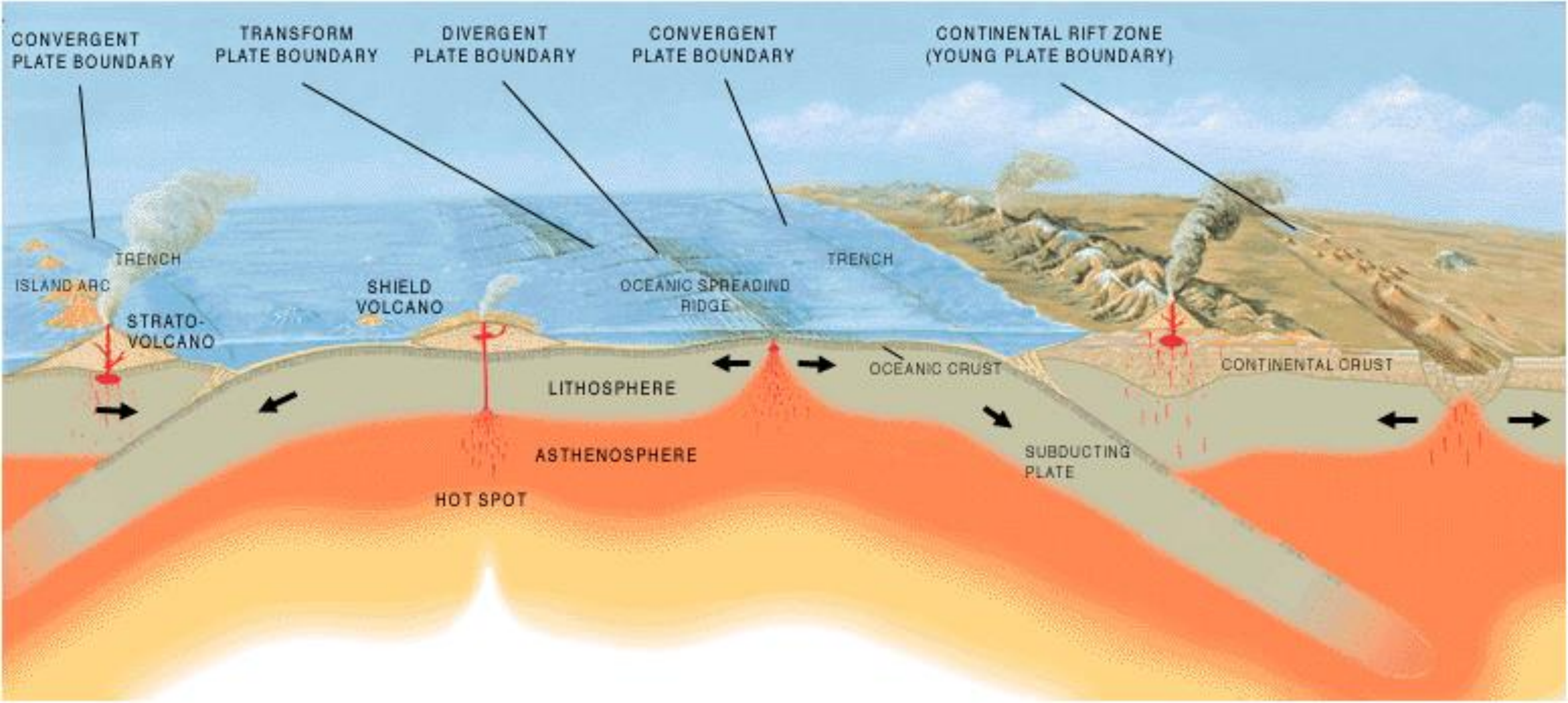
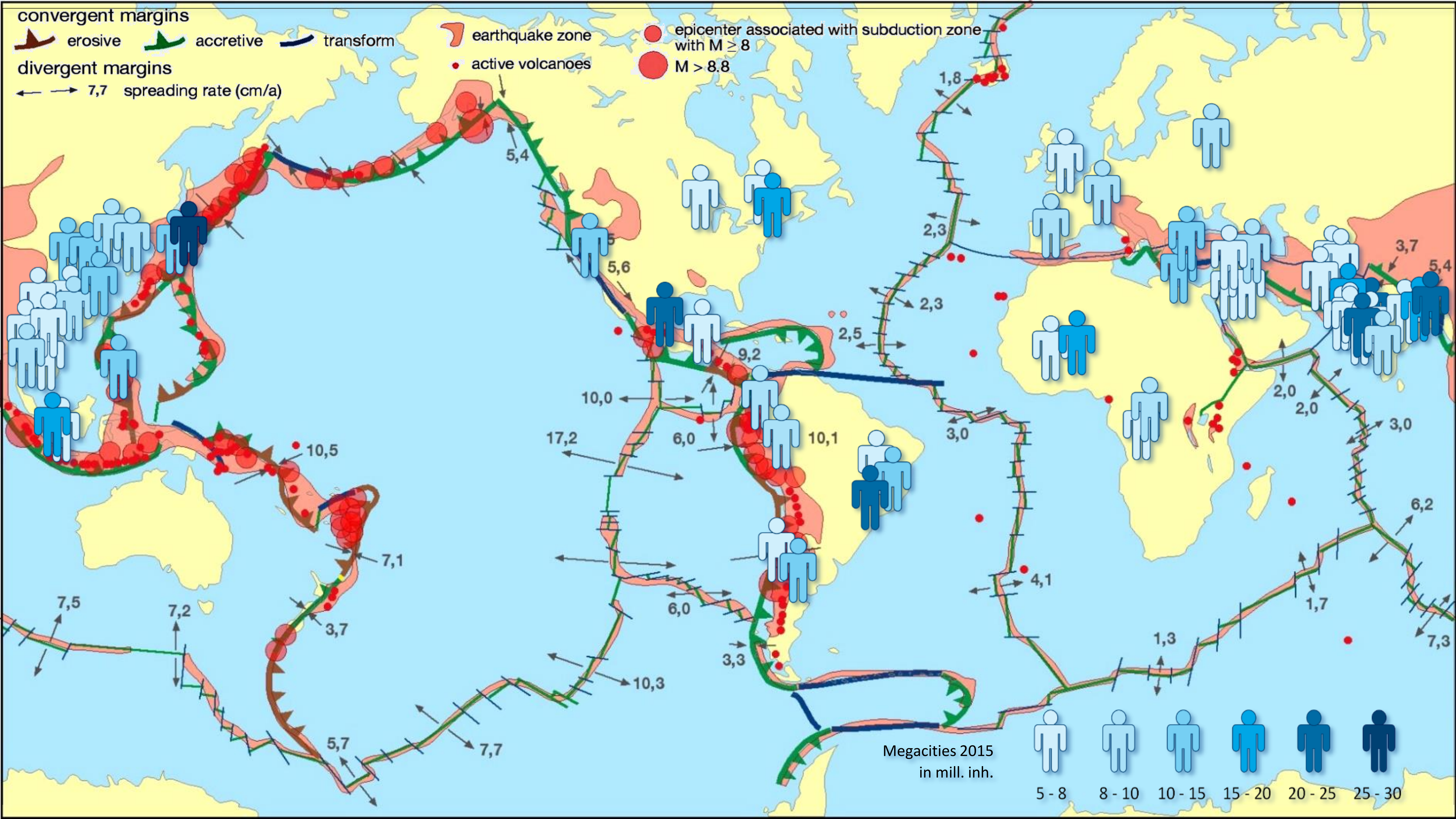
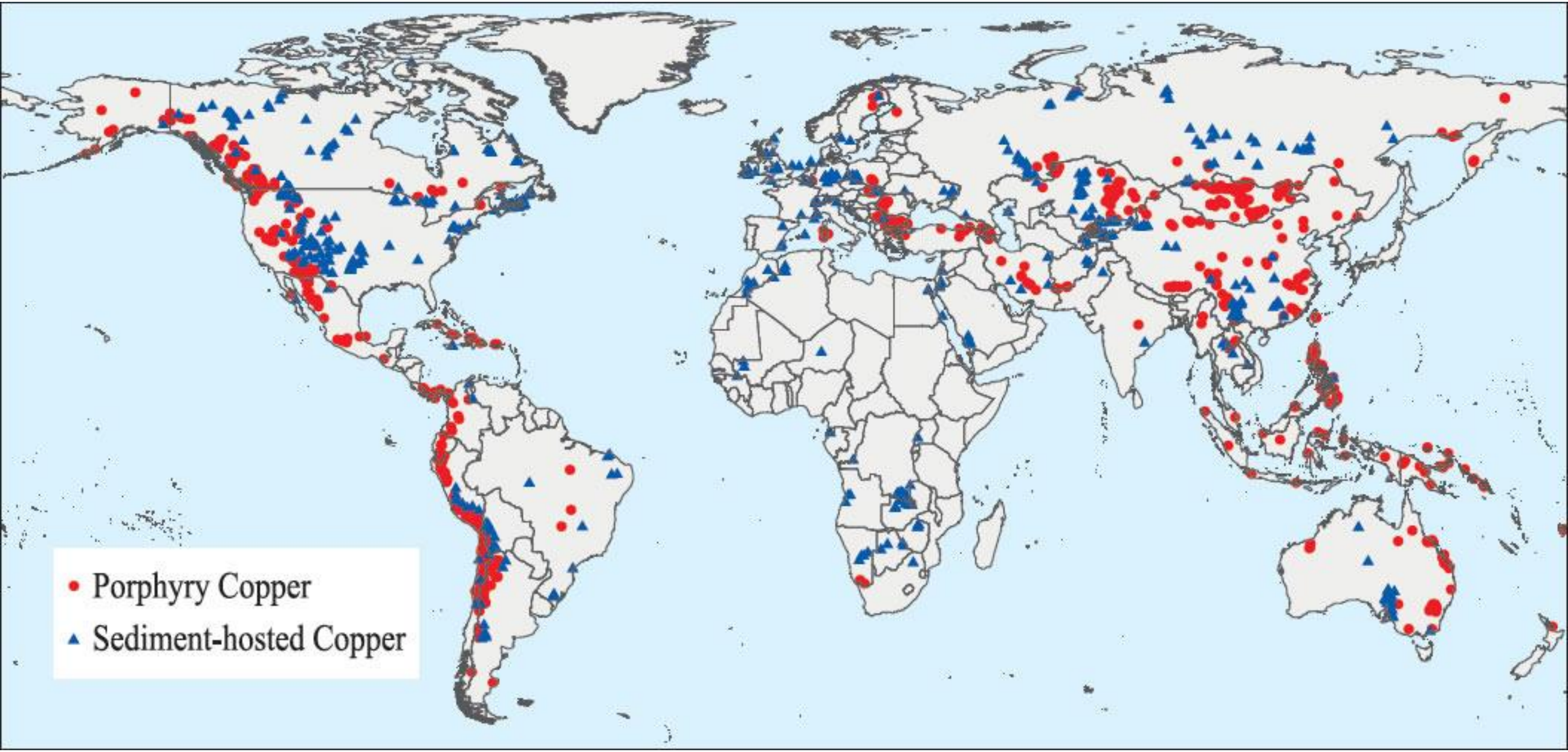
PLATE TECTONICS: A GEOLOGICAL PERSPECTIVE

Onno Oncken, GFZ Potsdam

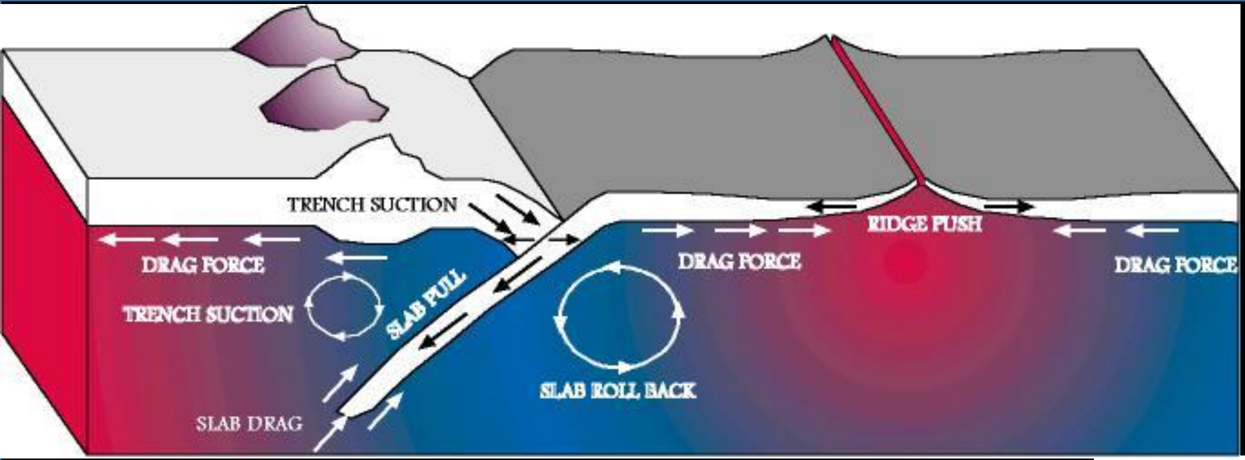


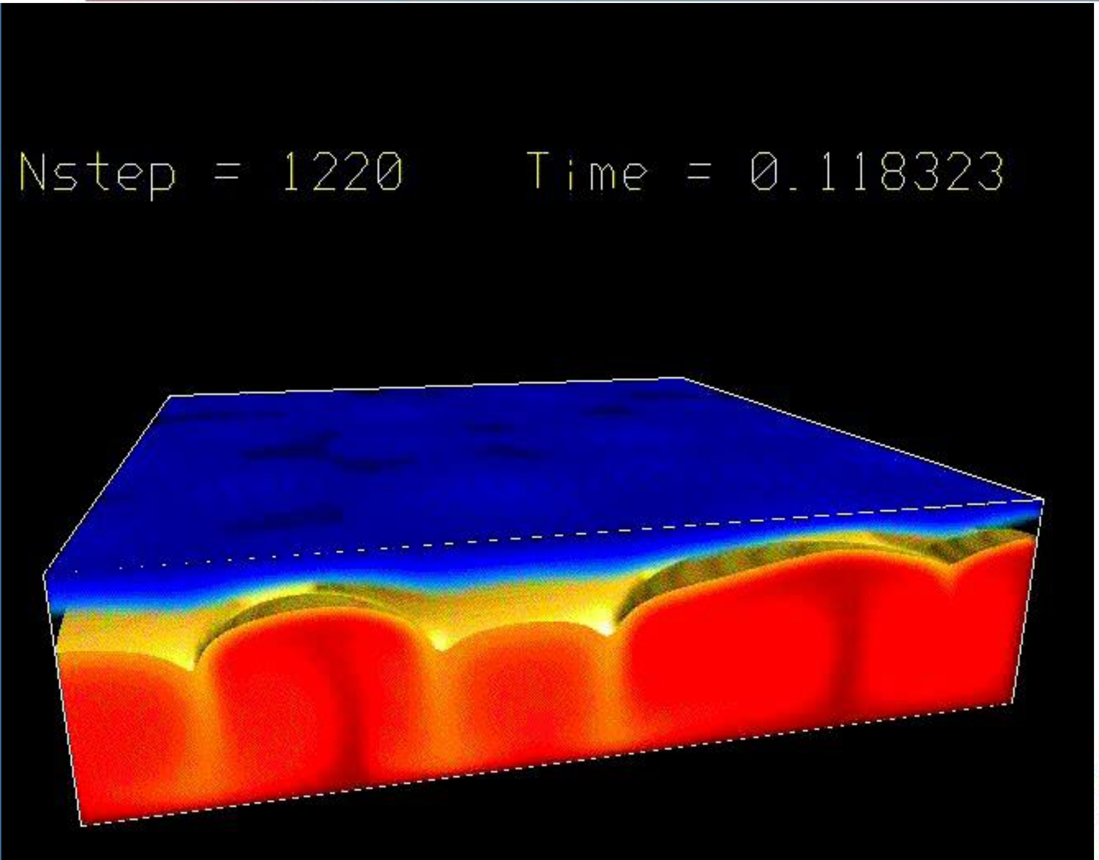

convergent margins
erosive
accretive
transform
divergent margins
7,7 spreading rate (cm/a)
earthquake zone
active volcanoes
epicenter associated with subduction zone with M ≥ 8
M > 8.8
1,8
5,4
2,3
5,6
2,3
2,5
9,2
10,0
17,2
6,0
10,1
3,0
3,7
5,4
2,0
2,0
3,0
10,5
7,1
6,2
4,1
1,7
7,5
7,2
3,7
6,0
3,3
1,3
7,3
10,3
7,7
5,7
Megacities 2015
in mill. inh.
5 - 8
8 - 10
10 - 15
15 - 20
20 - 25
25 - 30



