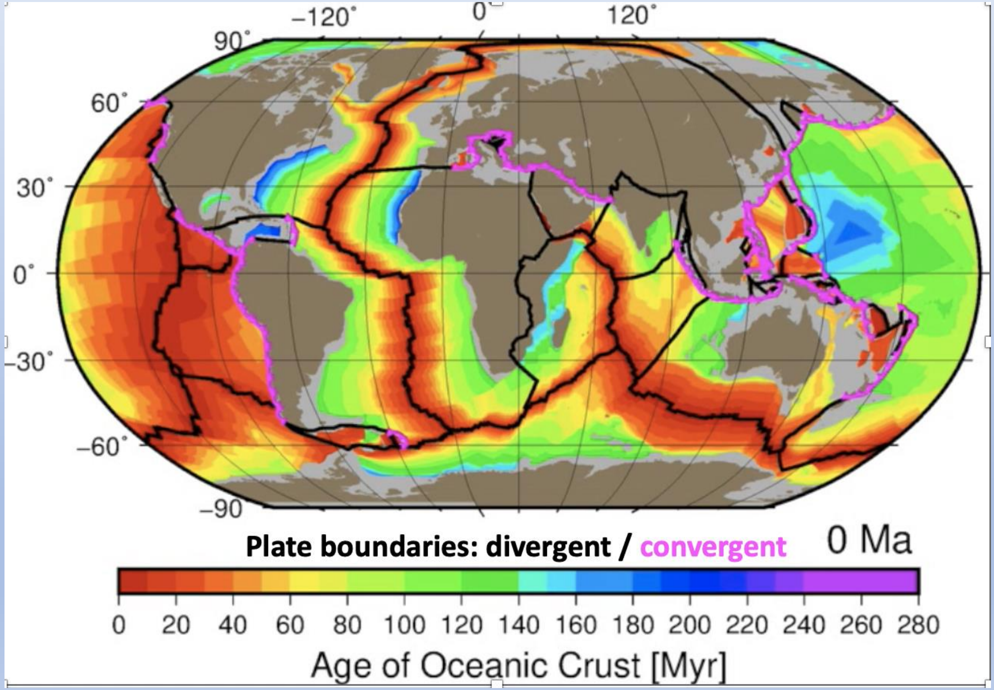
THE FORMATION OF THE OCEANIC CRUST AND THE TECTONIC AND MAGMATIC DIVERSITY OF MID-OCEAN RIDGES

The oceanic crust (and the ocean floor!) is constantly renewed at mid-ocean ridges and plunges into the mantle in subduction zones.

Plate tectonics and the age of the oceanic crust Muller et al., 2016



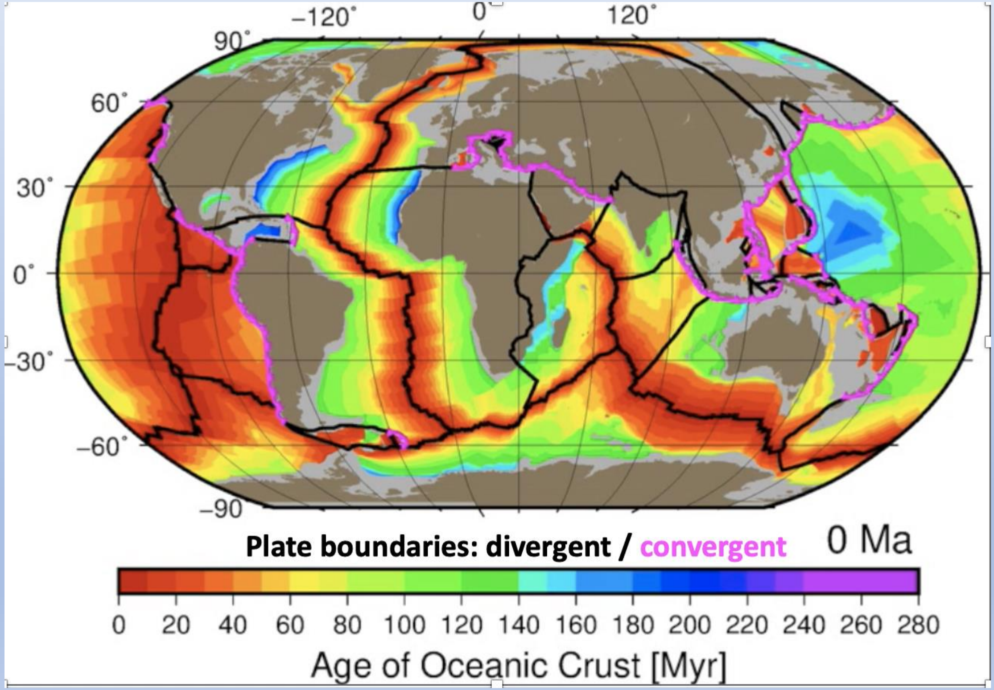
M. Cannat, GIFT-EGU 2025

THE FORMATION OF THE OCEANIC CRUST AND THE TECTONIC AND MAGMATIC DIVERSITY OF MID-OCEAN RIDGES

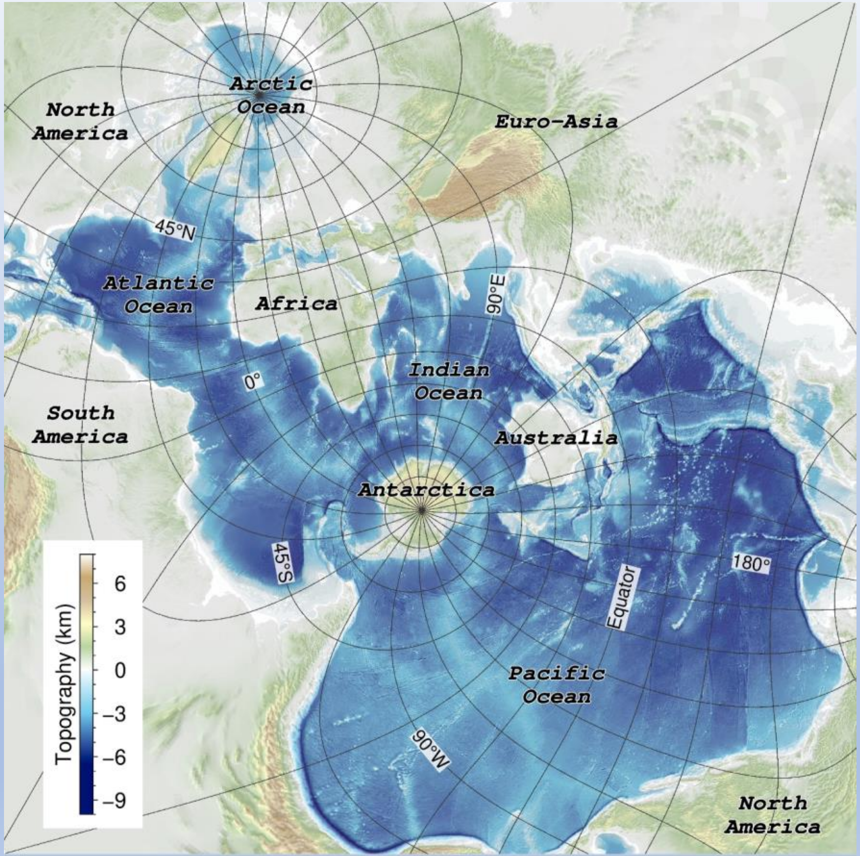
Organization of talk :

1. context, global relevance
2. magmatism, hydrothermalism and faulting : the three processes that build the oceanic crust
3. the thermal state of the ridge axis is a key variable, controlling the tectonic and magmatic diversity of mid-ocean ridges
4. melt fluxes, hydrothermal circulation and the thermal state of the ridge axis
5. key take-away points

Plate tectonics and the age of the oceanic crust Muller et al., 2016



1- Context and global relevance

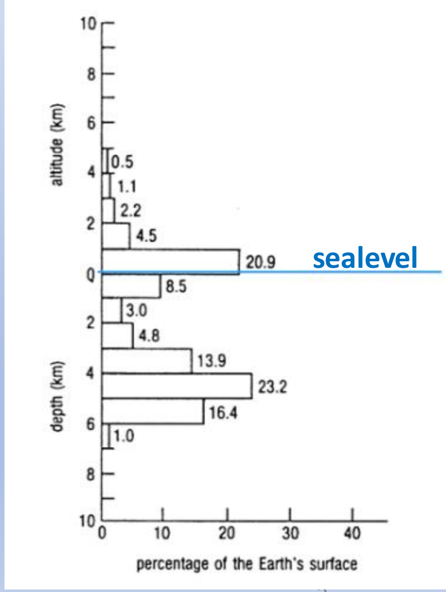


Oceans make 70.8 % of the Earth's surface.

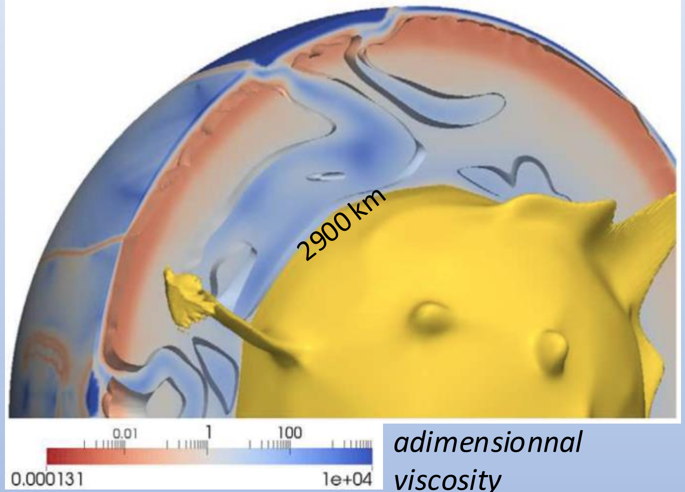
Oceanic basement in the geological sense (ie formed at mid-ocean ridges) makes 60 % of the Earth's surface.

