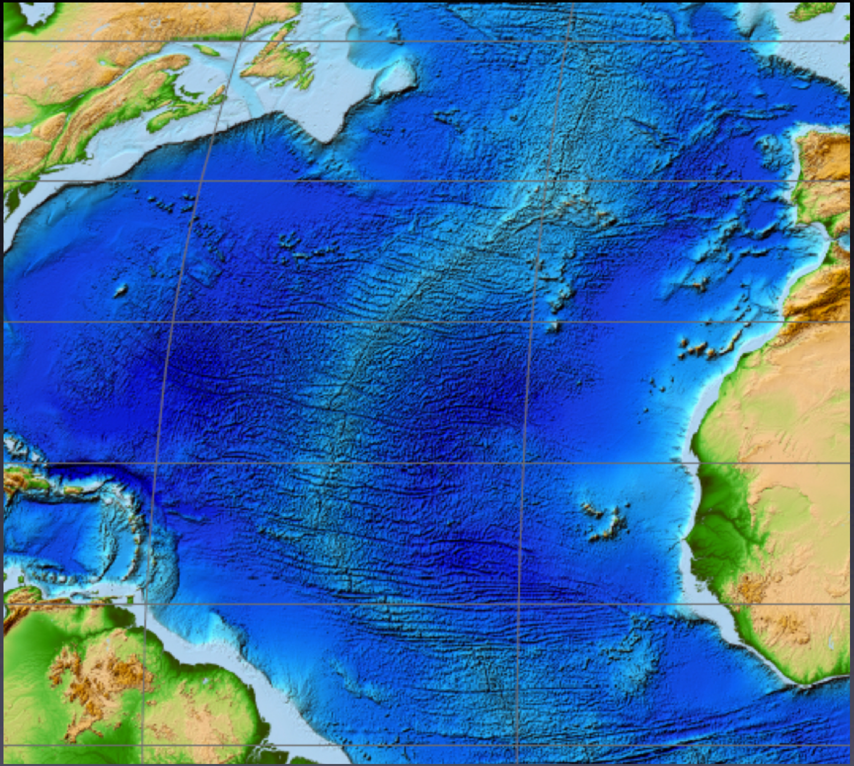
Seafloor spreading : plate divergence processes at mid-ocean ridges



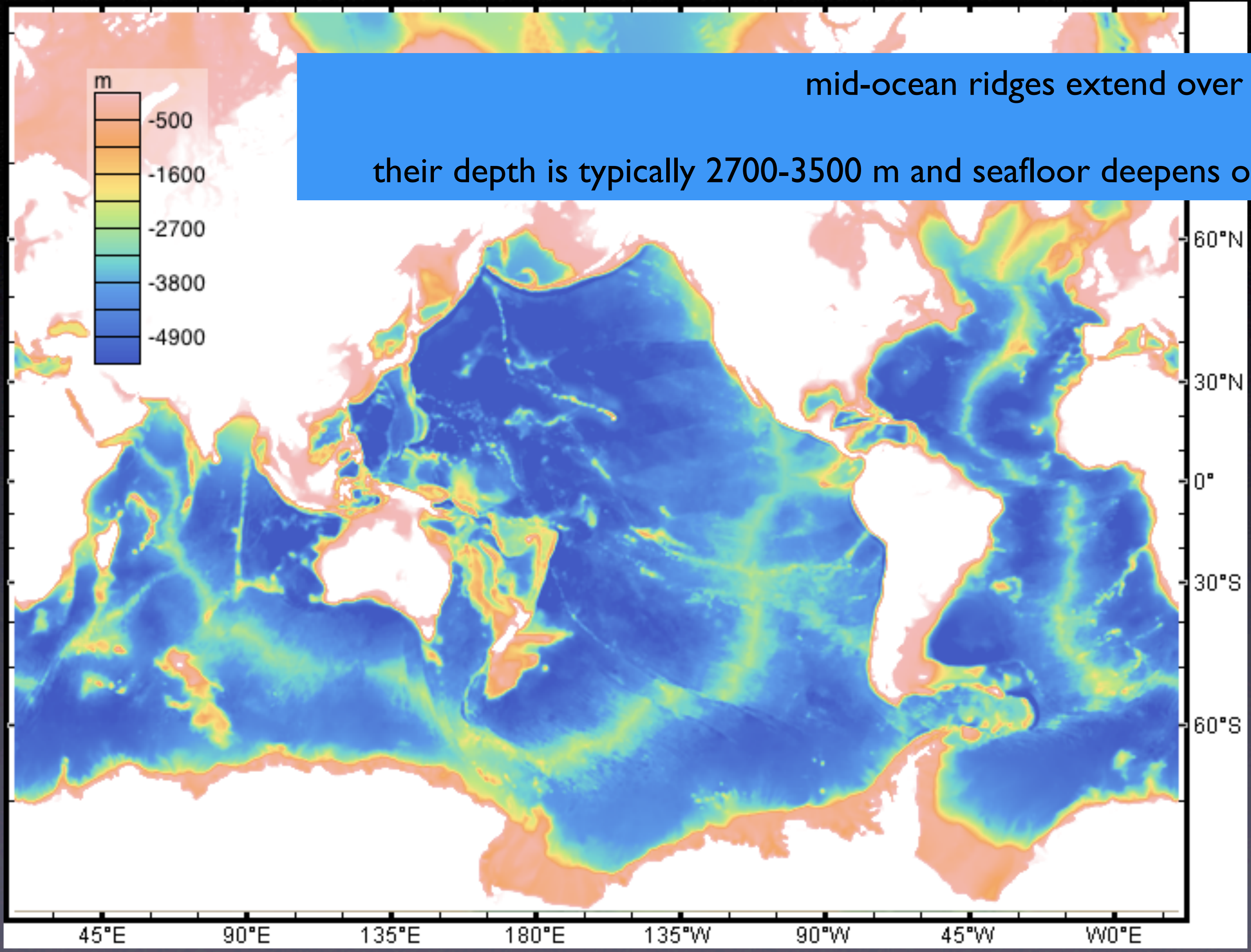
1. A very short map-based overview of the present-day mid-ocean ridge system
2. Mid-ocean ridge processes : discoveries, evolving concepts, new & old questions

M. CANNAT / 2019 GIFT workshop, EGU Vienna

Depth of the oceans (GMRT v3.3)

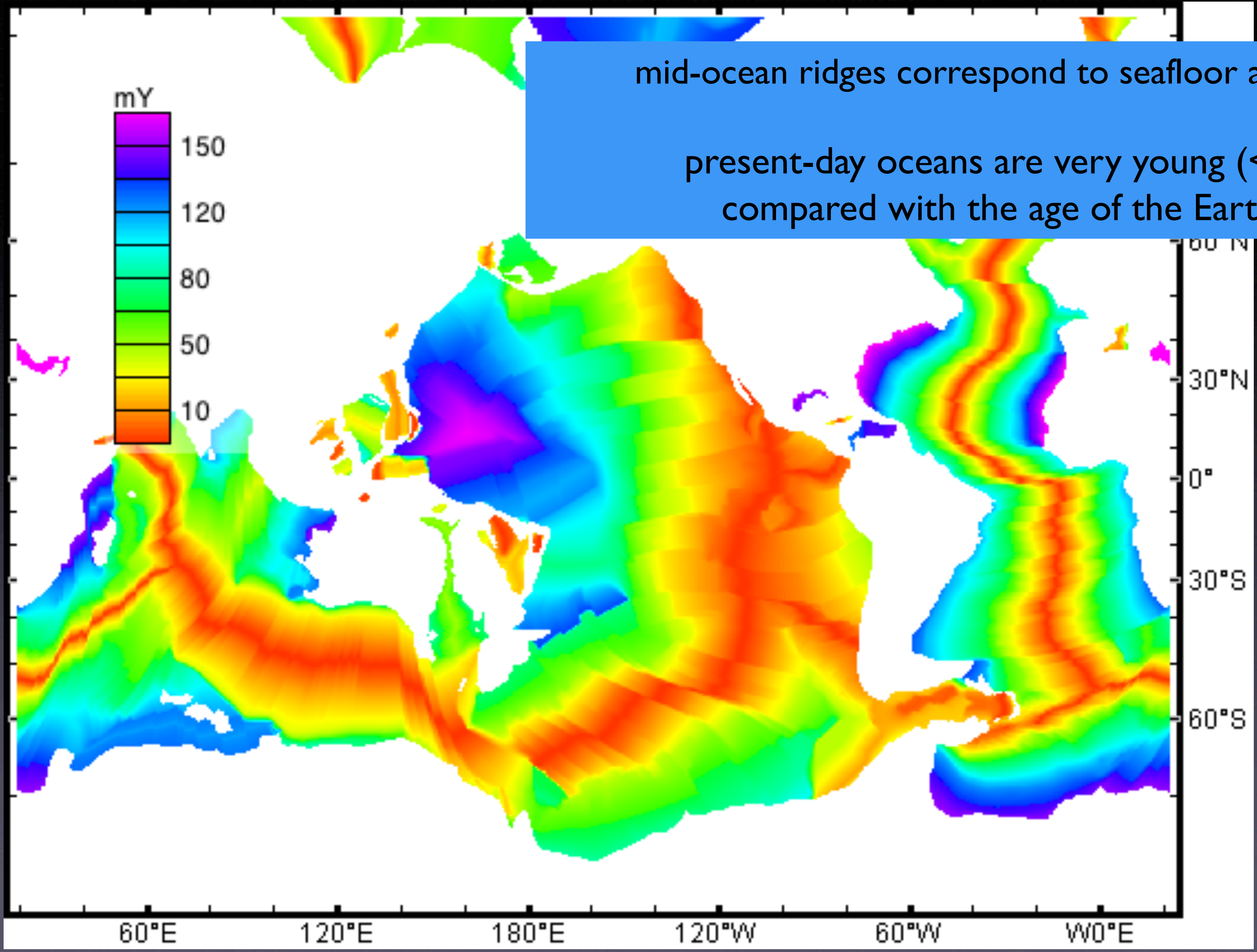
mid-ocean ridges extend over > 60 000 km

their depth is typically 2700-3500 m and seafloor deepens on their flanks



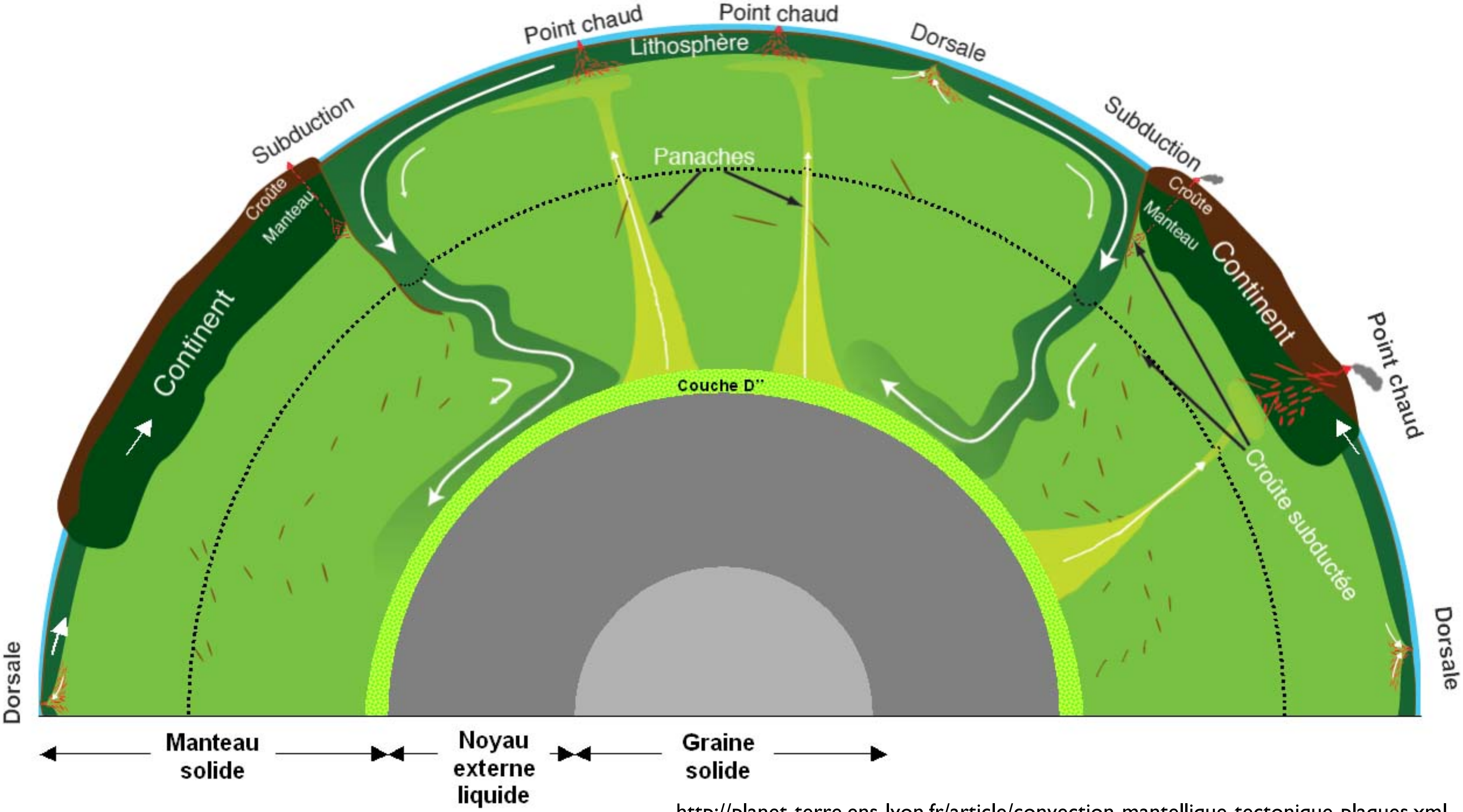
mid-ocean ridges correspond to seafloor ages < 1 Myr

present-day oceans are very young (< 200 Myrs) compared with the age of the Earth (4.5 Byrs)