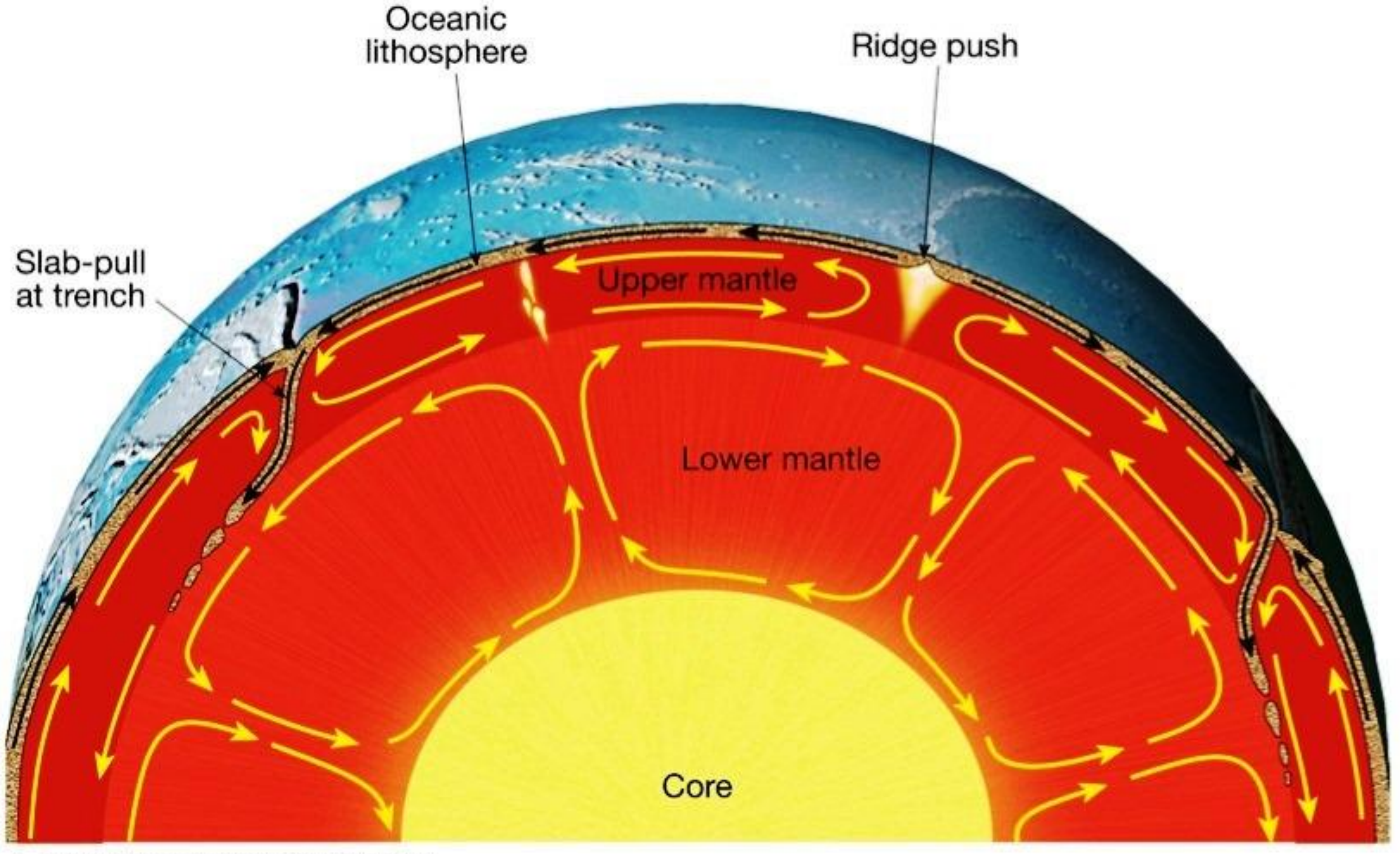
Source: USGS

Drivers and Forces

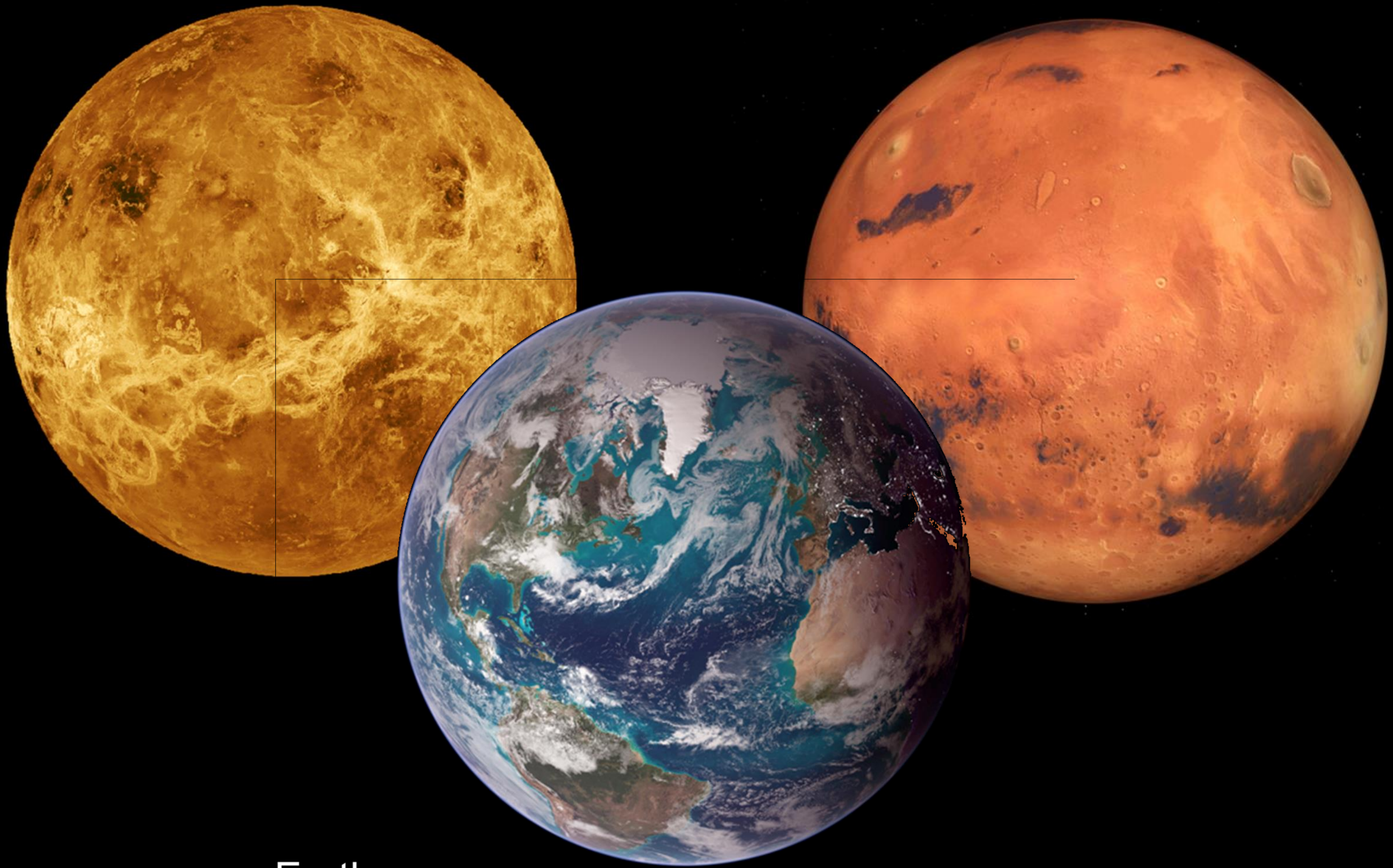




Convection model for 100 Myrs
courtesy of B. Hansen, Münster



A. Layering at 660 kilometers

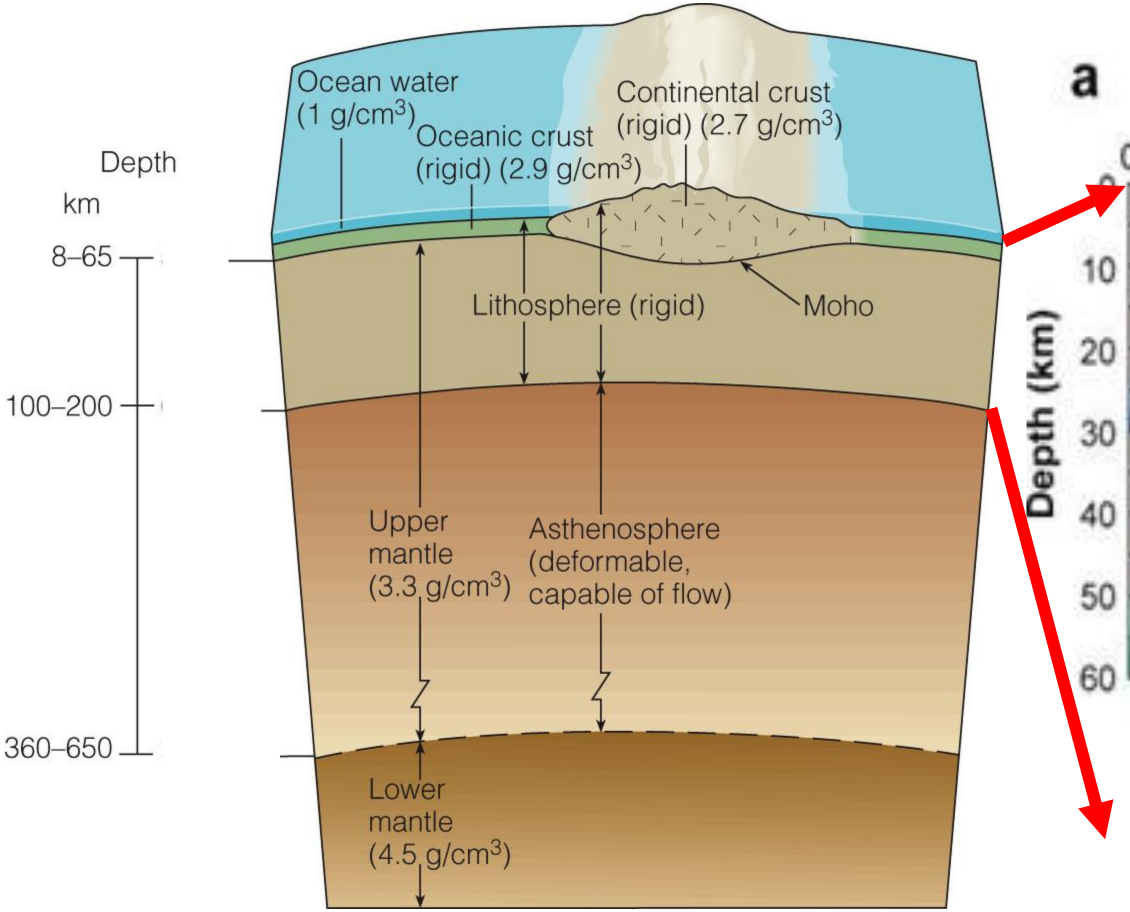


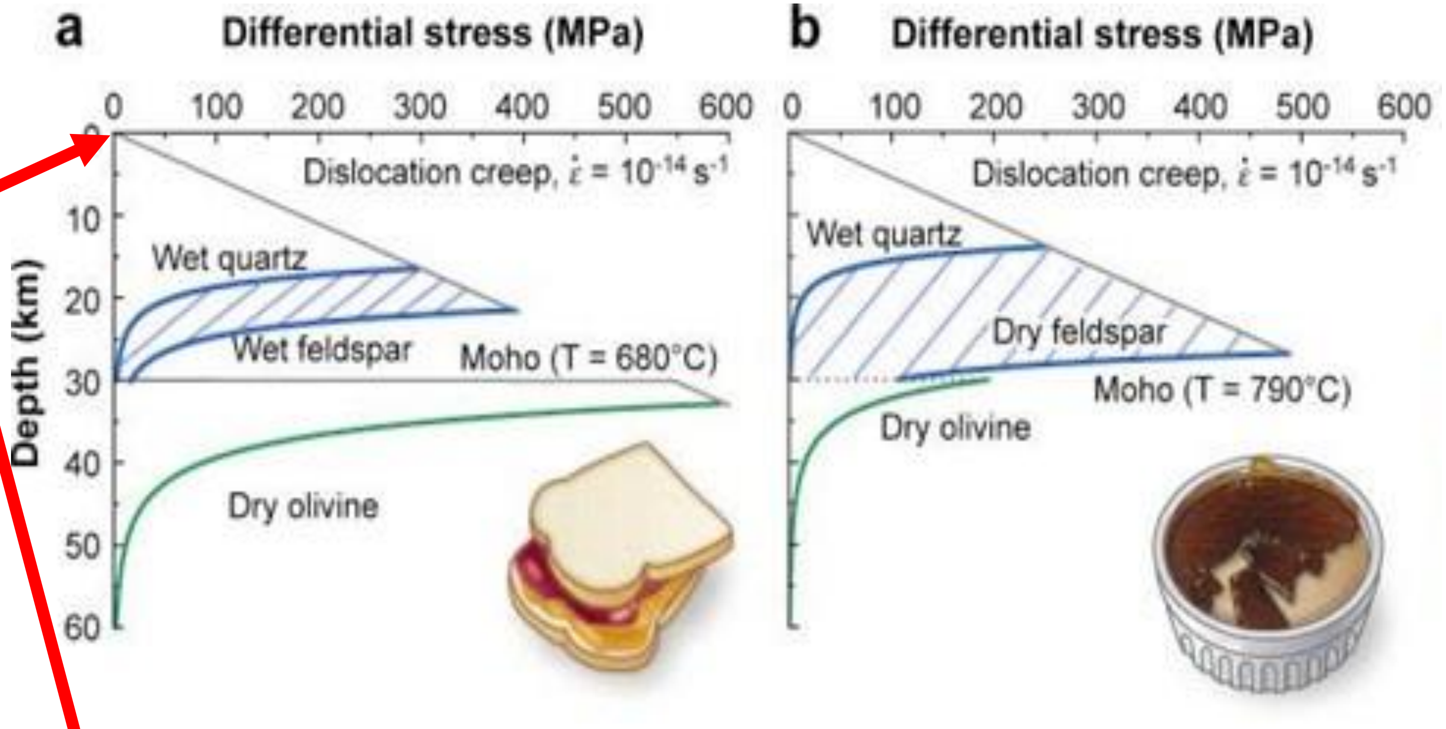
Venus

Mars

Earth

Lithosphere strength: A gourmet‘s perspective

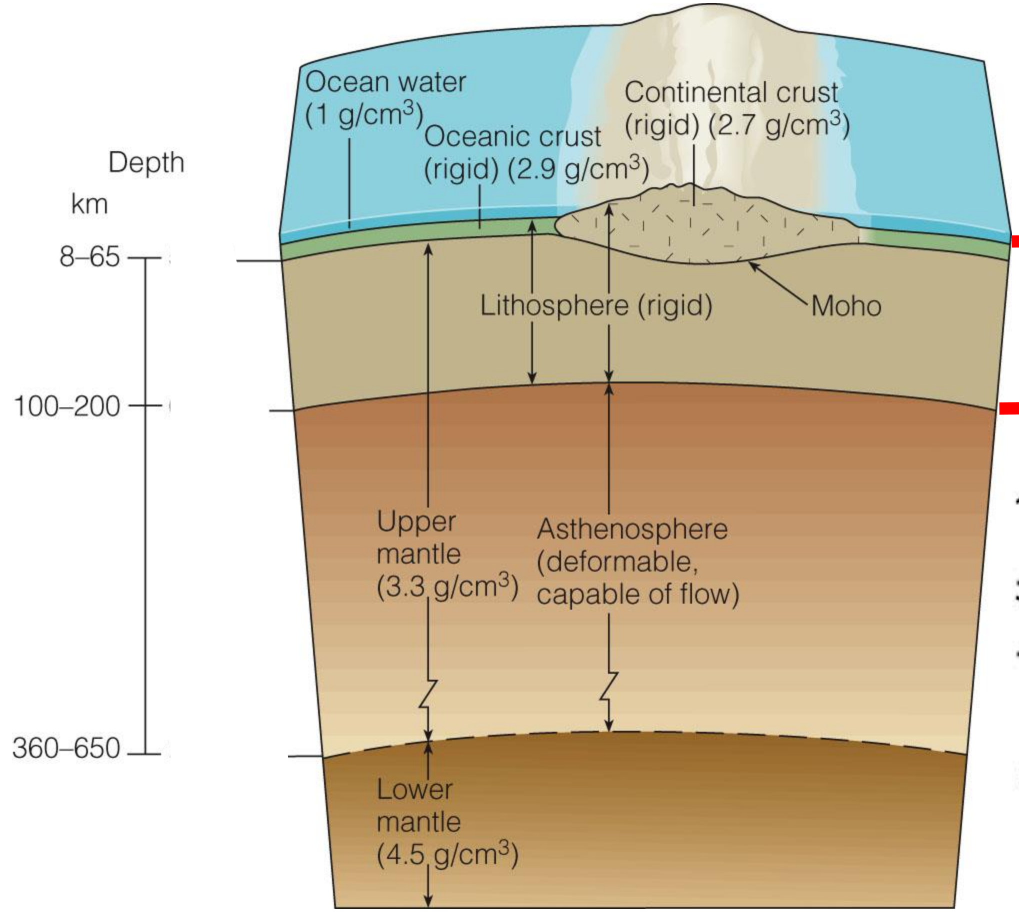


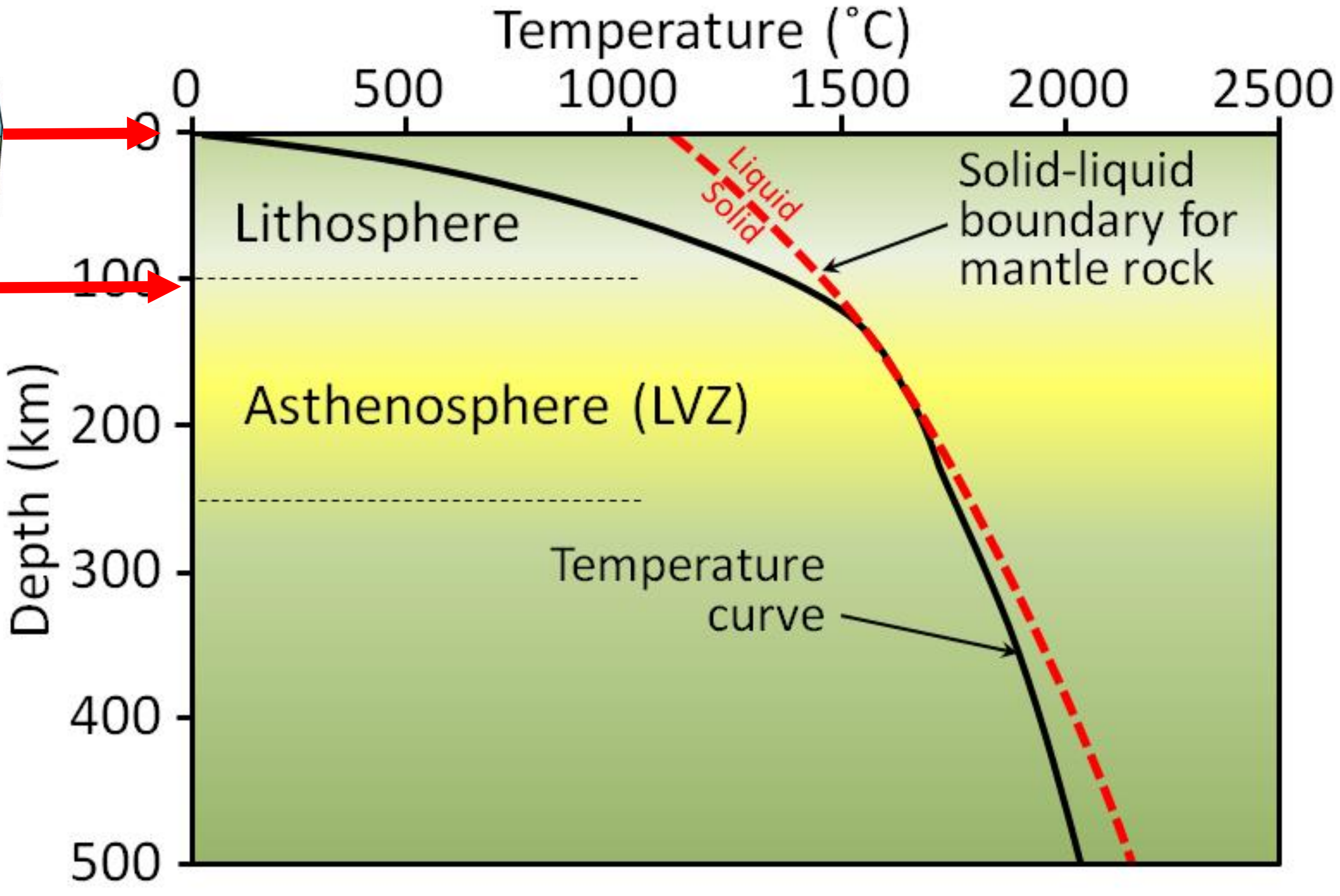


Jelly sandwich **Crème brulée**

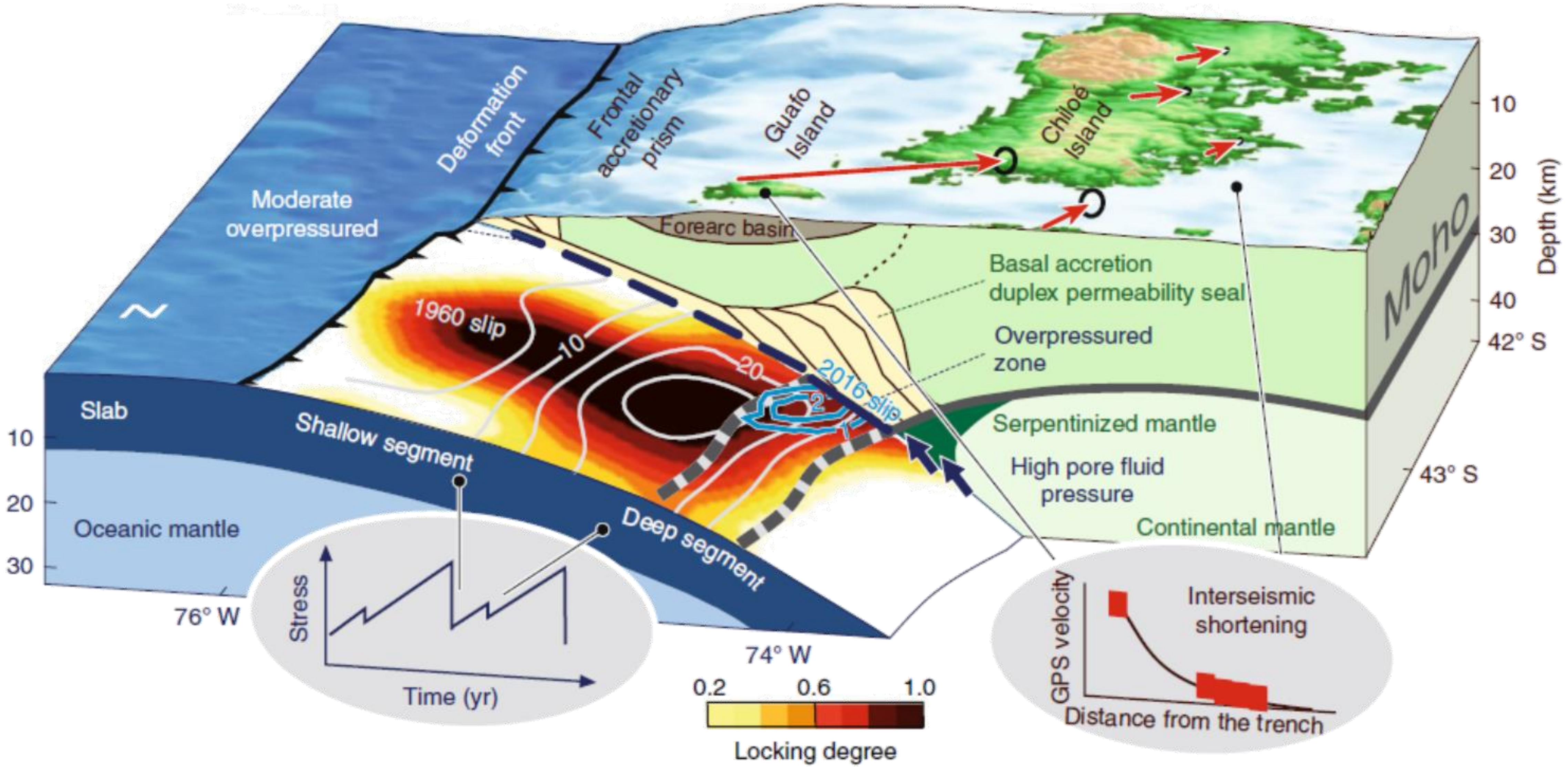
Source: Bürgmann & Dresen, 2008

… and why plates may move over the mantle



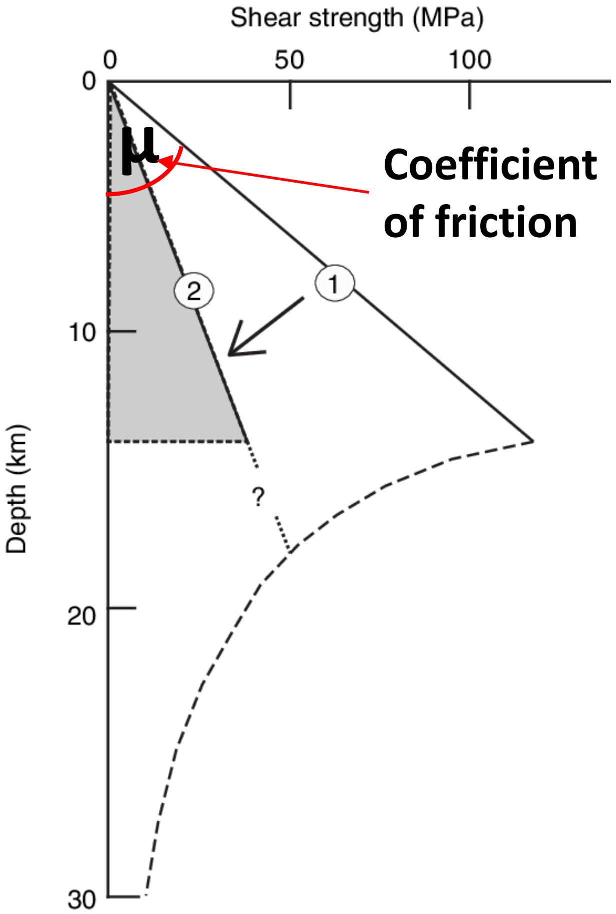


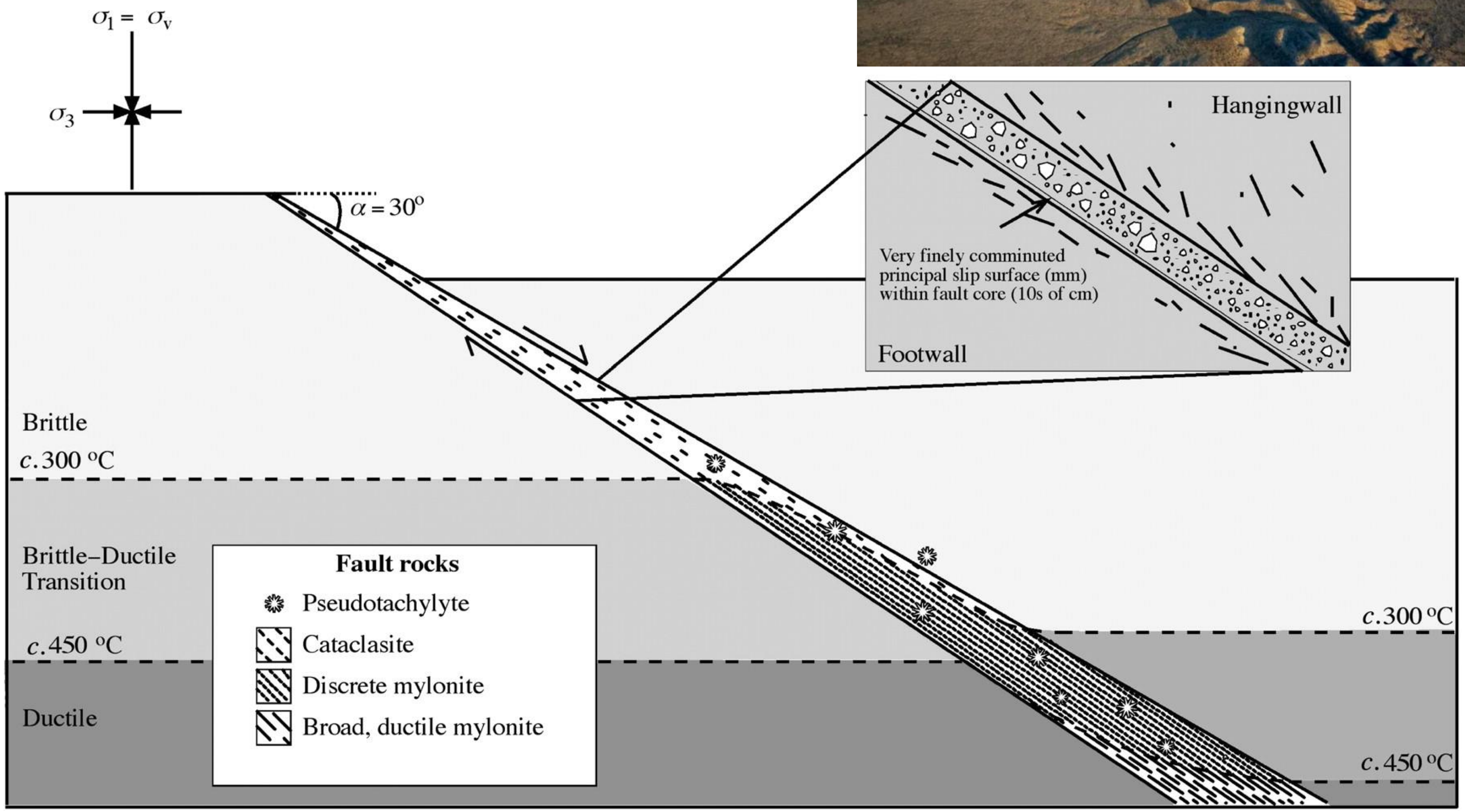
But why do they move past each other?



Source: Moreno et al., 2014, 2018

How weak are fault zone rocks?





What this means ….