Present-day ocean(s)
Spilhaus projection

The Earth's altitude/depth distribution
Gage et Tyler, 1991

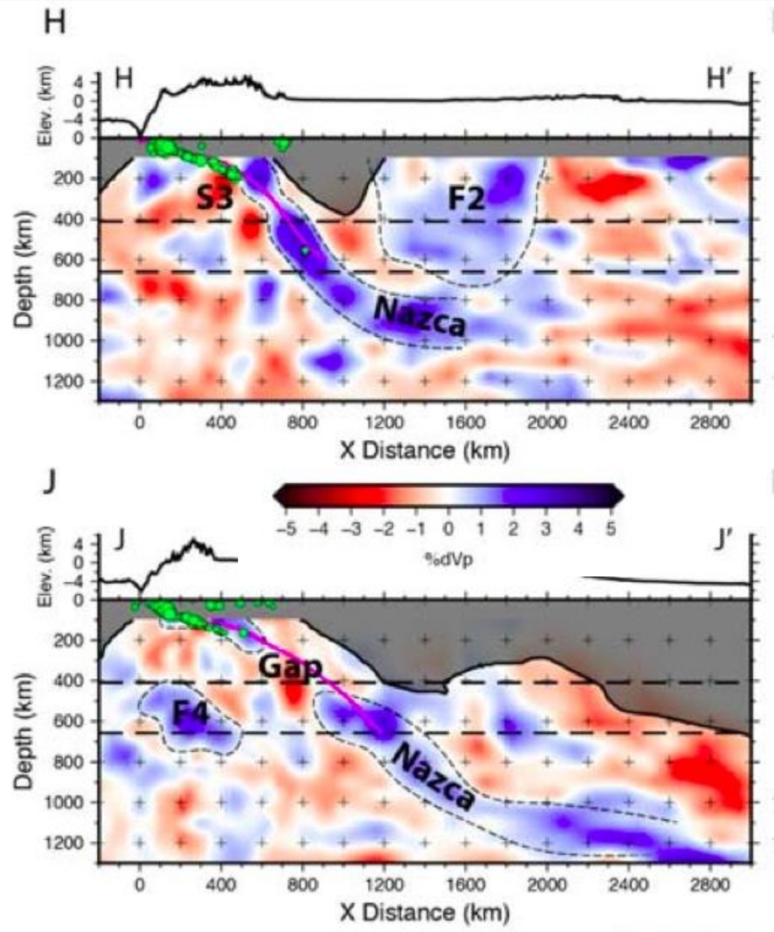


Cold oceanic plates plunge down, hot regions of the deep mantle rise, the deep Earth and it's external enveloppes exchange and interact !



adimensionnal viscosity

Numerical model of interaction between subductions and mantle plumes. Coltice, 2017

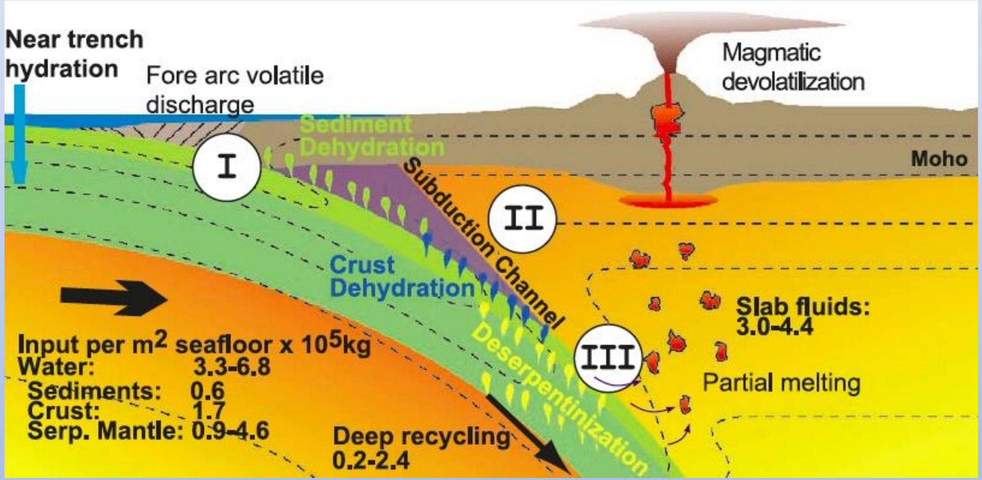


Two sections of a seismic velocity model across the coast of Chile showing subducted portions of the Nazca plate. Portner et al., 2020

the deep Earth and it's external enveloppes exchange and interact

.... the Earth is an extraordinarily dynamic planet !

first example : the deep water cycle



A sketch of estimated water fluxes associated to the subduction of oceanic lithosphere
Rüpke et al., 2004

Probable **feedback** effects: the incorporation of water facilitates the partial fusion of mantle rocks that produces volcanism and makes minerals easier to deform, thus reducing the viscosity of the mantle, making it more mobile

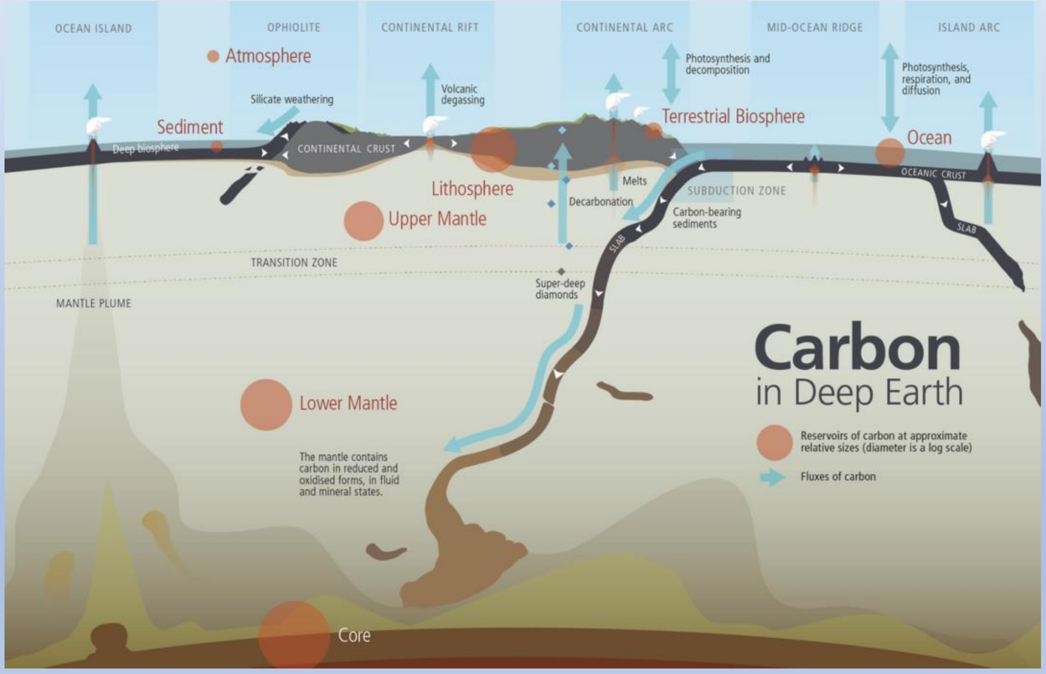
The incorporation of water into the mantle via subducted plates could accelerate plate tectonics Korenaga, 2012

the deep Earth and it's external enveloppes exchange and interact

.... the Earth is an extraordinarily dynamic planet !

another important example : the deep carbon cycle

Deep Carbon Observatory, 2019



(in)

- *subducted carbonate minerals and organic matter in sediments*
- ***subducted carbonate minerals and carbon-bearing fluid inclusions in oceanic crust***
- ***subducted organic matter from chemiosynthetic organisms in oceanic crust***

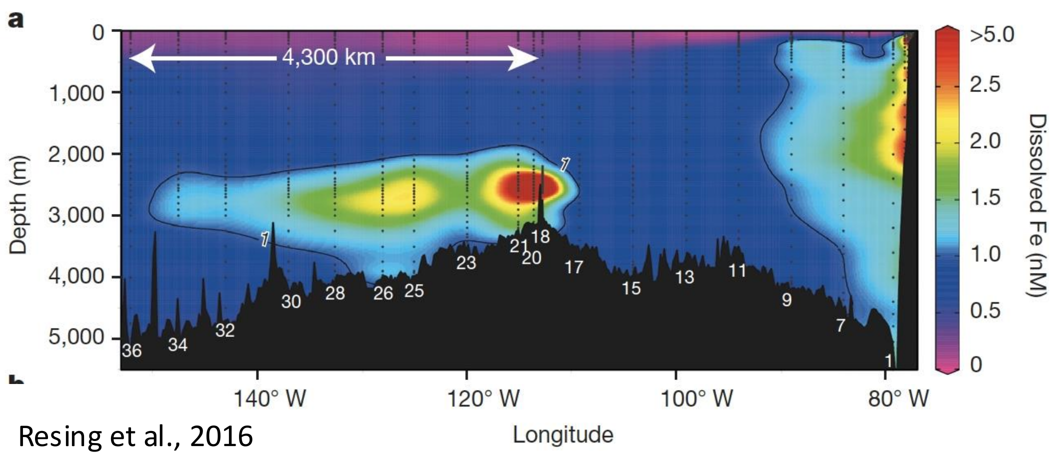
(out) ***volcanism and hydrothermalism***

the deep Earth and it's external enveloppes exchange and interact

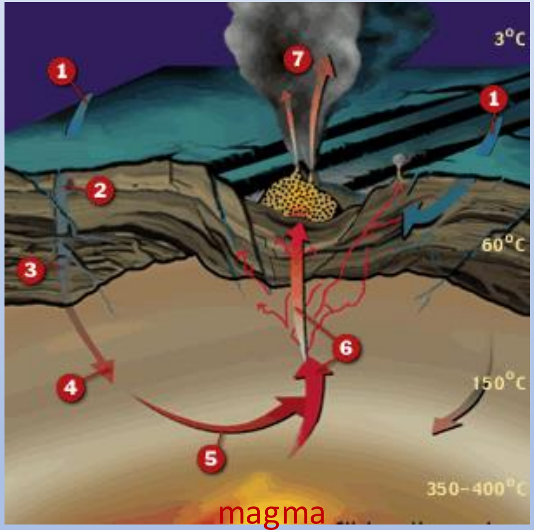
.... the Earth is an extraordinarily dynamic planet !

and a third example : mid-ocean ridge black smokers are a source of zinc, iron and manganese for deep ocean waters over thousands of kilometers from the hydrothermal vents!