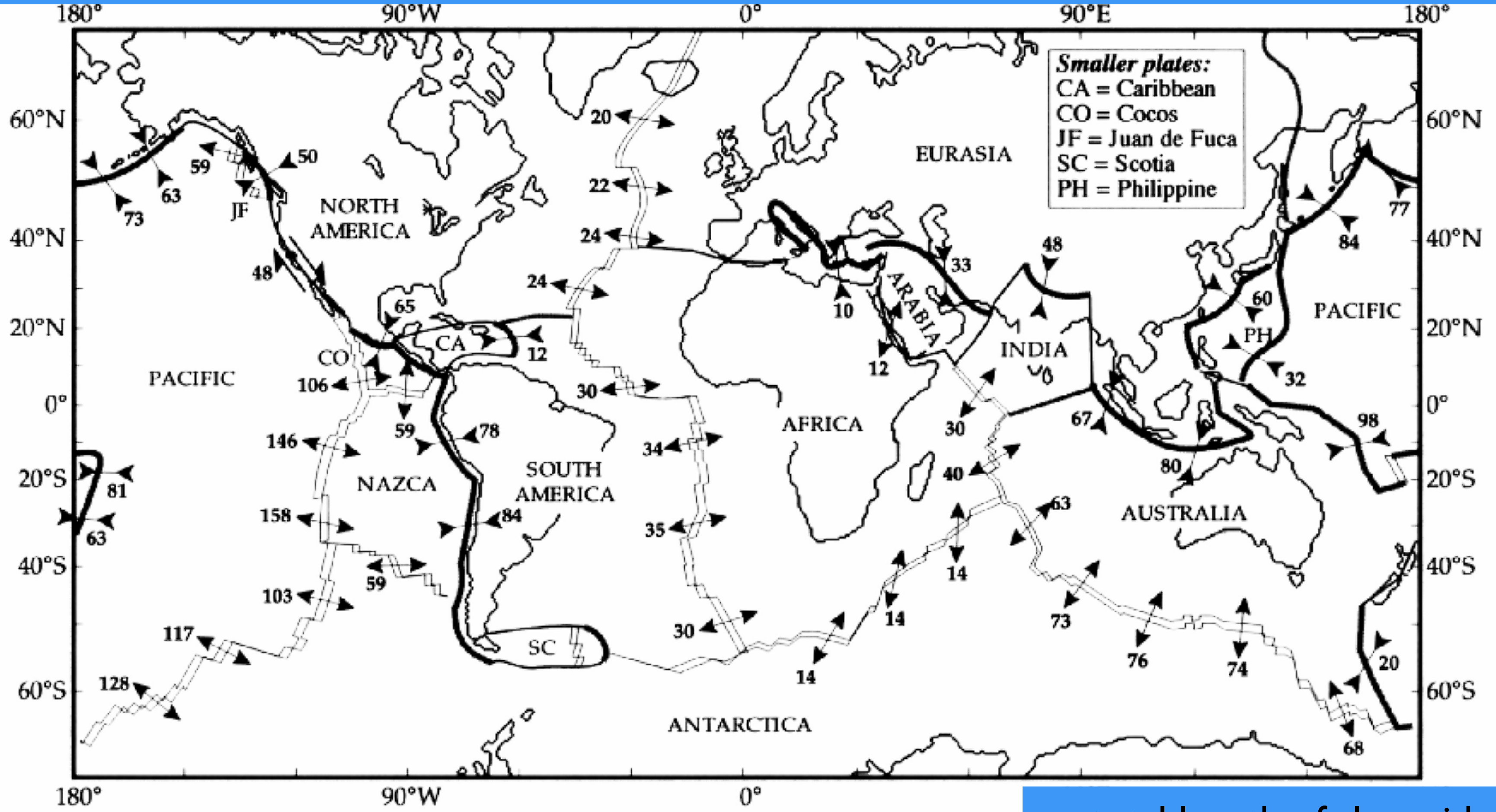
Age of the seafloor (Müller et al., 2008)

new plates created at mid-ocean ridges are continuously recycled into the Earth's mantle at subduction zones



http://planet-terre.ens-lyon.fr/article/convection-mantellique-tectonique-plaques.xml

the rate of creation of new seafloor at mid-ocean ridges varies (< 4 cm/yr at slow ridges and > 8 cm/yr at fast ridges)

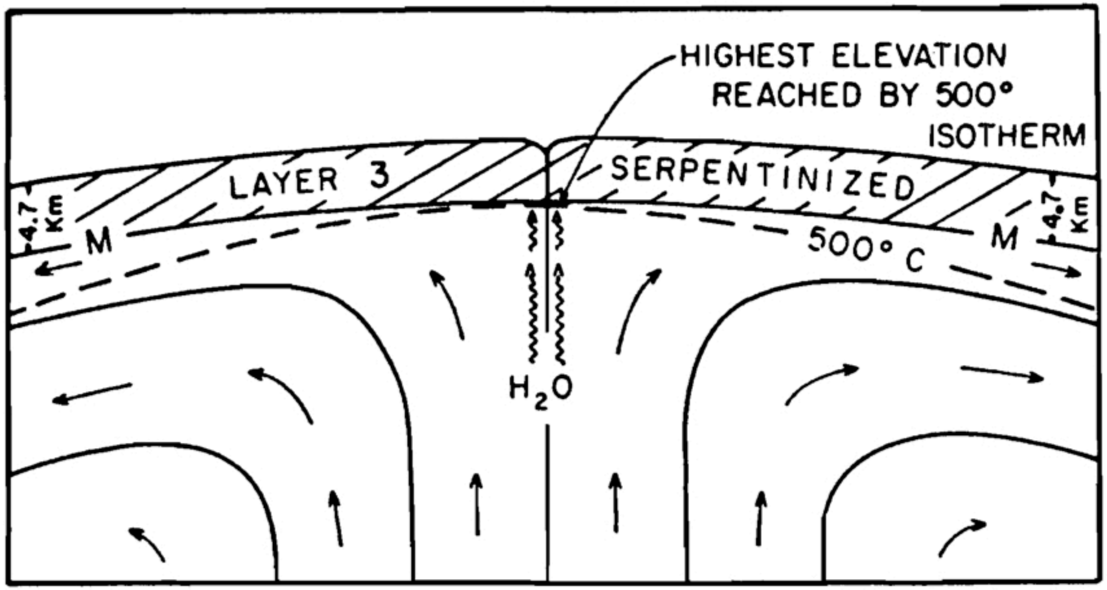


NUVEL1 model of relative plate motion (Demets et al., GJI 1990)

total length of slow ridges = 32 000 km

1962 : H. Hess (The History of Ocean Basins)

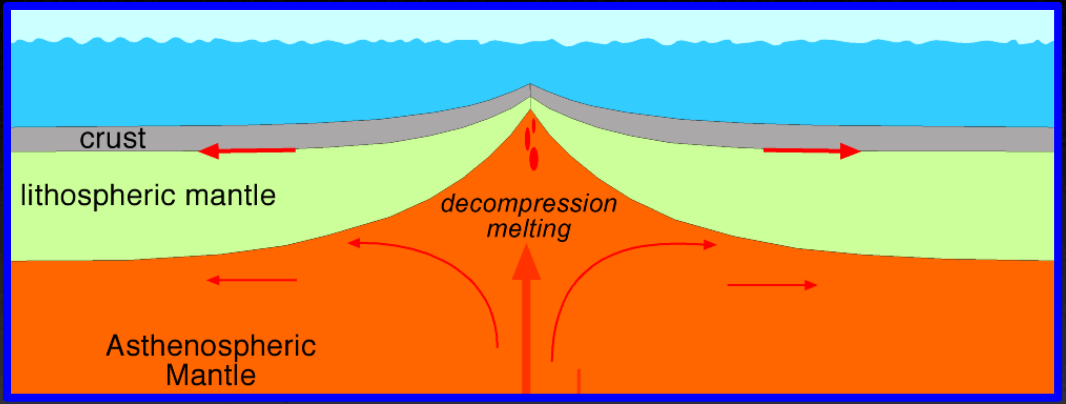
Mid-ocean ridge processes : discoveries, evolving concepts, new & old questions



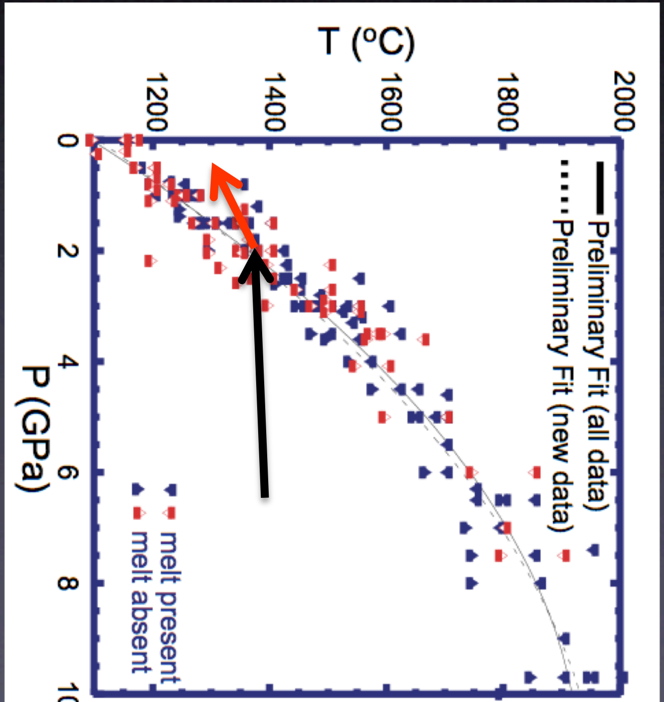
Hess, 1962

« Mid-ocean ridges represent the rising limbs of mantle-convection cells..... Convective flow comes right through to the surface, and the oceanic crust is formed by hydration of mantle material .... The water to produce serpentine of the oceanic crust comes from the mantle.... »

1962-1972 : mid-ocean ridges are the most important volcanic chain on Earth, the mantle melts as it rises to the ridge, the ocean crust is made of basaltic rocks



decompression melting :