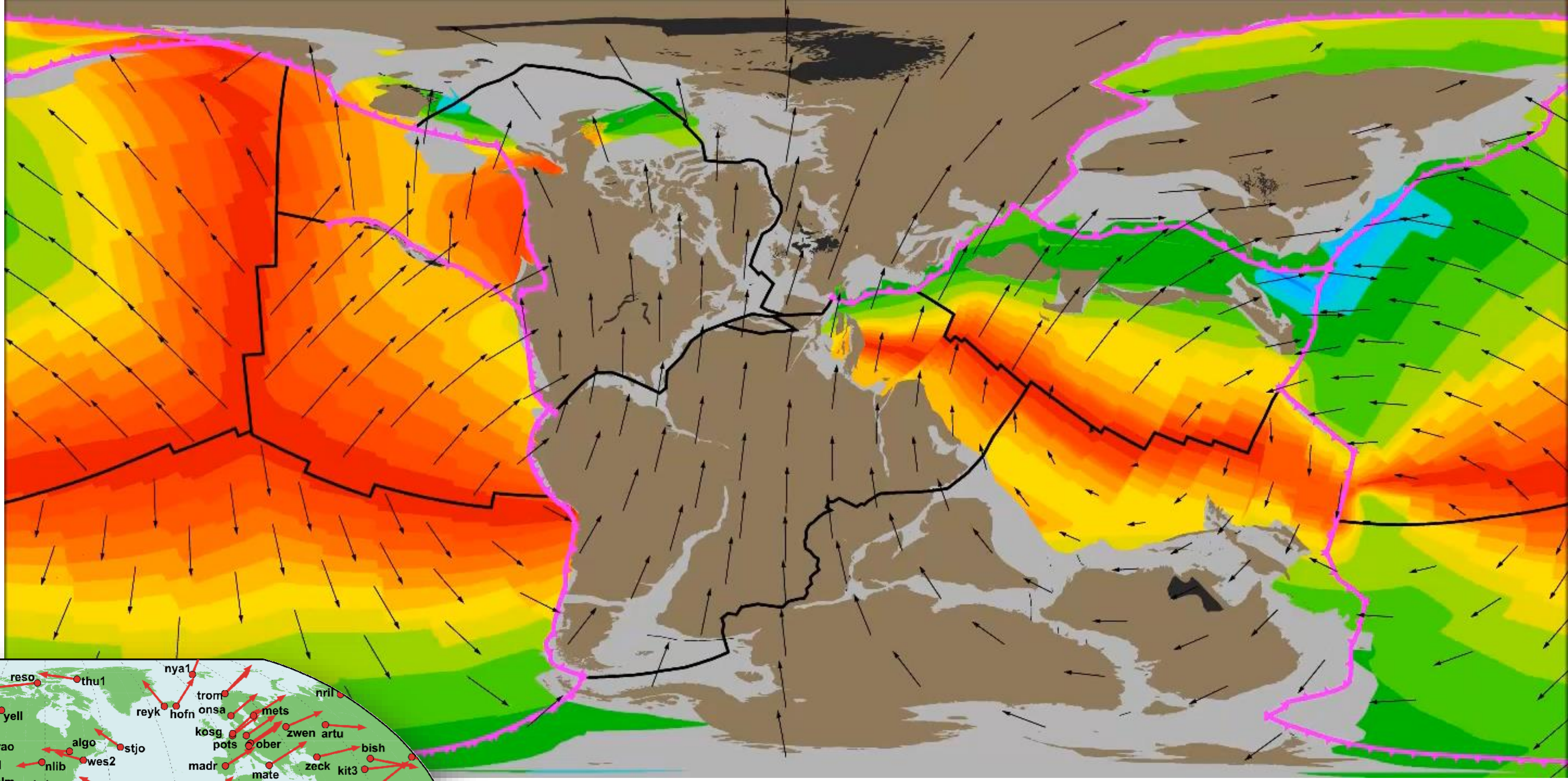
effective coefficient of friction on plate interface and active faults	< 0.1

friction of banana peel	≈ 0.07

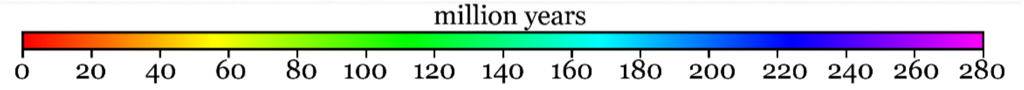
Awarded with 2014 Ig Nobel Prize

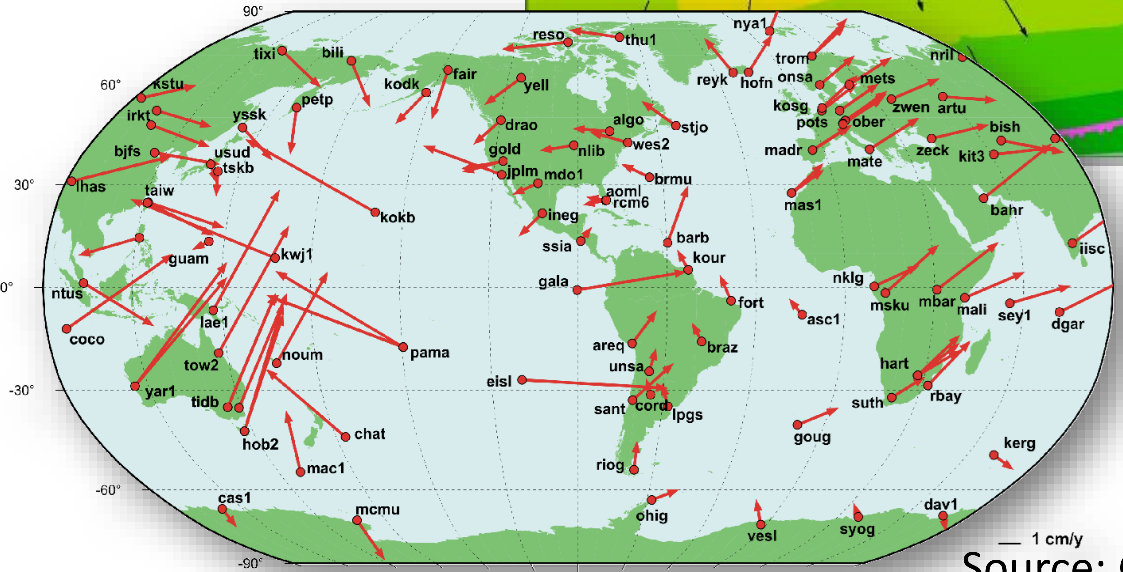
PHYSICS PRIZE:
for measuring the amount of friction between a shoe and a banana skin, and between a banana skin and the floor, when a person steps on a banana skin that's on the floor.
REFERENCE: "Frictional Coefficient under Banana Skin," Kiyoshi Mabuchi, Kensei Tanaka, Daichi Uchijima and Rina Sakai, Tribology Online 7, no. 3, 2012, pp. 147-151.

200 Mill. Years of plate motion – and present GPS

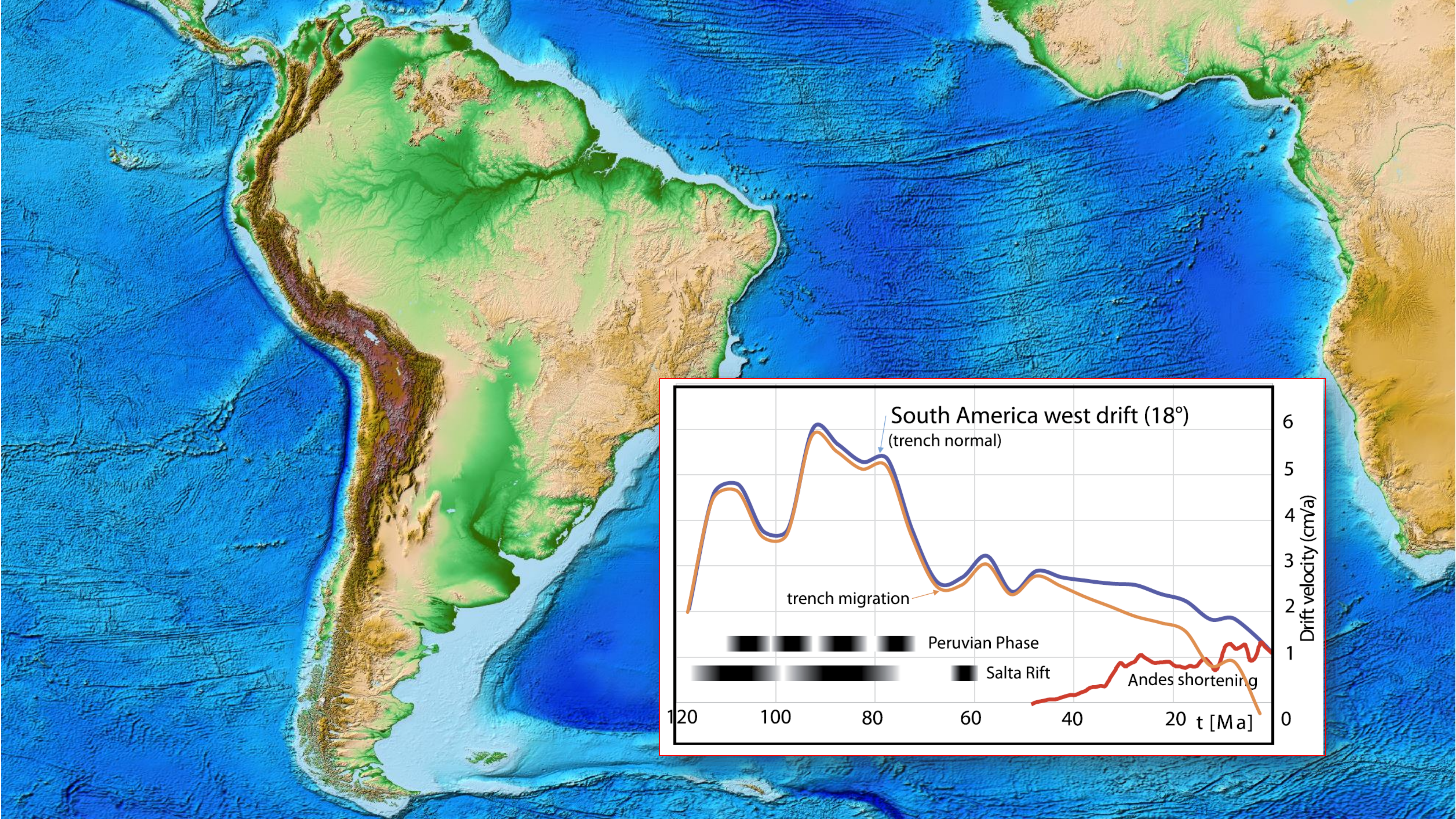


Gibbons et al., 2015

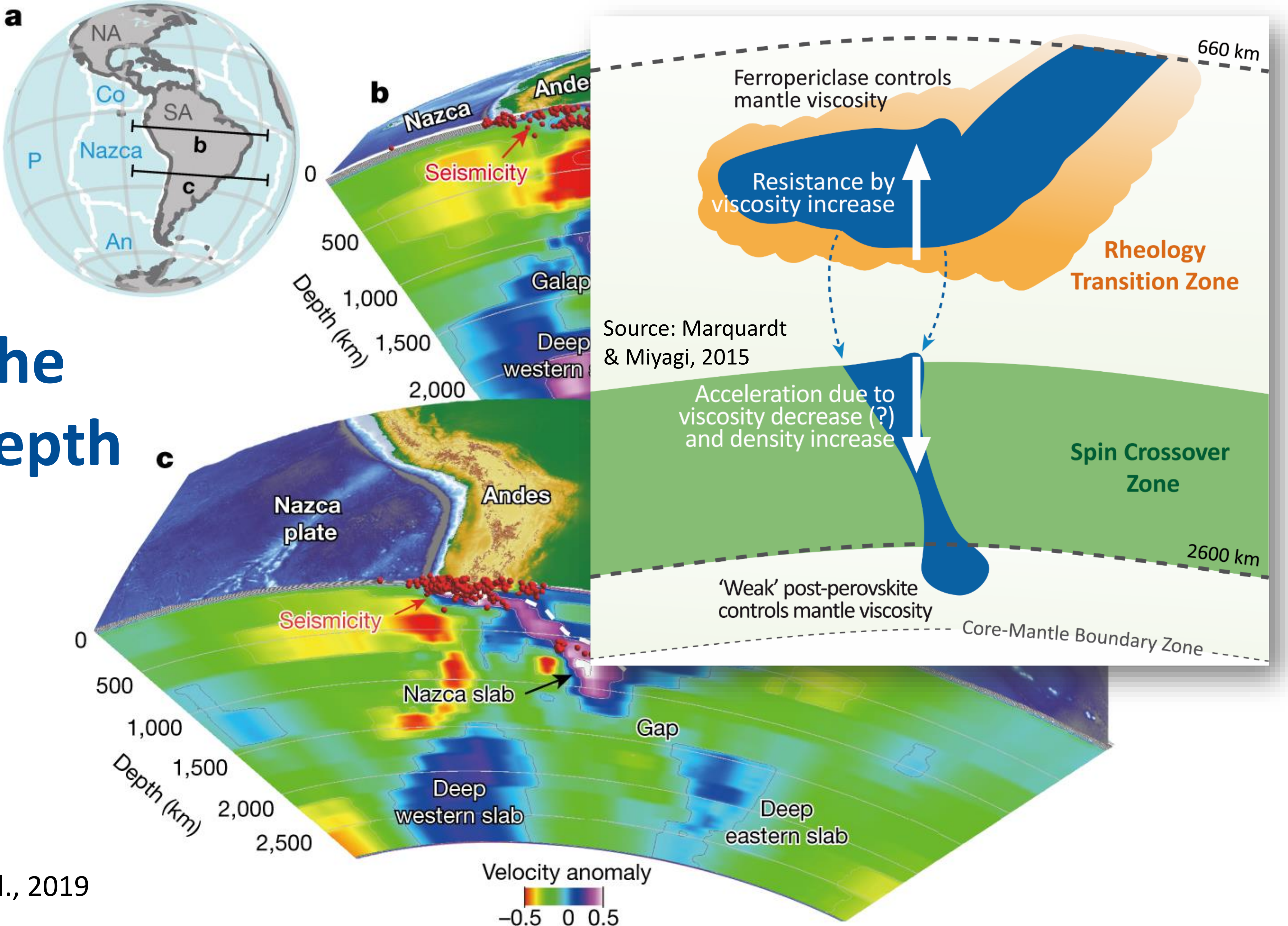




Source: GFZ

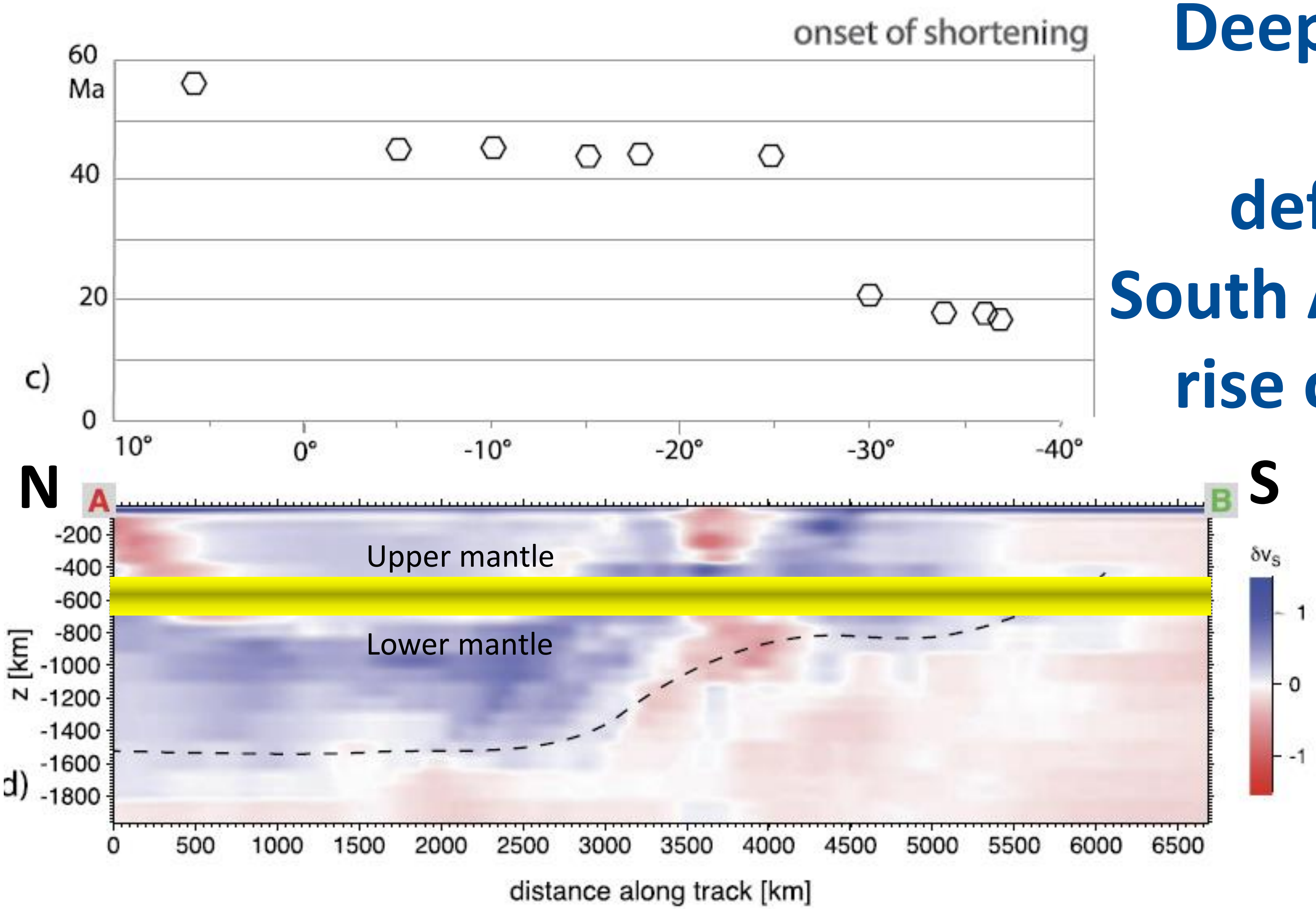

South America west drift (18°)
(trench normal)
trench migration
Peruvian Phase
Salta Rift
Andes shortening
Drift velocity (cm/a)
t [Ma]
120
100
80
60
40
20
0
1
2
3
4
5
6

Exploring the Andes at depth



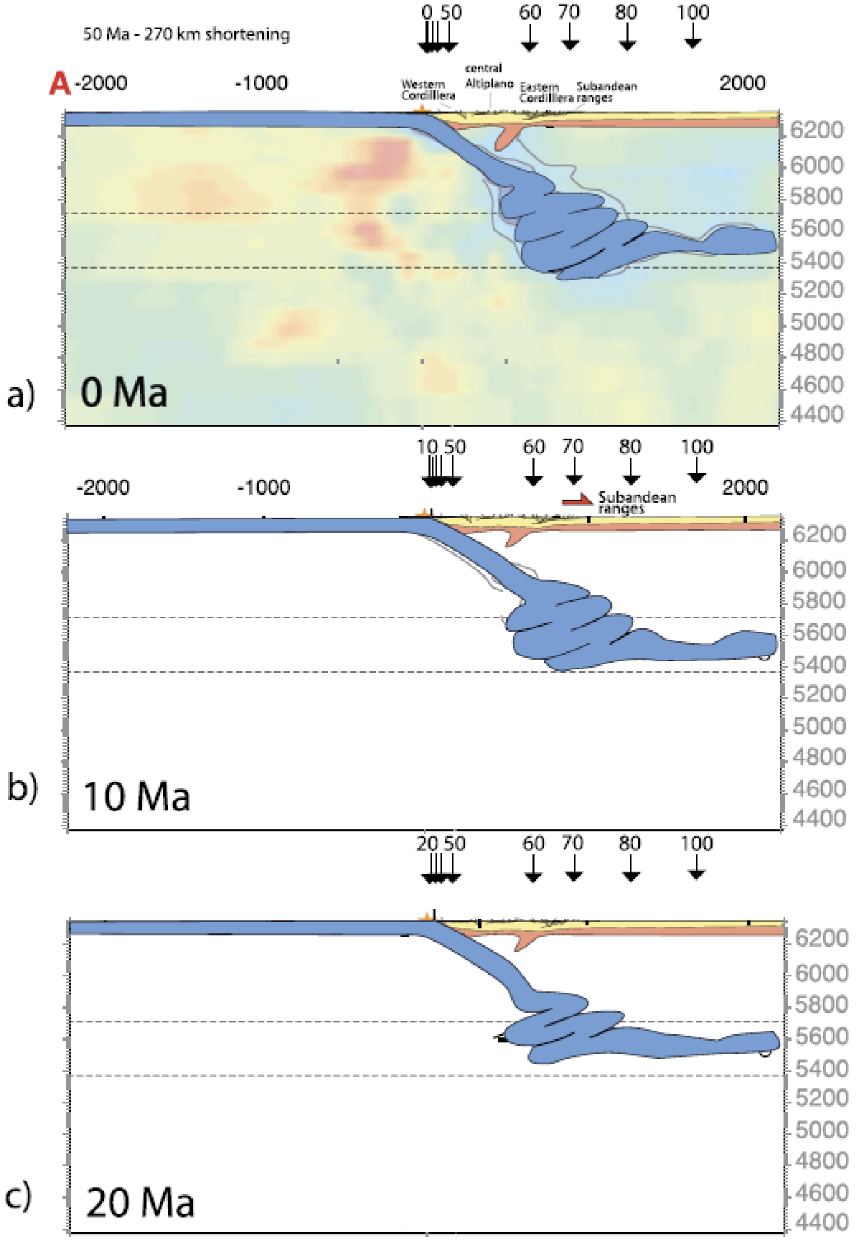
Source: Y-W. Chen et al., 2019

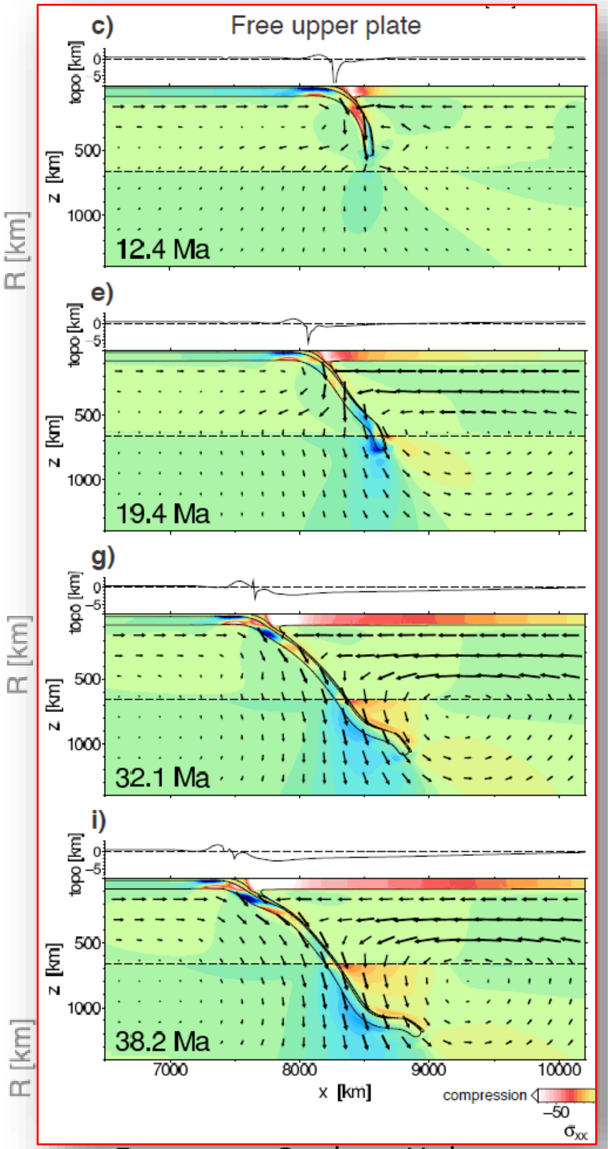
Deep subduction initiates deformation of South America and rise of the Andes