Zinc, iron and manganese are leached in the rocks by hydrothermal fluids and are essential nutrients for life and therefore for the ocean's biological carbon pump.

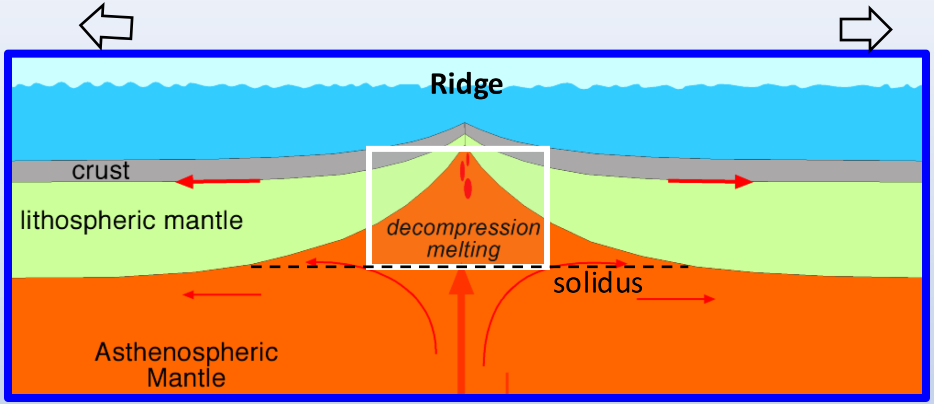


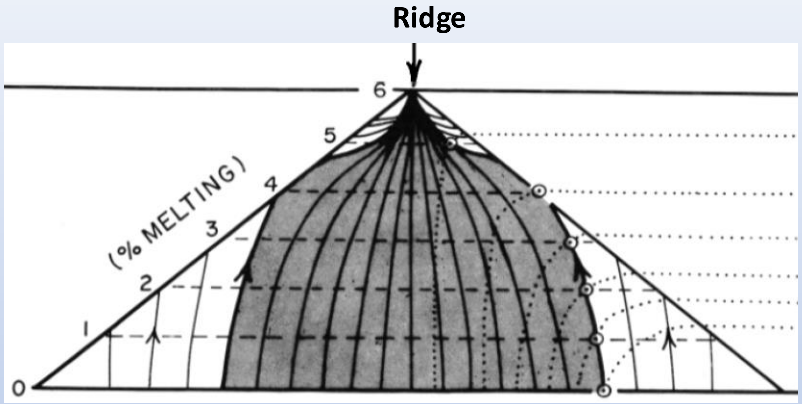
Resing et al., 2016



http://www.divediscover.whoi.edu/vents/chemistry.html

2- magmatism, hydrothermalism and faulting : the three processes that build the oceanic crust





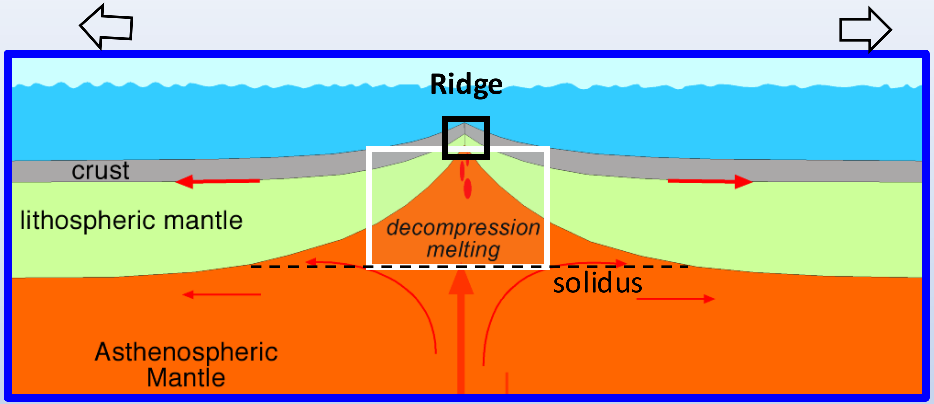
conceptual sketch (Plank et al., 1992) of the domain of magma production (domain of melt extraction in grey)

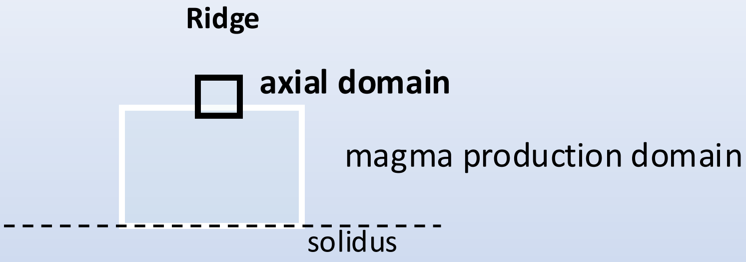
A- in the asthenospheric mantle beneath the ridge

- mantle moves up to fill gap between diverging plates

magmatism

- moving up causes decompression and mantle melting
- magma is extracted and also moves up, some of it is focused to the ridge

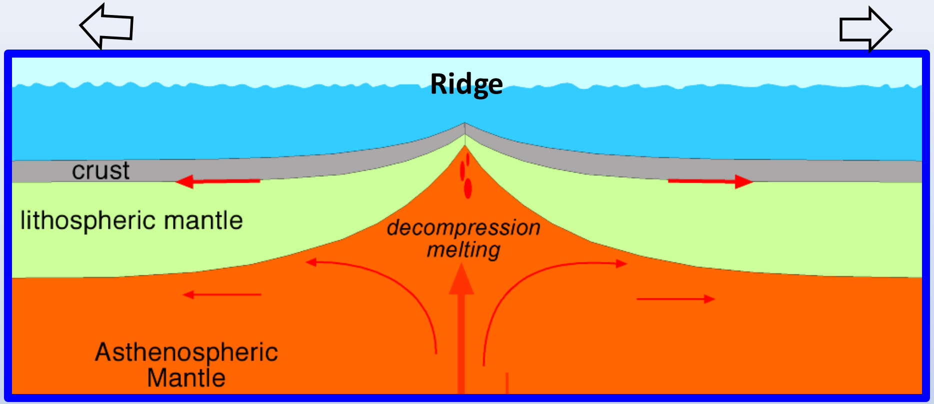




B- in the axial domain

- **magmatism** — injection, crystallization and eruption of magmas produced in the melting domain
- **hydrothermalism** — cooling of newly formed axial **lithosphere**
- **faulting** — deforms and breaks the axial **lithosphere** into the two diverging plates

a few words about terminology



oceanic crust

the geophysically-defined oceanic crust is a lower seismic velocity and lower density layer resting on the upper mantle

the petrologically-defined oceanic crust is a layer of magmatic rocks resting on the upper mantle

lithosphere

the upper layer of the Solid Earth, it is stronger (ie requires higher stresses to be deformed) than the asthenospheric mantle. It forms the tectonic plates.

seismogenic lithosphere : roughly equivalent to the brittle portion of the lithosphere

thermal lithosphere: the thermal boundary layer above the convecting asthenospheric mantle

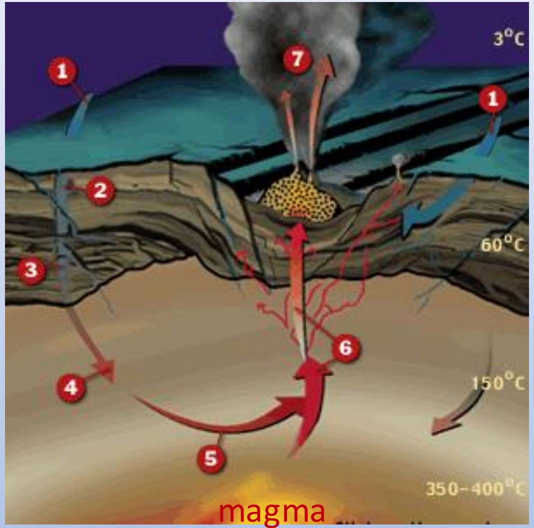
ROCK STRENGTH is primarilly controlled by **TEMPERATURE** therefore if the axial region is **colder**, its lithosphere will be **thicker**

magmatism brings new material and heat to the axial domain

hydrothermalism cools the axial domain ... and is enhanced by magmatic heat

magmatism and hydrothermalism combine to determine the thermal state of the axial domain