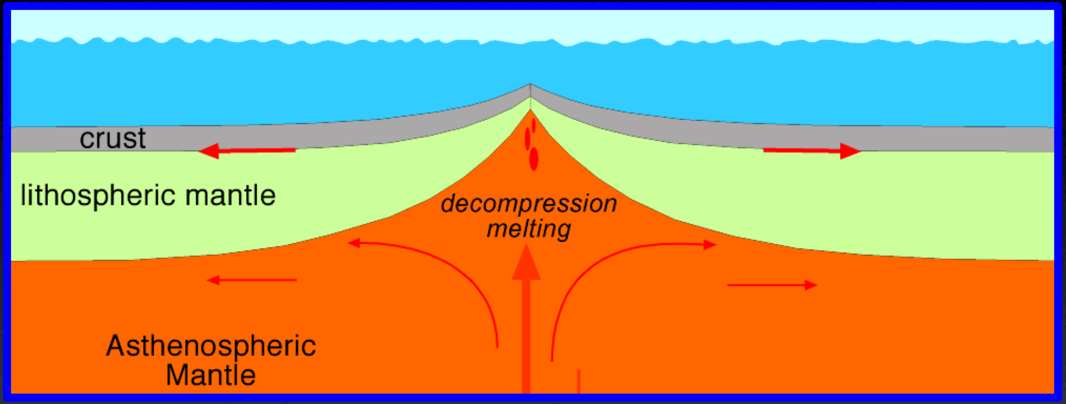


Hirschmann et al., 2000

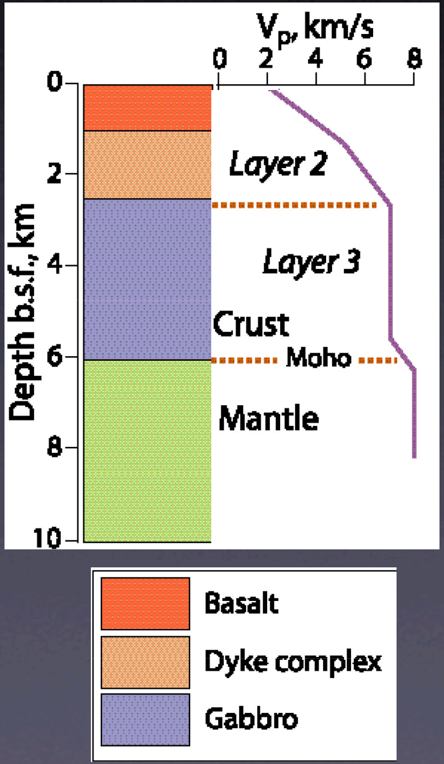
Based on results from many geophysical cruises (heat flow, gravity, seismics, magnetics), sampling cruises, ophiolite studies and experimental petrology …….

Vine and Matthews, 1963
Green and Ringwood, 1967….

1962-1972 : mid-ocean ridges are the most important volcanic chain on Earth, the mantle melts as it rises to the ridge, the ocean crust is made of basaltic rocks



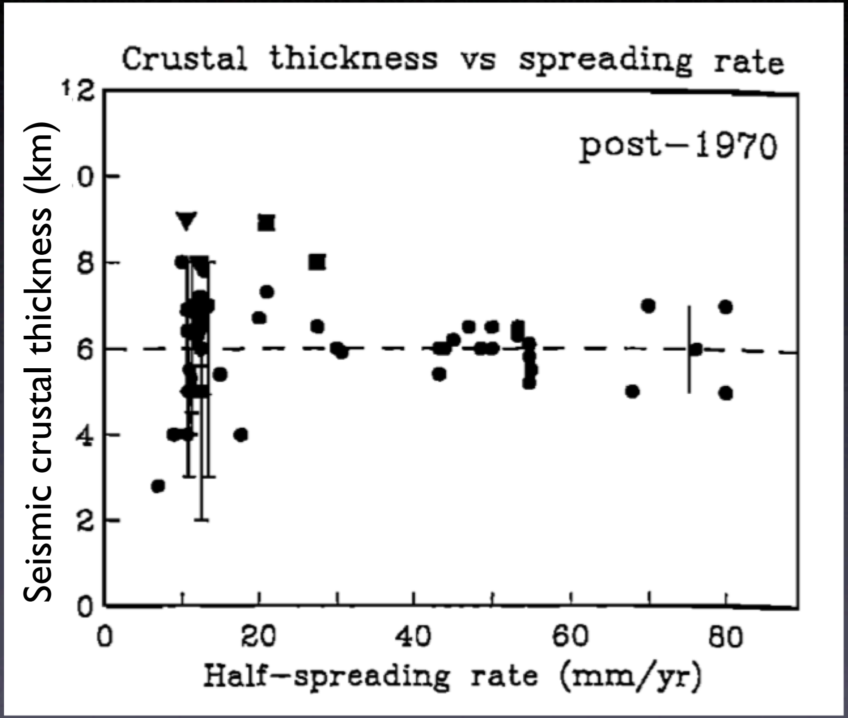
A geological model of the oceanic crust :



Based on results from many geophysical cruises (heat flow, gravity, seismics, magnetics), sampling cruises, ophiolite studies and experimental petrology …….

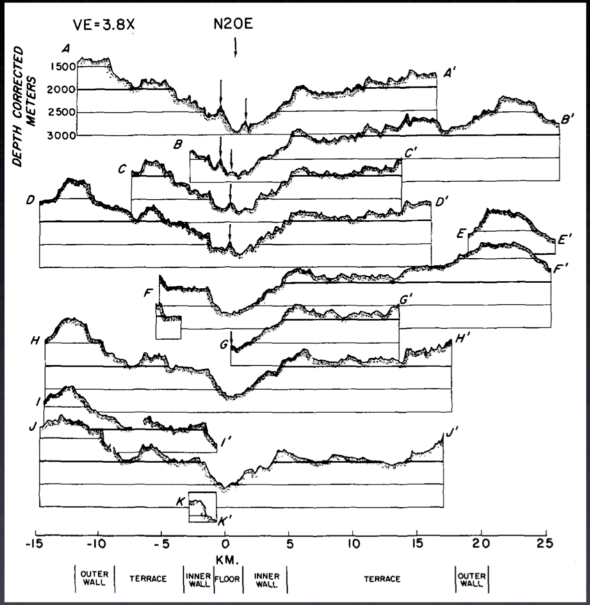
The 1972 Penrose field conference on ophiolites

The average thickness of the seismic crust (away from hot spots) is 6 km

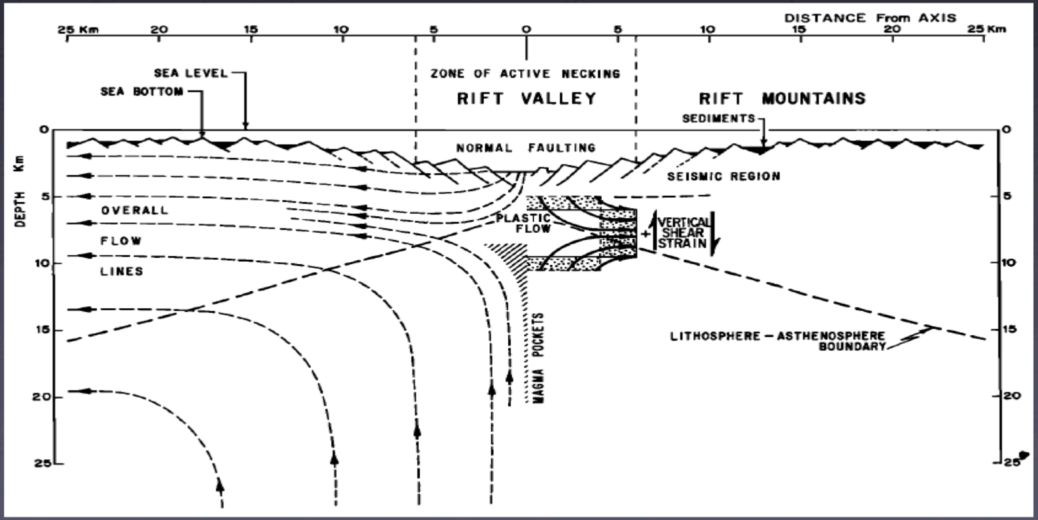


Chen, GRL 1992

1973-1978 : the axial valley of the mid-Atlantic ridge is a tectonic feature, controlled by normal faults. It is there because there is a rigid lithosphere in the axial region

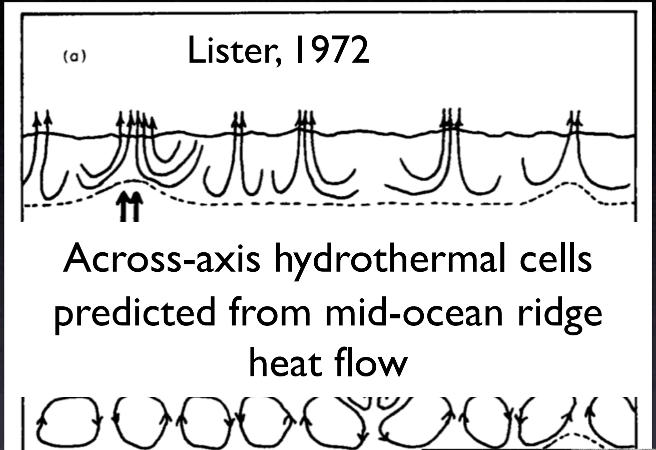


Needham and Francheteau, 1974
Macdonald et al., 1975



Tapponnier and Francheteau, 1978

1972-1979 : hydrothermalism is also a key process at mid-ocean ridges, hosting chemiosynthetic life, and transfering heat and chemical elements from the solid Earth to Ocean