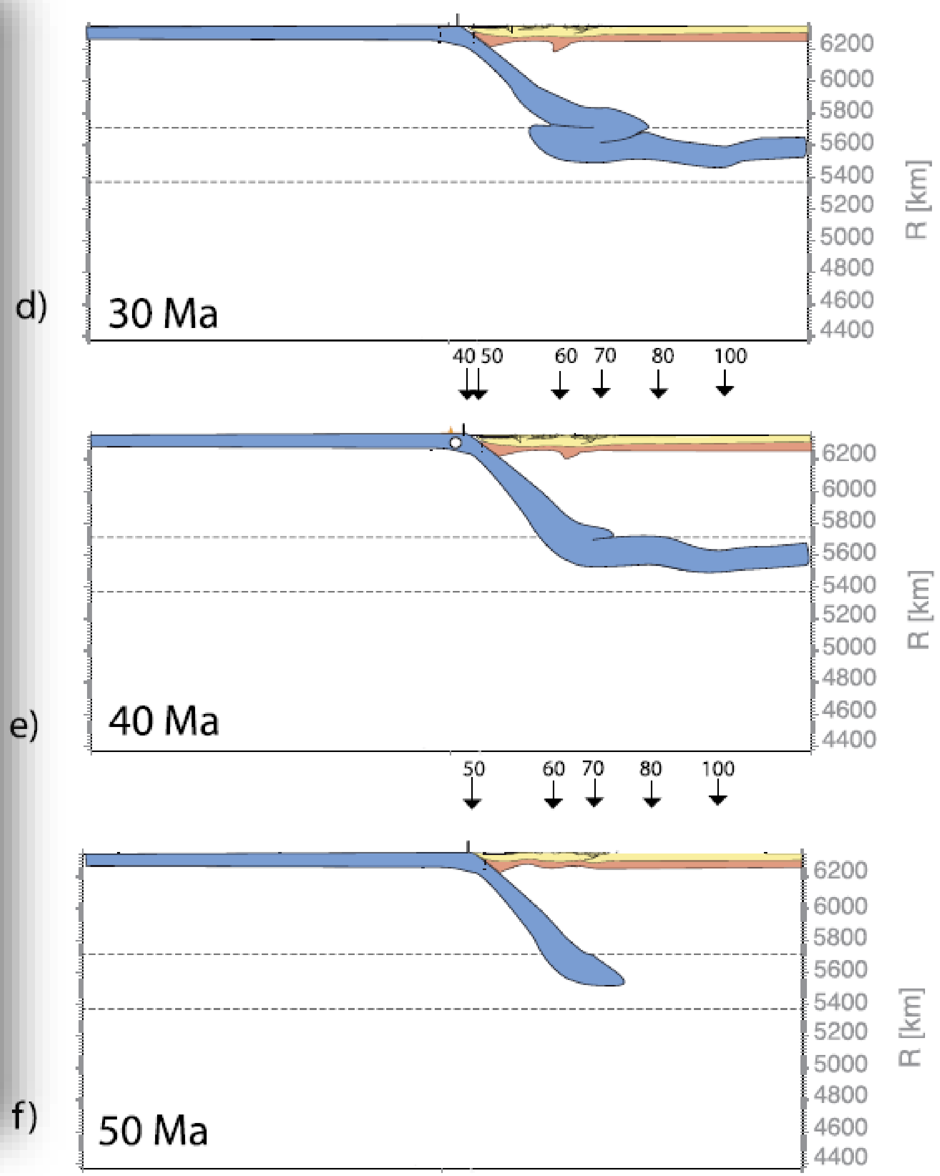


Source: Faccenna, Oncken, Holt, Becker, 2017

Nazca-Platte is anchored in viscous lower mantle

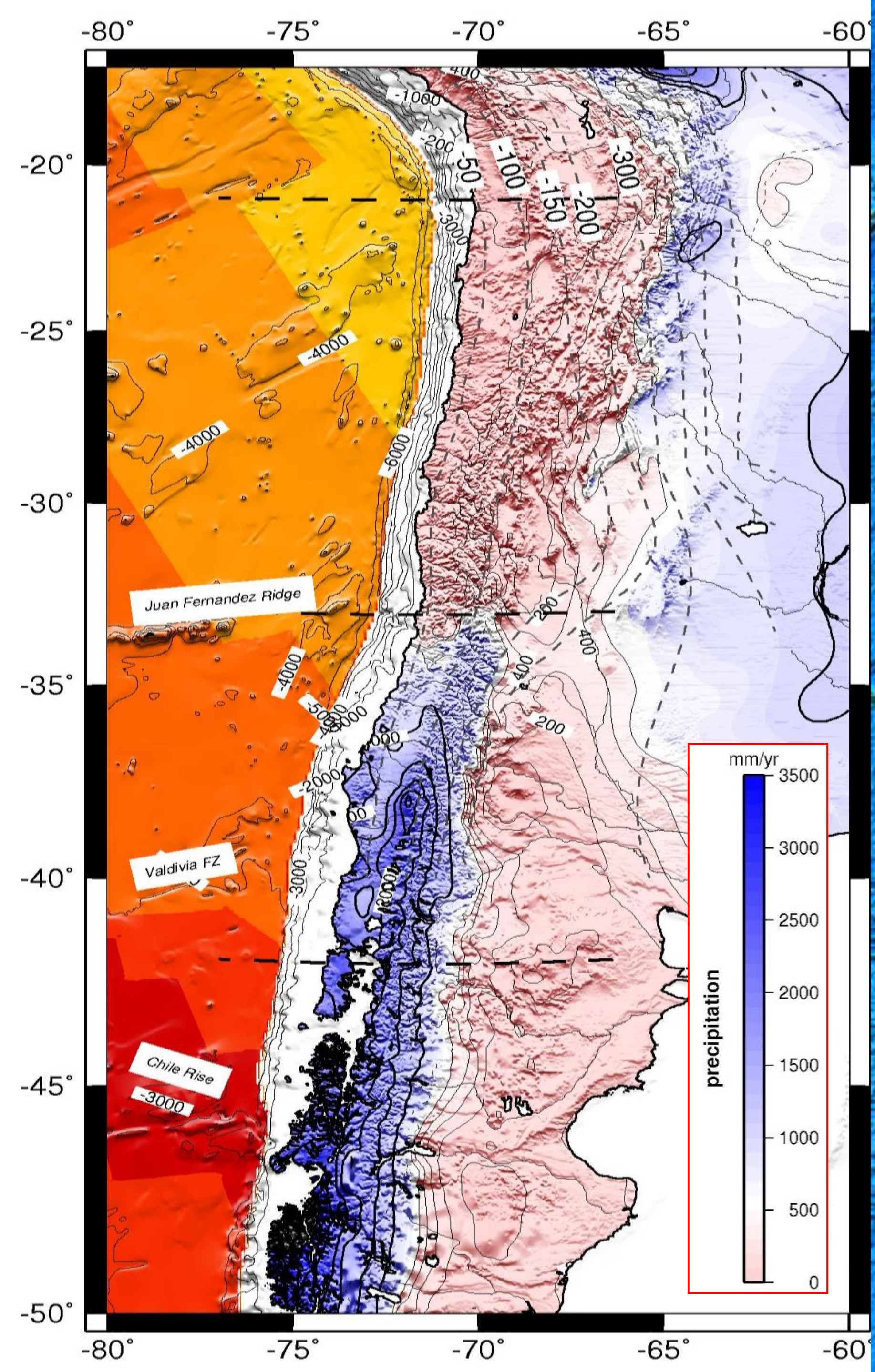


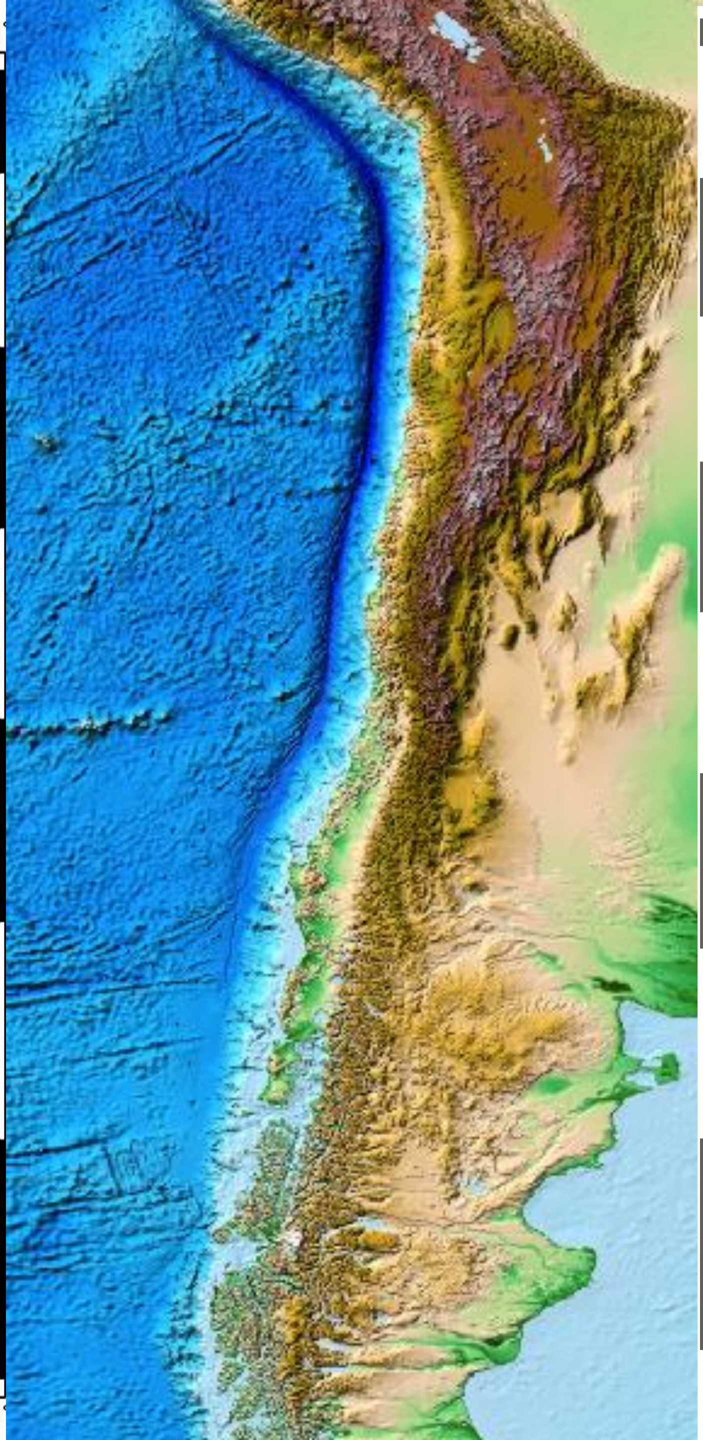


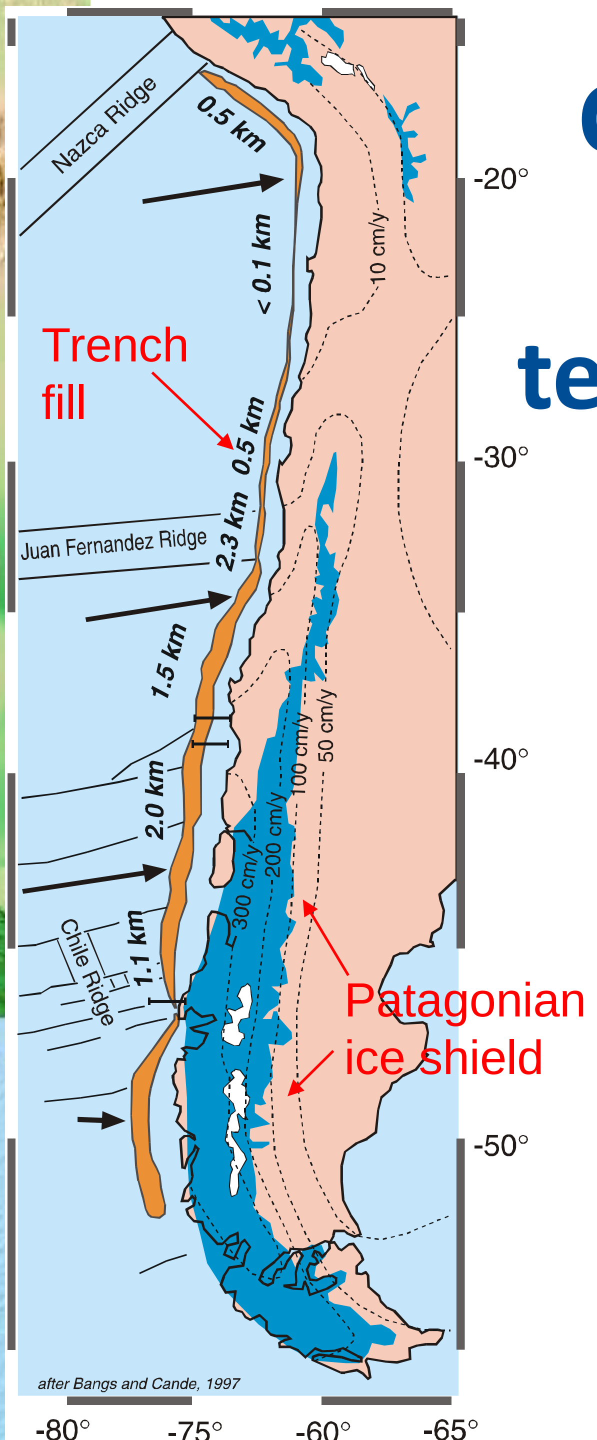


Faccenna, Oncken, Holt,
Becker, EPSL, 2017

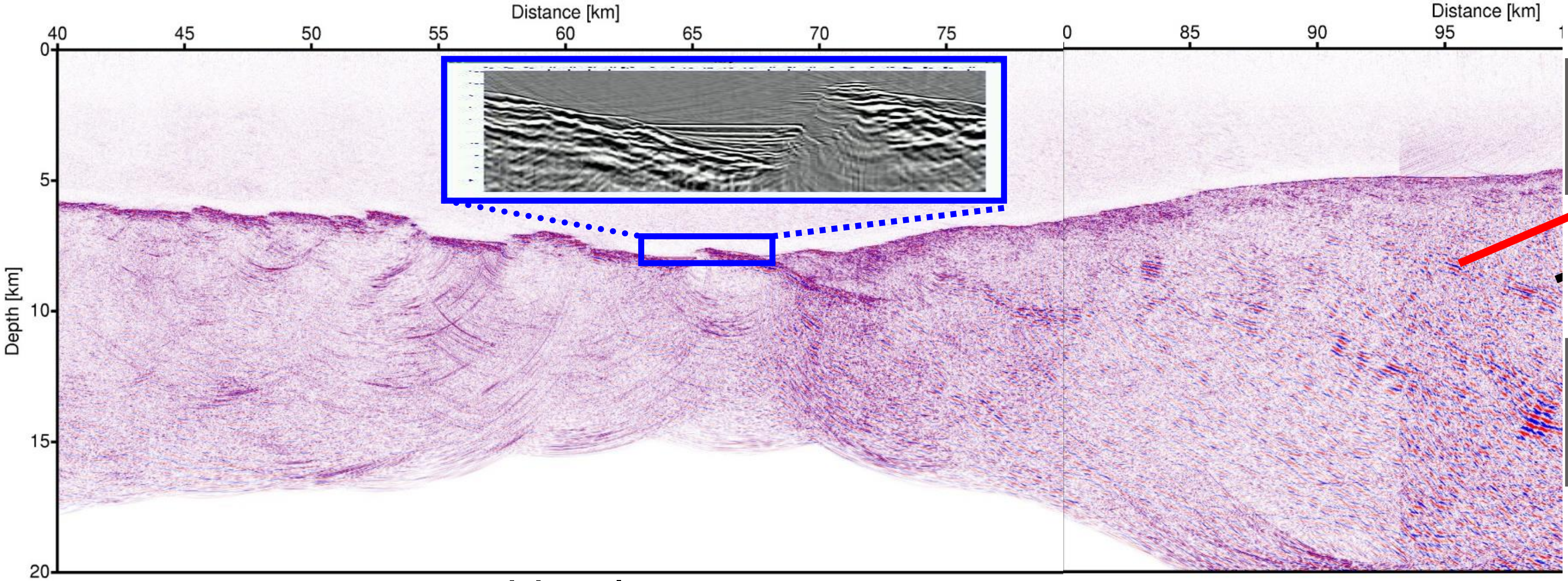
Climate and tectonics



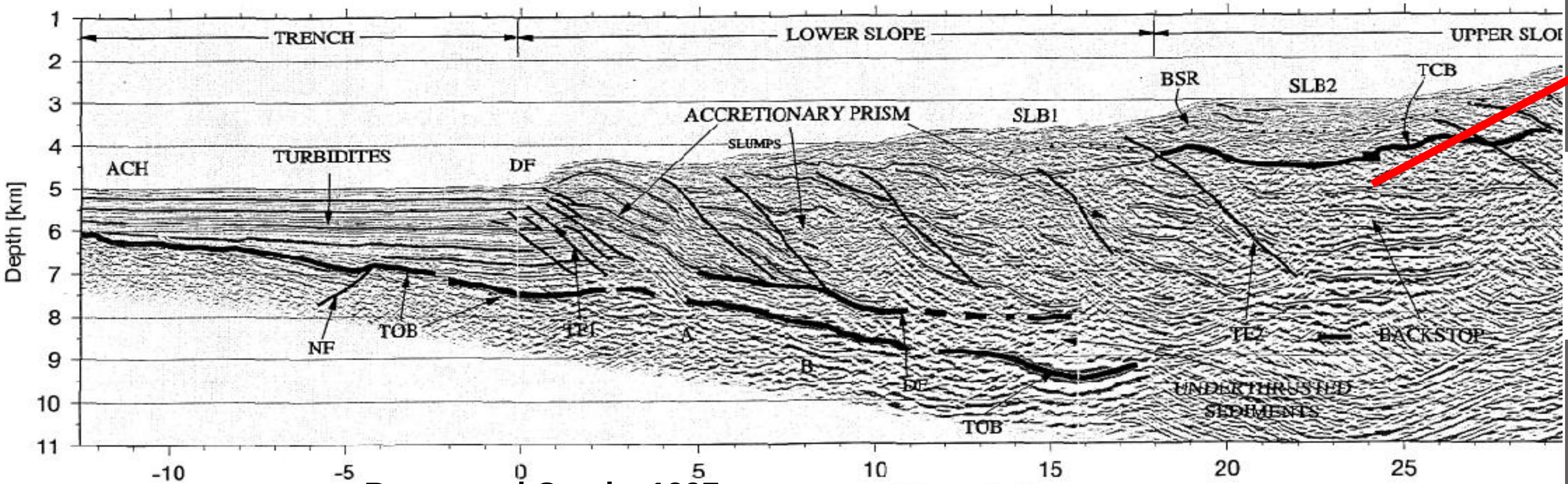




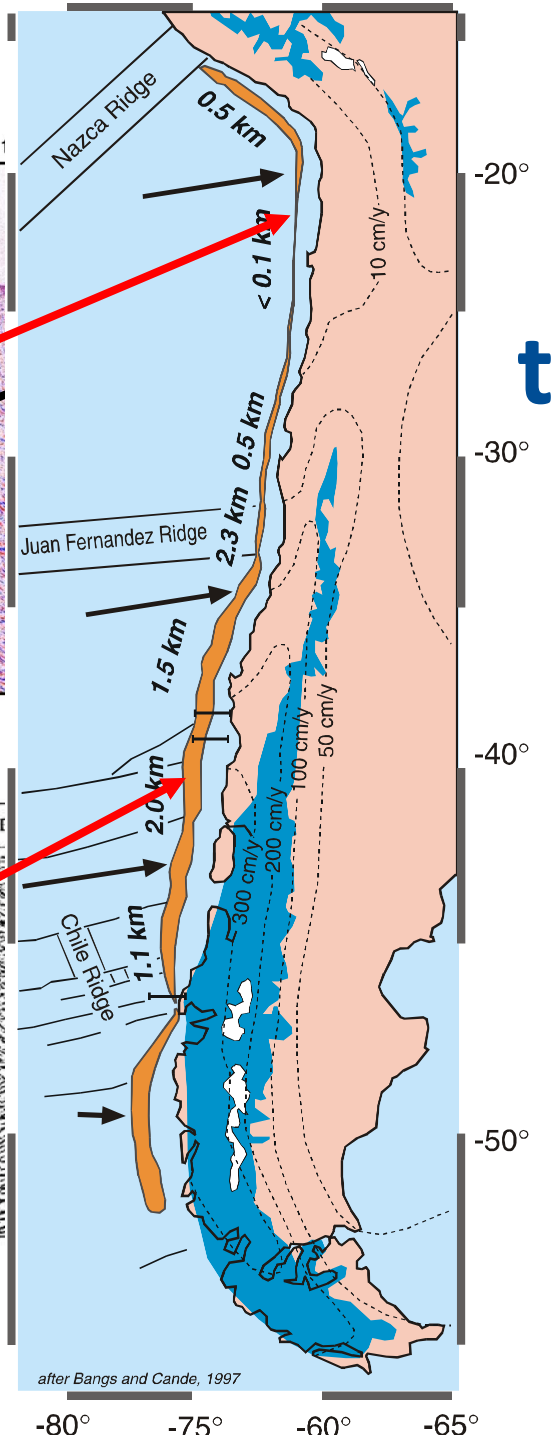
Climate and tectonics

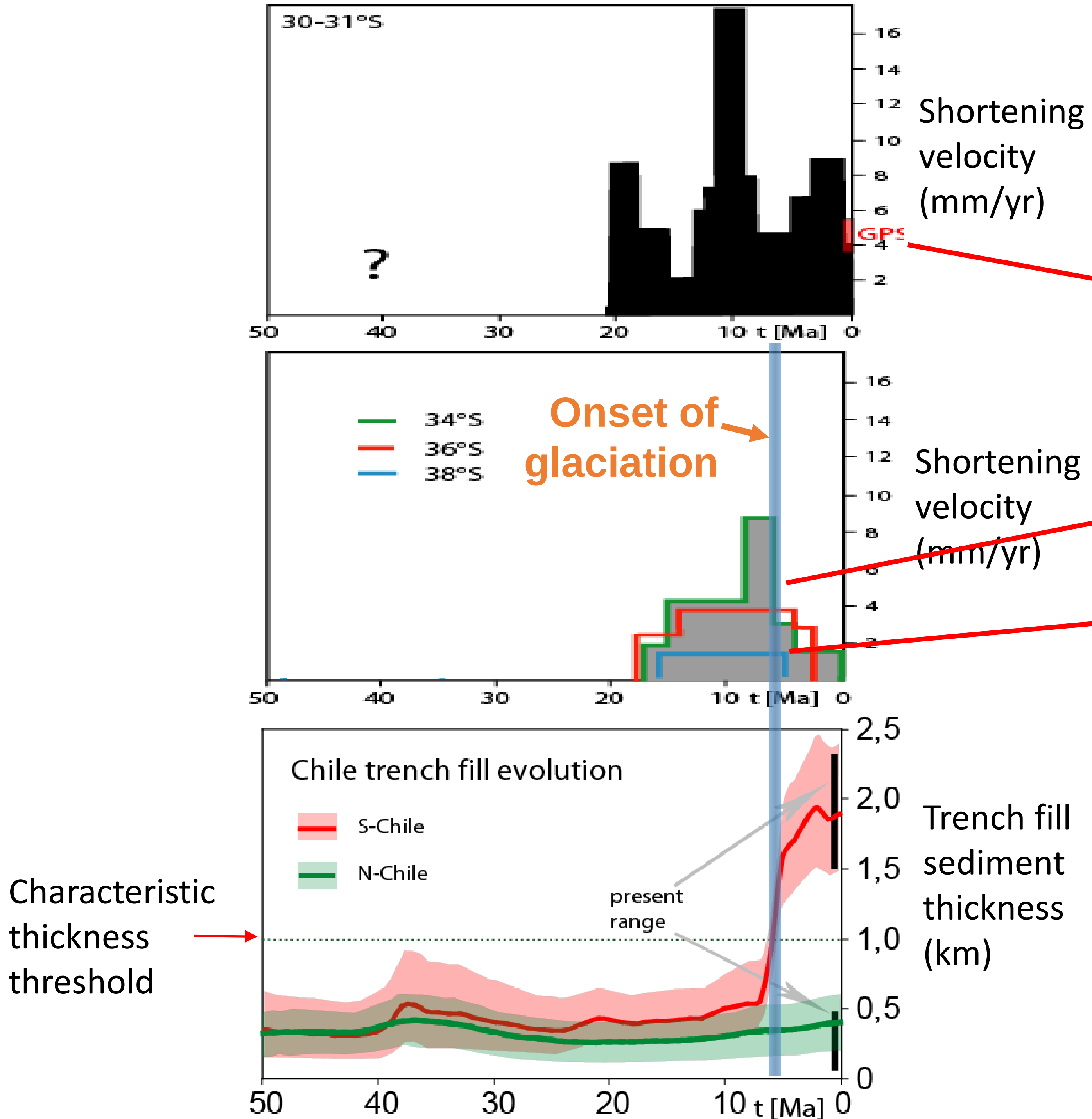


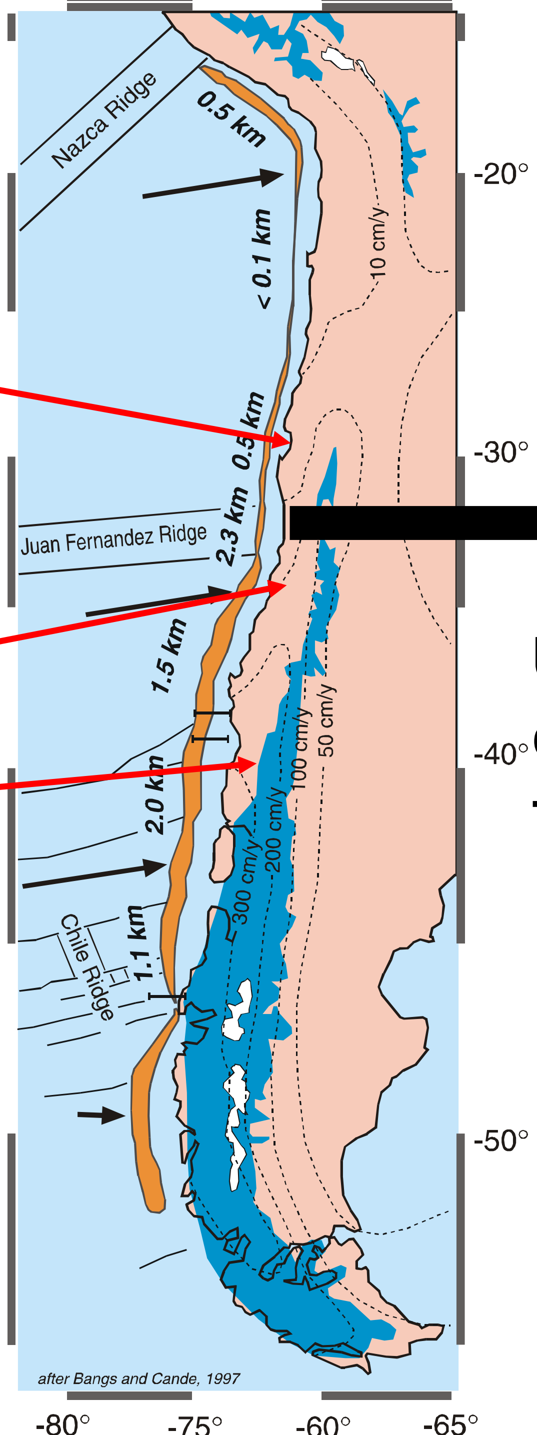
Sick et al., 2006



Bangs and Cande, 1997







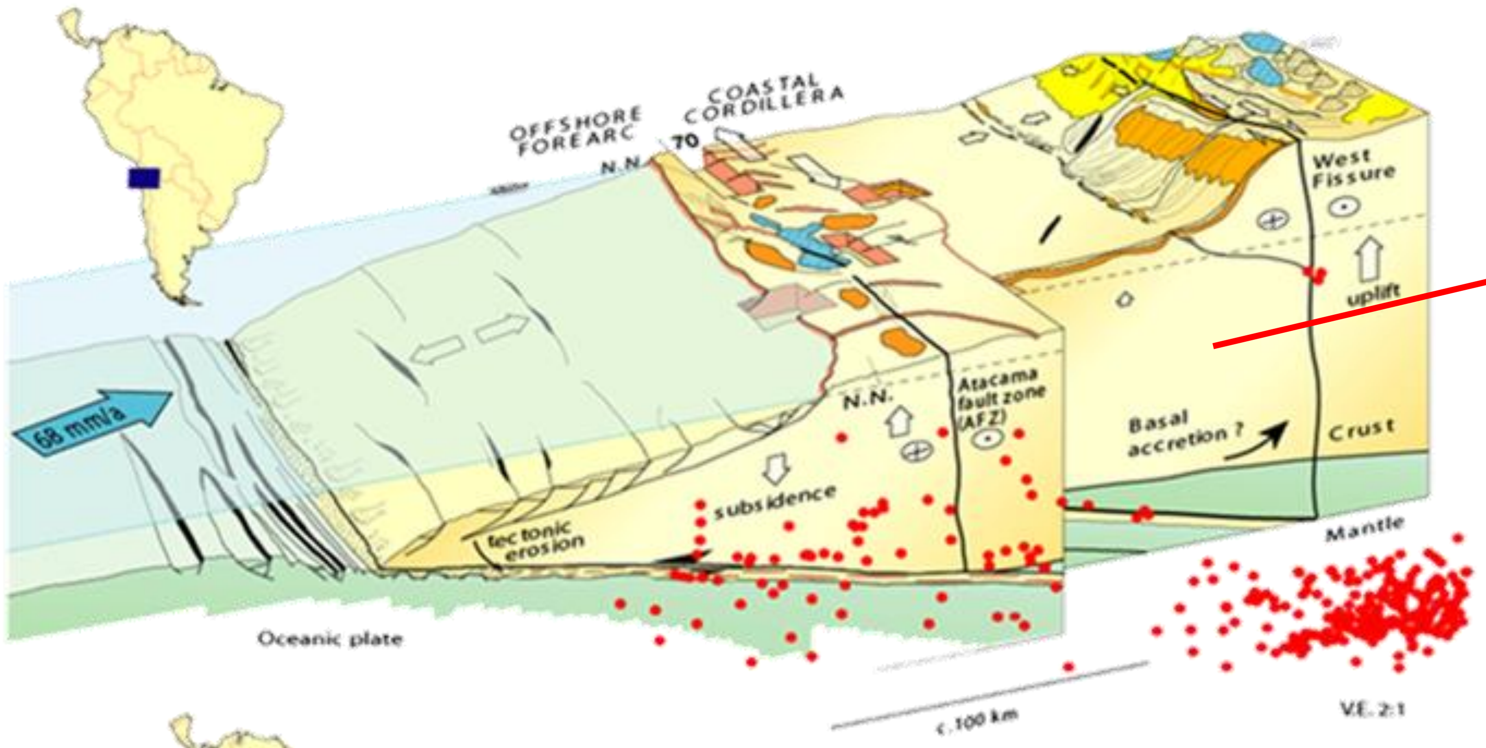
Continuous Neogene – recent upper plate contraction

Upper plate contraction fades at 6 Ma

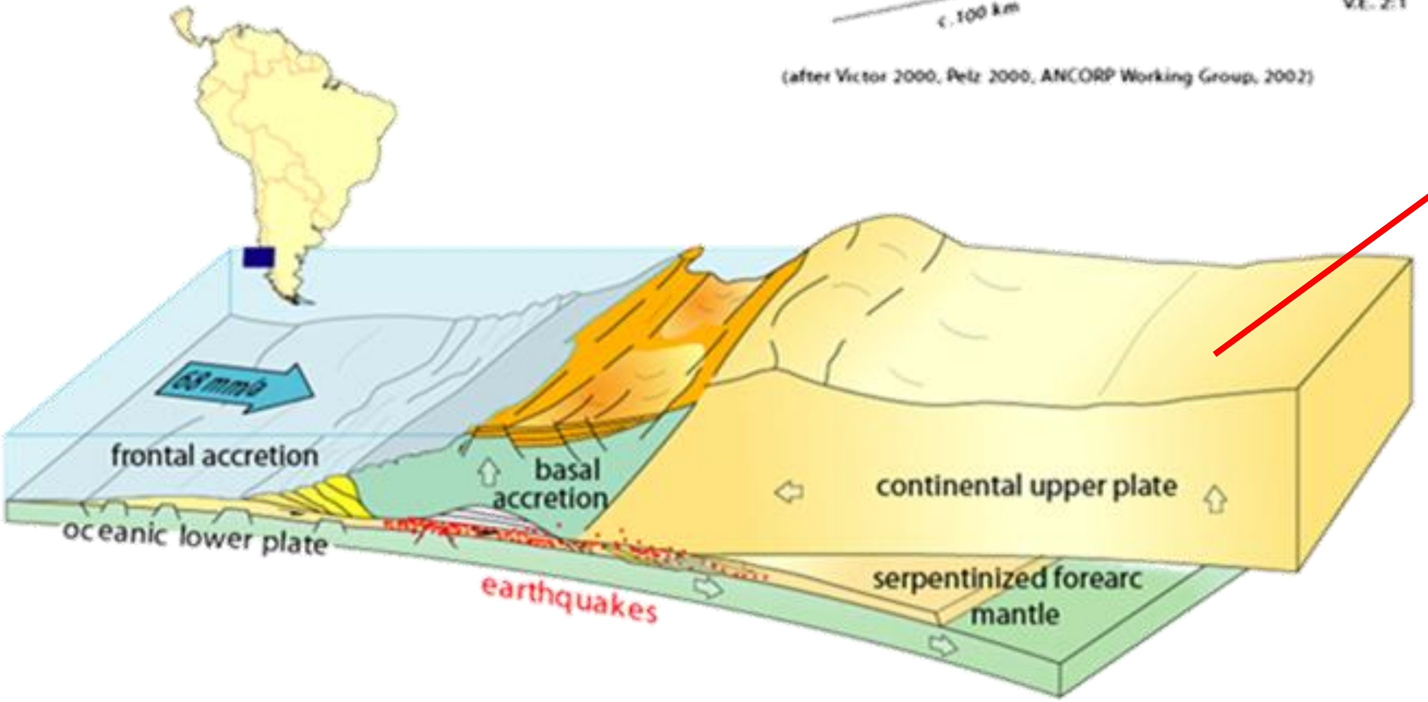