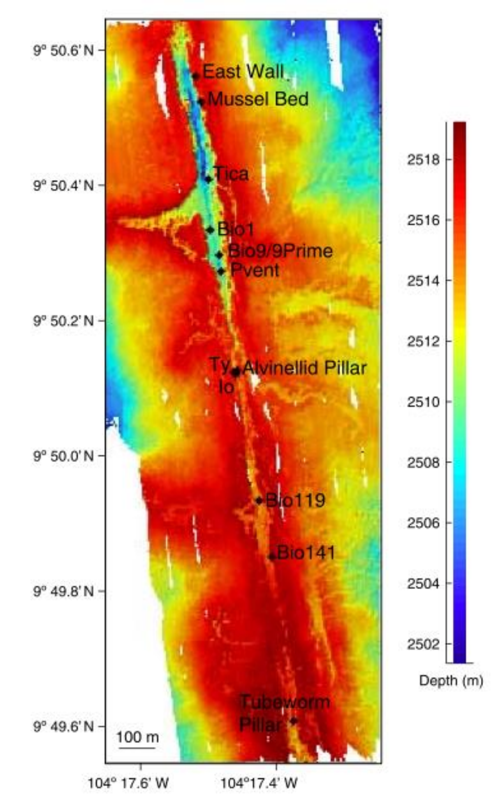
faulting is needed to break the resulting axial lithosphere into the two plates



http://www.divediscover.whoi.edu/vents/chemistry.html

3- the thermal state of the ridge axis is a key variable, controlling the tectonic and magmatic diversity of mid-ocean ridges

first example : a « hot » ridge



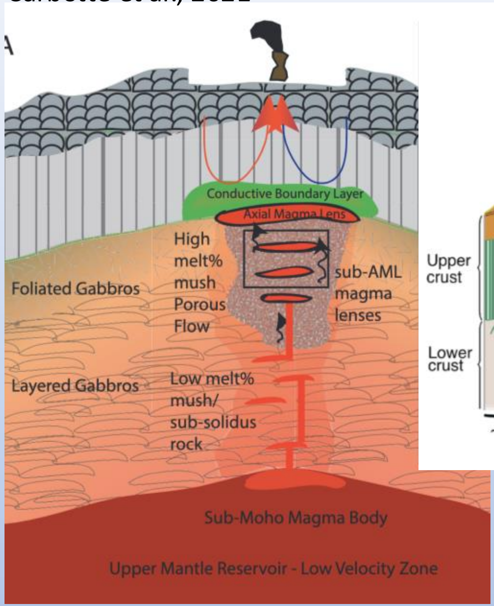
Ferrini et al., Gcubed 2007

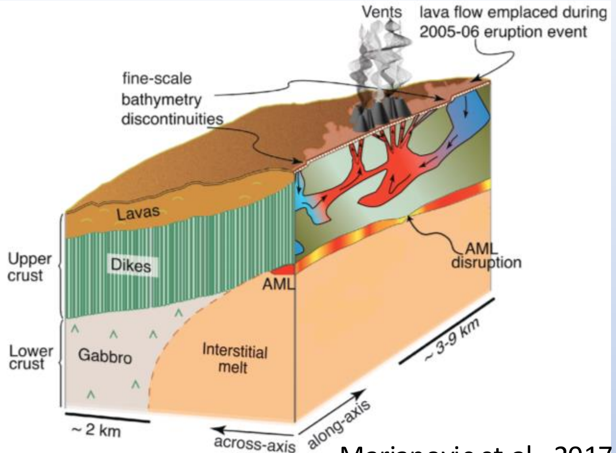
East Pacific Rise 9°N

the ridge is a topographic high with fissures, lava tunnels, lava flows and very little faulting...

seismic data in the axial domain indicate that magma resides in sills at several levels in the crust

Carbotte et al., 2021





Marjanovic et al., 2017

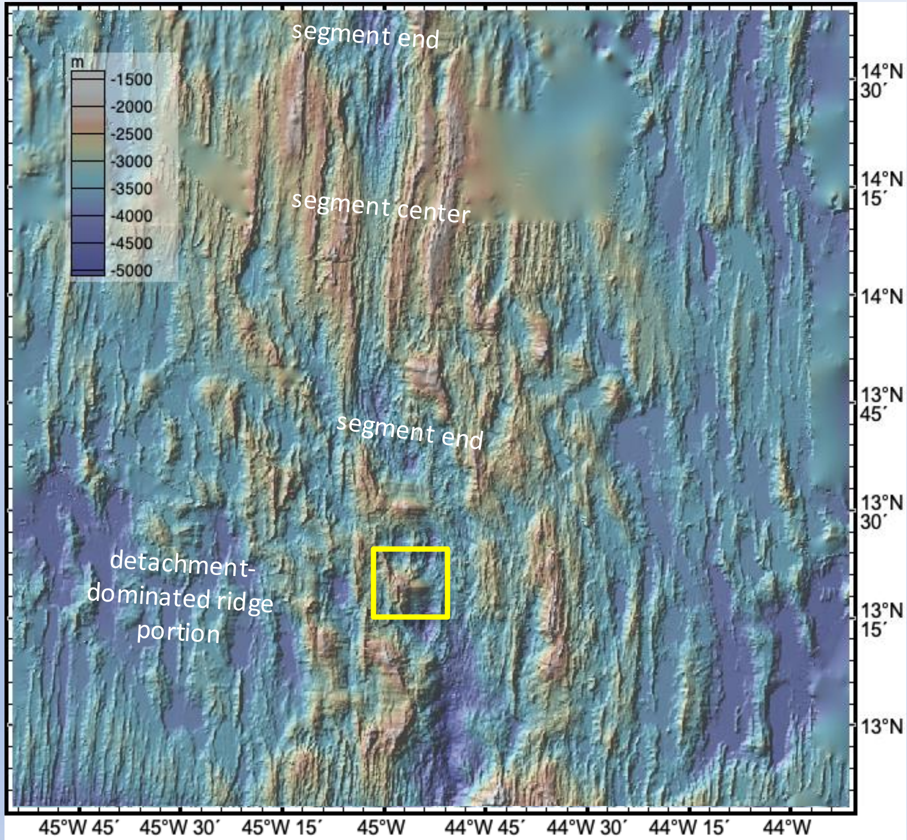
temperatures are above magma solidus (ie > 1000°C) up to only 2 km below seafloor and there is no lithospheric mantle in the axial domain

the geological interpretation is that the crust is made of gabbros, with up to 2 km of basaltic dikes and lava on top. Hydrothermal circulation is mostly restricted to the dike and lava sections

3- the thermal state of the ridge axis is a key variable, controlling the tectonic and magmatic diversity of mid-ocean ridges

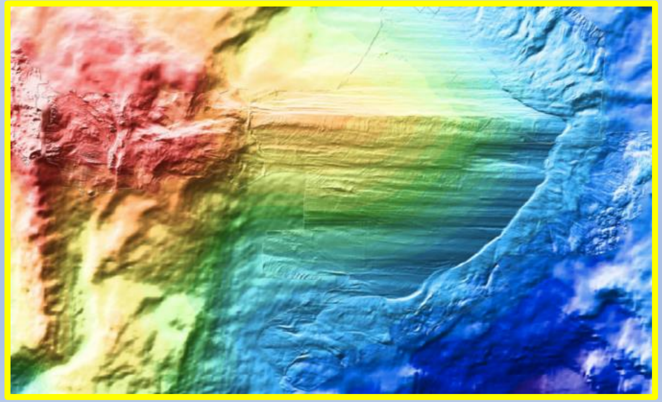
second example : a « cold » ridge

Mid-Atlantic Ridge 13-14°N



the ridge is a valley controlled by normal faults and very variable in width and depth (the ridge is segmented). Normal faults can have offsets ≥ 10 km (« detachment faults »)

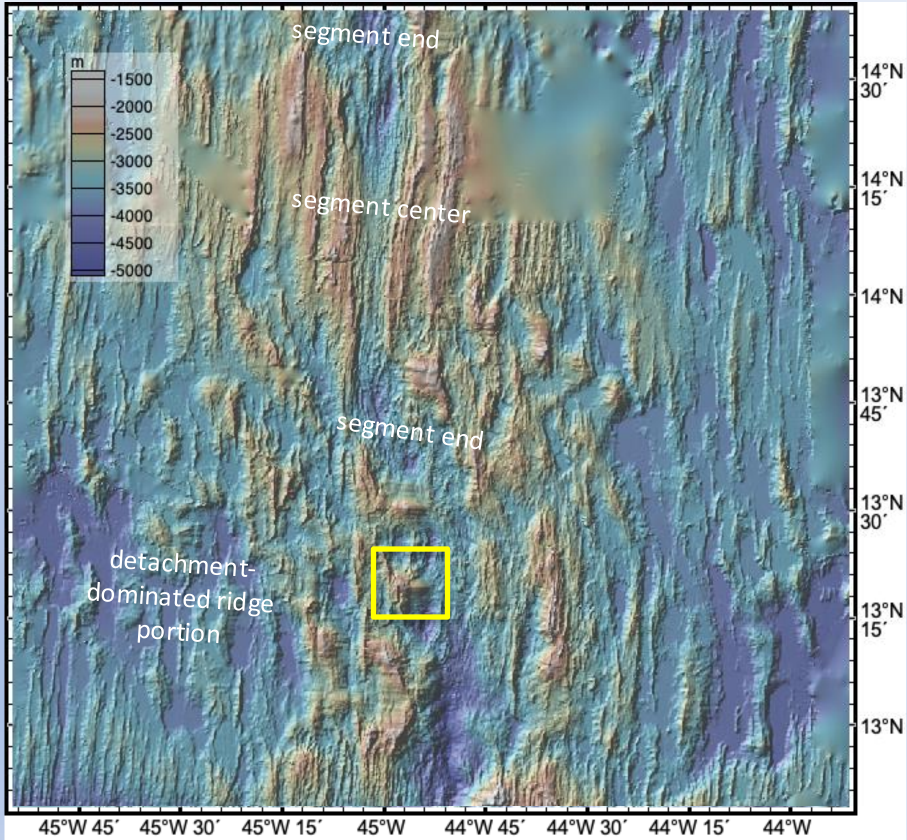
the footwalls of detachment faults have domal topographies, often with corrugations parallel to plate motion



Escartin et al., 2017

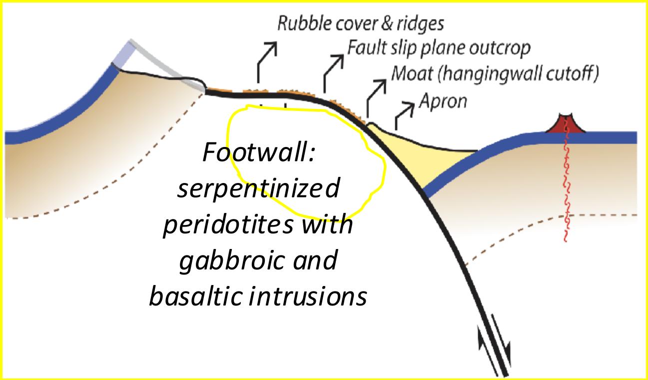
second example : a « cold » ridge

Mid-Atlantic Ridge 13-14°N



the ridge is a valley controlled by normal faults and very variable in width and depth (the ridge is segmented). Normal faults can have very large offsets (« detachment faults »)

detachment faults expose complex geological assemblages, including serpentinized mantle peridotite.. The geophysically-defined oceanic crust therefore comprises a non-magmatic, extensively hydrothermally-altered mantle-derived component