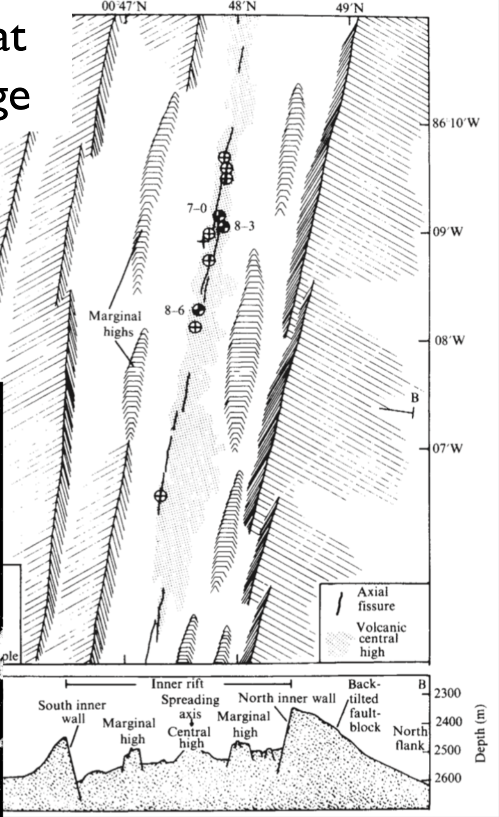


Lister, 1972

Across-axis hydrothermal cells predicted from mid-ocean ridge heat flow

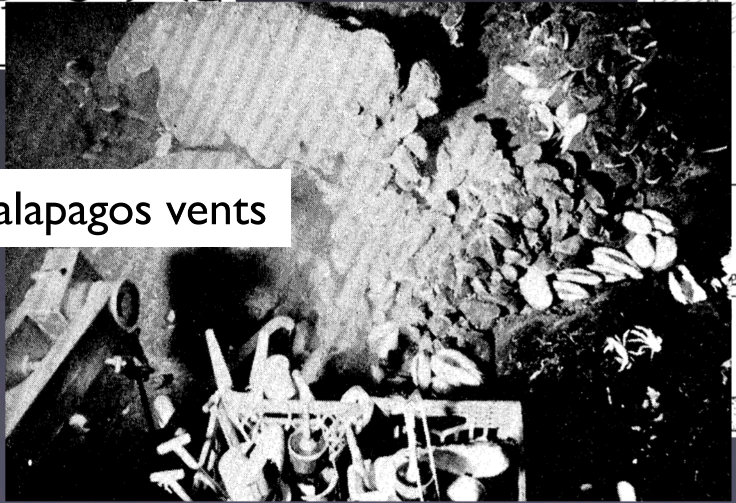
vents discovered at the Galapagos ridge

Weiss et al., 1977

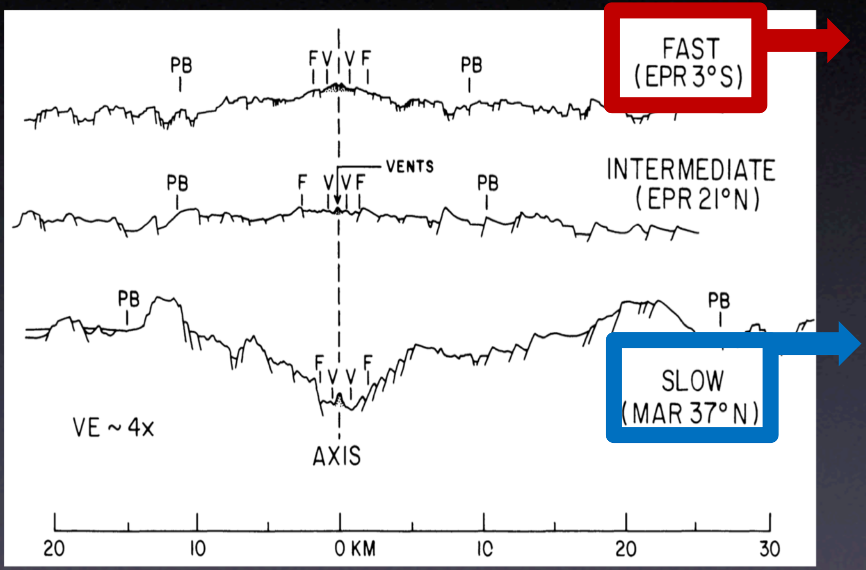


Life at Galapagos vents

Corliss et al., 1979

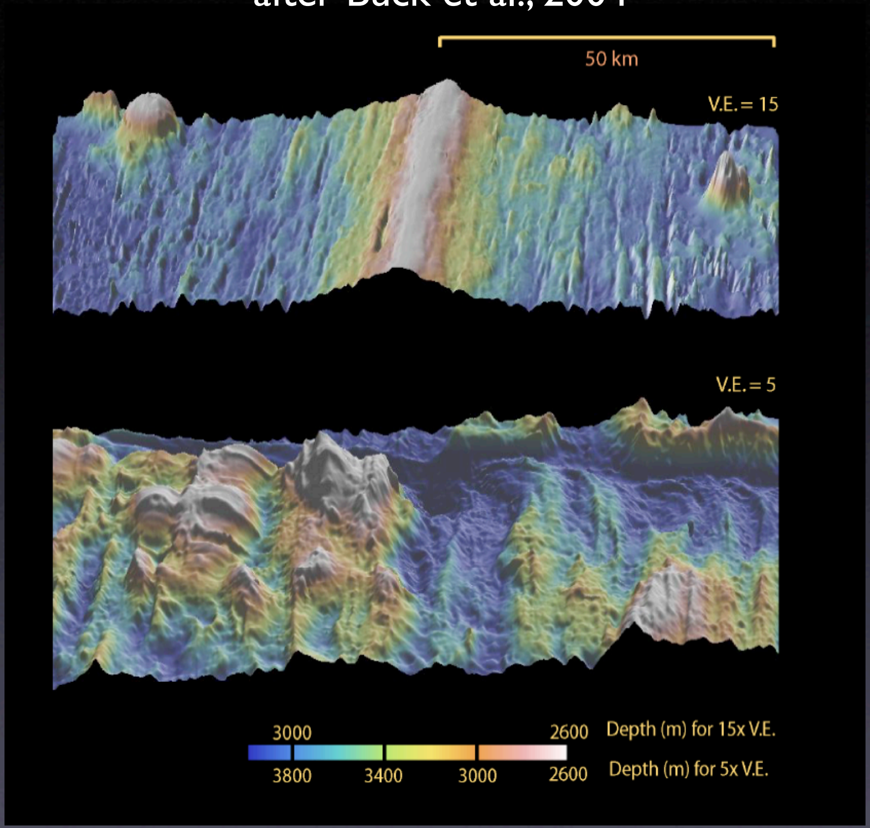


1978-present : spreading rate control on axial topography and on the balance between faulting and volcanism at mid-ocean ridges



Macdonald, 1982

after Buck et al., 2004



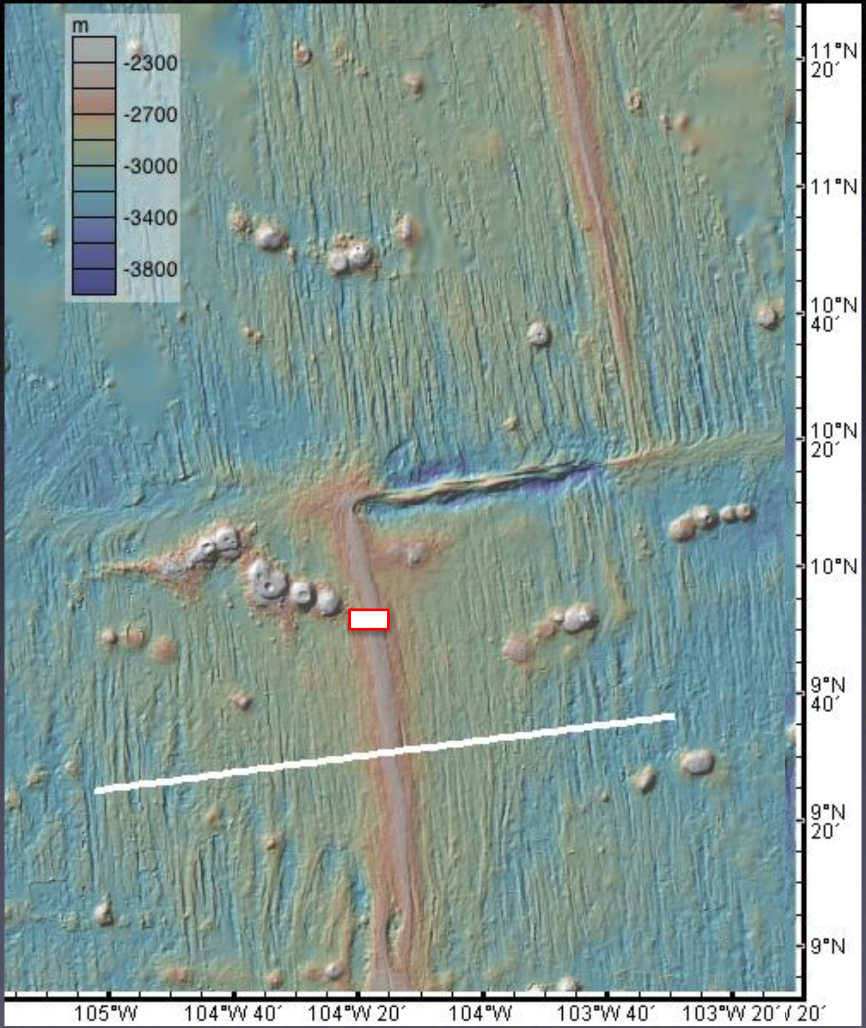
FAST SPREADING RIDGE : AXIAL HIGH
(relief : +400 m)

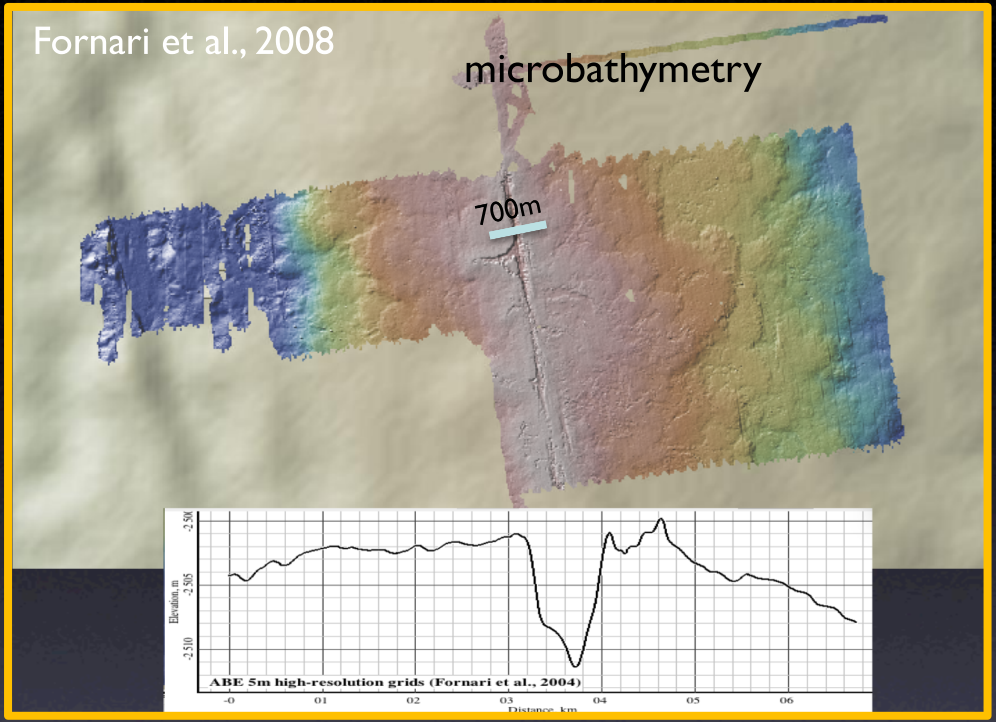
/

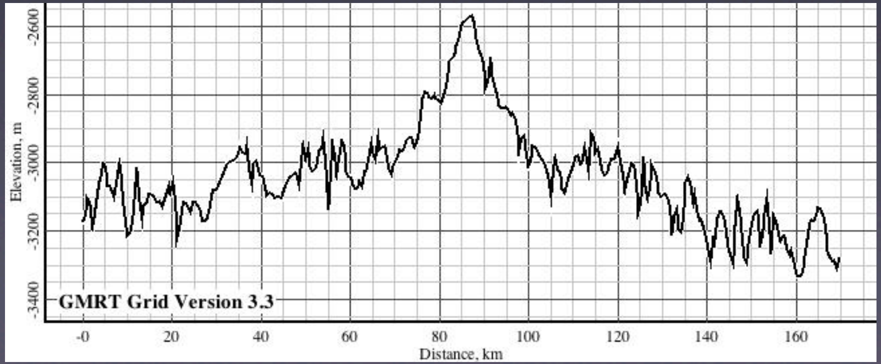
SLOW SPREADING RIDGE : AXIAL VALLEY
(relief : -300 to -4000 m)

