et al. (2017)

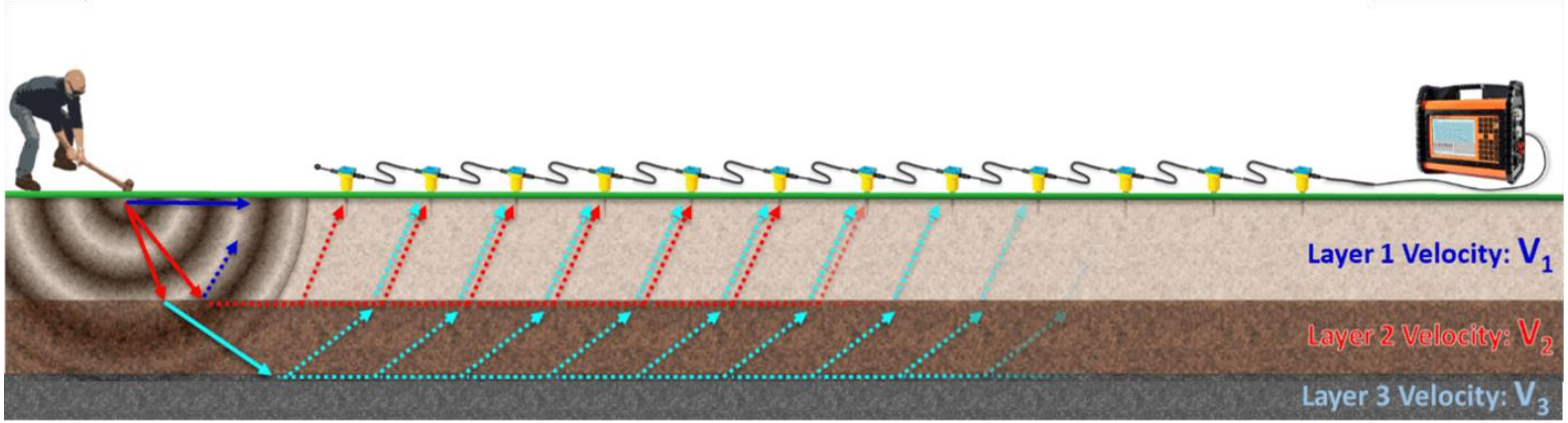
Seismic knowledge

Principle: A wave of energy that is generated by an earthquake or other earth vibration and that travels within the earth or along its surface to gain insights into the structure and behavior of the Earth.

- Body waves: P-waves and S waves
- Surface waves: Rayleigh and Love waves
- Source and receiver

Seismic tomography:

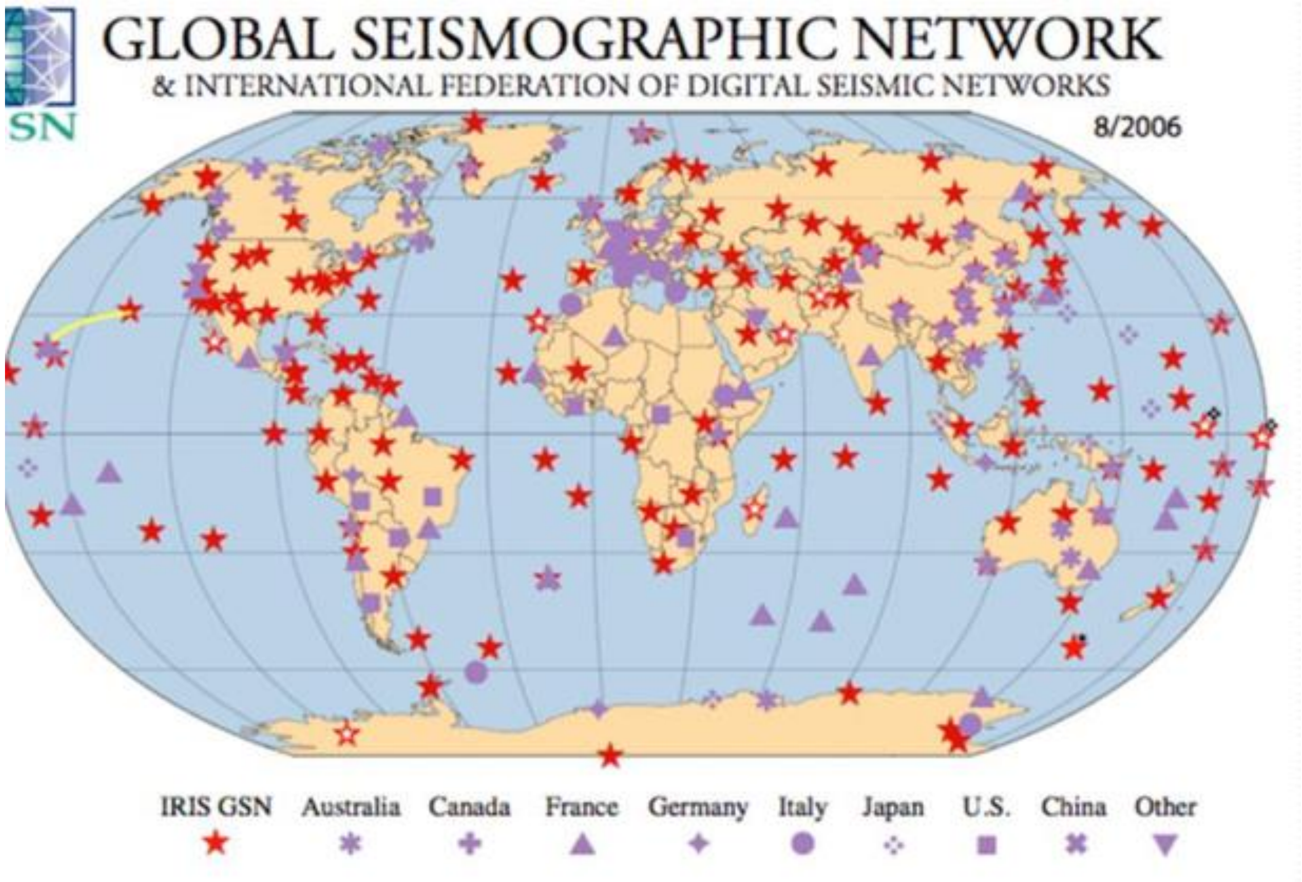
- Imaging technique
- 3D models
- Comparing traveltime



Seismic tomography

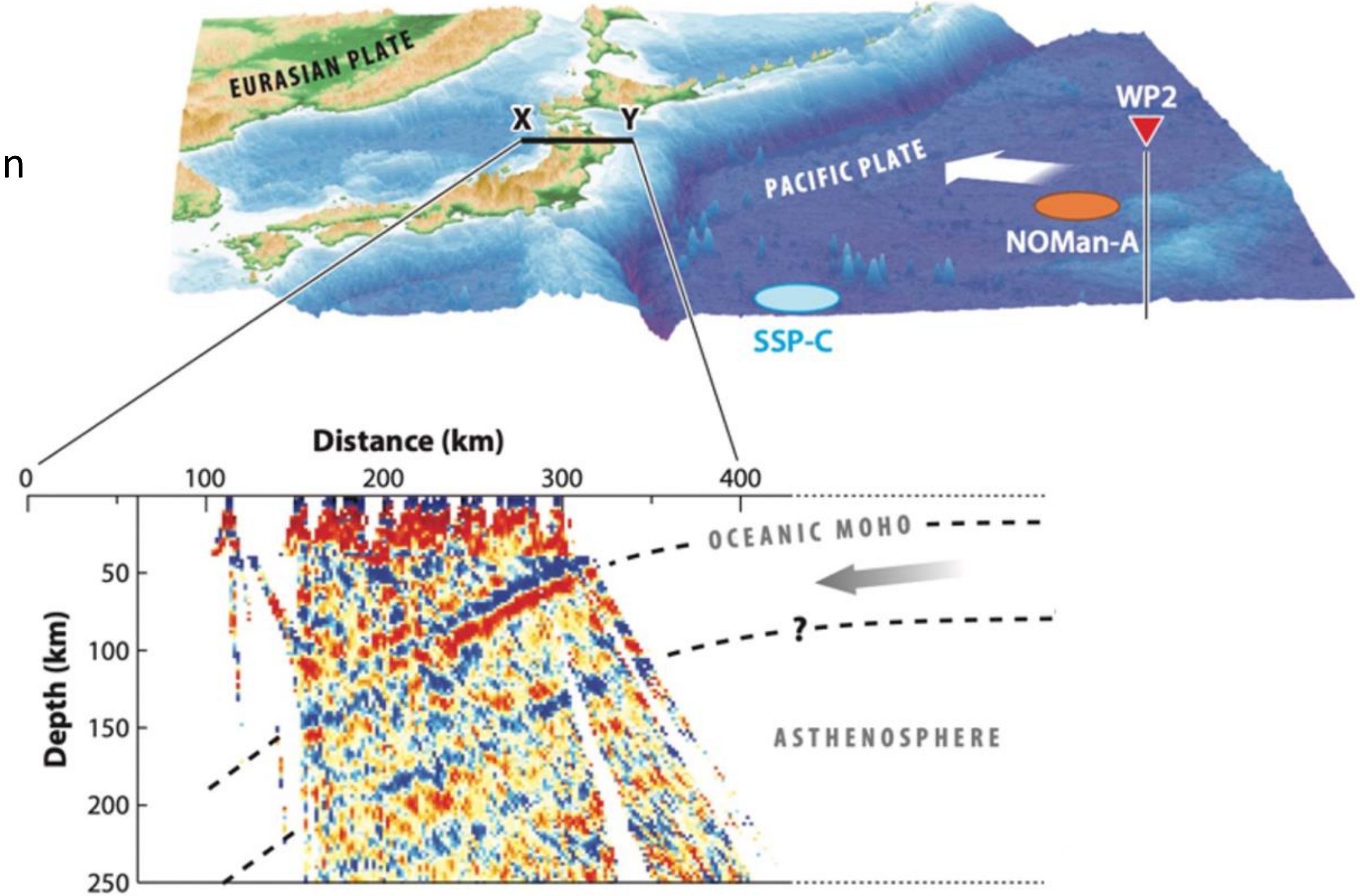
- **Body wave tomography**
  - P-waves and S-waves
  - Deep into the earth
  - Uneven coverage → continent/ocean north/south
  - Ocean station noise

- **Surface wave tomography**
  - Rayleigh and Love waves
  - Good coverage on the surface
  - Global coverage for the oceanic regions
  - Large scale
  - Less detailed
  - More complex data



Seismic imaging

- Dense land seismic data of Hi-net from Japan
- Stagnant slab study
- Can clearly see border oceanic lithosphere

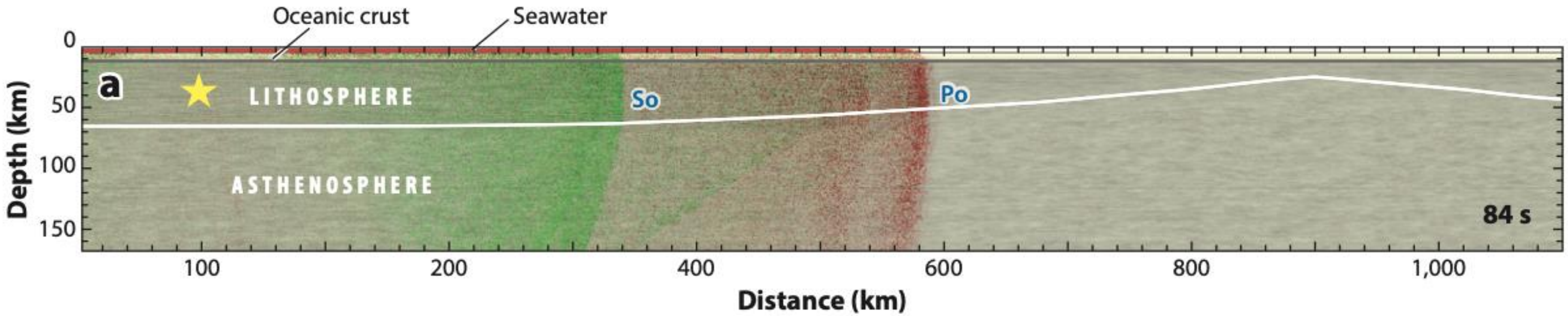


Kawakatsu et al. (2019)