Modified from Vietor & Echtler, 2006

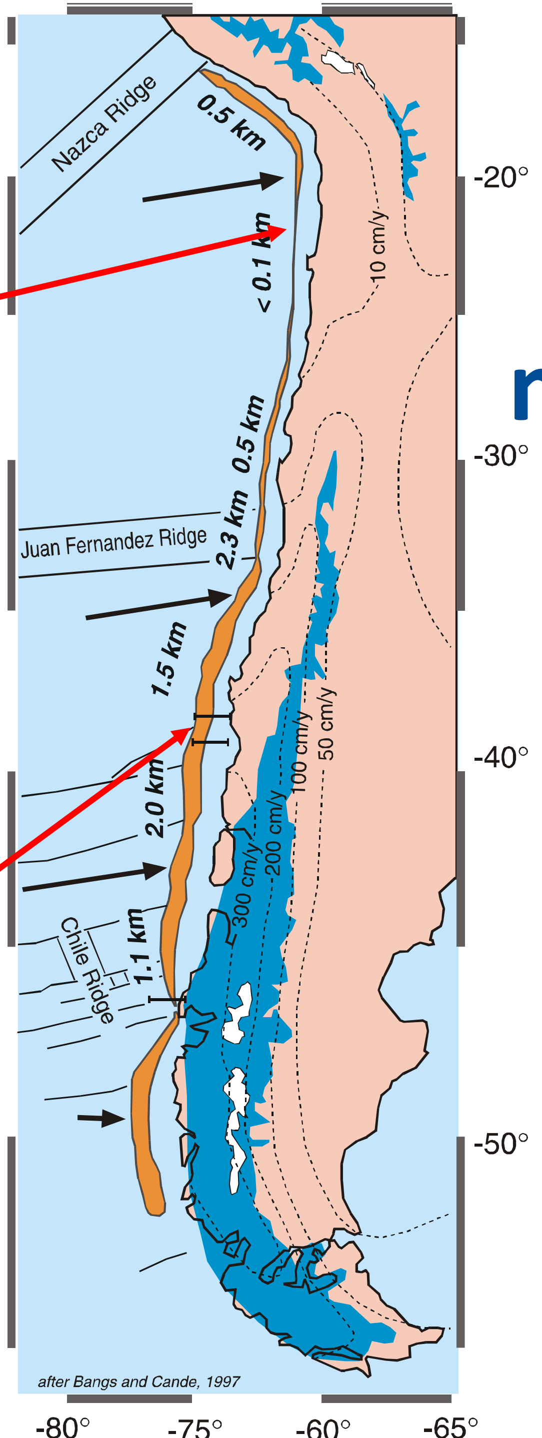
- key area
- width of trench fill with indicated thickness
- continental glaciation of the most recent major event (20 000 y BP)
- current ice coverage
- annual rainfall

Climate controls mass flux and crustal growth

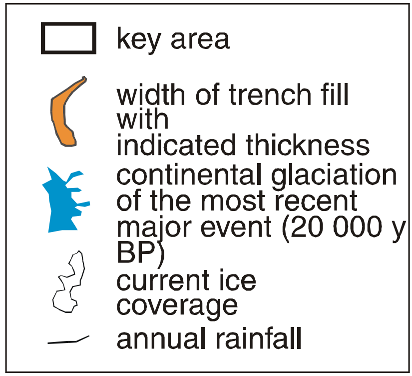


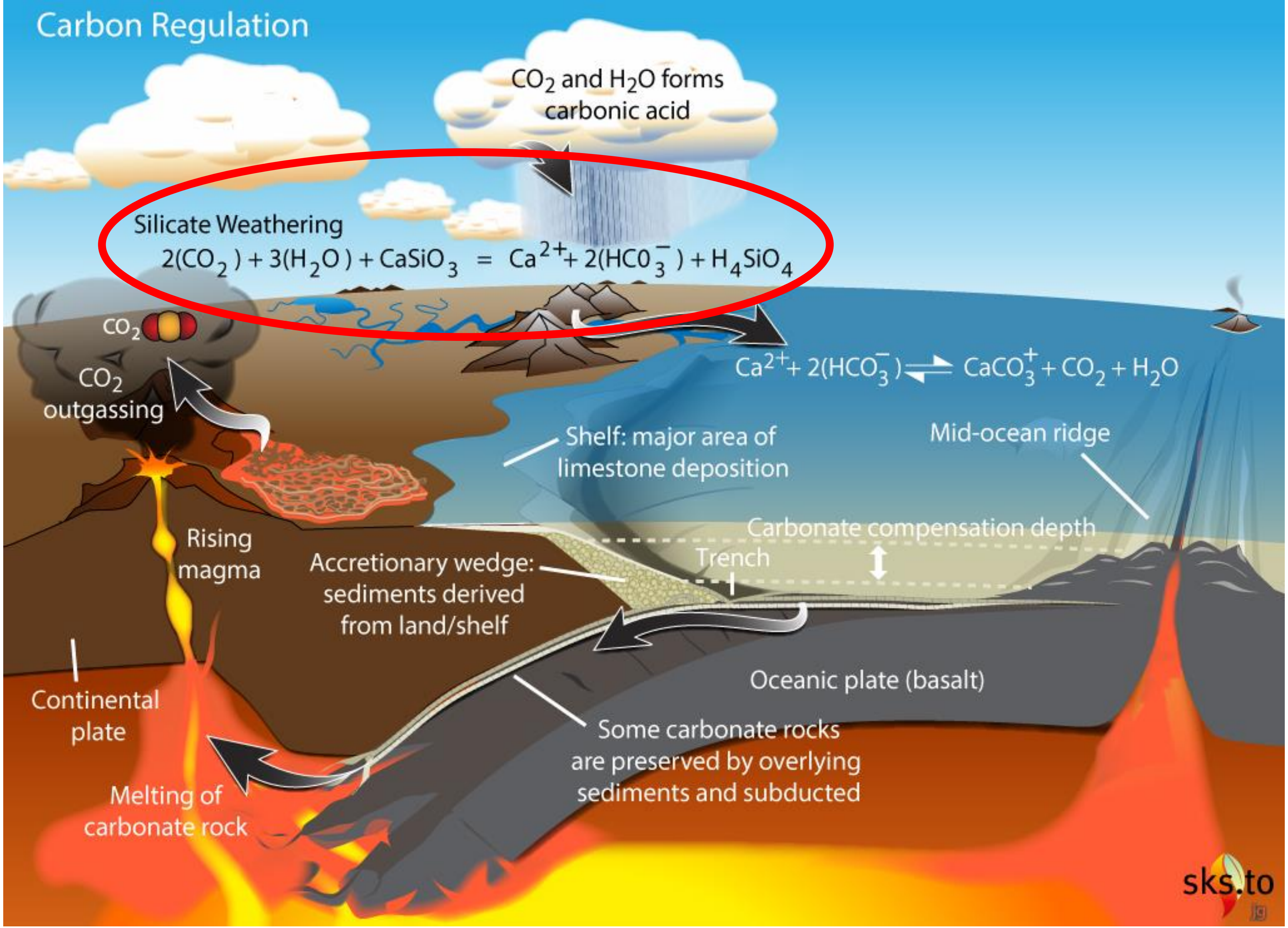
(after Victor 2000, Pelz 2000, ANCORP Working Group, 2002)





Modified from Vietor & Echtler, 2006





CO2, climate and the plate tectonic thermo-stat

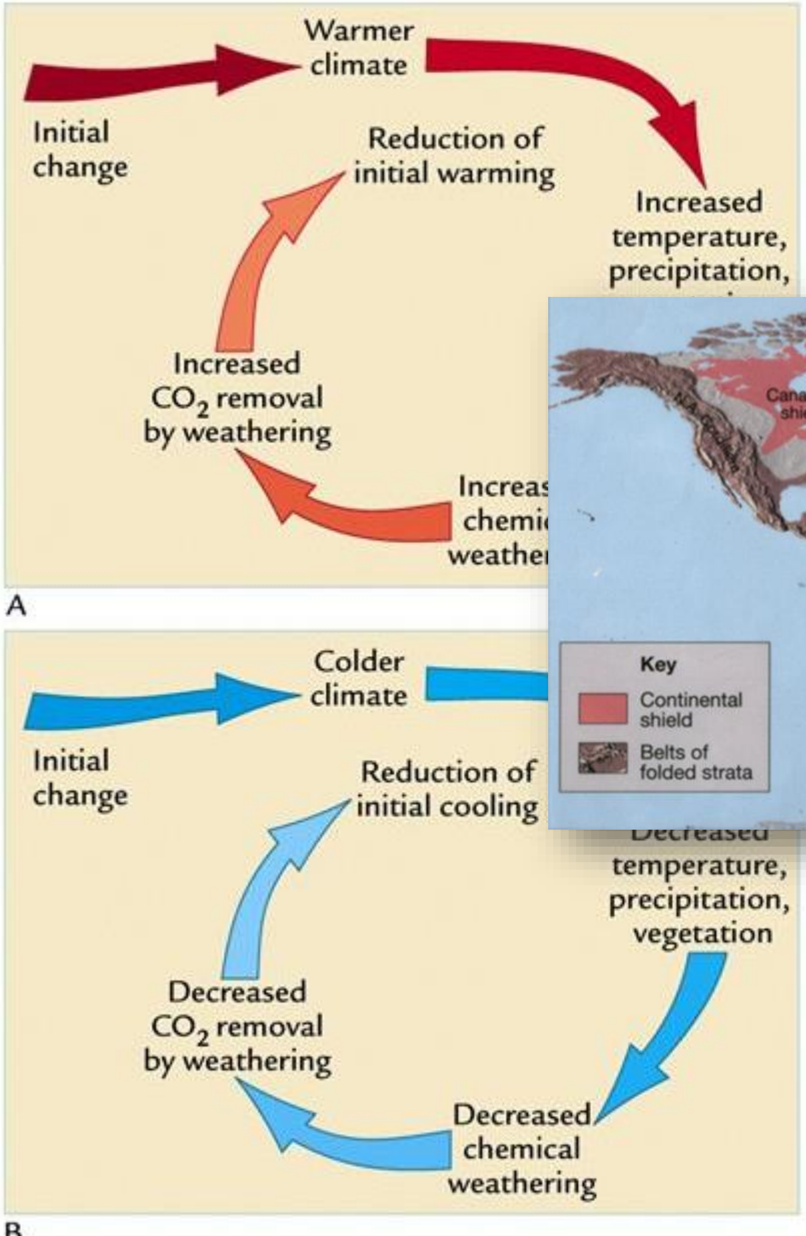
Image source: Wikipedia

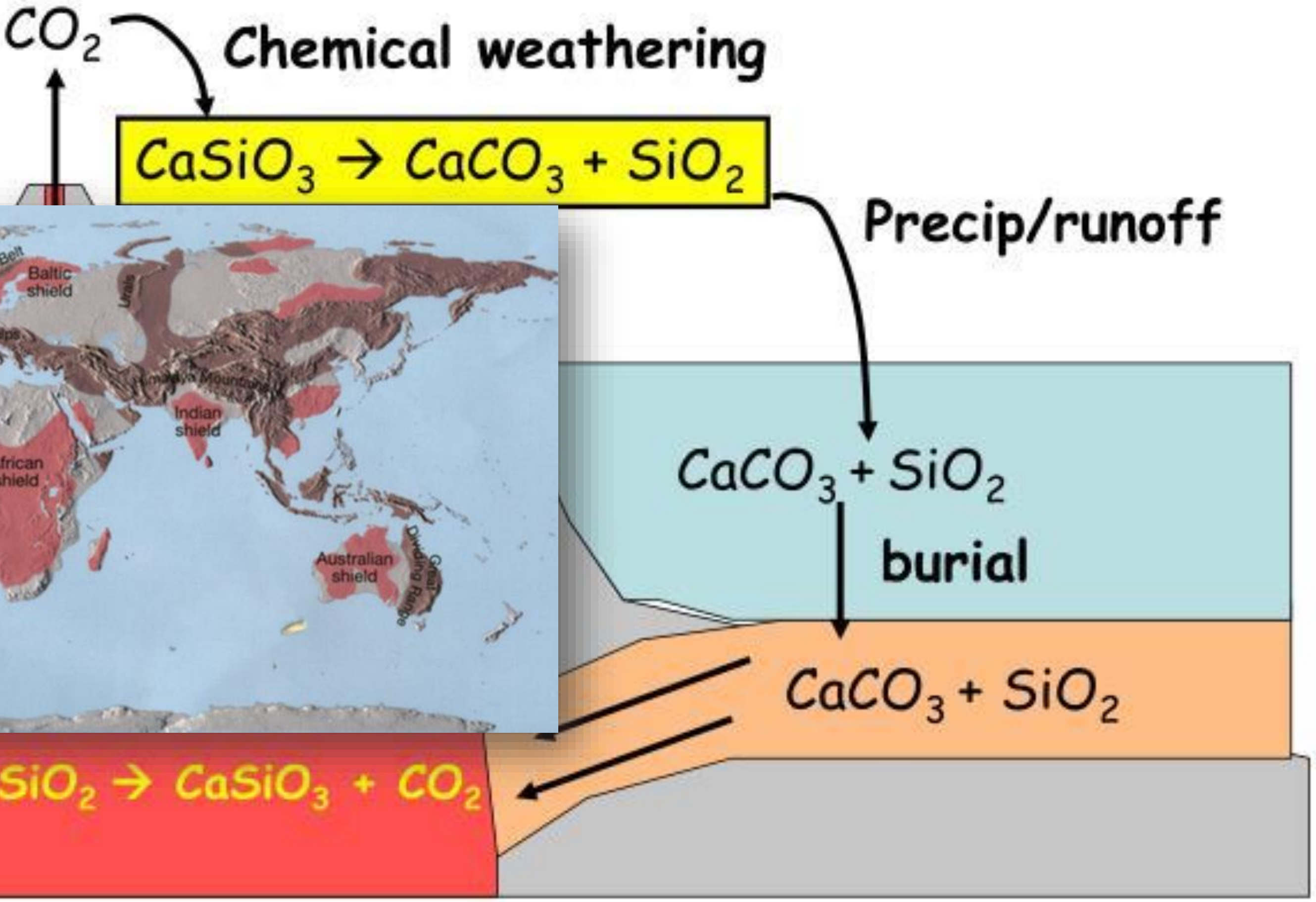
Storing and removing CO_2 by tectonics – example Alps

Marine carbonate sediments deformed and uplifted (Central Alps)

Weathering of mafic silicate rocks (Central Alps)