East Pacific Rise

11 cm/yr

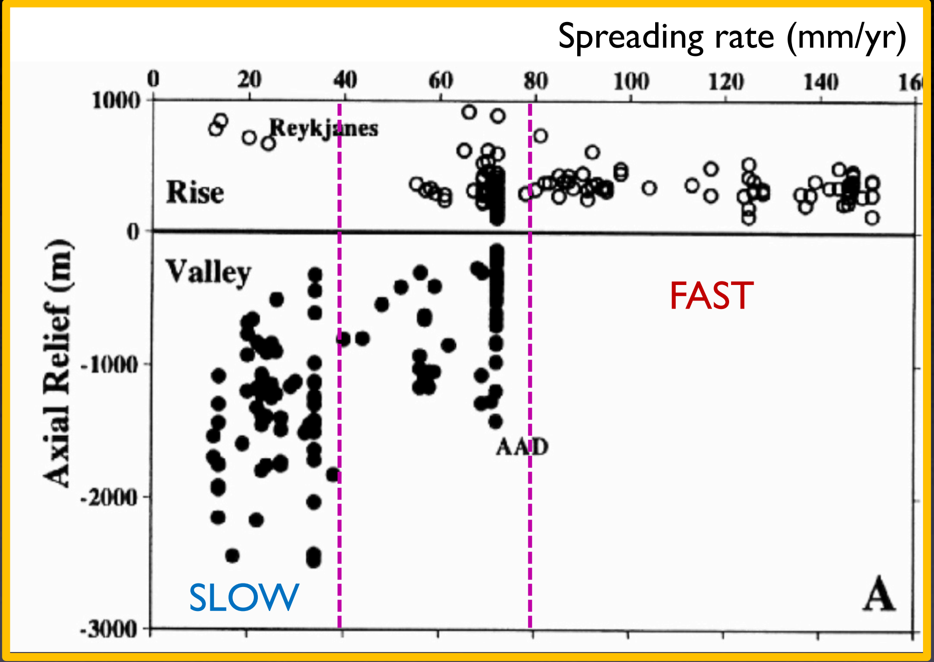


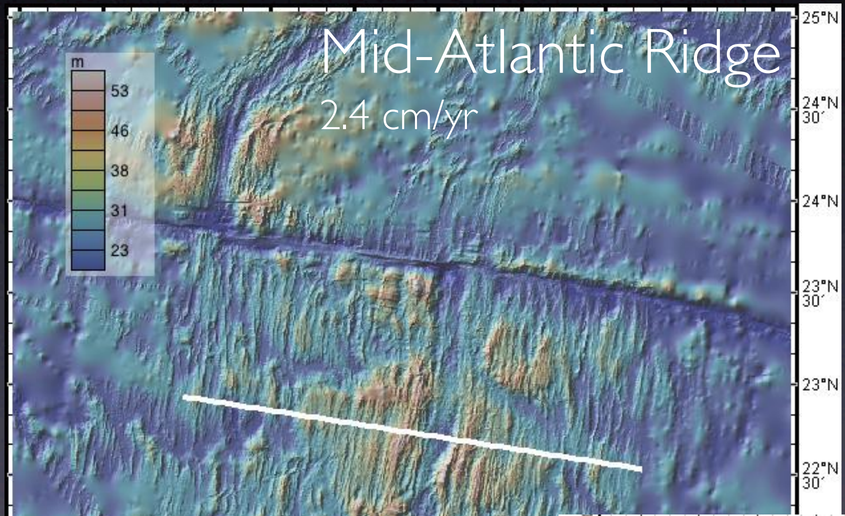

Fornari et al., 2008

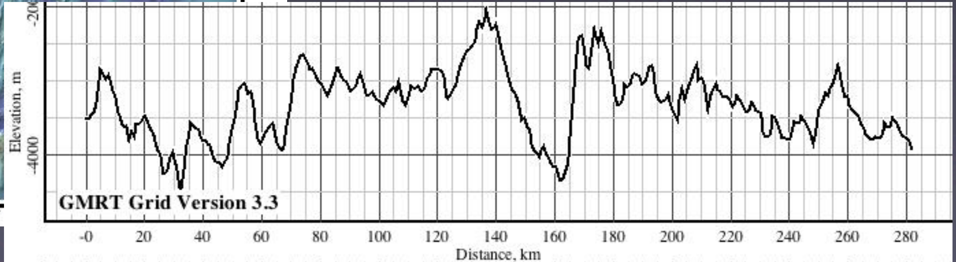


1978-present : spreading rate control on axial topography and on the balance between faulting and volcanism at mid-ocean ridges

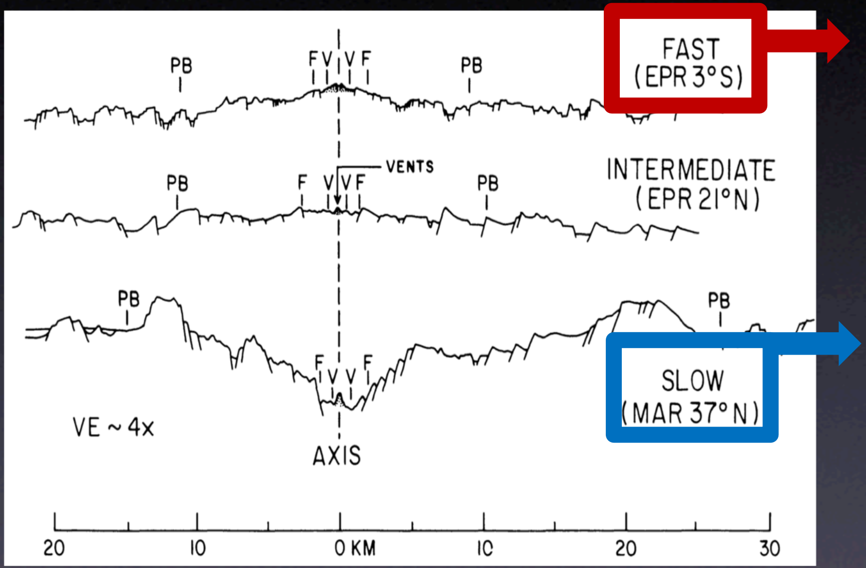
Small, AGU monogr., 1998



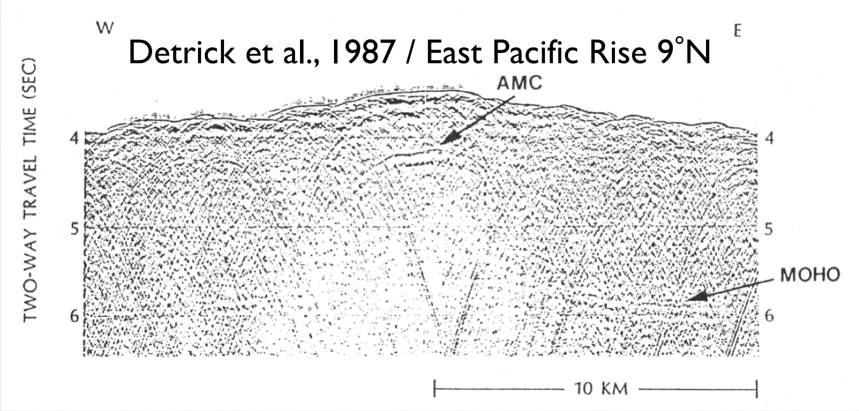




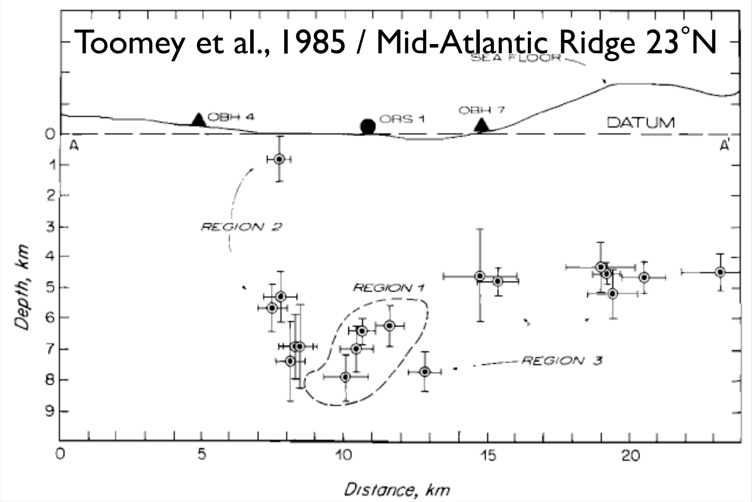
1985-present : spreading rate control on the thickness of the axial lithosphere



Macdonald, 1982

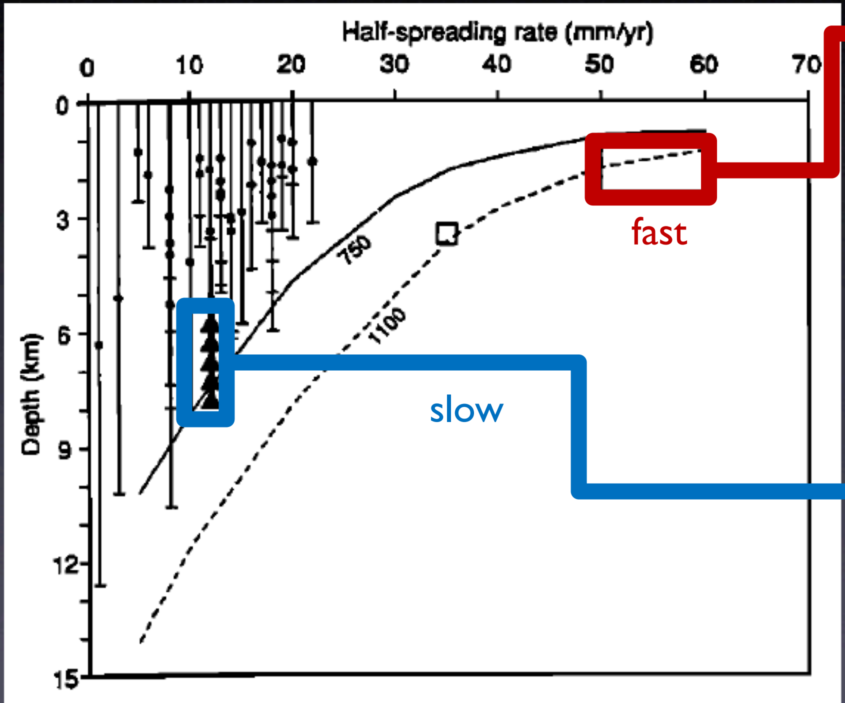

Detrick et al., 1987 / East Pacific Rise 9°N

FAST SPREADING RIDGE : permanent melt lense < 2 km below top of axial high

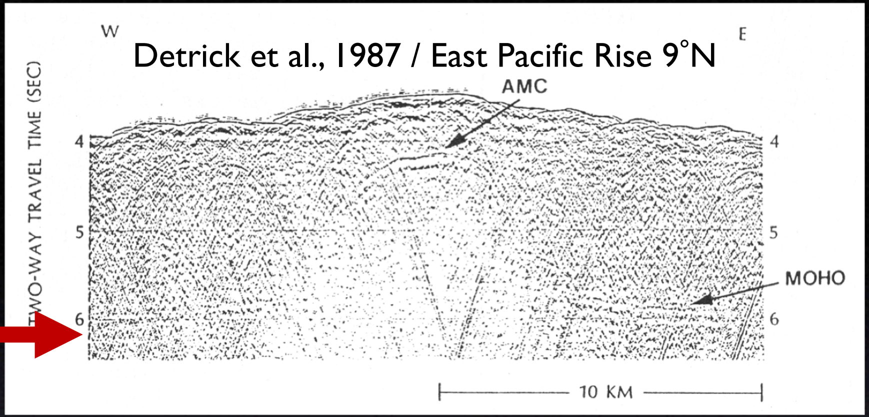

Toomey et al., 1985 / Mid-Atlantic Ridge 23°N

SLOW SPREADING RIDGE : earthquakes down to 8 km below axial valley floor

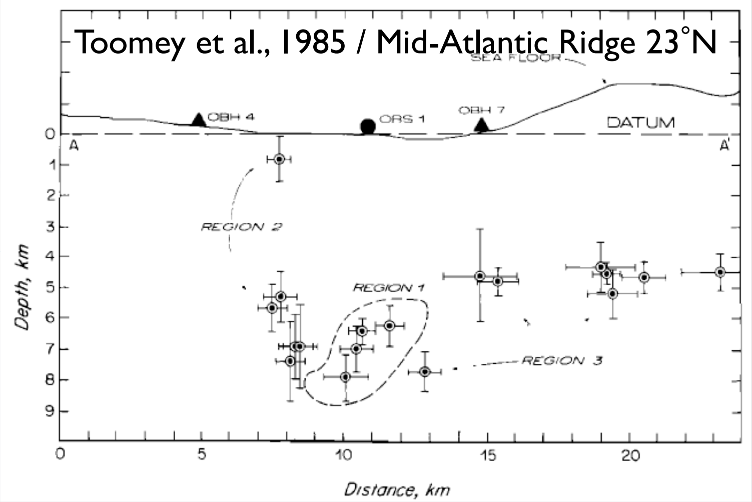
1985-present : spreading rate control on the thickness of the axial lithosphere (ie on the axial thermal regime)



Chen and Morgan, 1990


Detrick et al., 1987 / East Pacific Rise 9°N

FAST SPREADING RIDGE : permanent melt lense < 2 km below top of axial high

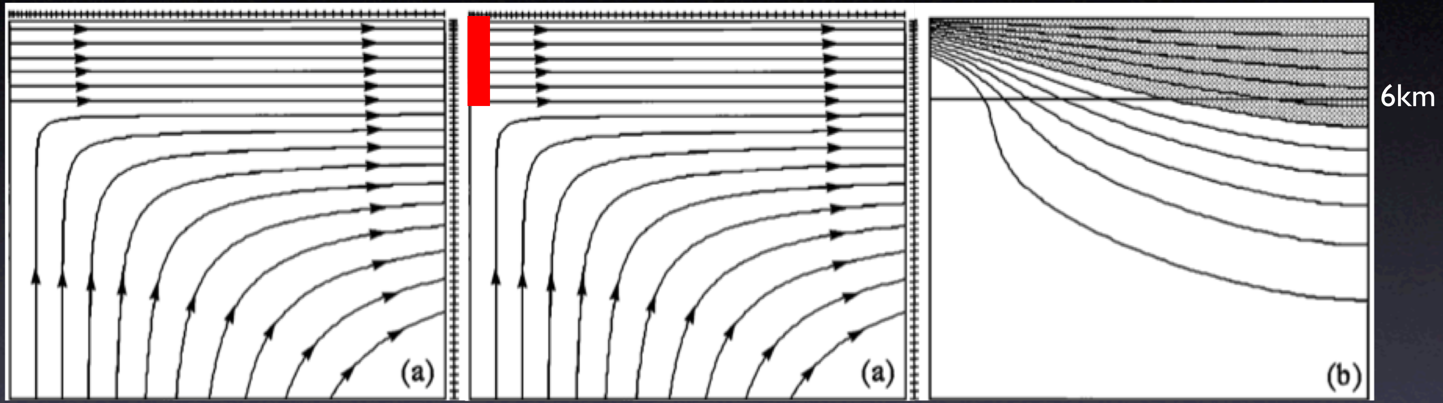

Toomey et al., 1985 / Mid-Atlantic Ridge 23°N

SLOW SPREADING RIDGE : earthquakes down to 8 km below axial valley floor

1987-1990 : hydrothermal circulation must transfer most of the magmatic heat of mid-ocean ridges*