Seismic scatters

- 2D model beneath Japan
- BBOBS (Broadband Ocean Bottom Seismometer)
- Pn and Sn waves

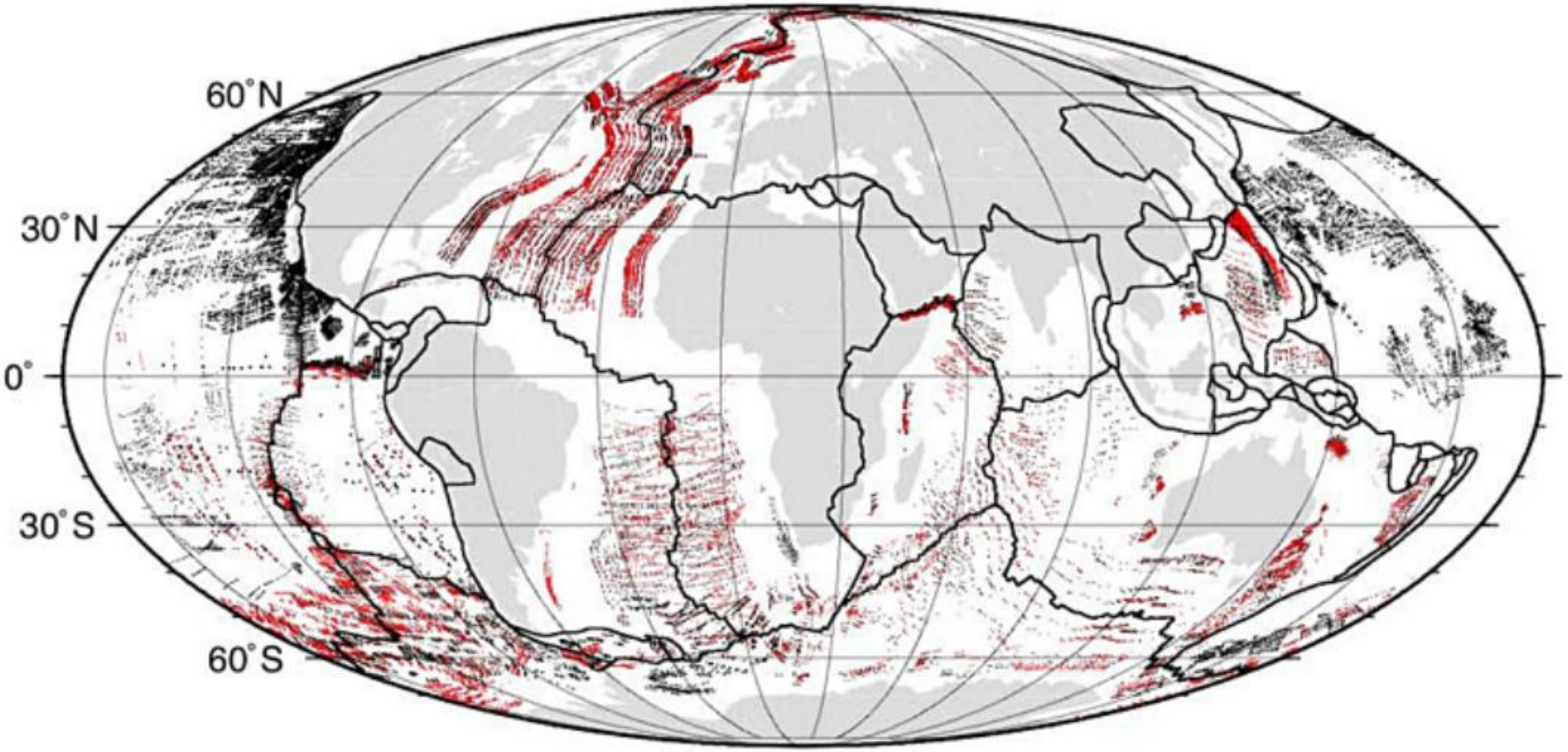
- Data had Laminar scatters
- "Layered" Variations
- Age-related observations



Shito et al. (2013)

Age

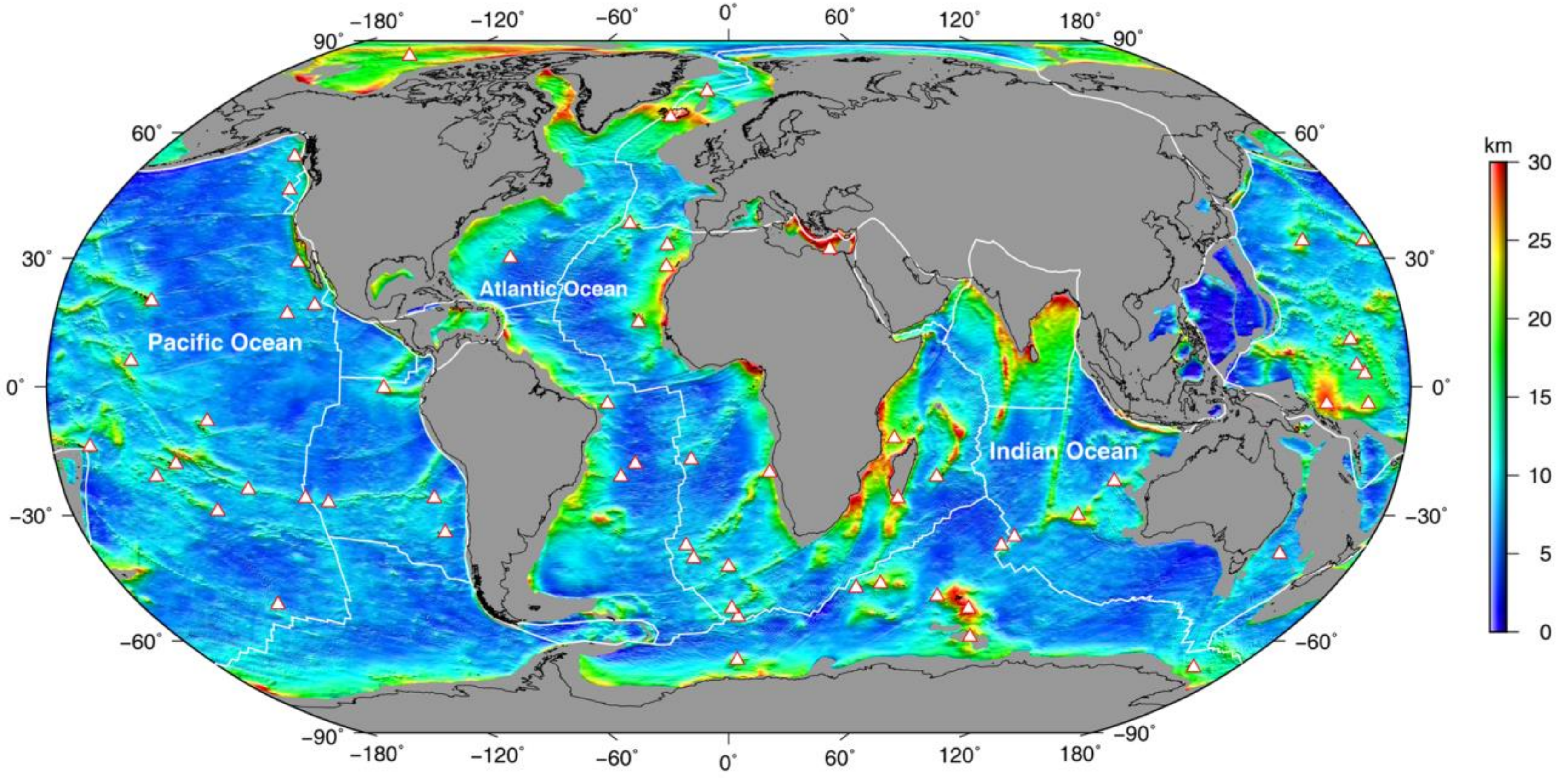
- Oldest→280 Ma
- Ages reconstructed from magnetic anomaly data
- Older away from spreading ridges



Müller et al. (2008)

Thickness: Oceanic Crust

- The oceanic crust is relatively thin compared to continental crust
- Average thickness 6-7 km thick
- Up to ca 40 km thick
- Seismic velocity data

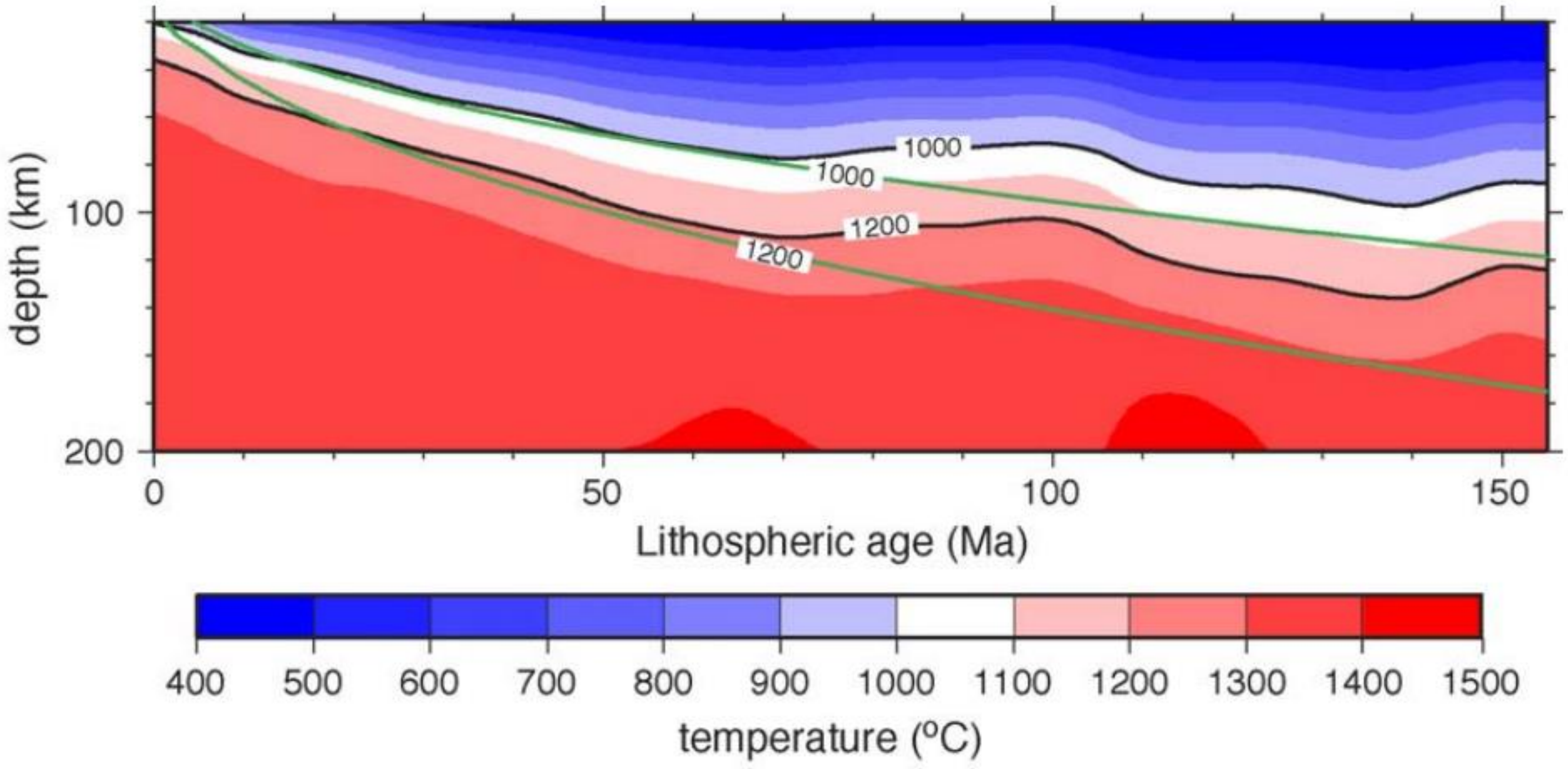


Duo et al. (2020)