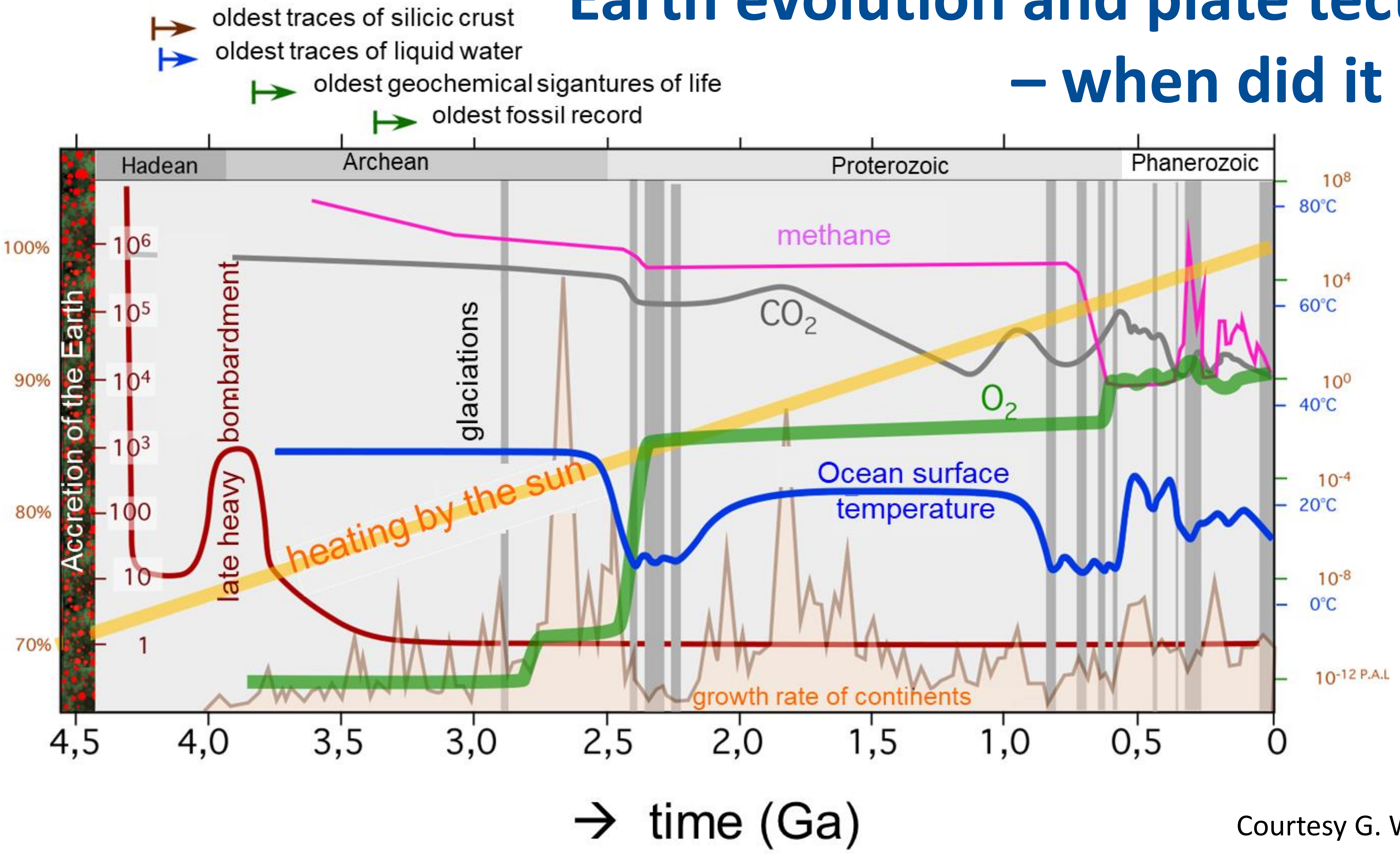
The silicate weathering thermostat is tuned by plate tectonics





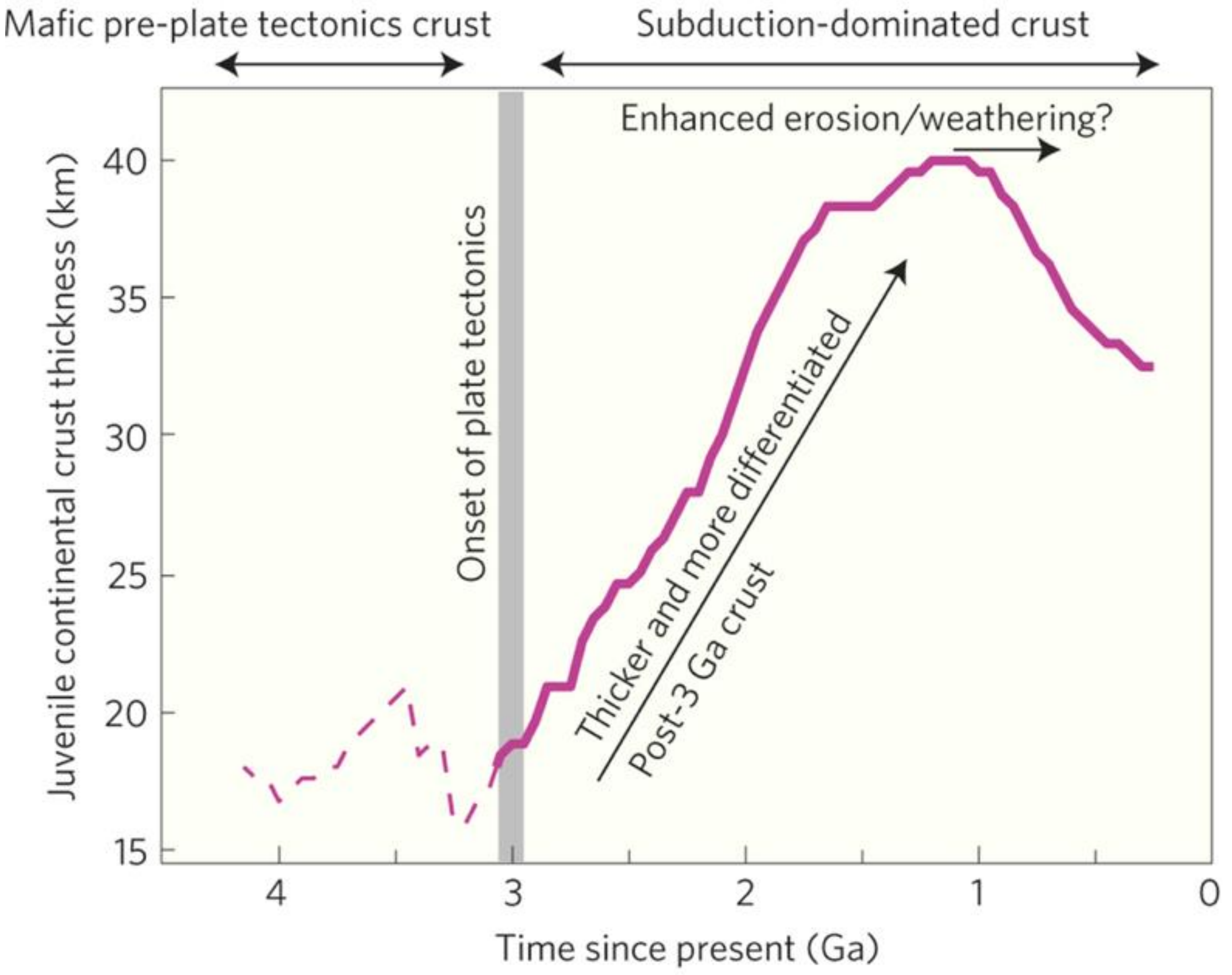
This cycle operates on 0.5 – 1 million year timescale.

Earth evolution and plate tectonics – when did it start?



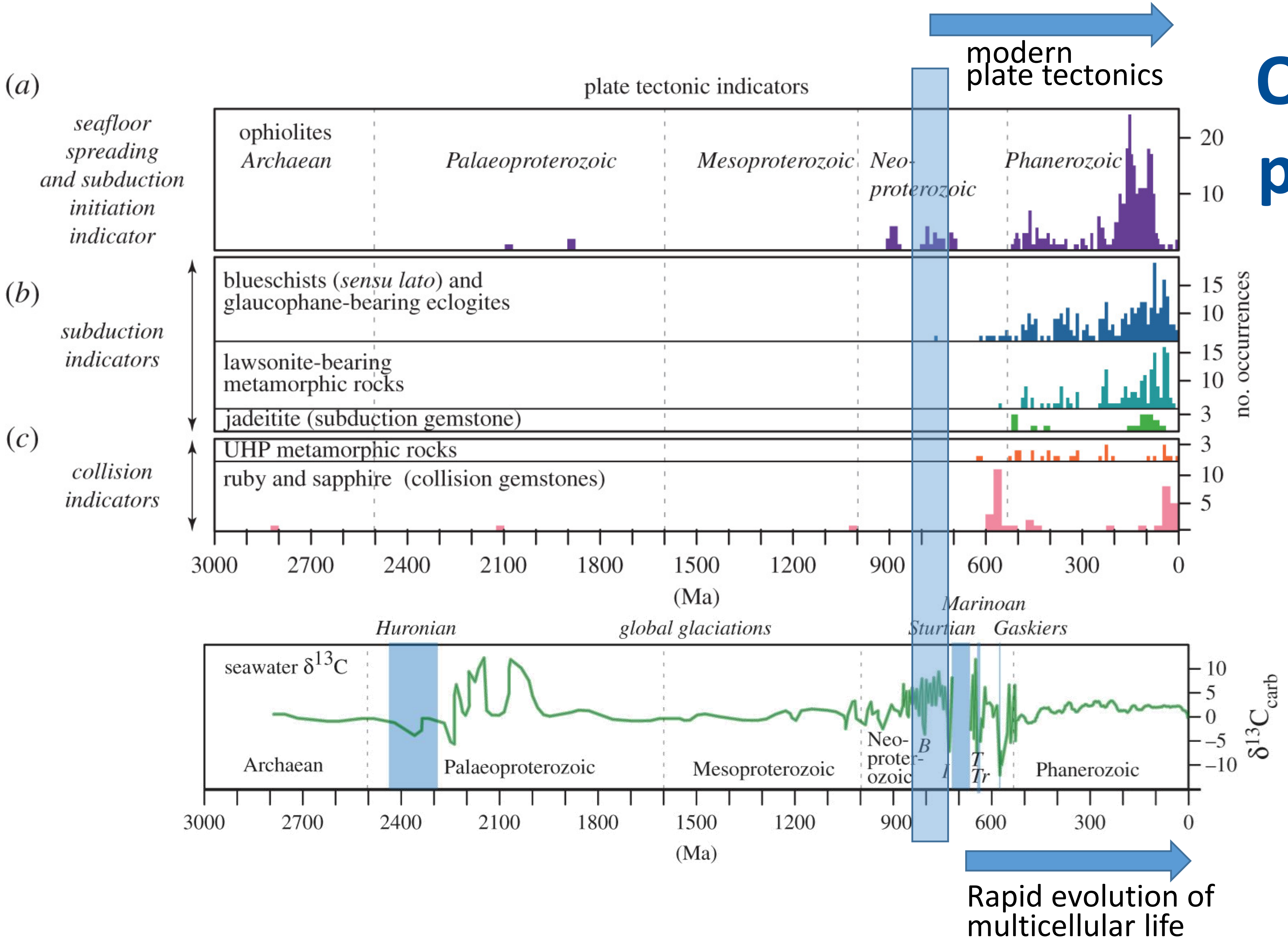
Courtesy G. Wörner

Crustal evolution suggests plate tectonics started around 3 Bill. Yrs ago?



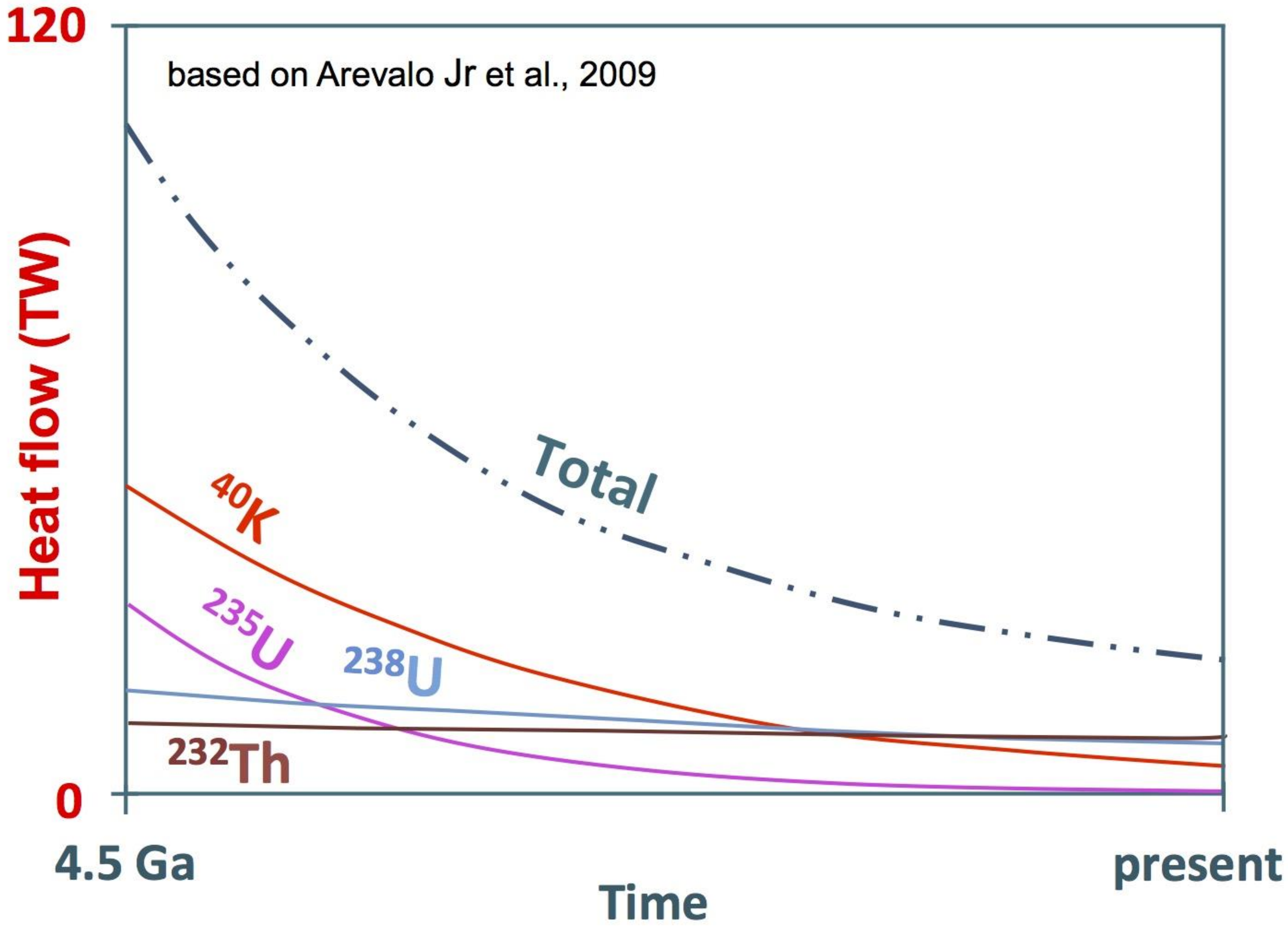
Source: Dhuime et al., 2015

Or did modern plate tectonics only exist in the past 750 Ma ??



Source: Stern, 2018

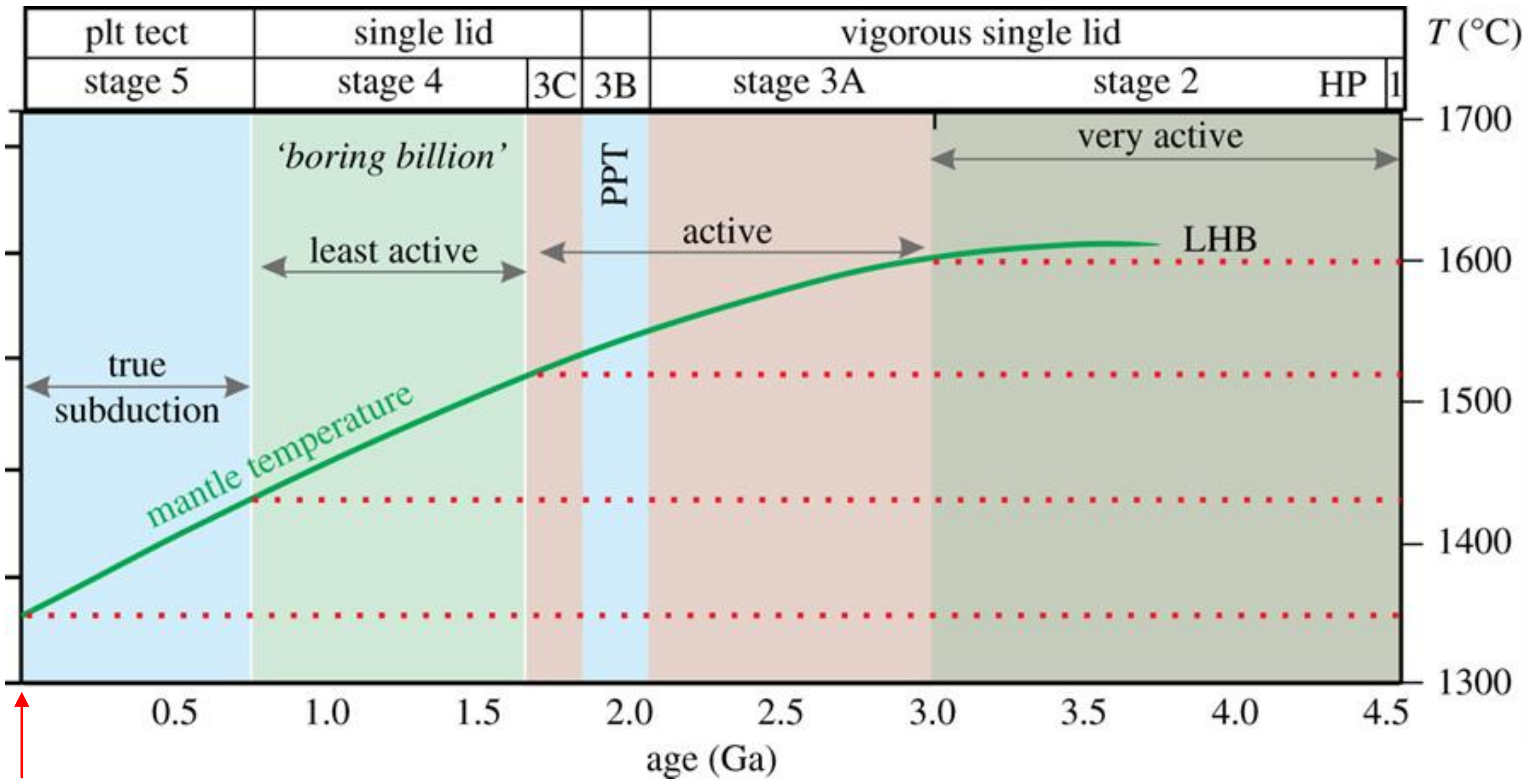
Fuelling the plate tectonic machine



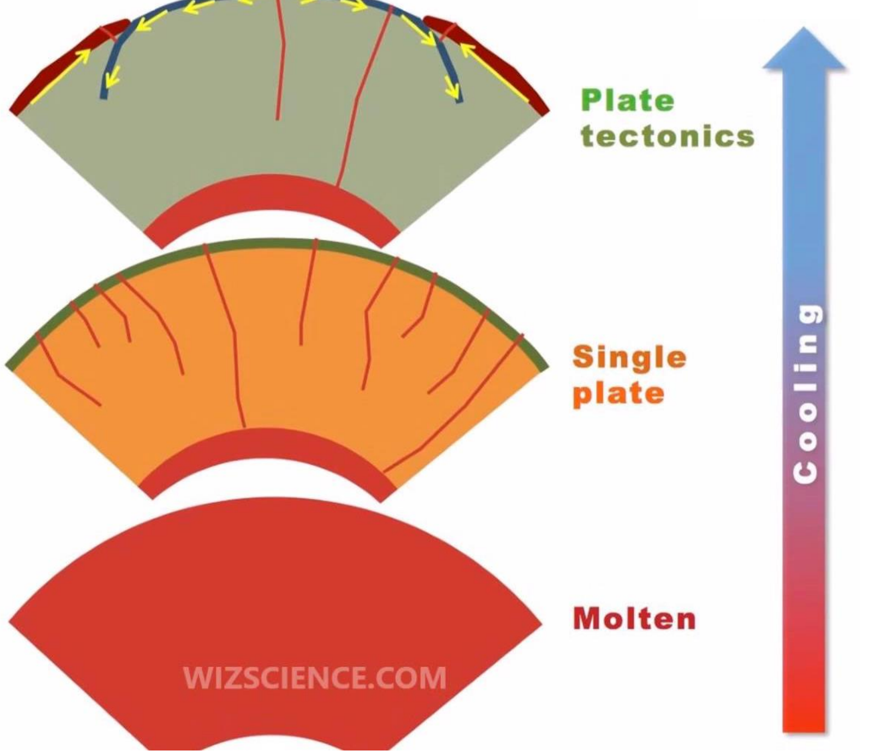
ca. 80% from radioactive decay

rest from
- residual energy from early Earth accretion
- crystallization of Earth‘s core
- friction