Escartin et al., 2017

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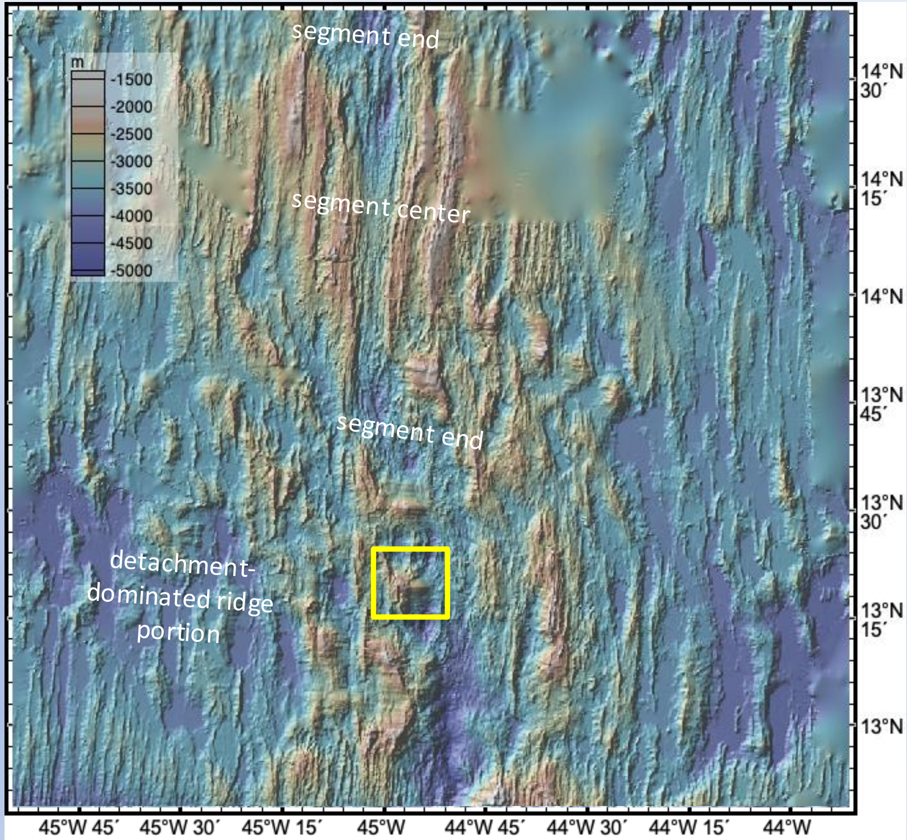
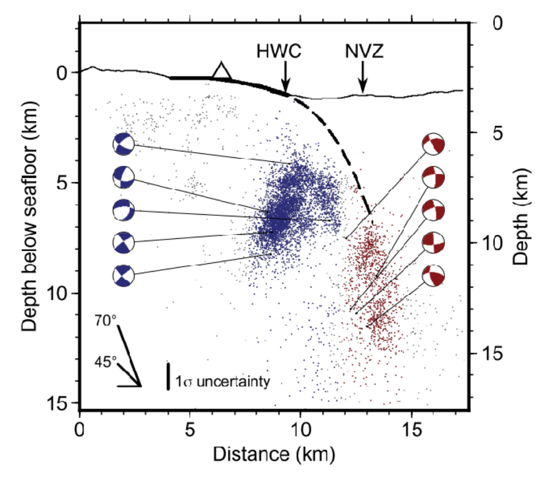


the ridge is a valley controlled by normal faults and very variable in width and depth (the ridge is segmented). Normal faults can have very large offsets (« detachment faults »)

seismicity traces the fault zone at depth, showing that it is steep and curves to lower dips near the seafloor

seismicity is detected down to > 12 km below seafloor (ie brittle lithosphere is at least that thick and the ridge is indeed cold)

Parnell-Turner et al., 2017

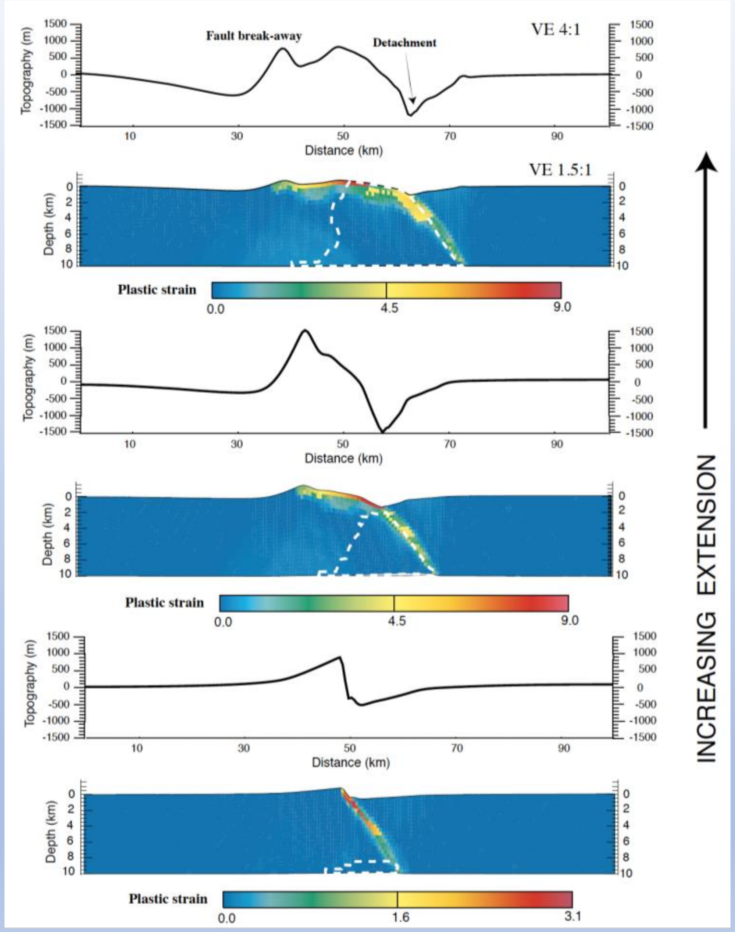


Numerical models help understand how mid-ocean ridge detachment faults work :

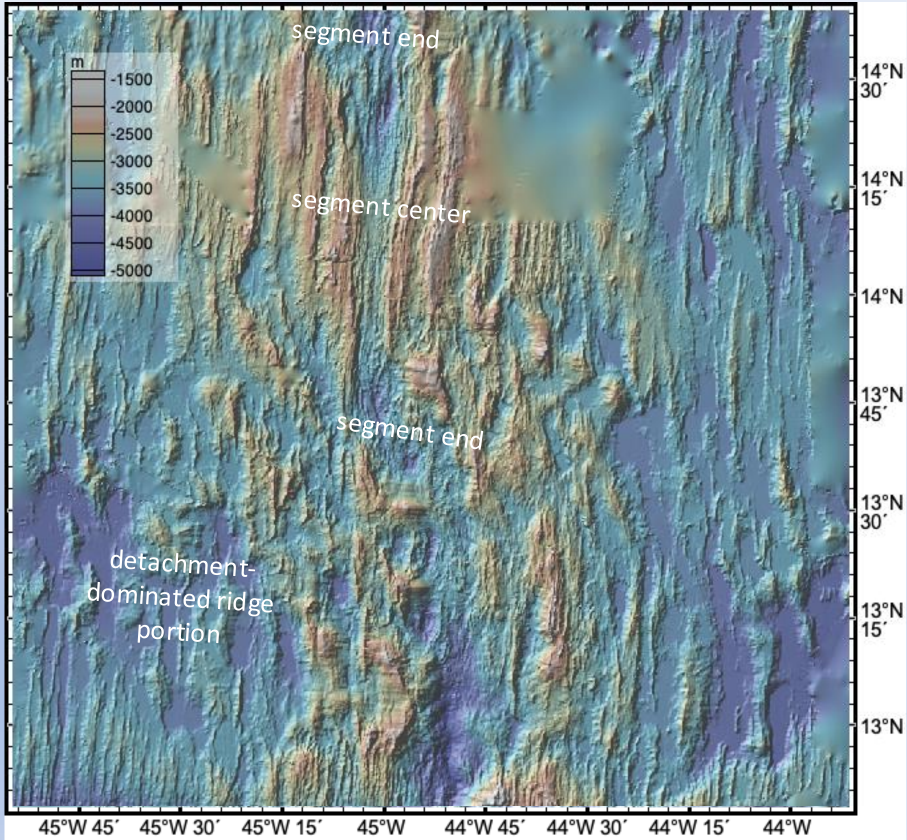
- domal structures similar to those observed at axial detachments are produced by rotation of the footwall in faults produced by stretching of a ~10 km-thick lithosphere

- the recipe to reach offsets ≥ 10 km on a normal fault (instead of initiating a new fault) is to reduce the rock strength in the fault zone with increasing strain. In nature this reduction in strength is primarily due to the formation of weak hydrated minerals in deformed rocks (hydrothermal alteration)