Thickness: Oceanic Lithosphere

- Oceanic lithosphere age and thickness increasing away from the ridge
- Reaches stable thickness of ca. 100 km at around 80 Ma

Thermal Structure of the Pacific – based on seismic observations

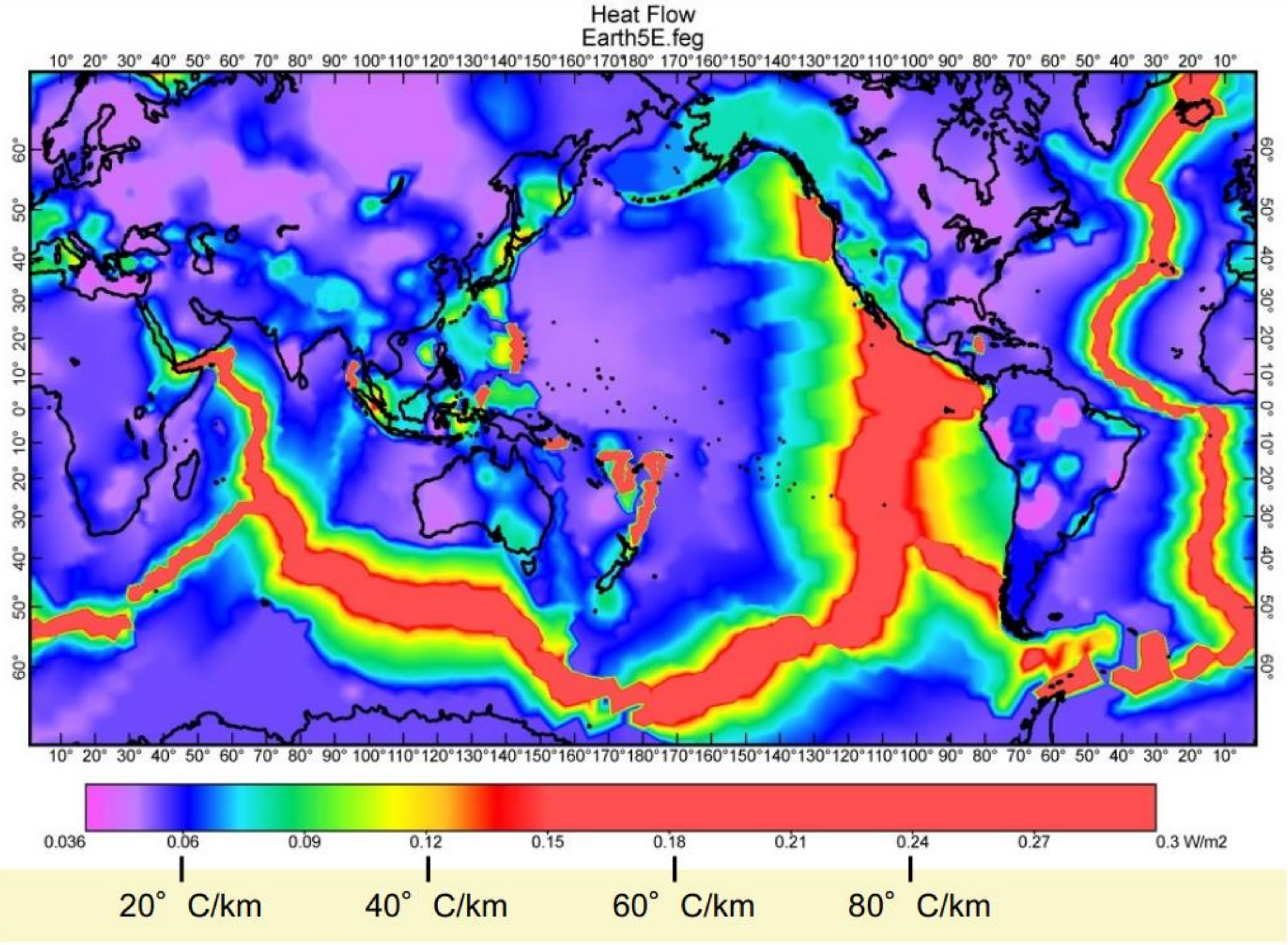


Follows halfspace (conductive) cooling

Ritzwoller et al. (2004)

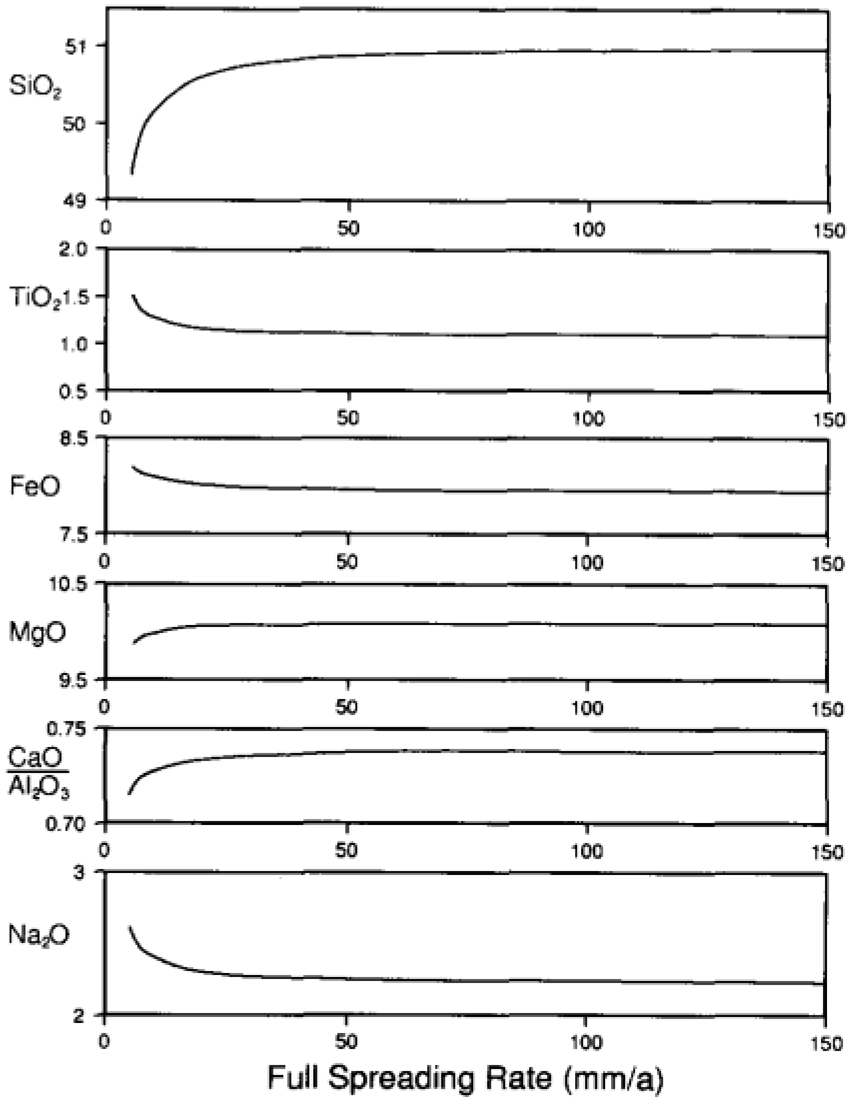
Heat Flow

- More heat flow/ steeper geotherms around Mid Ocean Ridges
- This coincides with a thinner lithosphere and high volcanic activity



Geochemistry

- Generally uniform REE concentrations
- Average chemical composition normalized to primitive mantle values:
  - Maximum concentrations of the moderately incompatible elements: Na, Ti, Zr, Hf, Y and the intermediate to heavy REE
  - This is only ca. 10 times the primitive mantle values
  - More incompatible elements in the continental crust
  - Suggests continental crust was extracted first from the primitive mantle
- Increase in the percentage of Na_20, and decreases in the FeO content and CaO/Al_2O_3 with spreading rate <15 mm/a



Bown and White (1993)

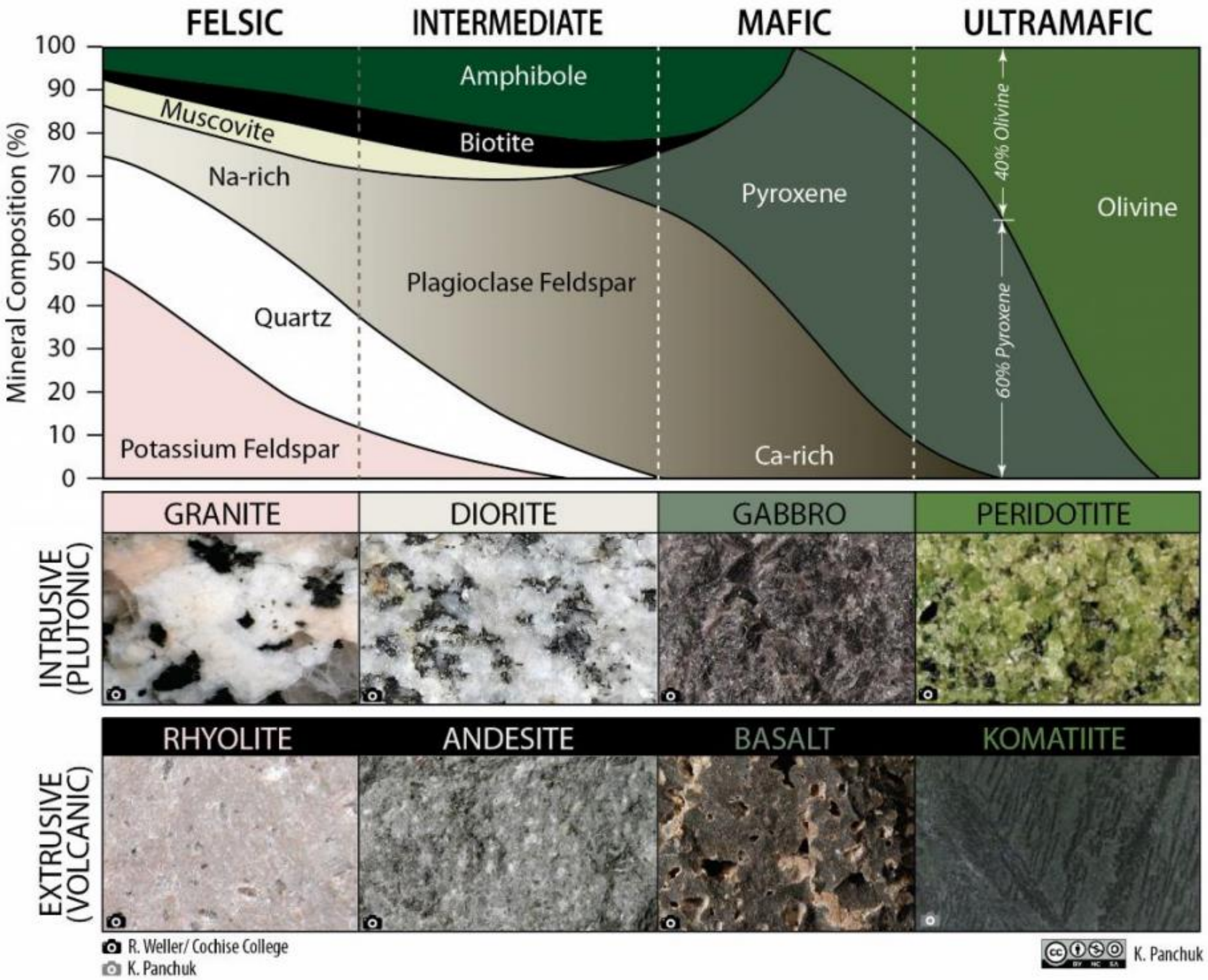
Mineralogy

Oceanic Crust:

- Composed of mafic rocks created by partial melting of mantle peridotite
    - More Mg- and Fe-rich minerals
- Olivine, Pyroxene, Ca-Plagioclase, Amphibole and Biotite

Lithospheric Mantle:

- Composed of ultramafic rocks with lots of Olivine (40-90%), pyroxene and small amount of Ca-rich plagioclase
- We know this through petrography, geochemistry analyses and experiments



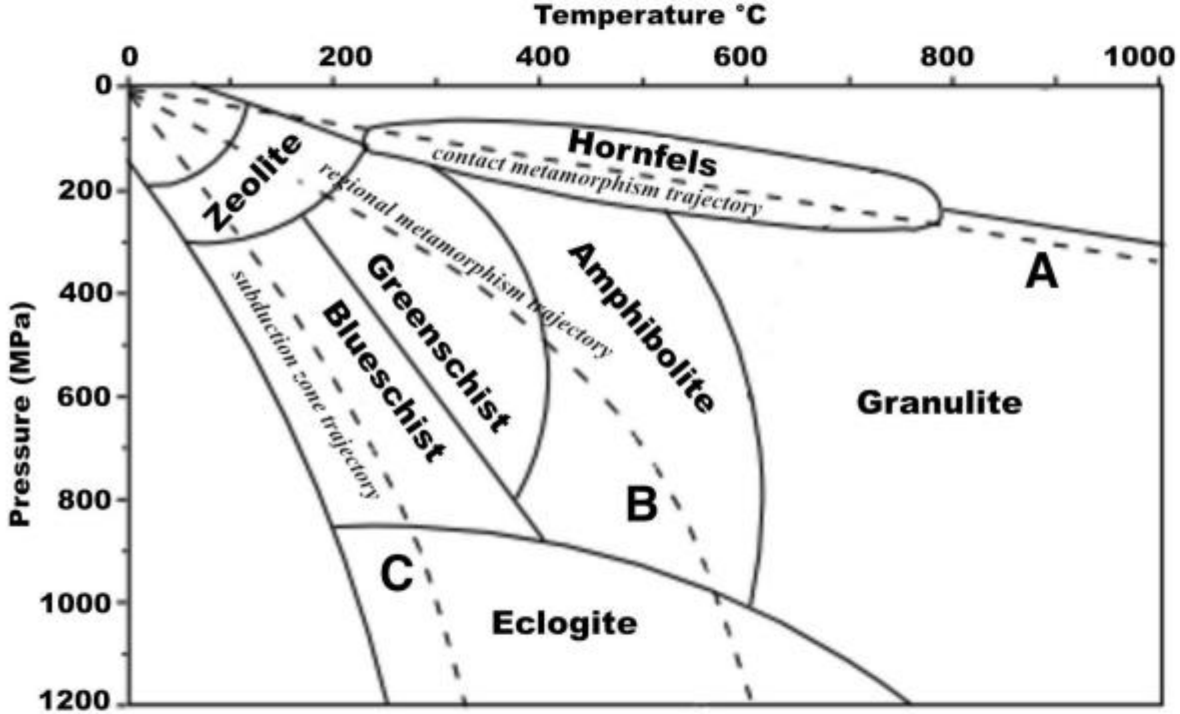
Earle (2015)

Rock types

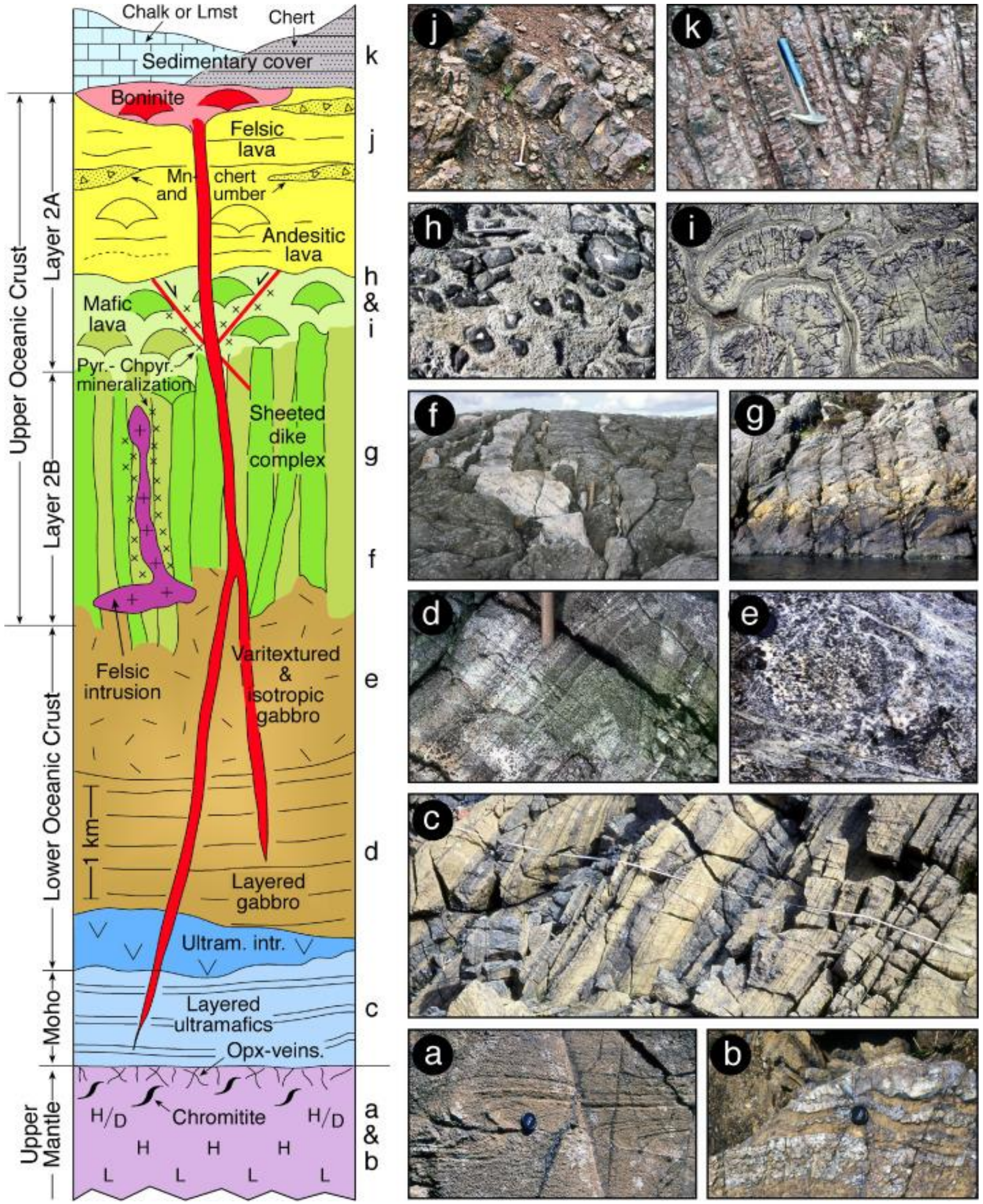
- Sediments on top
- Tholeiitic basalt (extrusive)
- Partial melting: calc-alkaline rocks (more enriched in aluminium, less in iron)
- Amphibolite and hornblende gabbro (intrusive or plutonic)
  - Often crystallization under hydrous conditions and metamorphism near the Mid Ocean Ridge
- Lithospheric mantle peridotite: dunite (>90% Olivine) to lherzolite (>40% Olivine)
- In subduction zones: Metamorphic rocks due to subduction (Eclogite and blueschist facies)

Basalt

Gabbro



Barnes (2018)



Furnes and Dilek (2022)

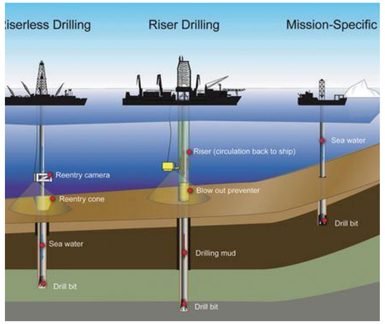
Oceanic crust facies (cross-section)

1. sediments (clays/limestones)
2. pillow lavas (+ rare sheet flows) ~500 m
   - upper 2/3 weakly fractured, radial collumnar joints in pillow lavas
   - below fracturing is stronger, single pillows difficult to distinguish
3. sheeted dykes ~1000 m
4. massive gabbro
5. layered gabbro
6. ultramafic intrusions
7. ultramafic cumulates (layered)
8. chromitites

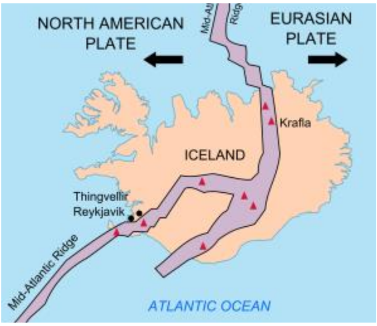
How do we know this?