Evolving Earth – evolving plate tectonics



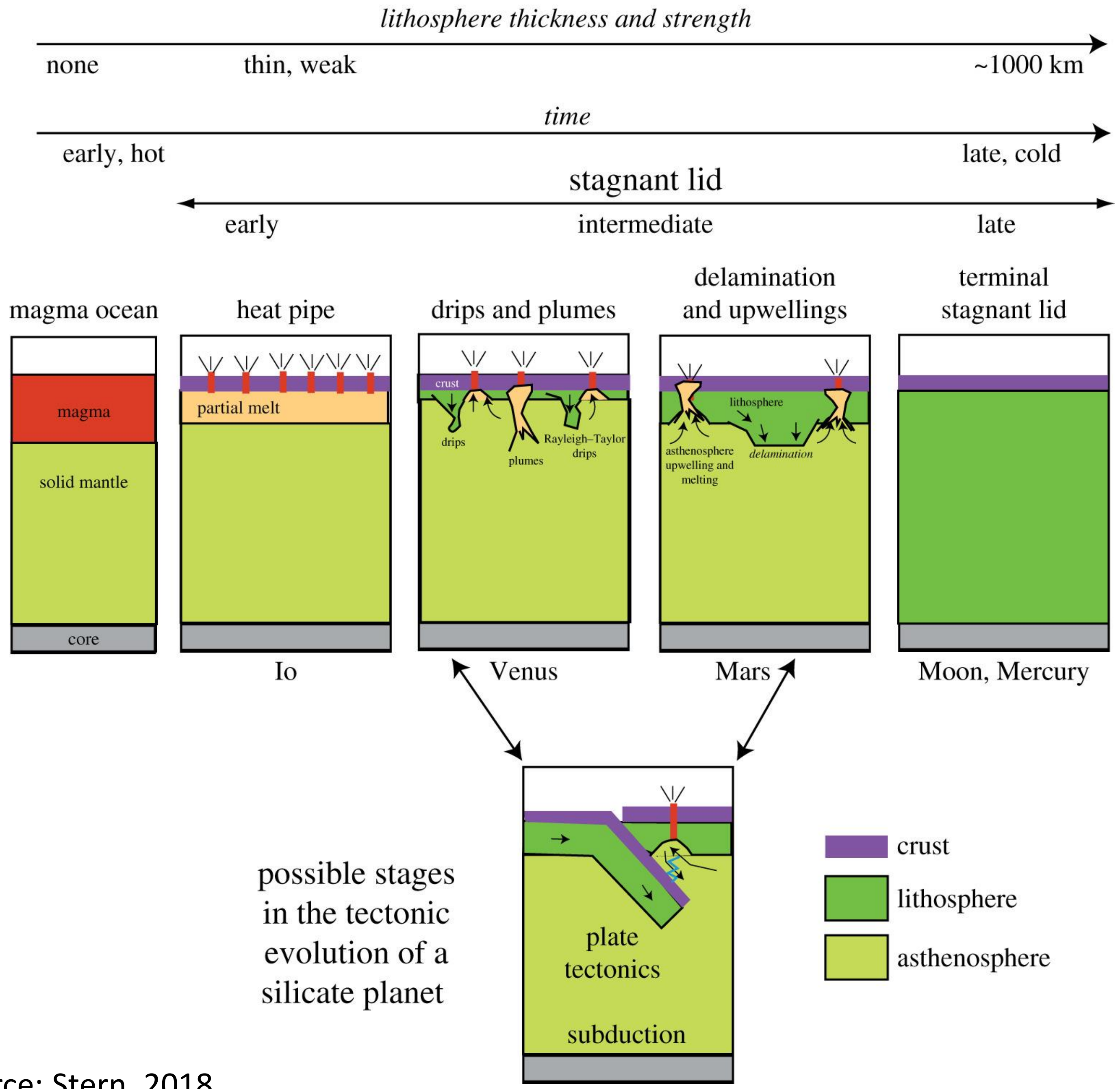
Present



Present

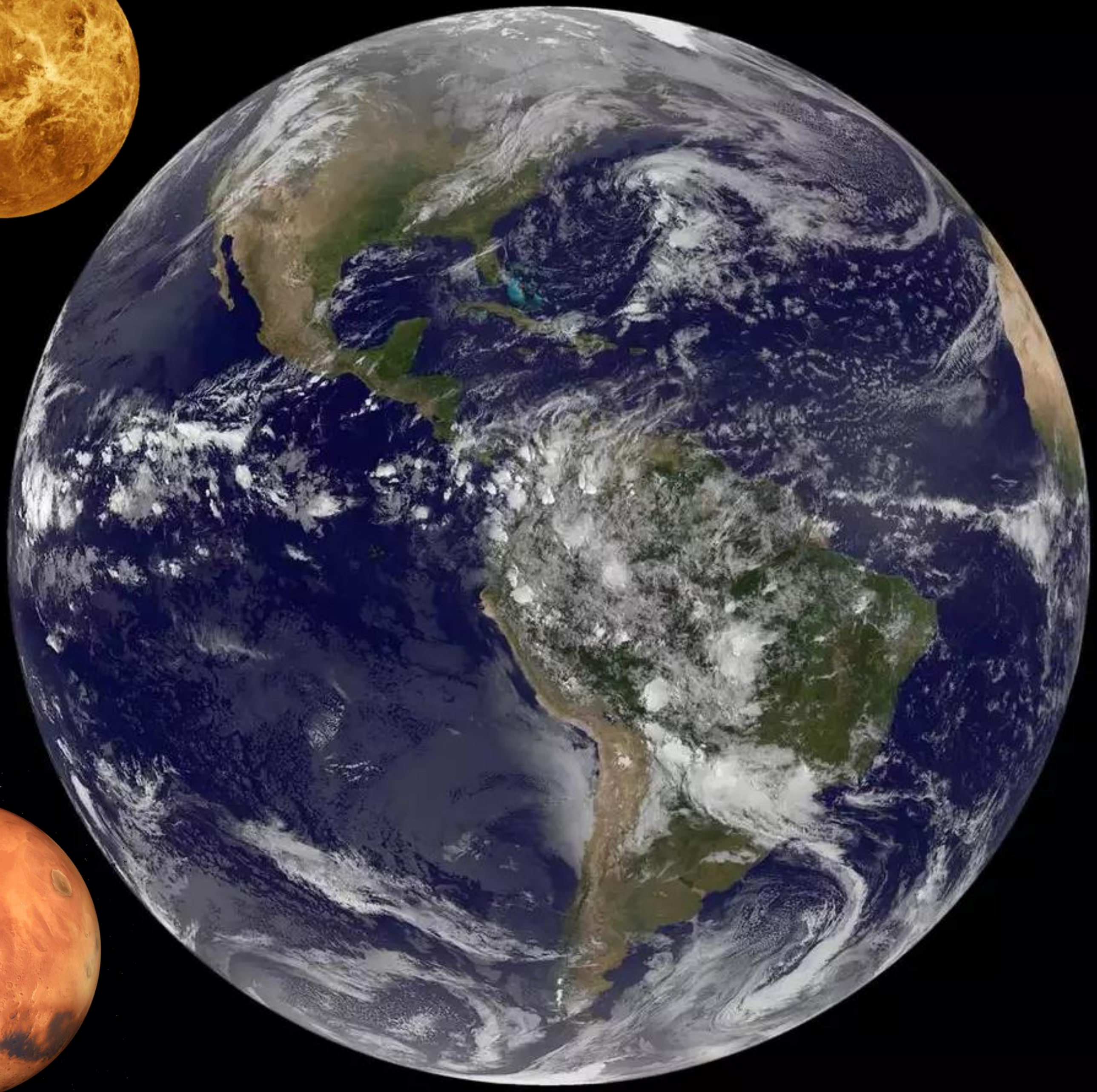
Source: Stern, 2018

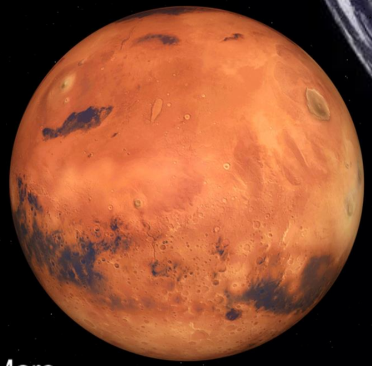
Plate tectonics is not an inevitable fate of radiogenic silicate planets



Source: Stern, 2018

Venus

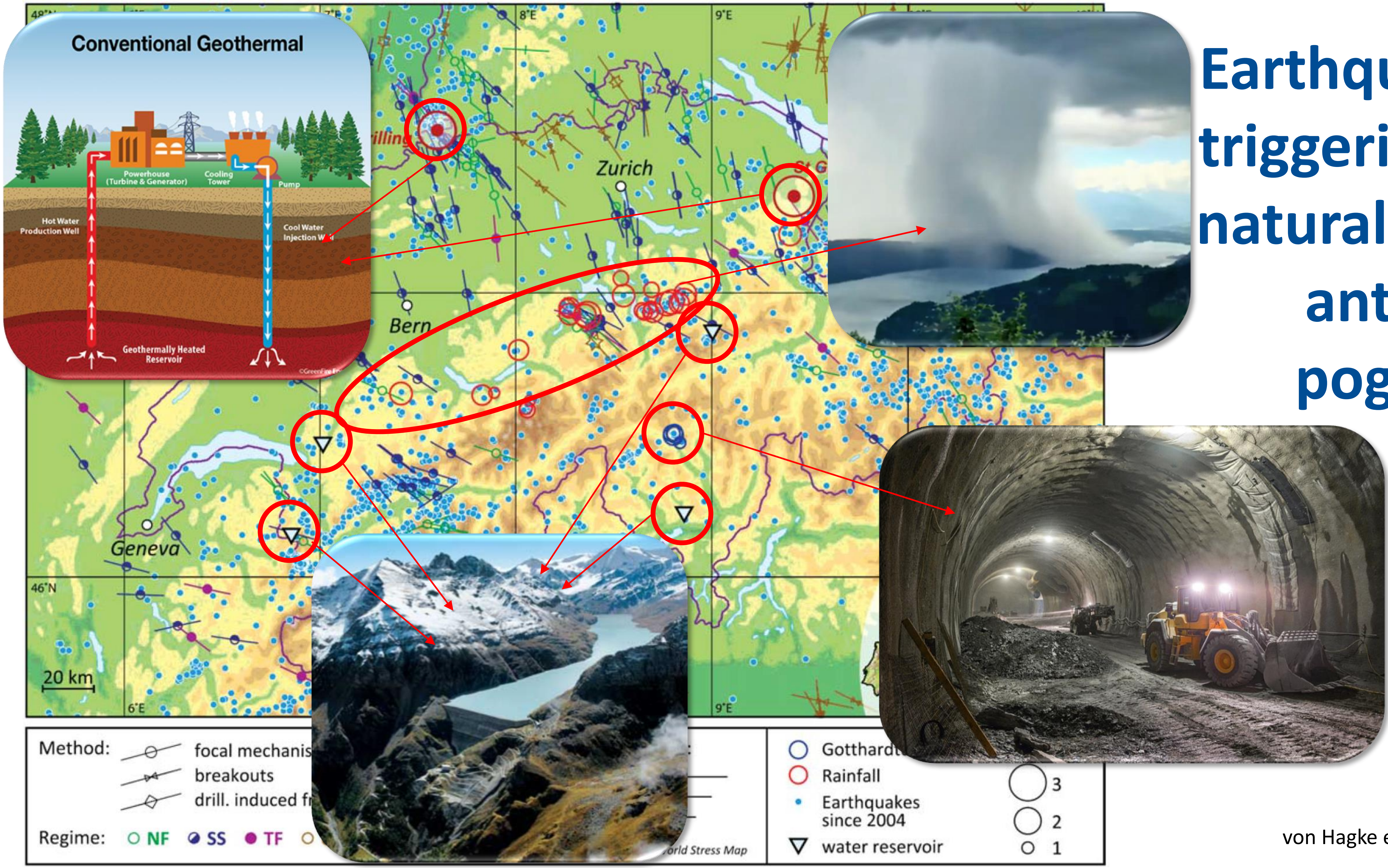




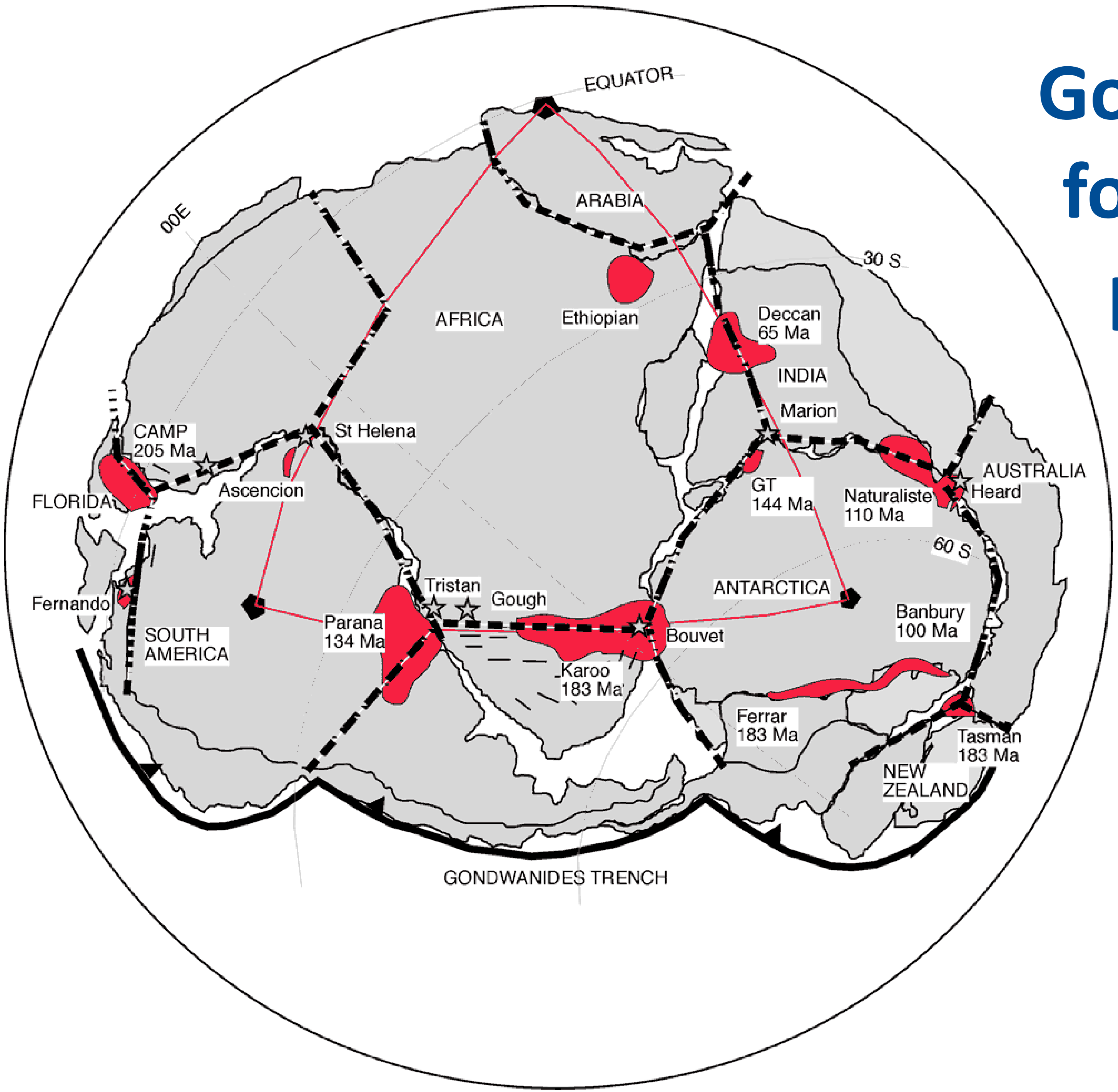
Mars

Plate tectonics, mountain building, atmosphere evolution and life appear to form a system coupled via multiple feedbacks

Earthquake triggering – natural and anthro-pogenic

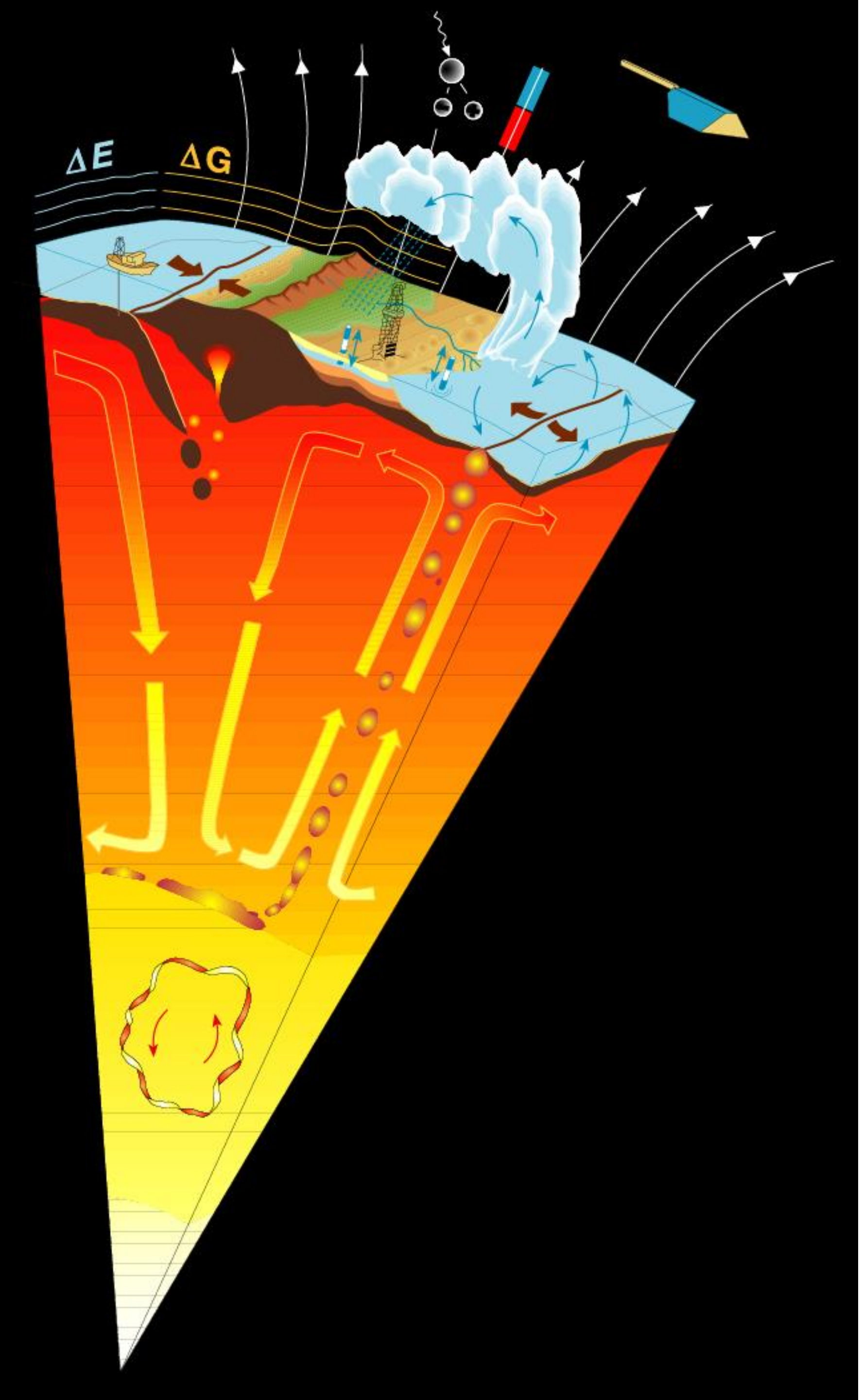


von Hagke et al., 2013



Gondwana fragmentation follows simple geometric principles on a sphere – a consequence of self organization

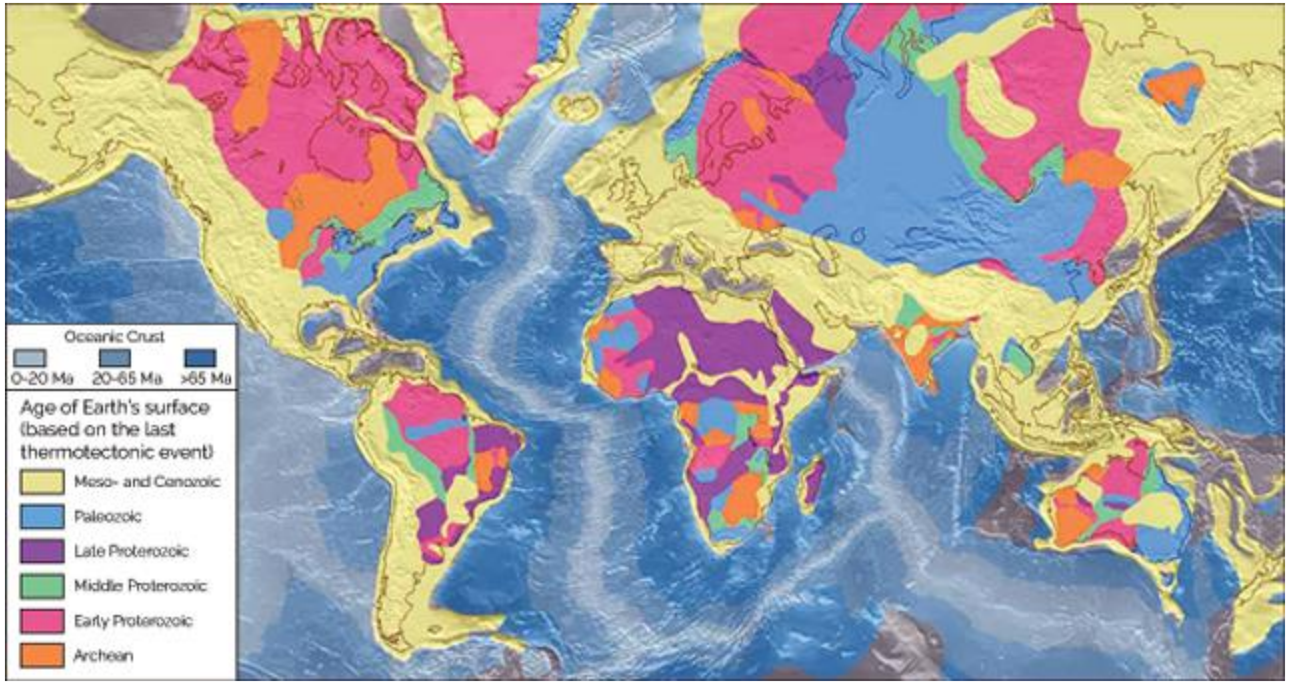
Source: Anderson, 2002;
Sears et al., 2005



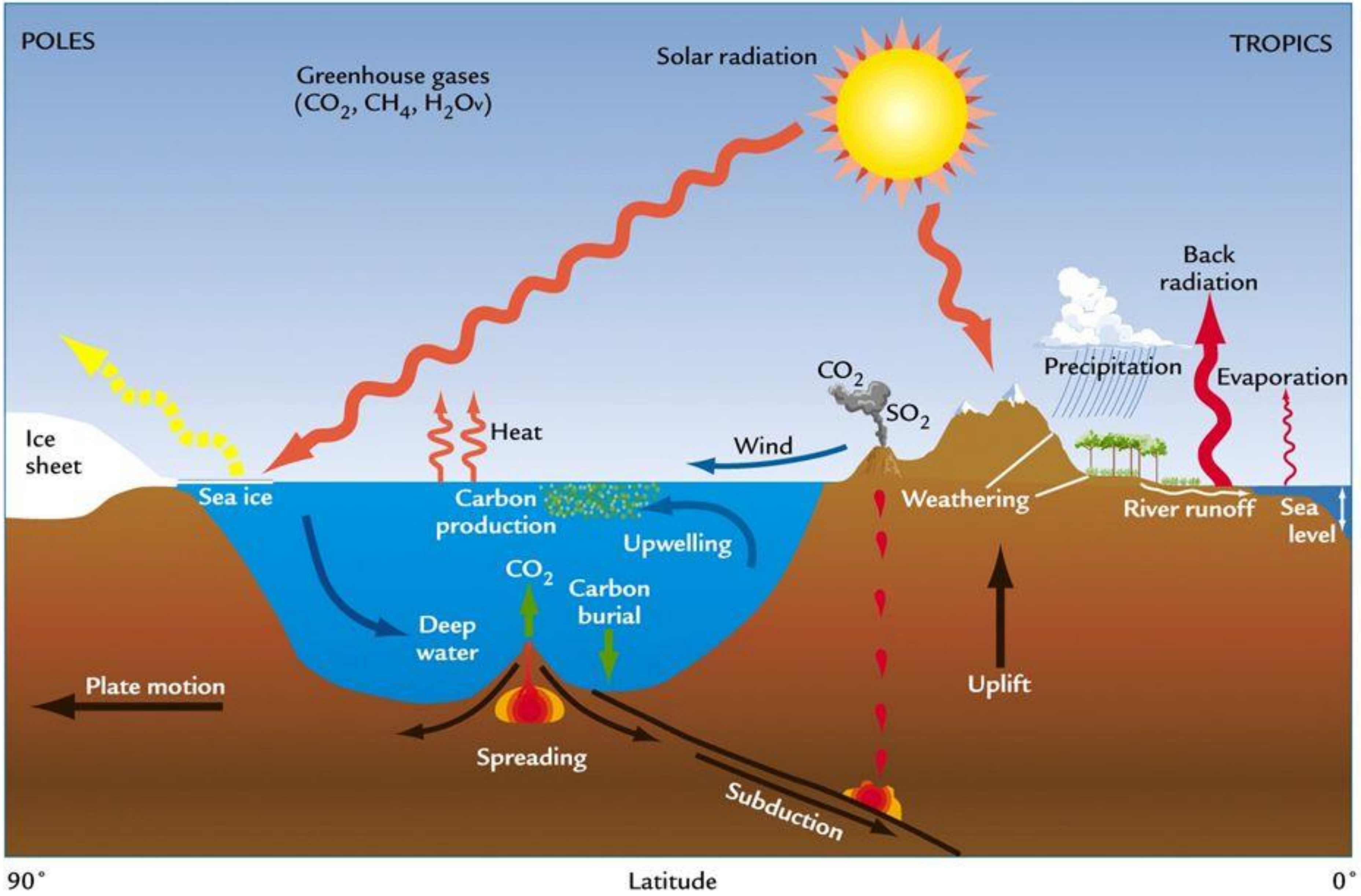
Emerging picture of ‚Earth-style' plate tectonics shows these attributes …