Lavier et al., 1999



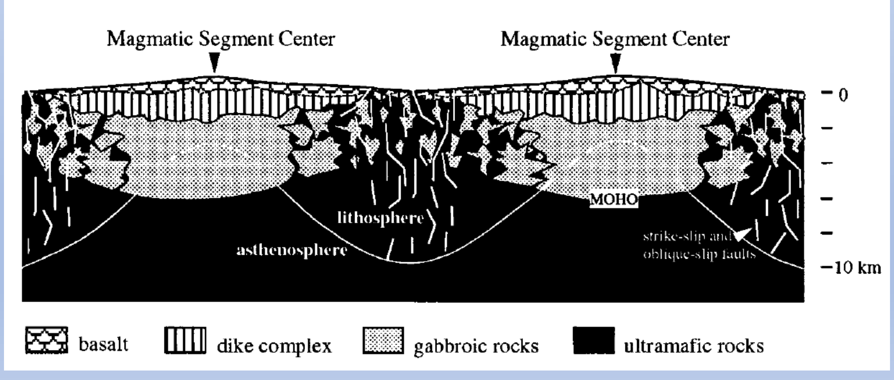
Mid-Atlantic Ridge 13-14°N



segment centers: seismic data indicate that the crust is thicker and seafloor morphology indicates more active volcanism

segment ends: seafloor morphology and rock sampling indicate that serpentinized peridotites crop out, with gabbros and basalts in the footwall of detachment faults

a conceptual model of crustal architecture at « cold » mid-ocean ridges

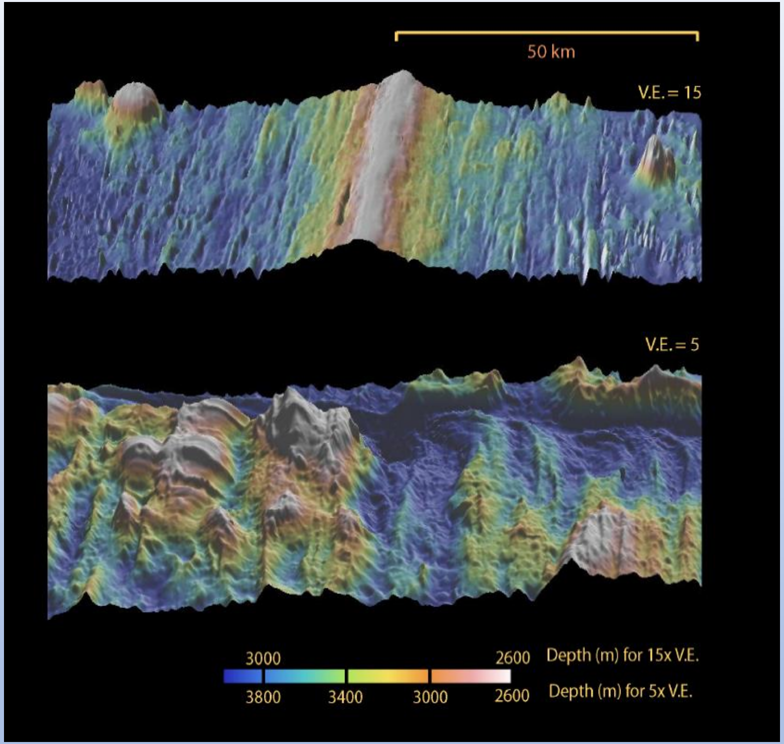


Cannat et al., 1995

3- the thermal state of the ridge axis is a key variable, controlling the tectonic and magmatic diversity of mid-ocean ridges

« hot » ridge the crust is not significantly faulted. It is made of gabbros, with up to 2 km of basaltic dikes and lava on top. Hydrothermal circulation is mostly restricted to the dike and lava sections

« cold » ridge the crust is extensively faulted and made of variable proportions of magmatic (gabbros, dikes, lava) and exhumed mantle-derived rocks. Hydrothermal alteration is pervasive in deformed horizons



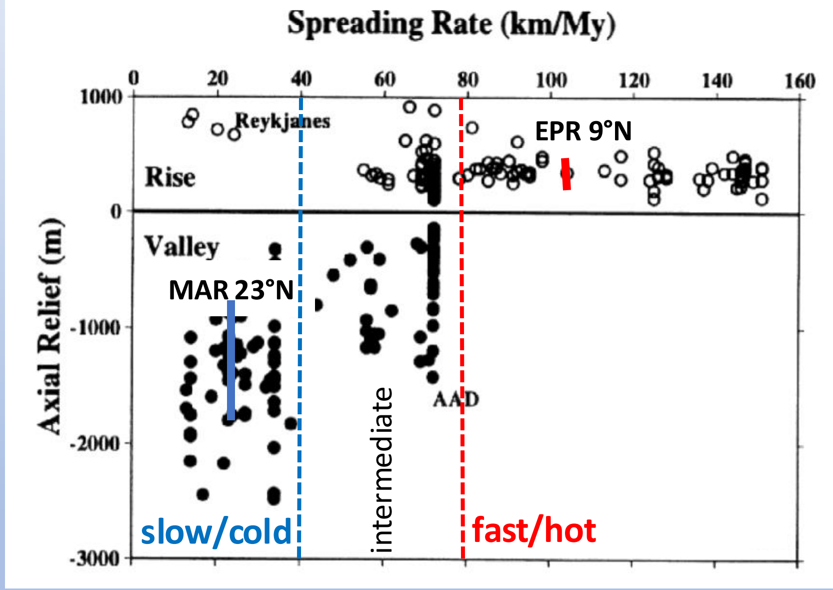
East Pacific Rise 9°N

Mid-Atlantic Ridge 23°N

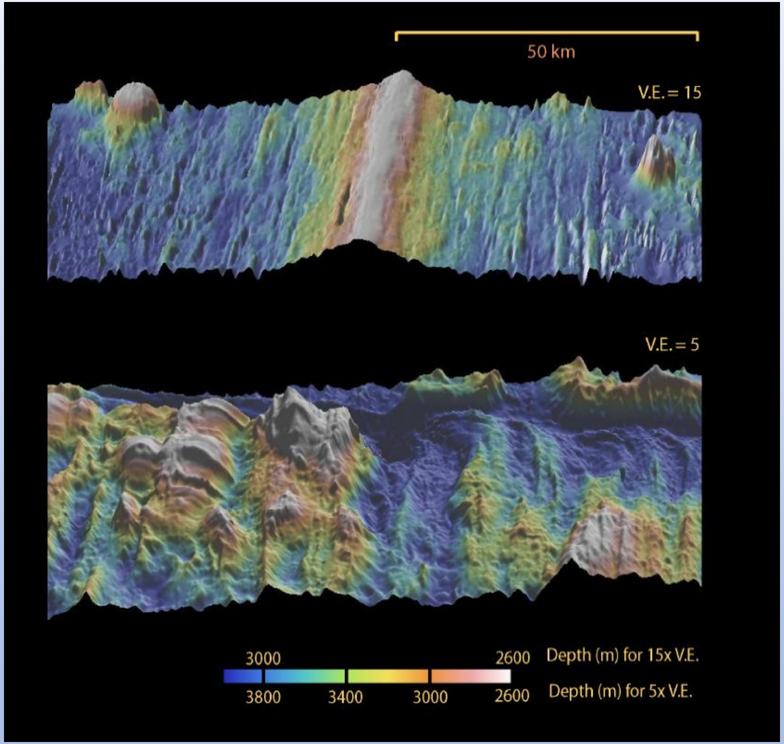
Buck et al., 2004

3- the thermal state of the ridge axis is a key variable, controlling the tectonic and magmatic diversity of mid-ocean ridges

fast ridges (≥ 8 cm/yr) are hot (they have an axial high)
slow ridges (≤ 4 cm/yr) are cold (they have an axial valley)



Small, 1998



Buck et al., 2004

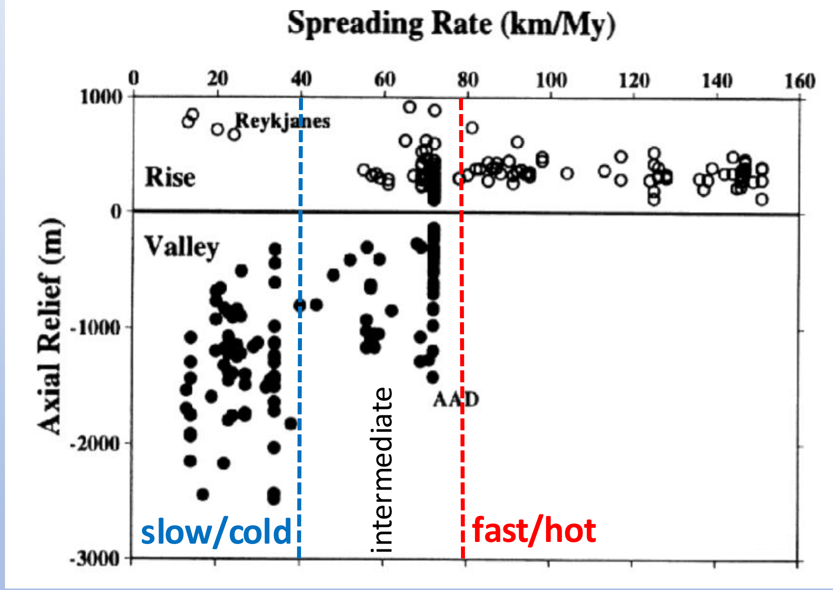
East Pacific Rise 9°N

spreading rate 11 cm/yr

Mid-Atlantic Ridge 23°N

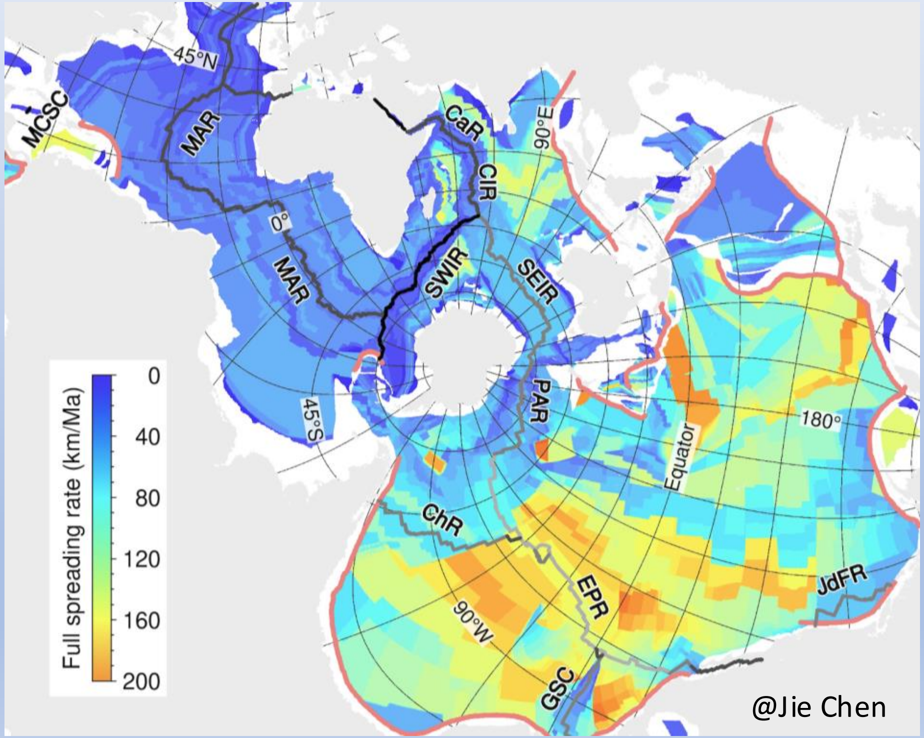
spreading rate 2.4 cm/yr

fast ridges (≥ 8 cm/yr) are hot (they have an axial high)
slow ridges (≤ 4 cm/yr) are cold (they have an axial valley)