Ocean crust by its nature is generally unaccessible for direct observation (11 km of rocks covered by up to 11 km of ocean). Ways to learn about its composition and structure:

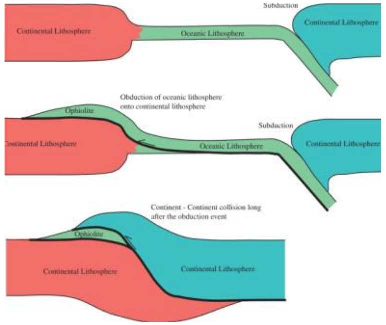
direct observation of seafloor



ocean drilling

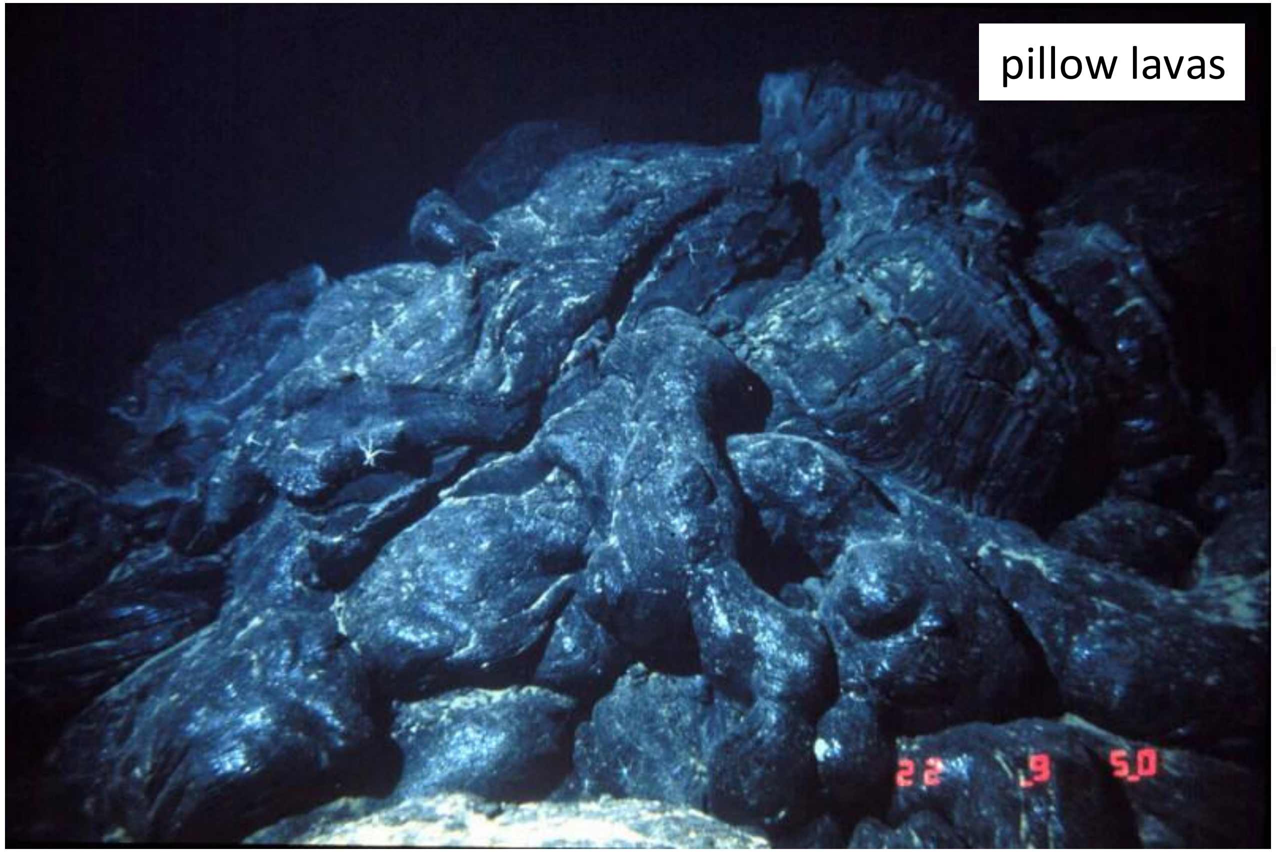


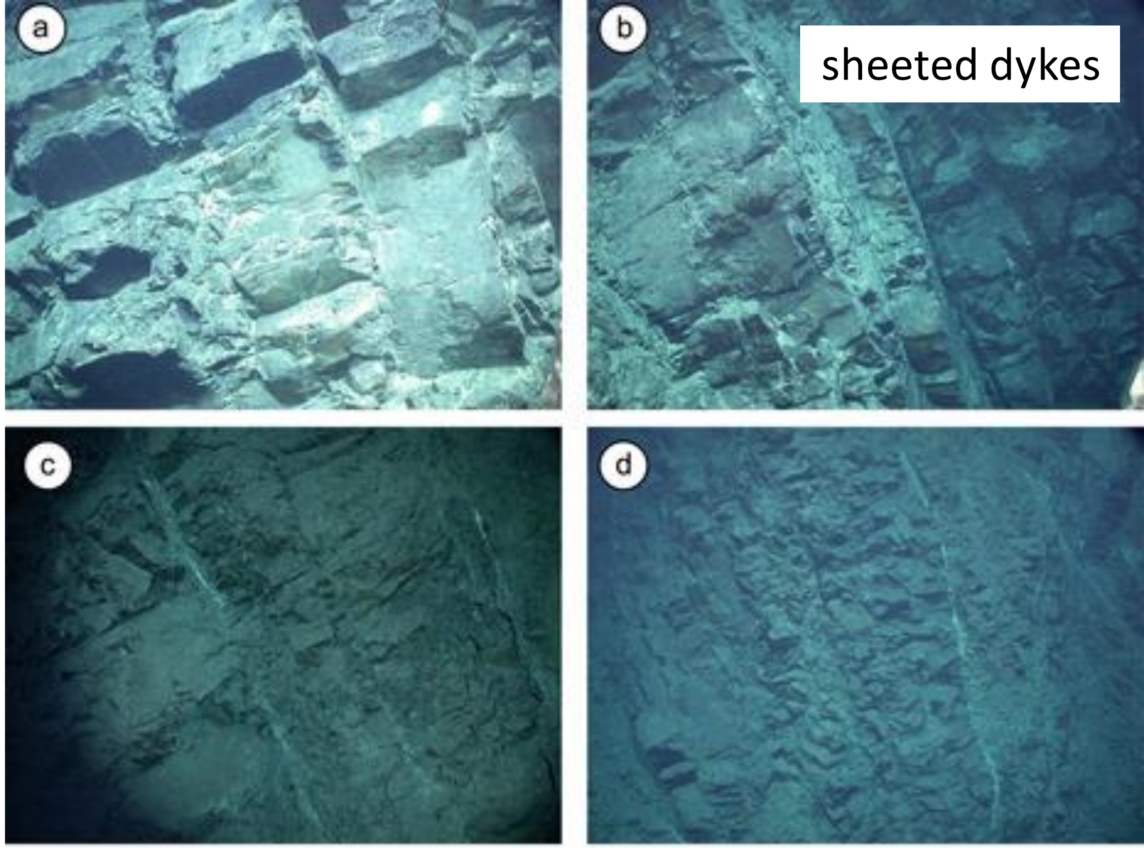
ocean rift on the surface

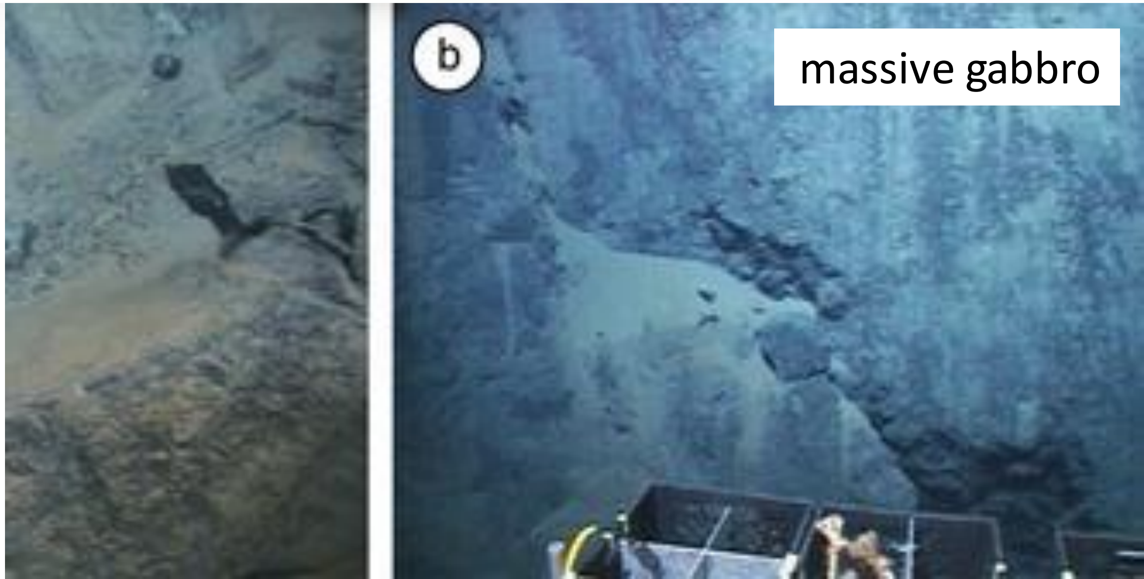


ancient oceanic crust remnants

Direct observations of seafloor







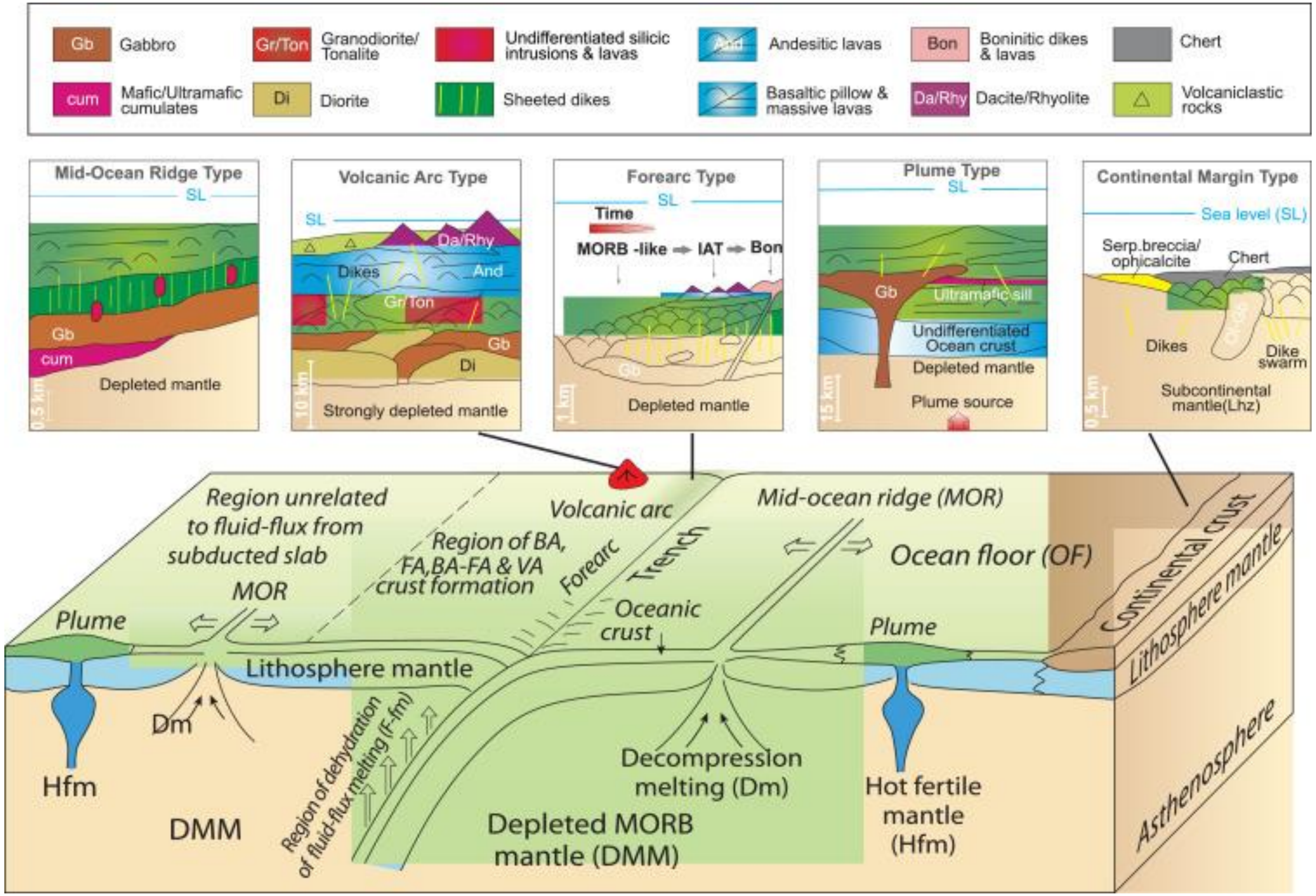
https://oceanexplorer.noaa.gov/okeanos/explorations/; Karson et al. (2023)