A 2D conductive model of the axial thermal regime

Phipps Morgan et al., 1987



Passive mantle upwelling beneath the ridge (spreading rate is 2 cm/yr)

+

Magma is emplaced over the whole thickness of the crust (6 km) and at a steady state rate

=

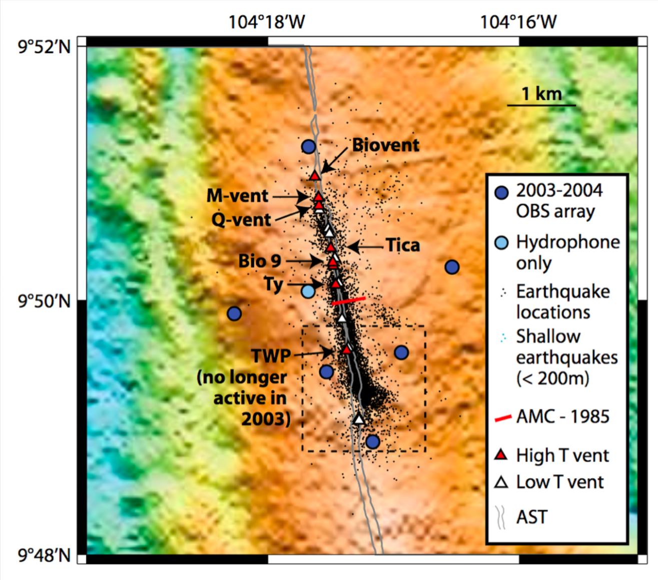
Modelled thermal regime for conductive cooling is too hot !

Isotherms spaced by 100°C
Shaded : < 600°C (brittle lithosphere)

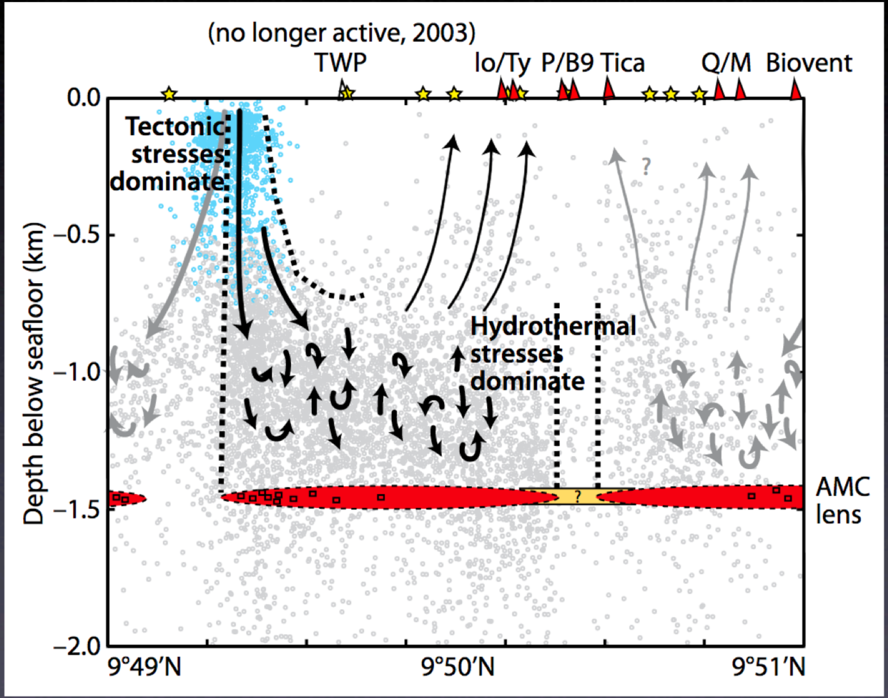
---

* mid-ocean ridges are the most important volcanic chain on Earth

FAST RIDGES : hydrothermal systems operate ALONG-AXIS in the narrow domain where most eruptions occur. They appear coupled with magma dynamics in the axial magma lense.



East Pacific Rise 9°N

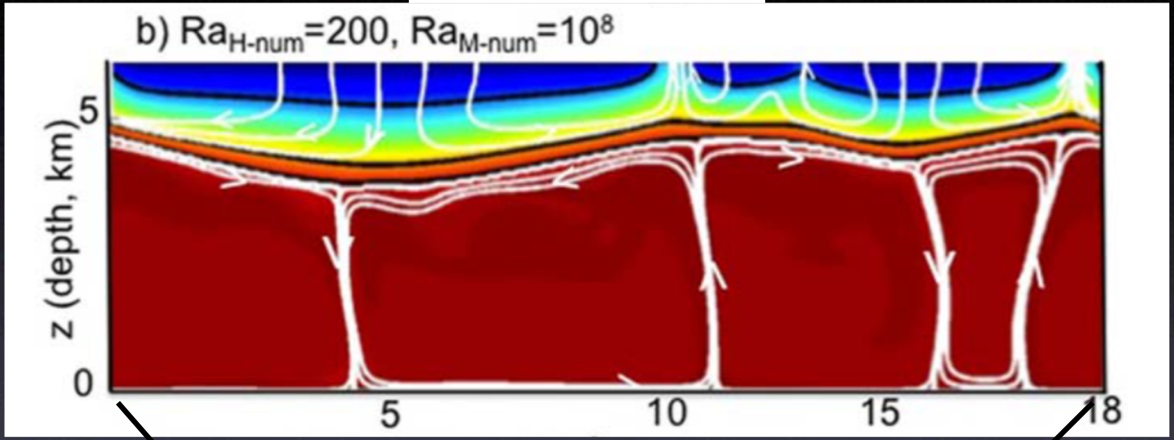


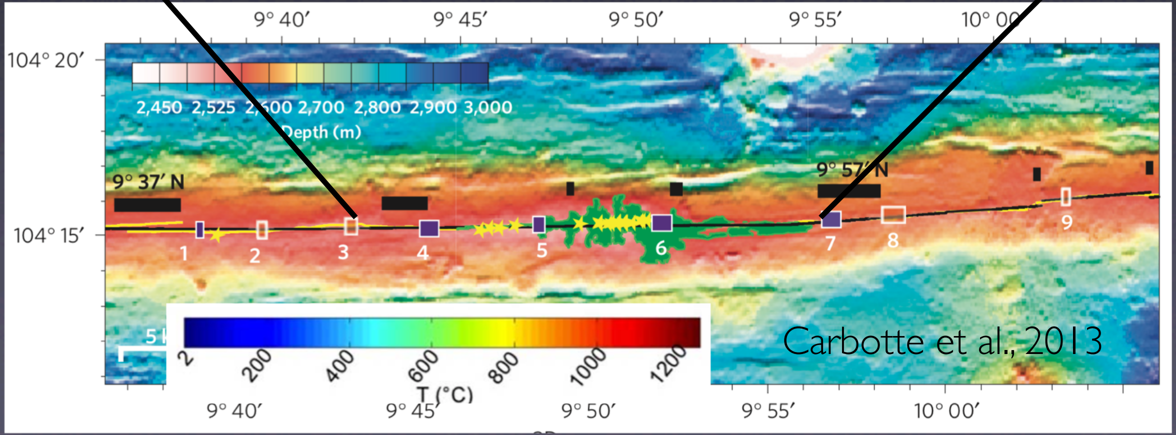
Figures in Tolstoy et al., 2008; Lowell et al., 2012; Wilcock et al., 2009; Carbotte et al., 2013; Marjanovic et al., 2017

FAST RIDGES : could ALONG-AXIS hydrothermal convections be coupled to convection of melt+crystals mush in narrow melt rich axial domain ?

ALONG-AXIS

Fontaine et al., 2017

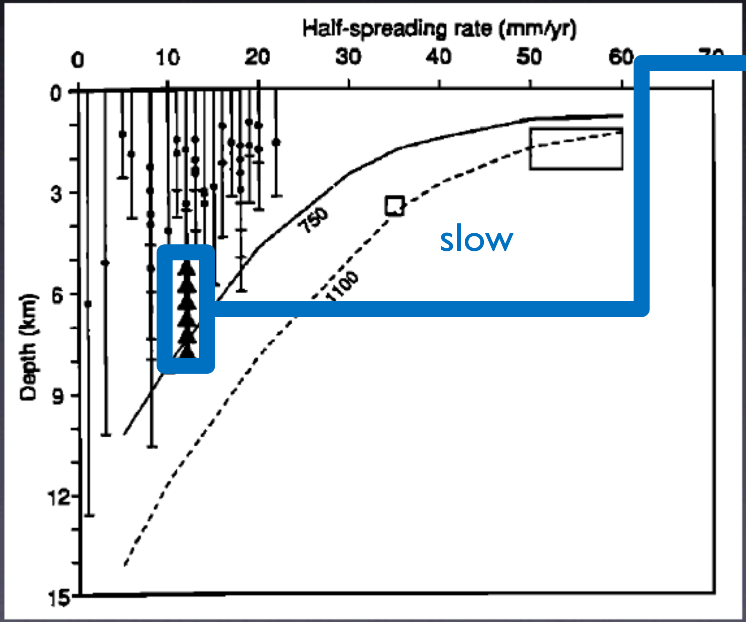




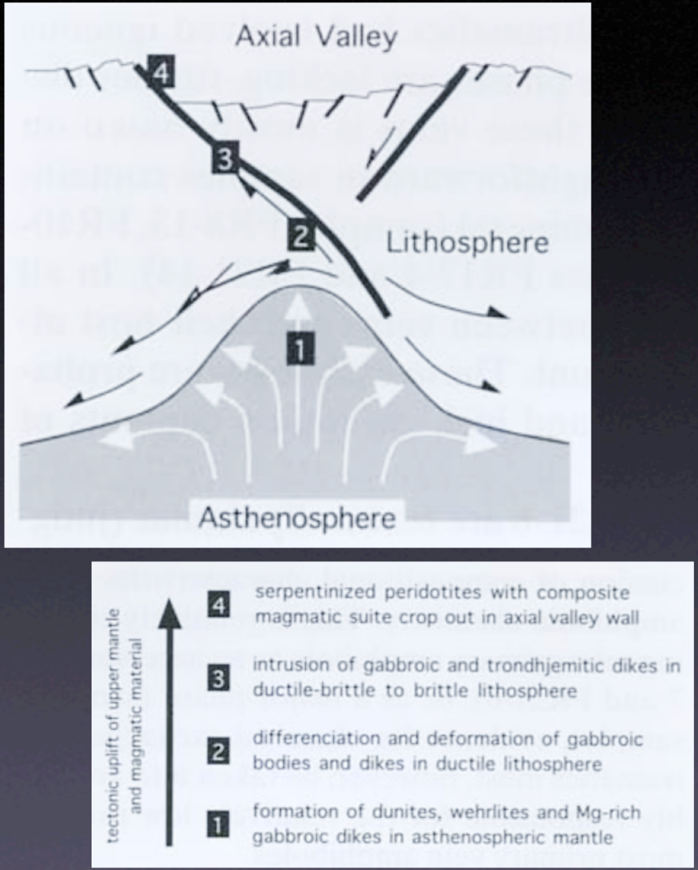
Carbotte et al., 2013

AT SLOW RIDGES thick axial lithosphere (cold axial thermal regime) causes the formation of large offset normal faults and impacts magmatic processes.

These faults accommodate the emplacement of mantle-derived peridotites at the seafloor.