Small, 1998

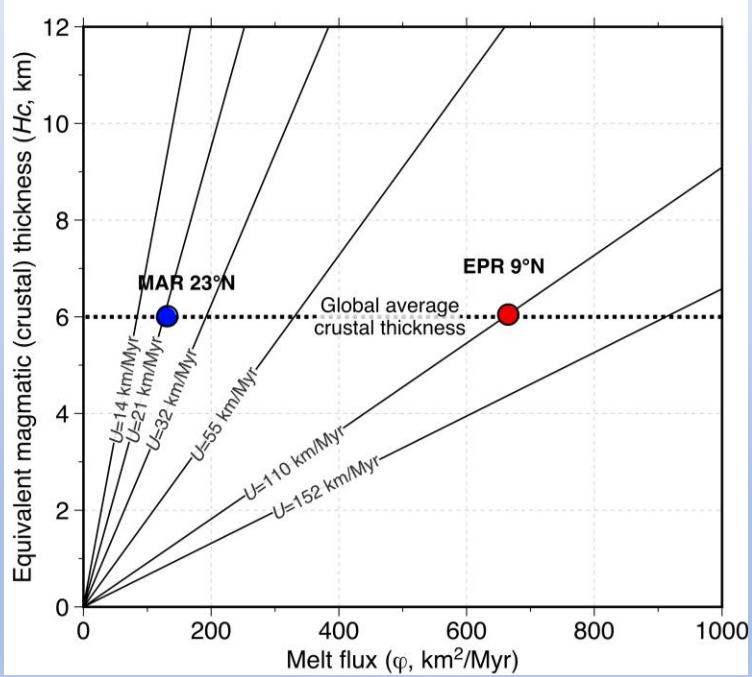
slow-spread, geologically more complex oceanic crust forms along 54% of total length of present-day ridges and makes 23% of total surface of present-day oceanic domains



but why this relation between spreading rate and the axial temperature regime ?

East Pacific Rise 9°N
spreading rate
11 cm/yr
Hc= 6 km
M = 660 km^2/km

Mid-Atlantic Ridge 23°N
spreading rate
2.4 cm/yr
segment center
Hc ~ 6 km
M = 144 km^2/km



Chen, Olive and Cannat, 2023

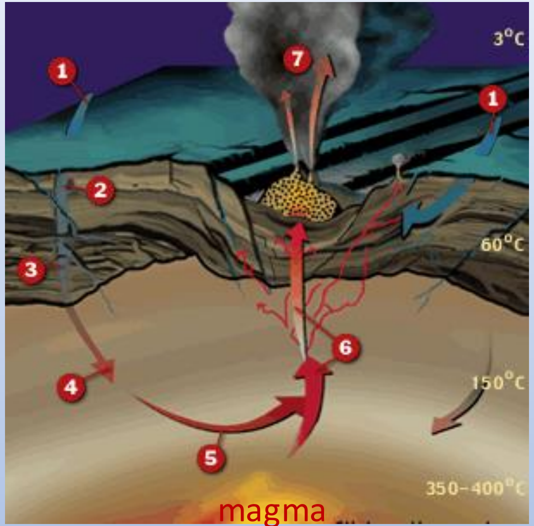
because the melt flux is a function of spreading rate .. and since it brings heat to the axial domain, fast ridges will always receive way more heat than slow ones

estimated time integrated melt flux per km of ridge is crustal thickness time spreading rate

4- melt flux, hydrothermal circulation and the thermal state of the ridge axis

magmatism brings new material and heat to the axial domain

hydrothermalism cools the axial domain ... and is enhanced by magmatic heat

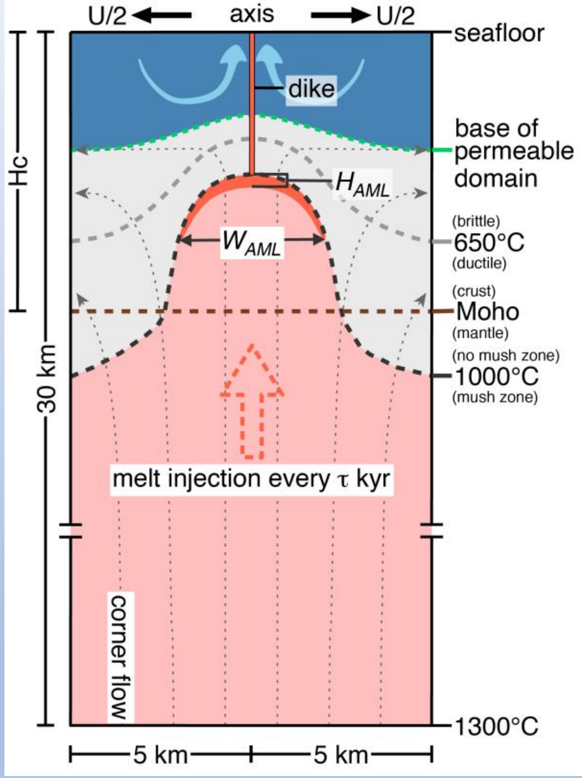


http://www.divediscover.whoi.edu/vents/chemistry.html

The next few slides show examples of numerical simulations that test the following statement:

« The thermal state of the ridge axis is controlled by melt fluxes and is modulated by the accessibility of magmatic heat to hydrothermal circulation »

MODEL SETUP



Chen, Olive and Cannat, 2023 (model modified from Olive et al., 2018; Fan et al., 2021; and Chen , Olive and Cannat, 2022)

Hydrothermal heat output

- *Hydrothermal circulation is controlled by Darcy flow in a uniform permeable layer*
- *Cut-off depth of hydrothermal system (cracking front)*

Magmatic heat input

- Melt flux is adjusted by changing the time interval (t) between melt injections.
- *Axial Melt Lens (4-km wide and 200-m thick) is repeatedly emplaced beneath basaltic solidus (1000℃ isotherm), building the lower crust.*
- **Dike is emplaced between AML and seafloor and accommodates plate spreading in the crust.**
- **F_{dike}: dike-accommodated fraction of plate separation** (the rest being taken by faults)

Other heat sources

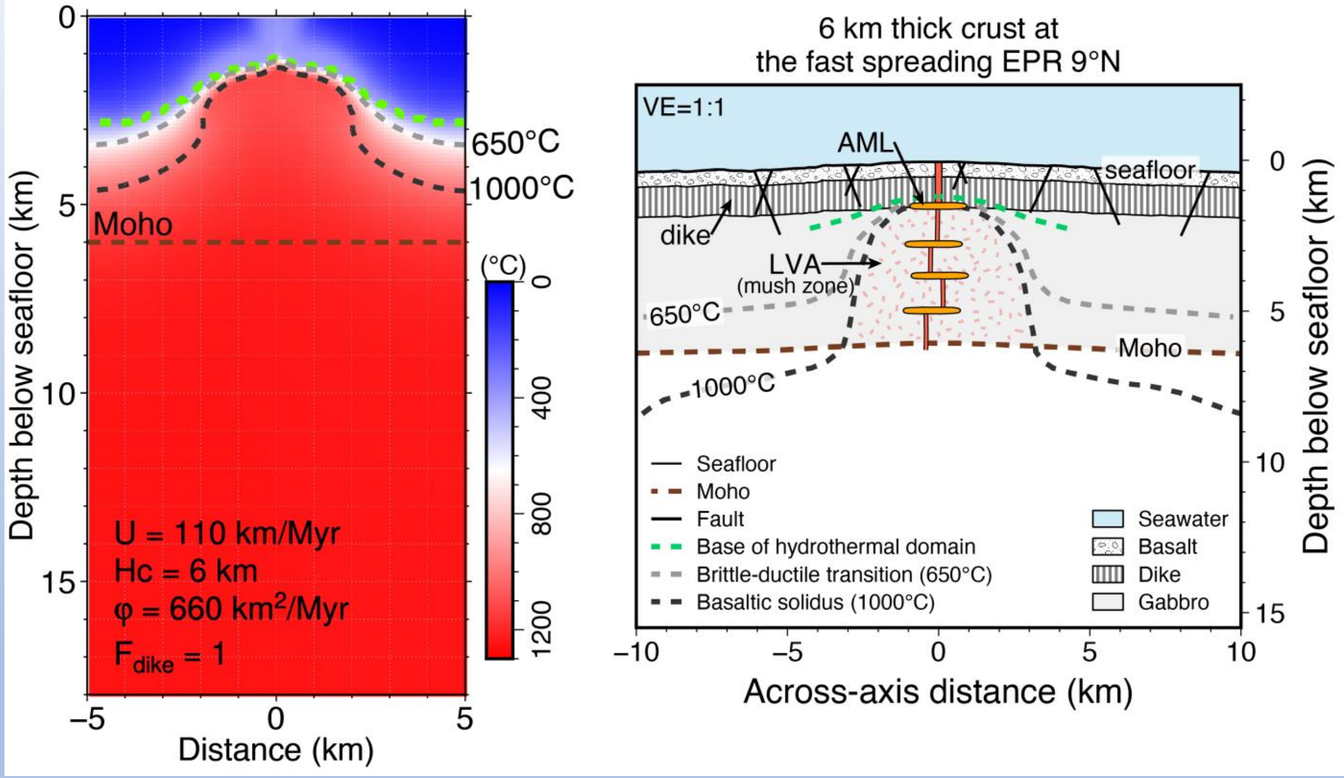
- **Mantle upwelling (corner flow)**
- *Conductive heating (imposed bottom temperature)*