Ancient oceanic crust remnants - ophiolites

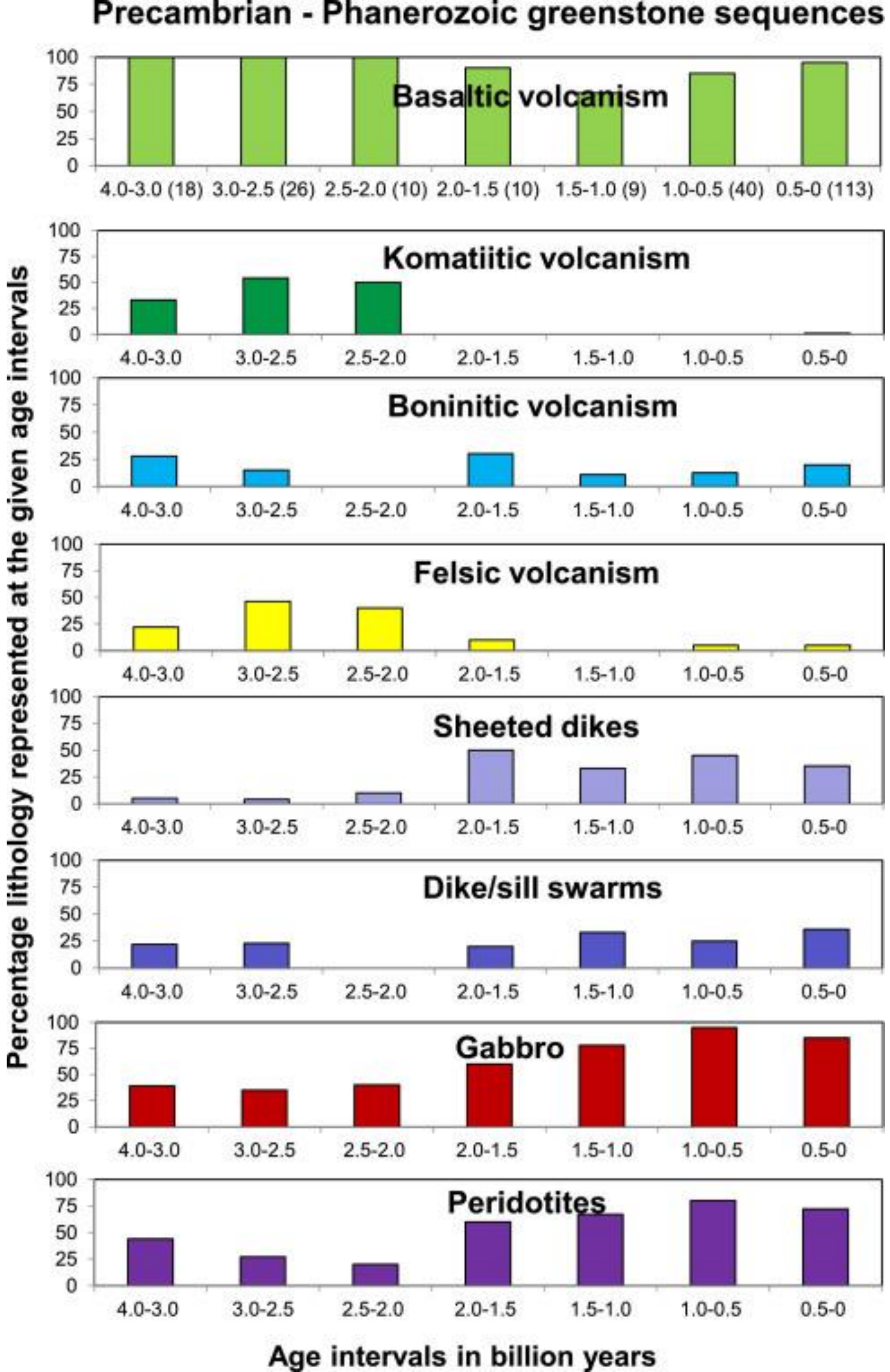
Ophiolites – remnants of former oceanic crust occuring as parts of orogenic belts, consisting of upper mantle and overlying crustal components.

Not all of them are preserved during subduction; some can result from e.g. continent-continent or arc-continent collision.

Ophiolites can represent various parts of the oceanic litosphere.

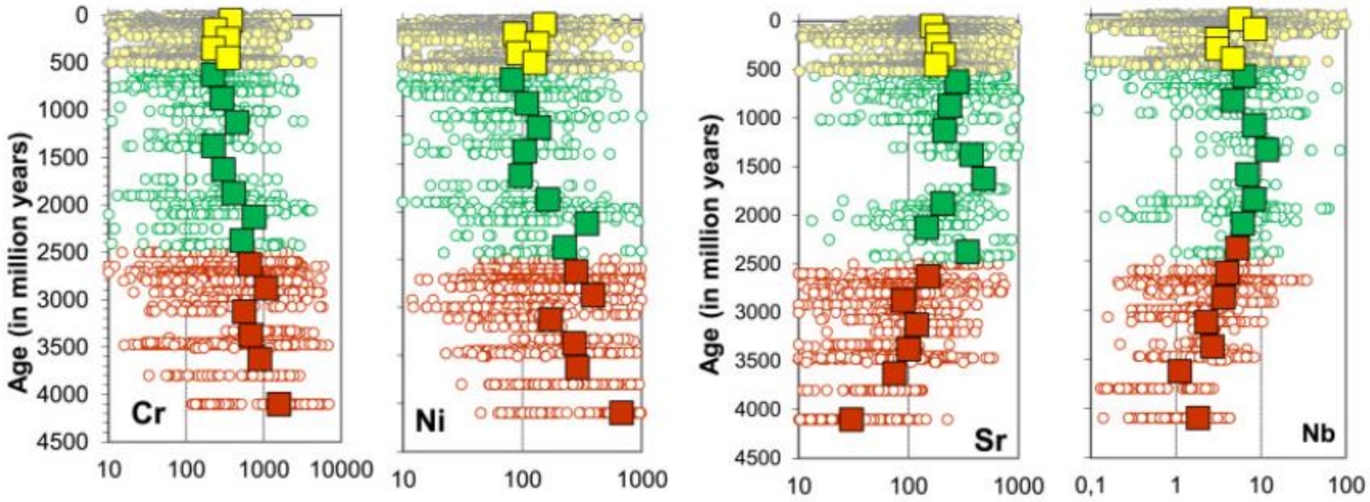


Furnes and Dilek (2022)



How ophiolites changed through time

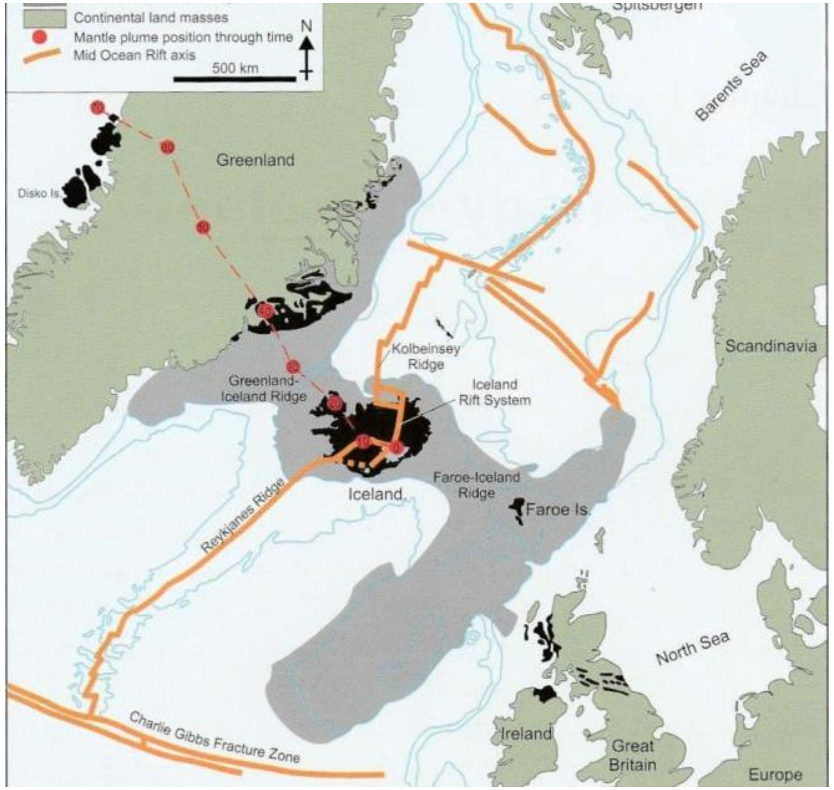
Ophiolites used to change through time, just as plate tectonic modes did. Here variations in lithology and geochemistry are presented. Archean ophiolites are mostly controlled by accretionary cycle tectonics, while Proterosoic/Phanerosoic ones show a combination of accretionary cycle and Wilson cycle tentonics (Furnes and Dilek 2022).

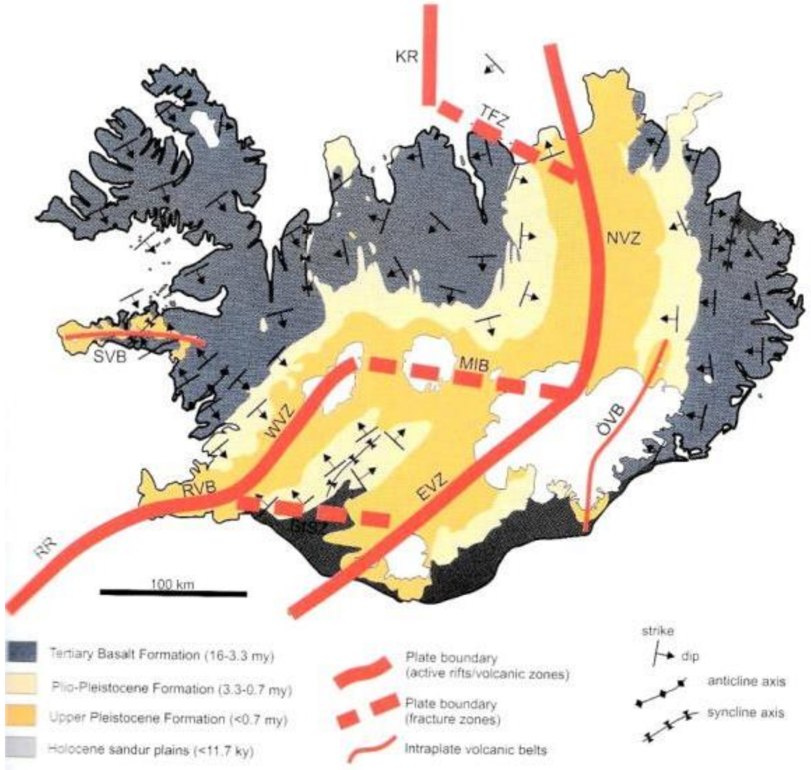


2 Ga ago incompatible elements decrease, while compatible increase

MOR on the surface - Iceland

- the only place with oceanic rift (spreading zone) on the surface
- Mid-ocean ridge and mantle plume
- easy access to rift-related processes and their products