Chen and Morgan, 1990



4 serpentinized peridotites with composite magmatic suite crop out in axial valley wall

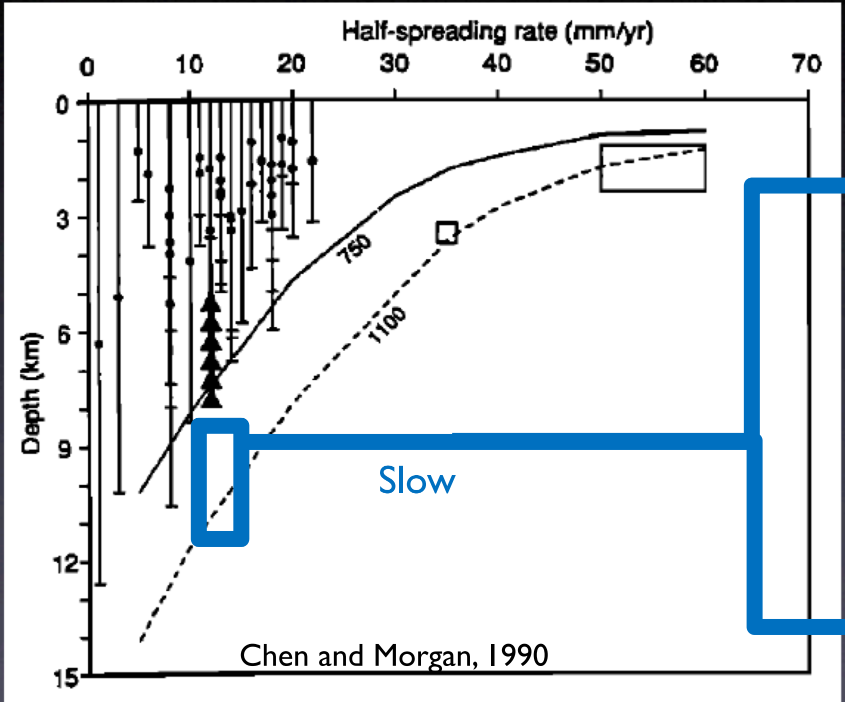
3 intrusion of gabbroic and trondhjemitic dikes in ductile-brittle to brittle lithosphere

2 differenciation and deformation of gabbroic bodies and dikes in ductile lithosphere

1 formation of dunites, wehrlites and Mg-rich gabbroic dikes in asthenospheric mantle

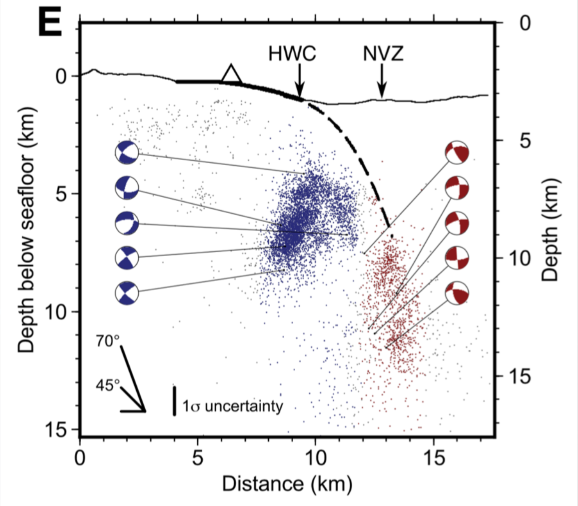
Cannat, 1993; figure from Cannat and Casey, 1995

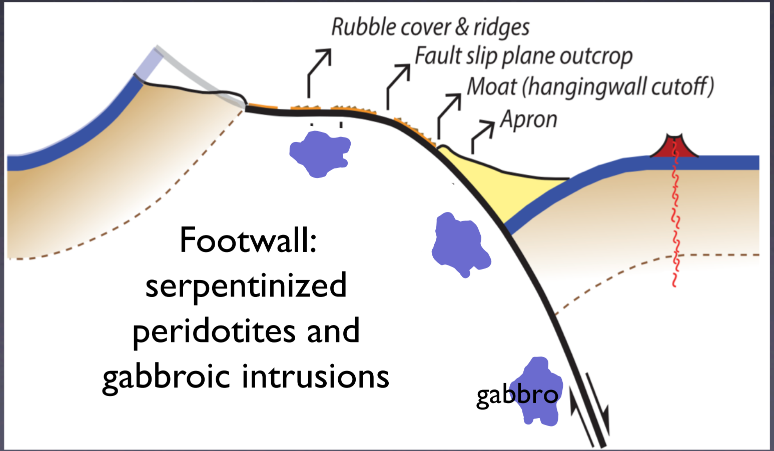
AT SLOW RIDGES thick axial lithosphere (cold axial thermal regime) causes the formation of large offset normal faults and impacts magmatic processes.



Chen and Morgan, 1990

Parnell-Turner et al., 2017
Mid-Atlantic Ridge 13°N





Cann et al., 1997; Lavier et al., 1999; Smith et al., 2006; deMartin et al., 2007; MacLeod et al., 2009; figure after Escartin et al., 2017

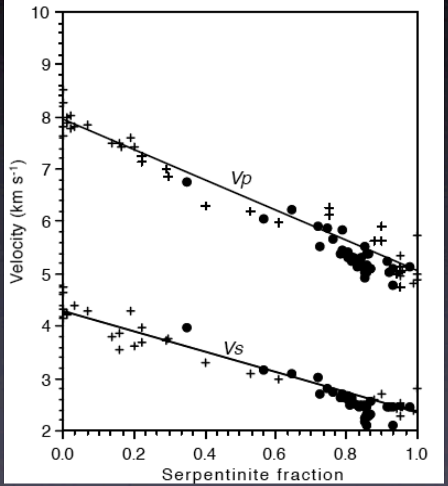
2 TYPES OF OCEANIC CRUST :

-I-

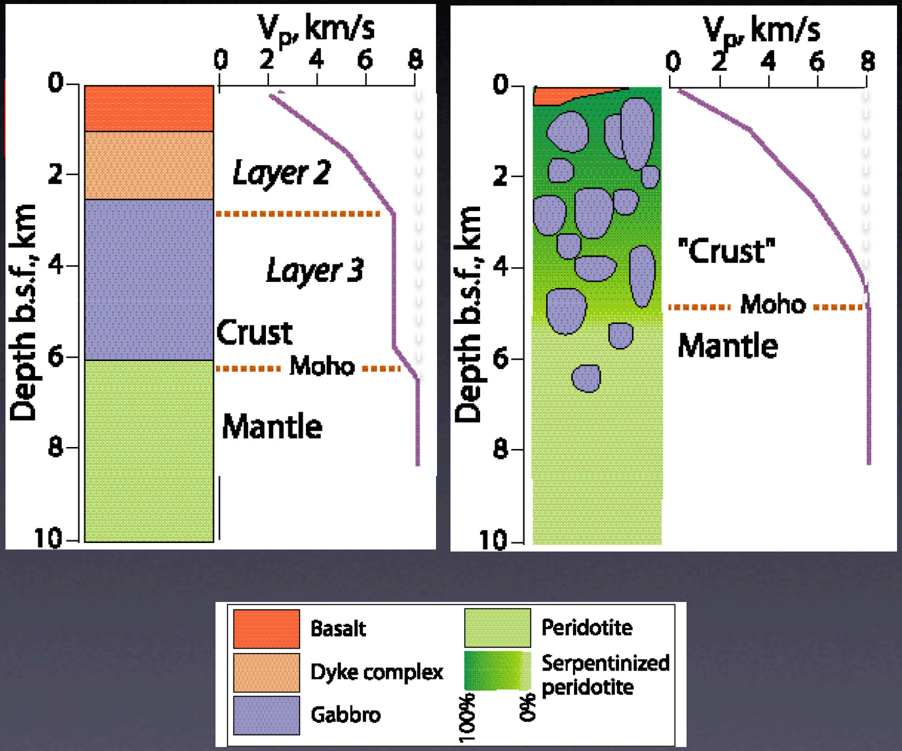
Penrose-type oceanic crust

-II-

Footwall of axial detachment faults at slow ridges

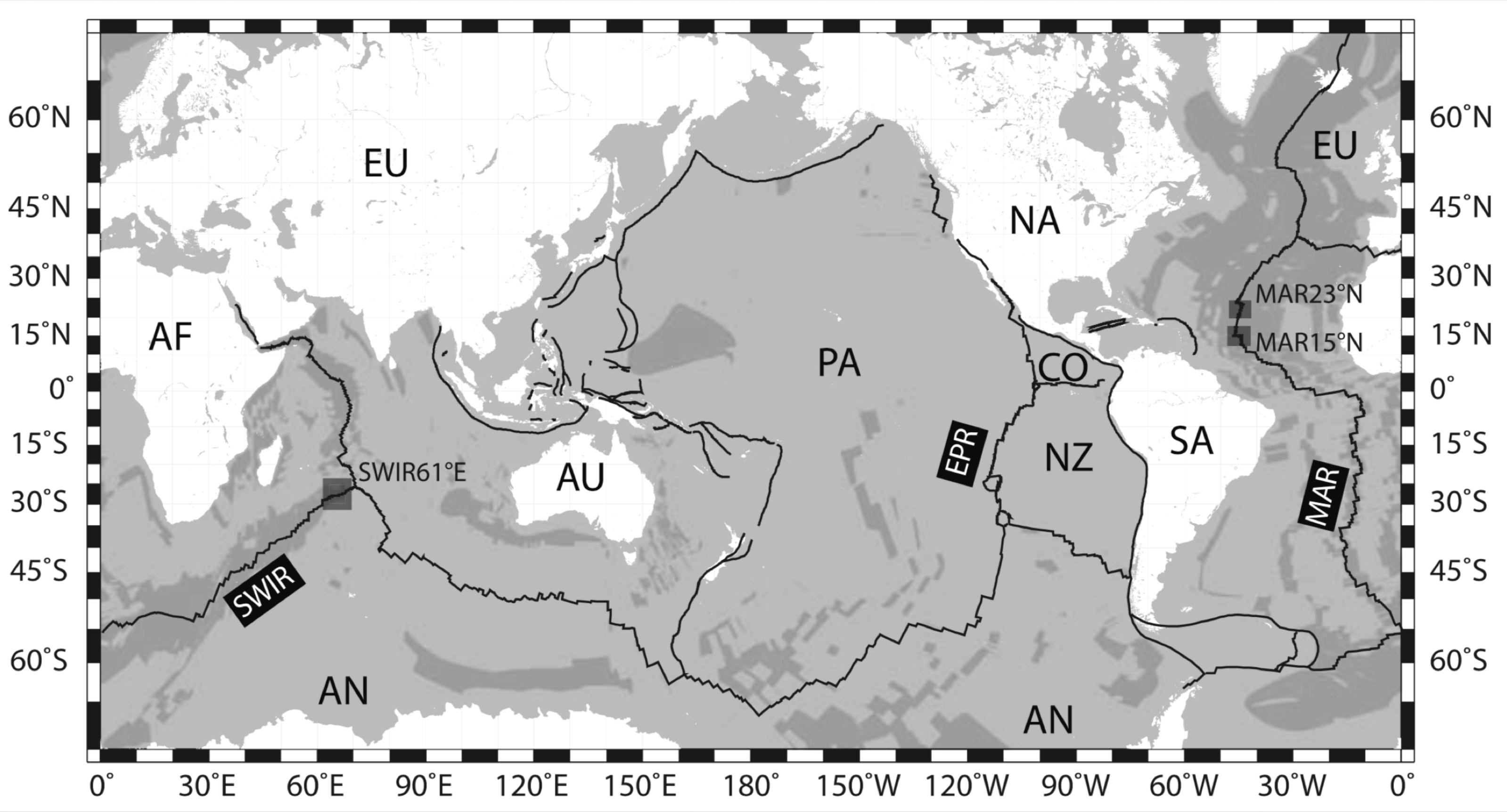


Miller & Christensen, 1997



Cannat et al., Geology 1995

Ultramafic seafloor (= footwall of detachment faults) represents ~25% of slow-spread seafloor (darker grey areas in map)



Cannat et al., 1995; Escartin et al., 2008; figure in Cannat et al., 2010 after Bird 2003

FAST & SLOW RIDGES : a diversity of hydrothermal systems

Basalt-hosted &
magma-fueled
(sulfide deposit)

@ CNRS-Ifremer. Lucky Strike vent field Mid Atlantic Ridge

ultramafic-hosted &
non magma-fueled
(carbonate deposit)

@ CNRS-Ifremer. Old City vent field Southwest Indian Ridge

FAST & SLOW RIDGES : a diversity of hydrothermal systems

$HCO_3^- + Ca^{2+} + OH^-$

$Mg^{2+} + 2\ OH^-$

$\Downarrow$

$CaCO_3 + H_2O$

$Mg(OH)_2$

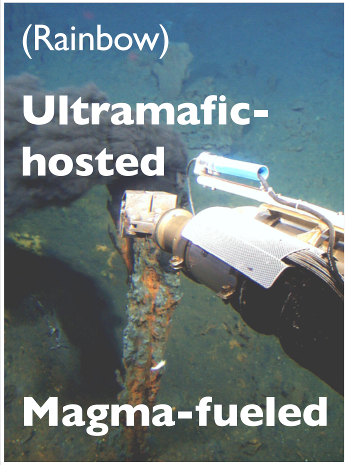
non magma-fueled ultramafic-hosted vents have low fluxes (heat, volume) of high pH serpentinization-derived fluids, yet cause the precipitation of large volumes of carbonates …

ultramafic-hosted & non magma-fueled (carbonate deposit)

@ CNRS-Ifremer. Old City vent field Southwest Indian Ridge

Ludwig et al., 2006; Kelley et al., 2005; Cannat et al., in prep.