Chen, Olive and Cannat, 2023

« hot » ridge

East Pacific Rise 9°N

spreading rate 11 cm/yr
Hc= 6 km
M = 660 km²/km



Thermal state as constrained by field observations is successfully simulated

« cold » ridge

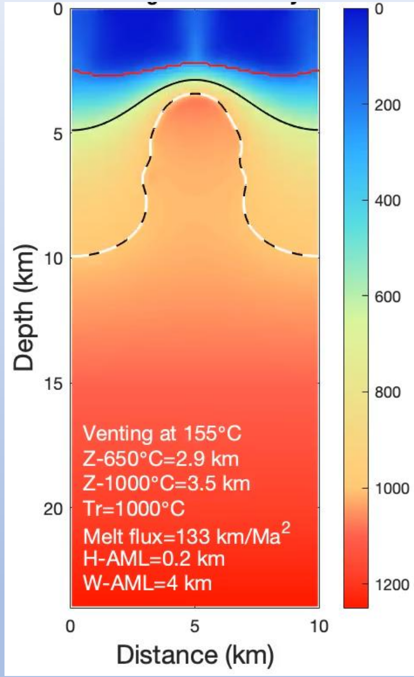
Mid-Atlantic Ridge 34°N
spreading rate 2.2 cm/yr
mid-segment Hc ~ 6 km
M = 133 km^2/km

The simulated thermal state is also highly dependant on the depth of magma emplacement (ie of the dynamics of axial volcanism): if magma is preferentially injected in the upper crust the prediction is dramatically colder... (also, hydrothermal vents are black smokers)

.... this could be an additional factor, with melt flux variations, to explain the geological variability along slow/cold ridge segments

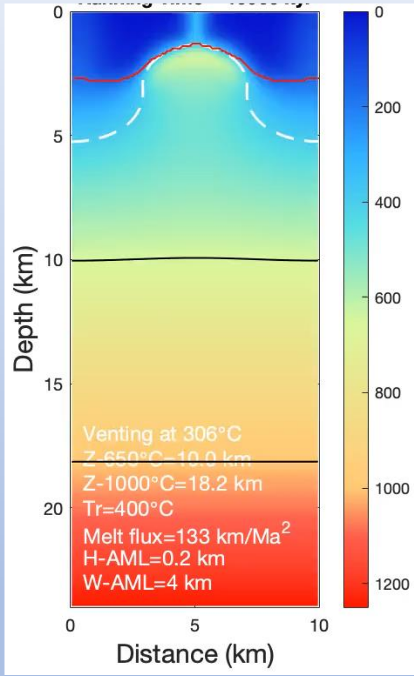
Chen, Olive and Cannat, 2022

1- magma emplaced at the 1000°C isotherm



brittle lithosphere ~ 4 km

2- magma emplaced at the 400°C isotherm



brittle lithosphere ~ 10 km

red line: base of hydrothermal domain
black lines : 650° and 1000°C isotherms
dashed white line: isotherm where magma is emplaced

5- key take-away points

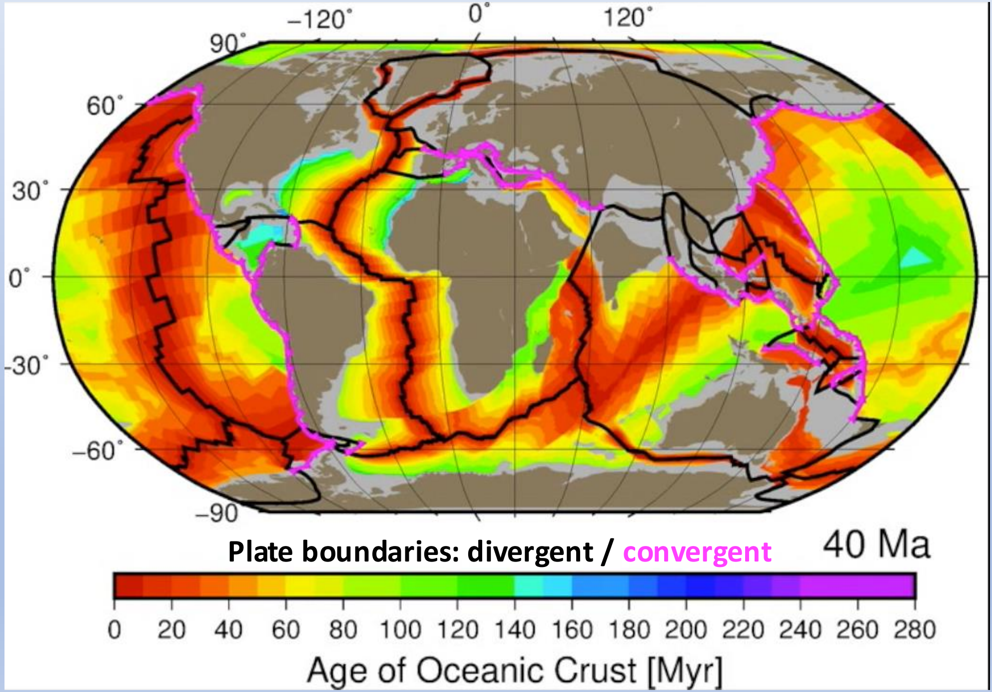
1. topic relevance : mid-ocean ridge processes and ocean crust geology account for 60% of the surface of the Earth and are key to understand and quantify chemical exchanges between the deep Earth and it's external enveloppes
2. mid-ocean ridge processes that build the oceanic crust : magmatism and hydrothermalism combine to determine the thermal state of the axial domain, faulting breaks the resulting axial lithosphere into the two diverging plates
3. hot ridges have a fully magmatic crust; cold ridges have a more complex geology: the crust they form contains variable amounts of tectonically exhumed serpentinized mantle rocks in addition to maglmatic rocks
4. slow ridges are cold, fast ridges are hot because melt flux controls the thermal state of ridge axes. At slow ridges this is modulated by the accessibility of magmatic heat to hydrothermal circulation and therefore by the depth at which melt is emplaced in the lithosphere... which can vary in space and in time ...

thank you for listening !

THE FORMATION OF THE OCEANIC CRUST AND THE TECTONIC AND MAGMATIC DIVERSITY OF MID-OCEAN RIDGES

The oceanic crust (and the ocean floor!) is constantly renewed at mid-ocean ridges and plunges into the mantle in subduction zones.

Plate tectonic reconstruction < 40 myrs Muller et al., 2016

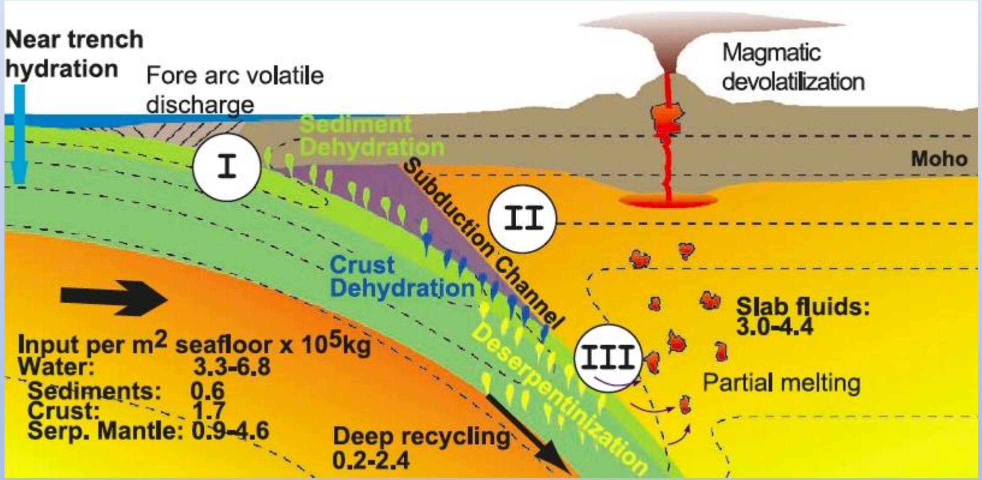


M. Cannat, GIFT-EGU 2025

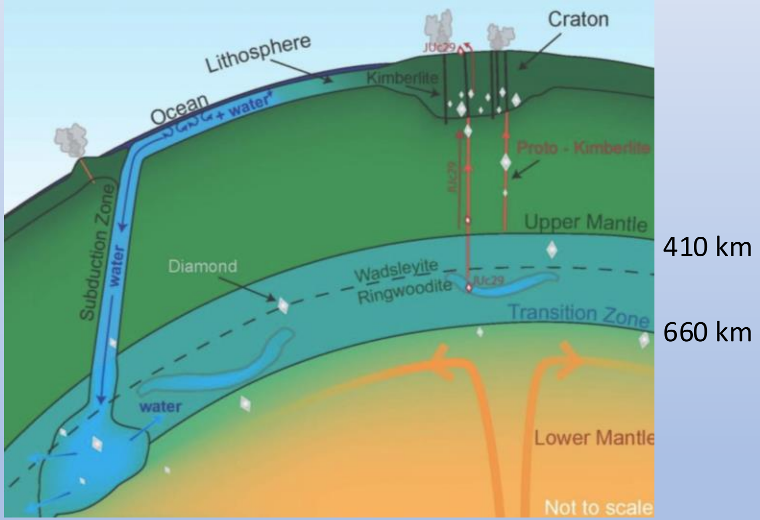
the deep Earth and it's external enveloppes exchange and interact

example : the deep water cycle

.... the Earth is an extraordinarily dynamic planet !



A sketch of estimated water fluxes associated to the subduction of oceanic lithosphere
Rüpke et al., 2004



The possible fate of recycled water in the Earth's mantle. Kathy Mather after Pearson et al., 2014