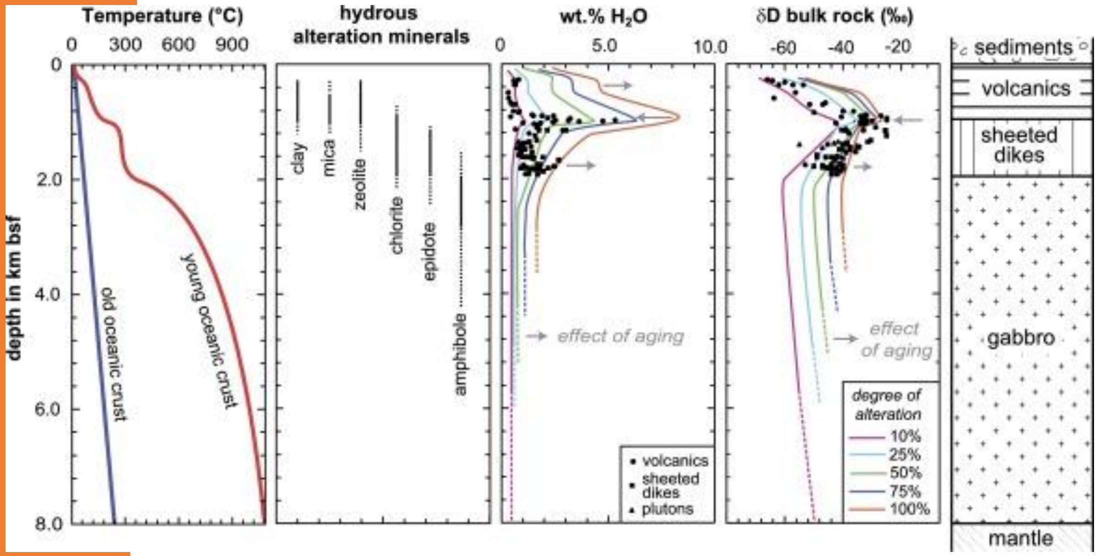


Saunders et al. (1997), Sæmundsson (1979)

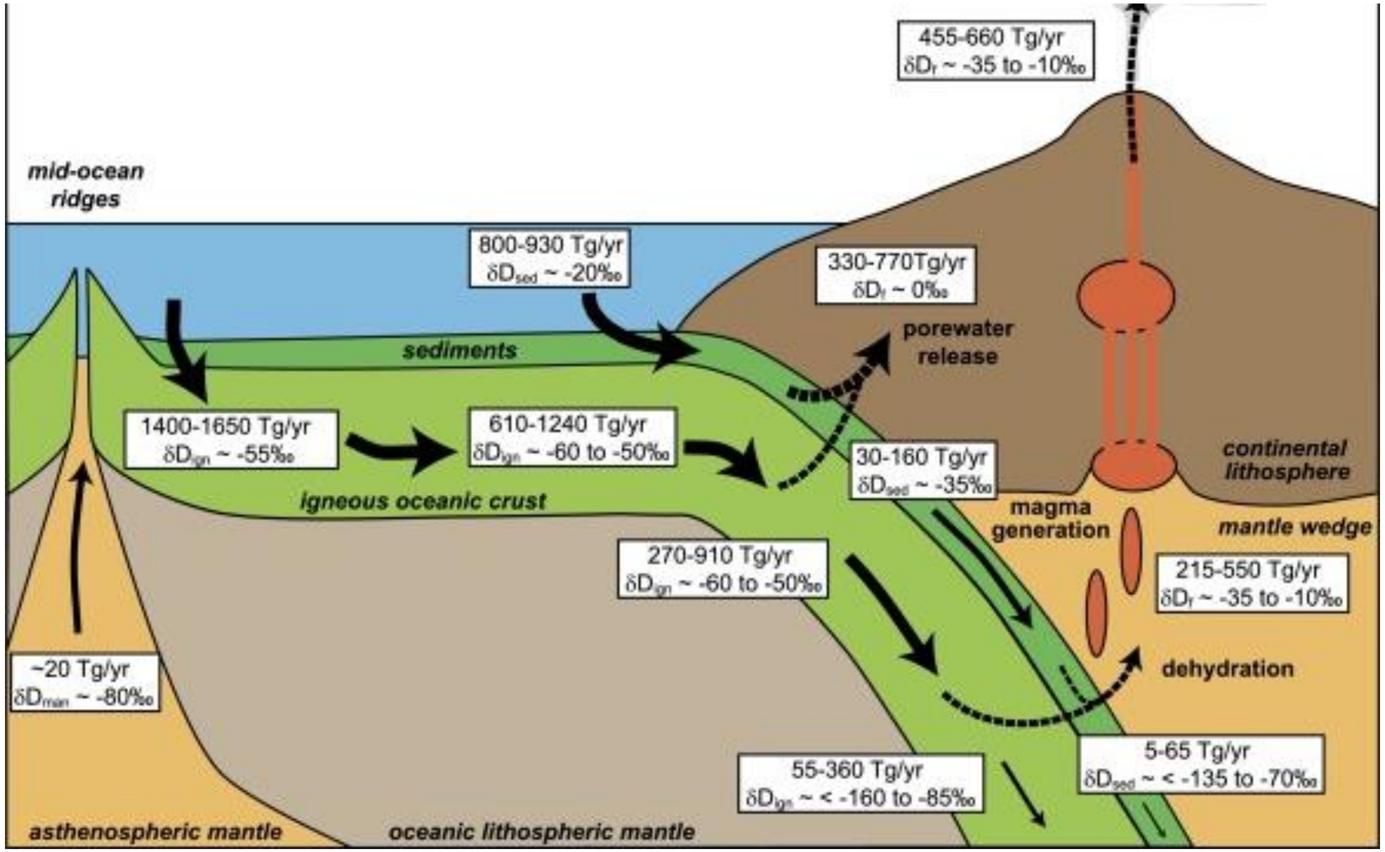
MOR on the surface - Iceland

Hydration of oceanic crust and subducted water flux (Kleine *et al.* 2020)

- oceanic crust is the major transport medium of water into the mantle, yet its water content remains unclear
- hydrogen isotope data of geothermal fluids and alteres basalts of three geothermal systems: meteoric fed system at Krafla and seawater fed at Reykjanes and Suertsey
- hydrogen isotope composition and bulk water content was measured
- combined with geochemical and isotope modeling, the results were used to unreveal processes controlling crustal hydration...
- ...and expanded to constrain the hydration state of oceanic crust (similar lithology, mineralogy etc.)