FAST & SLOW RIDGES : a diversity of endmember hydrothermal fluids

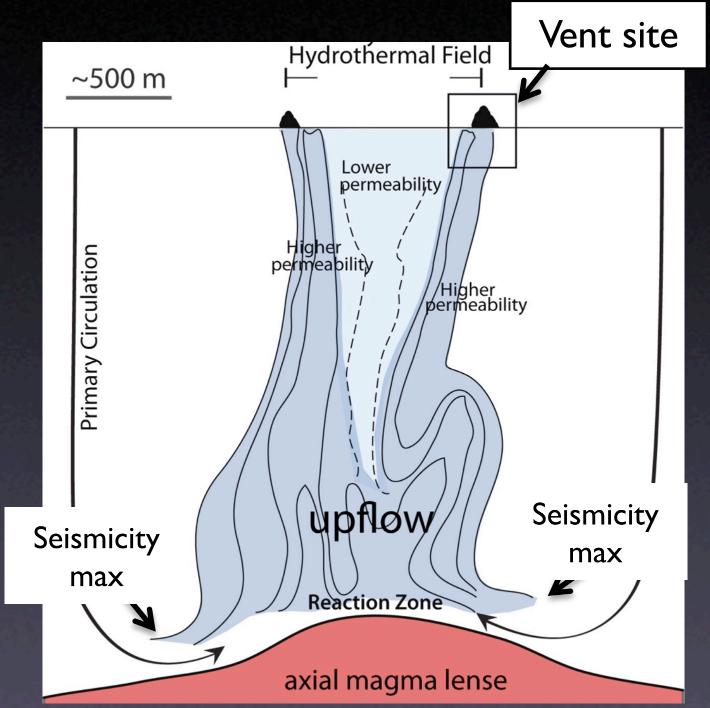


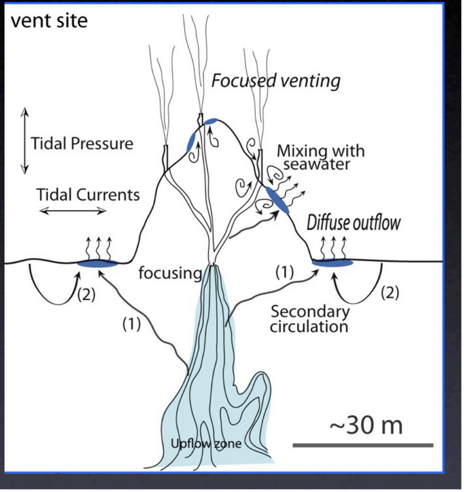
	T °C	**pH**	**H2** mmol/kg	**CH4** mmol/kg	**CO2** mmol/kg	**Fe** µmol/kg
Lucky Strike	330	3	0.02-0.7	0.5-0.9	13-28	30-862
Rainbow	365	2.8	16	2.5	16	24000
Lost City	90	11	0.5-15	1-2	$<10^{-3}$	-

Charlou et al., 2002;
Kelley et al., 2005

FAST & SLOW RIDGES: hydrothermal fluxes are poorly constrained and partitionned into focused (<<) and diffuse (>>) vents.

Ex: 9°50'N EPR smokers
40±15 MW / diffuse 300±200 MW *





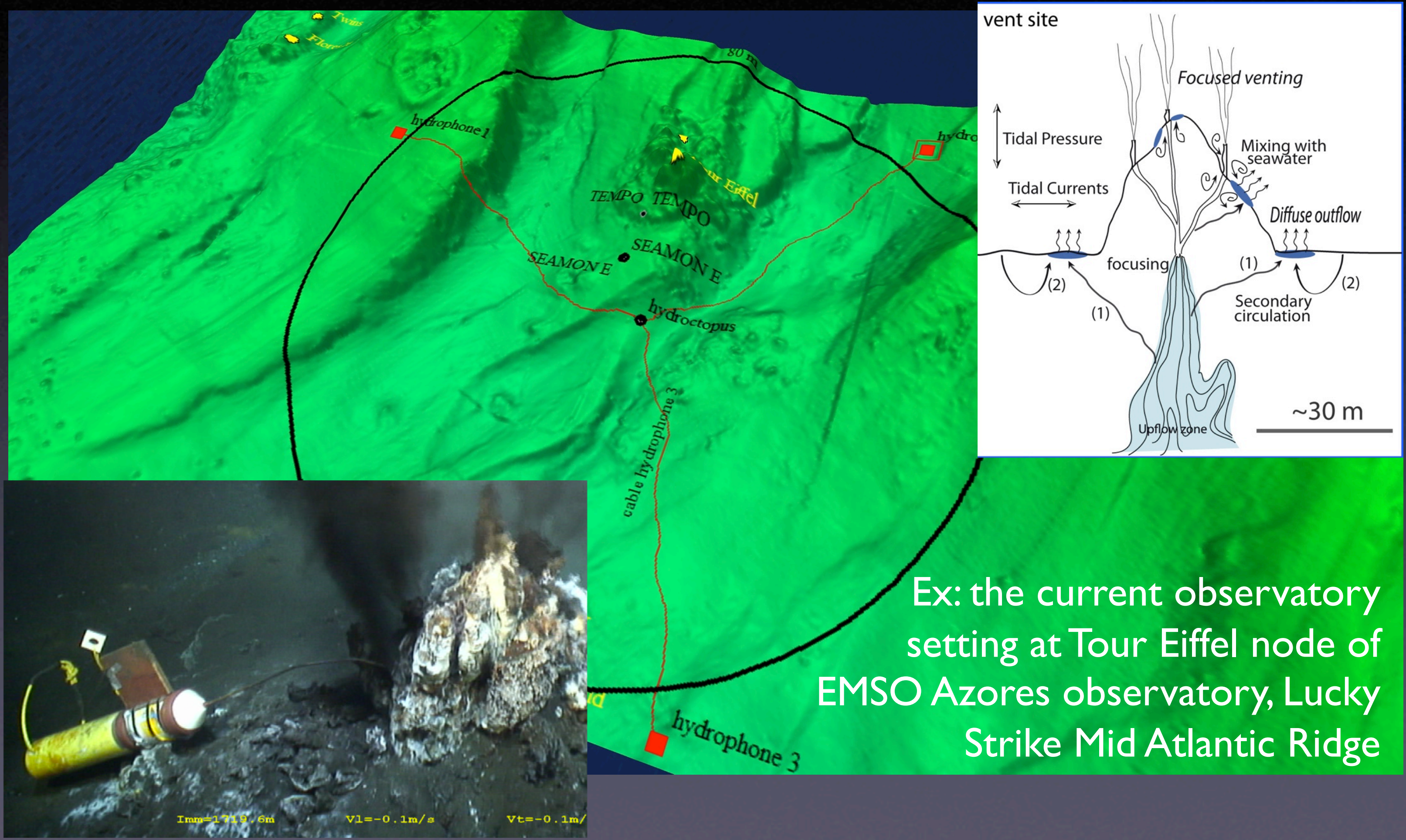
Focused vent (black smoker)

Diffuse vents (where life is)

@ CNRS-Ifremer. Lucky Strike vent field Mid Atlantic Ridge

Tivey, 2007; Humphris and Cann, 2000; * Ramondenc et al., 2006; Barreyre et al., 2012

FAST & SLOW RIDGES: observatories to monitor primary and secondary hydrothermal circulations and their impact on life and heat+chemical transfers to ocean

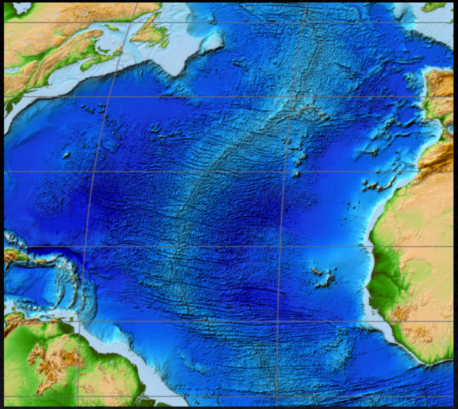


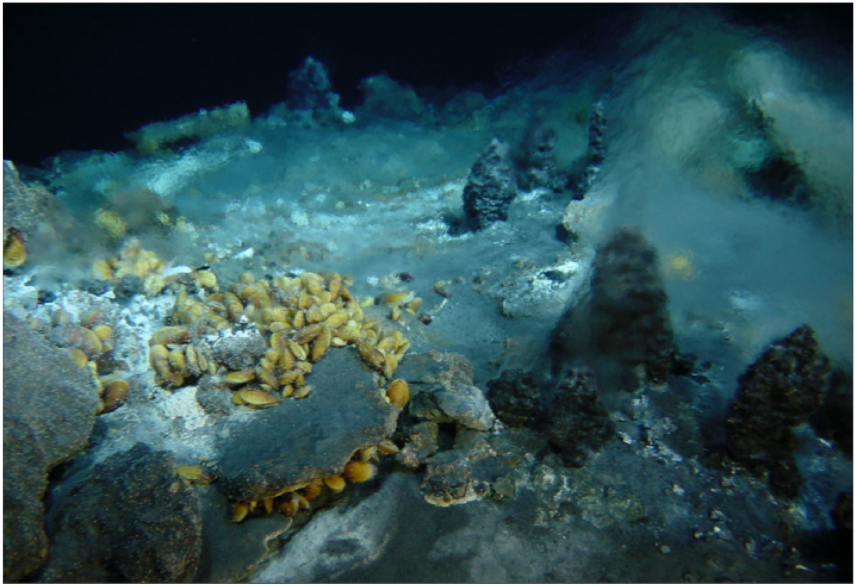
Ex: the current observatory setting at Tour Eiffel node of EMSO Azores observatory, Lucky Strike Mid Atlantic Ridge

mid-ocean ridge research perspectives (1)

Study mid-ocean ridges as part of a more global system that includes life and the ocean.

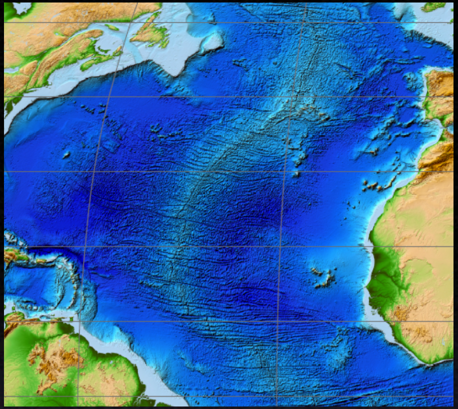
Use mid-ocean ridges as natural laboratories to monitor active processes such as faulting and seismicity, volcanism, and fluid-rock-life interactions





@ CNRS-Ifremer. Lucky Strike vent field Mid Atlantic Ridge

mid-ocean ridge research perspectives (2)



Look at the old mantle under the young seafloor, understand the impact of plumes and the inheritance of past plate tectonic cycles