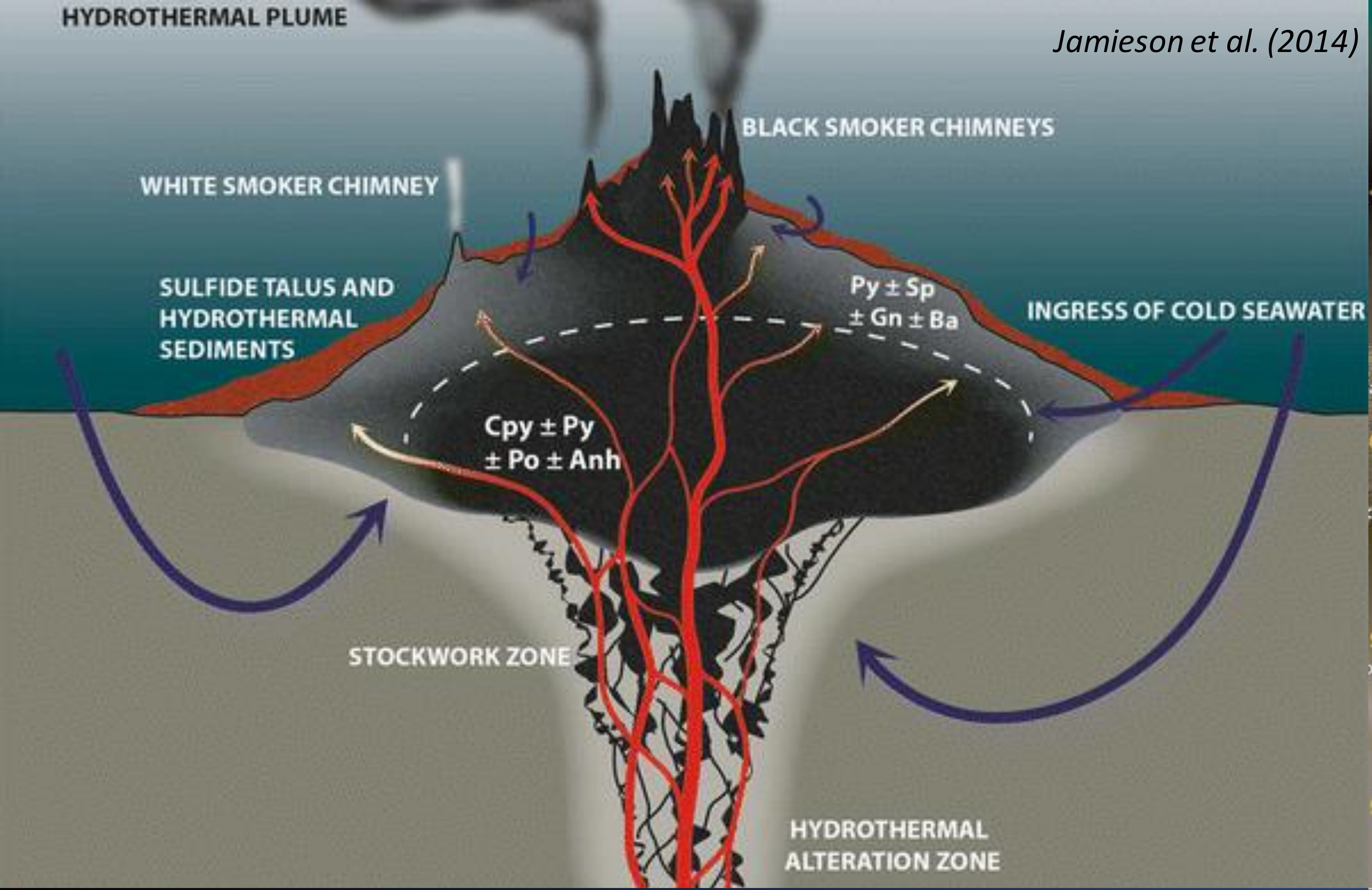


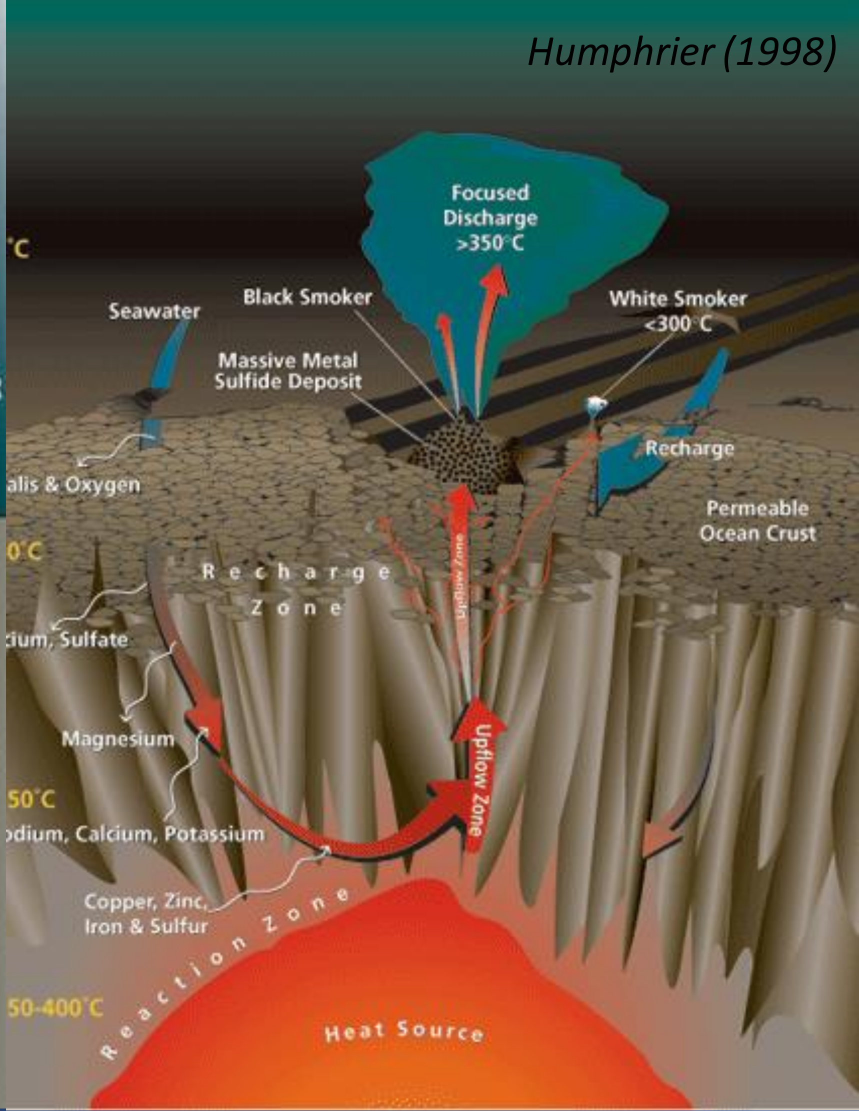
Hydration of oceanic crust and subducted water flux (Kleine *et al.* 2020)



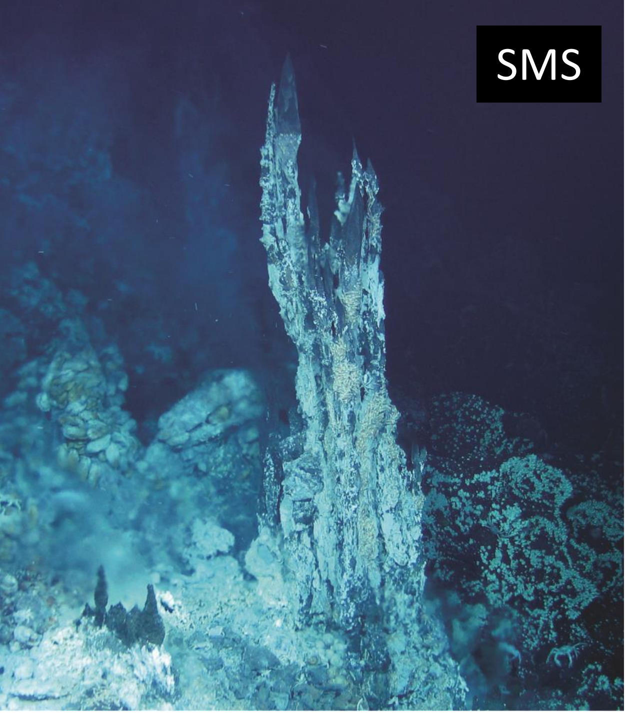
Tg = teragram = 10^{12} g = 1 mln tonnes

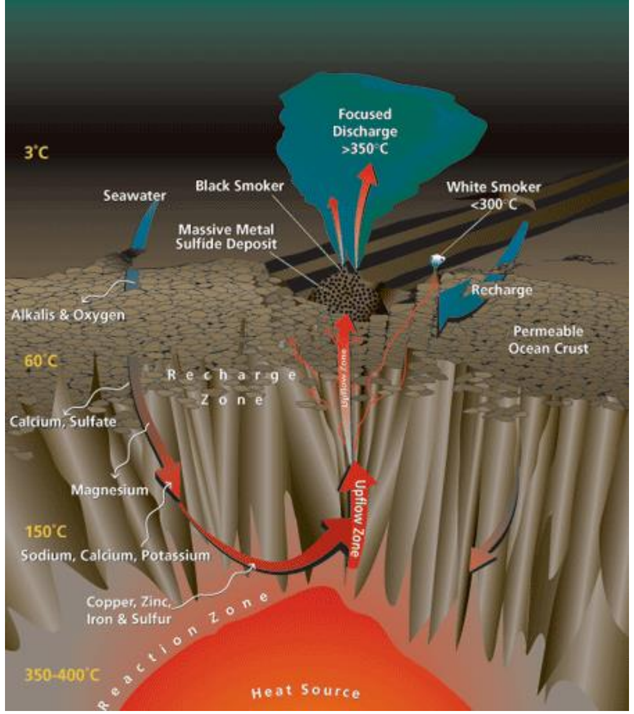
- 1400 to 1650 Tg H_2O/yr is added to the igneous oceanic crust upon alteration by seawater
- the upper part (<2 km) of oceanic crust hosts almost 50% of the added water
- δD values on average −55 ± 6 ‰
- Upon subduction and subsequent dehydration, 80–90% of water with δD values of −35 to −10‰ will be released to the crustal forearc and mantle wedge
- dehydrated slab with δD values of ~−160 to −85‰ is expected to be transported to deeper levels modifying the mantle's water budget and isotopic composition

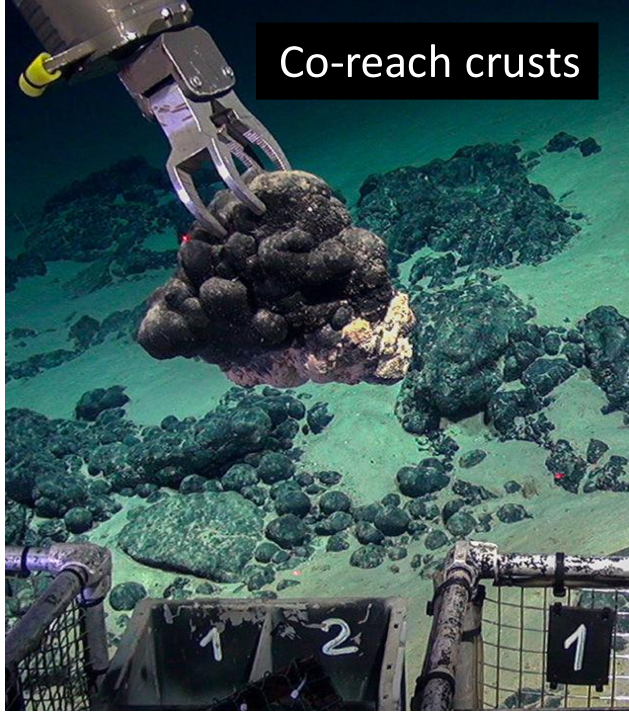




Water circulation in oceanic lithosphere





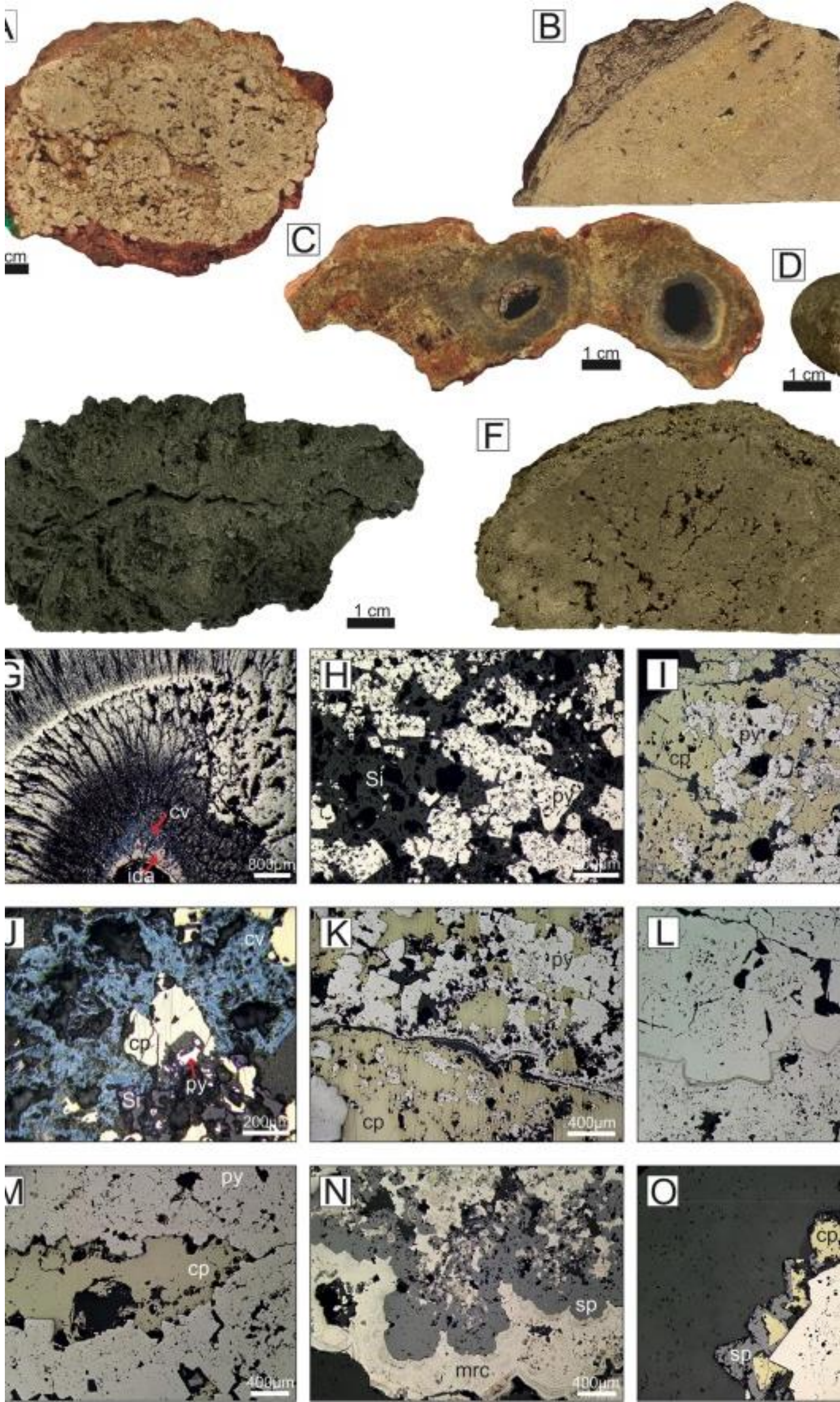


Seafloor deposits

- MARUM Research Center Ocean Margins, Bremen University
- Humphrier 1998
- https://dsmobserver.com/2019/10/a-primer-on-cobalt-rich-crusts/
- https://www.usf.edu/marine-science/news/2020/

Deposits

- SMS – Seafloor Massive Sulphide deposits
- polymetallic nodules
- cobalt-rich crusts
- all are associated with hydrothermal vents; 1 400 – 3 700 m depth
- mined for Ag, Au, Cu, Mn, Co, Zn
- Costly method, environmental impact disputed
- in 2024 Norway approved commercial deep-sea mining (80% of pairlament)



Murton et al. (2019)

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Thank you

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