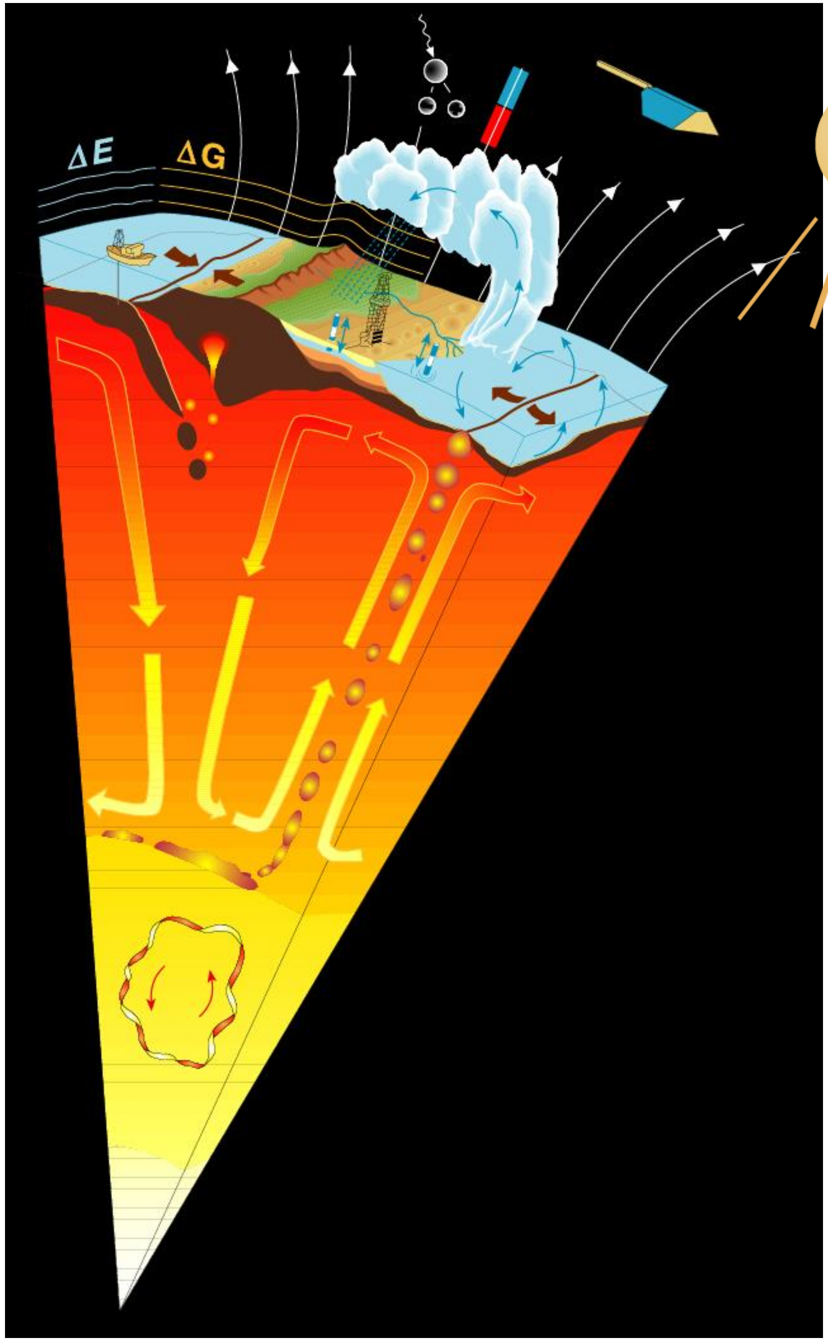
- …a silicate planet with characteristic chemical and mechanical properties
- …a limited temperature regime with stable (radiogenic) heat source
- … positive and negative feedbacks stabilizing thermal boundary conditions (internal **<u>and</u>** at surface) and mass flux
- … self-organization of system components maintains one of potentially several stable tectonic regimes

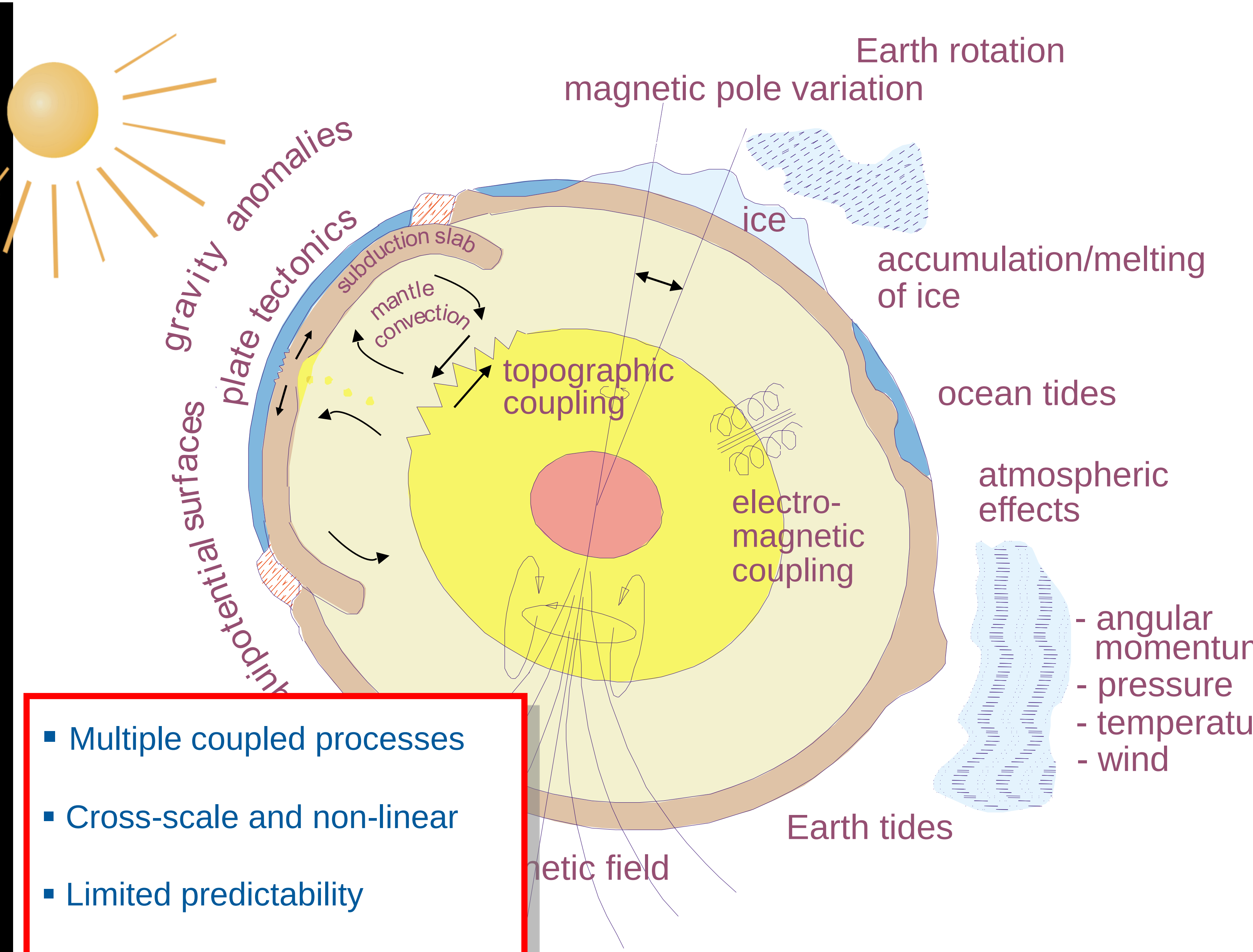
…, but many open questions remain


Oceanic Crust
0-20 Ma
20-65 Ma
>65 Ma
Age of Earth's surface (based on the last thermotectonic event)
Meso- and Cenozoic
Paleozoic
Late Proterozoic
Middle Proterozoic
Early Proterozoic
Archean

Generalized diagram of the Earth system

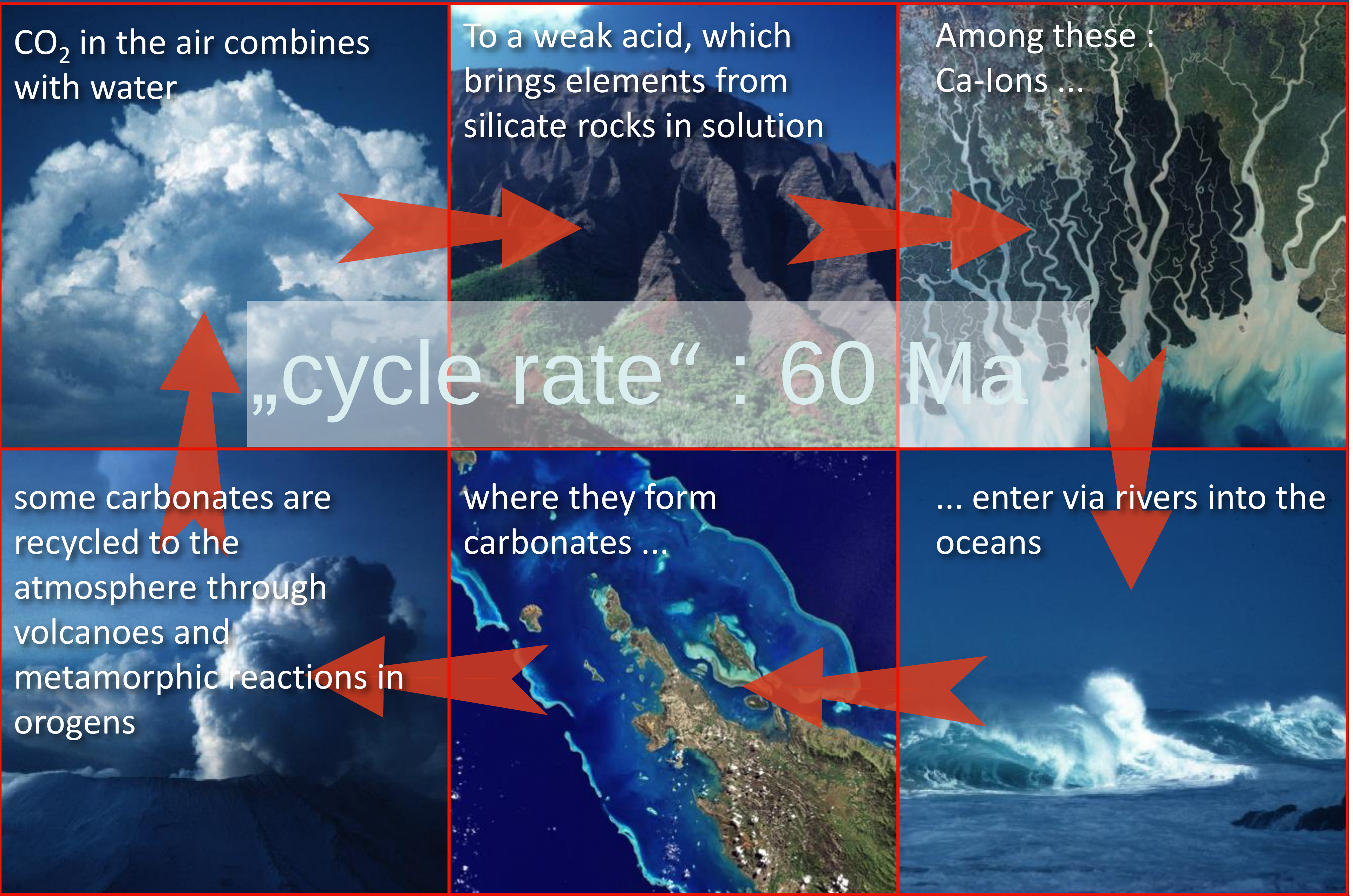


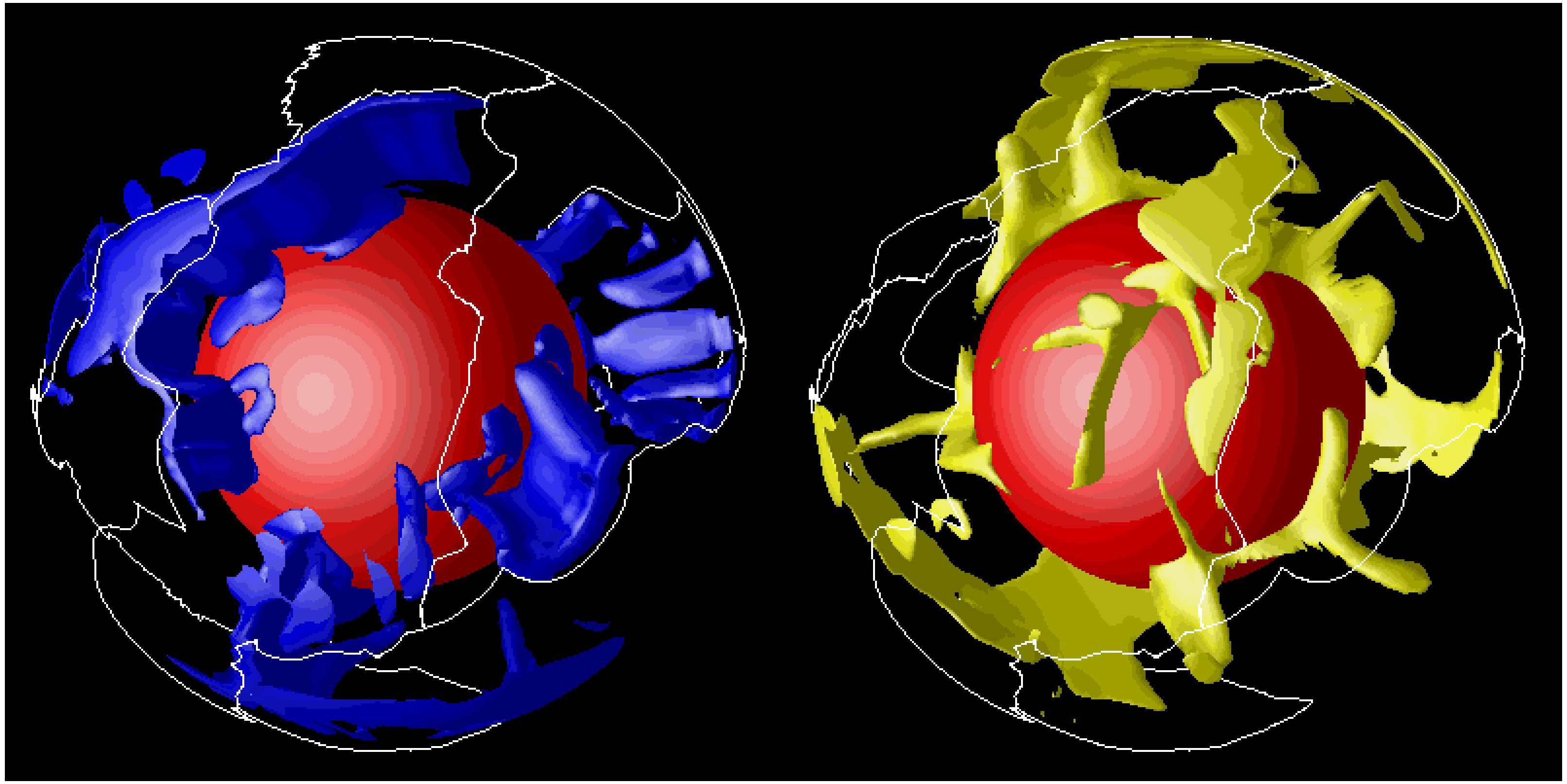




- Multiple coupled processes
- Cross-scale and non-linear
- Limited predictability
- Incomplete observability

The geological cycle of CO_2





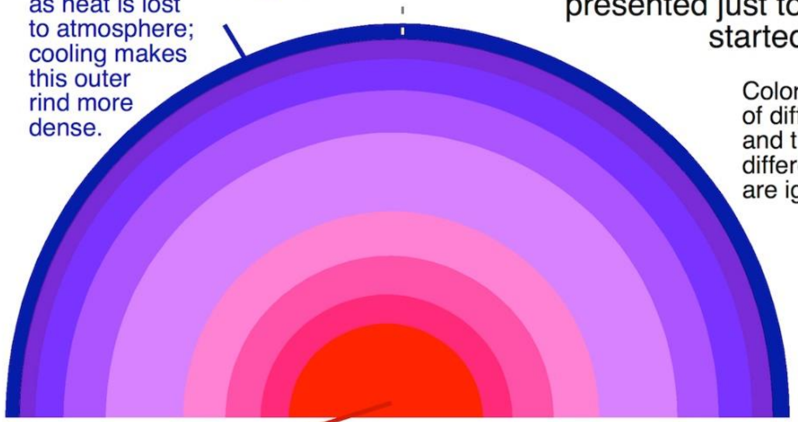
Source: S. Zhong

Plate tectonics and Earth dynamics

One might ask **"why is there plate tectonics?"** This page provides this answer: because heating of Earth's interior by radioactivity, and cooling of Earth's surface, create inversions of density. Those density inversions lead to vertical movements that result in horizontal movements of Earth's cold brittle outer rind. We call those horizontal movements of Earth's cold brittle outer rind "plate tectonics".

A. A metastable static Earth

(an unsustainable hypothetical construct, presented just to get started)



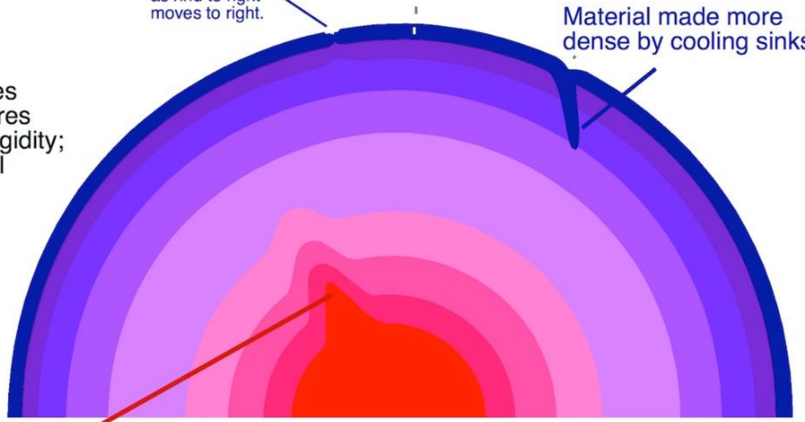
Colors represent zones of different temperatures and thus of differing rigidity; differences of material are ignored here.

COLD

HOT

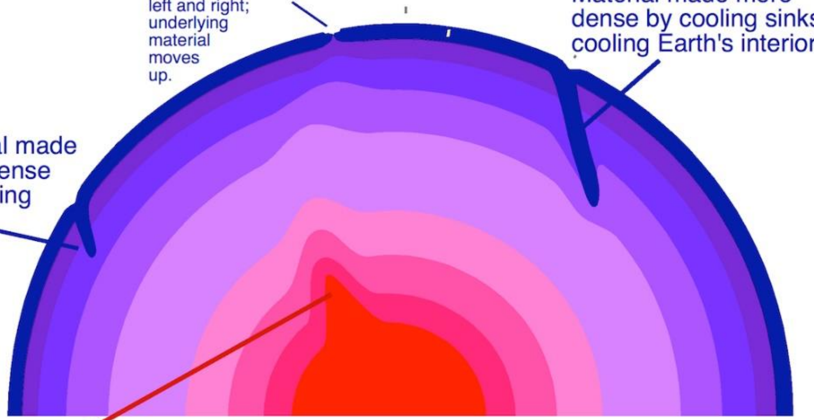
Earth's interior is also under great pressure, which makes materials more dense. Additionally, denser materials have settled to Earth's interior through time. Thus, in a hypothetical perfect Earth, compromises of temperature, pressure, and material could give layers of upward-decreasing density all the way from core to surface, and thus a perfectly stable Earth – but how long would perfection persist?

B. Metastability fails

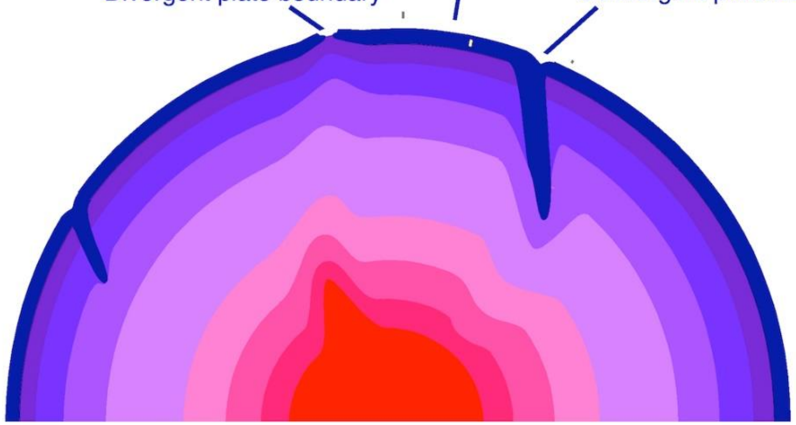


Differential heating in the atmosphere produces rising thermals and falling rain in a matter of hours. Much the same concept is illustrated here, but with a time scale of tens of millions of years.

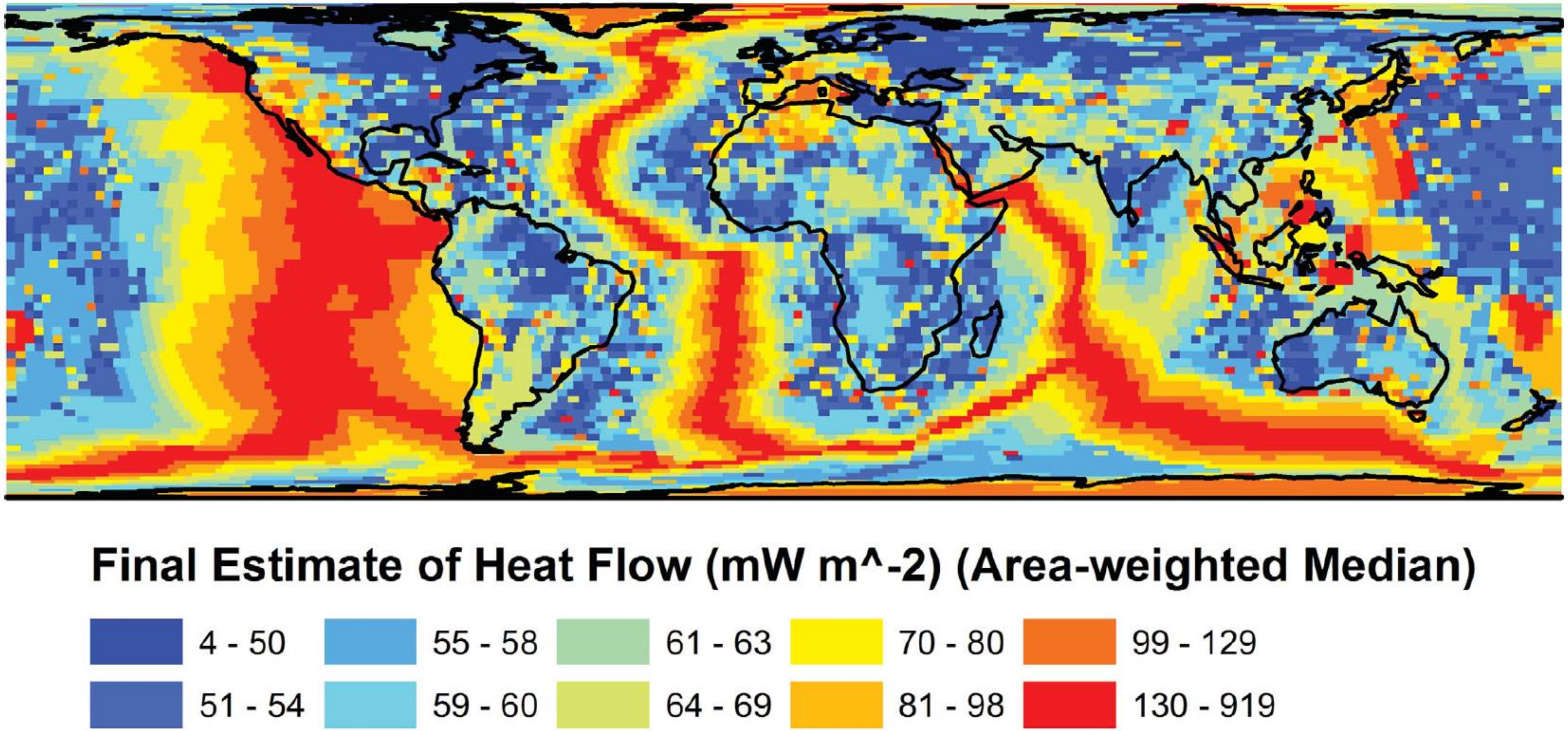
C. Earth becomes dynamic



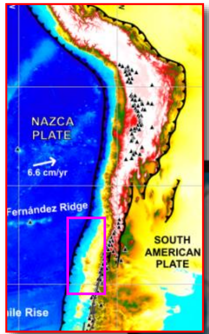
D. Dynamic Earth



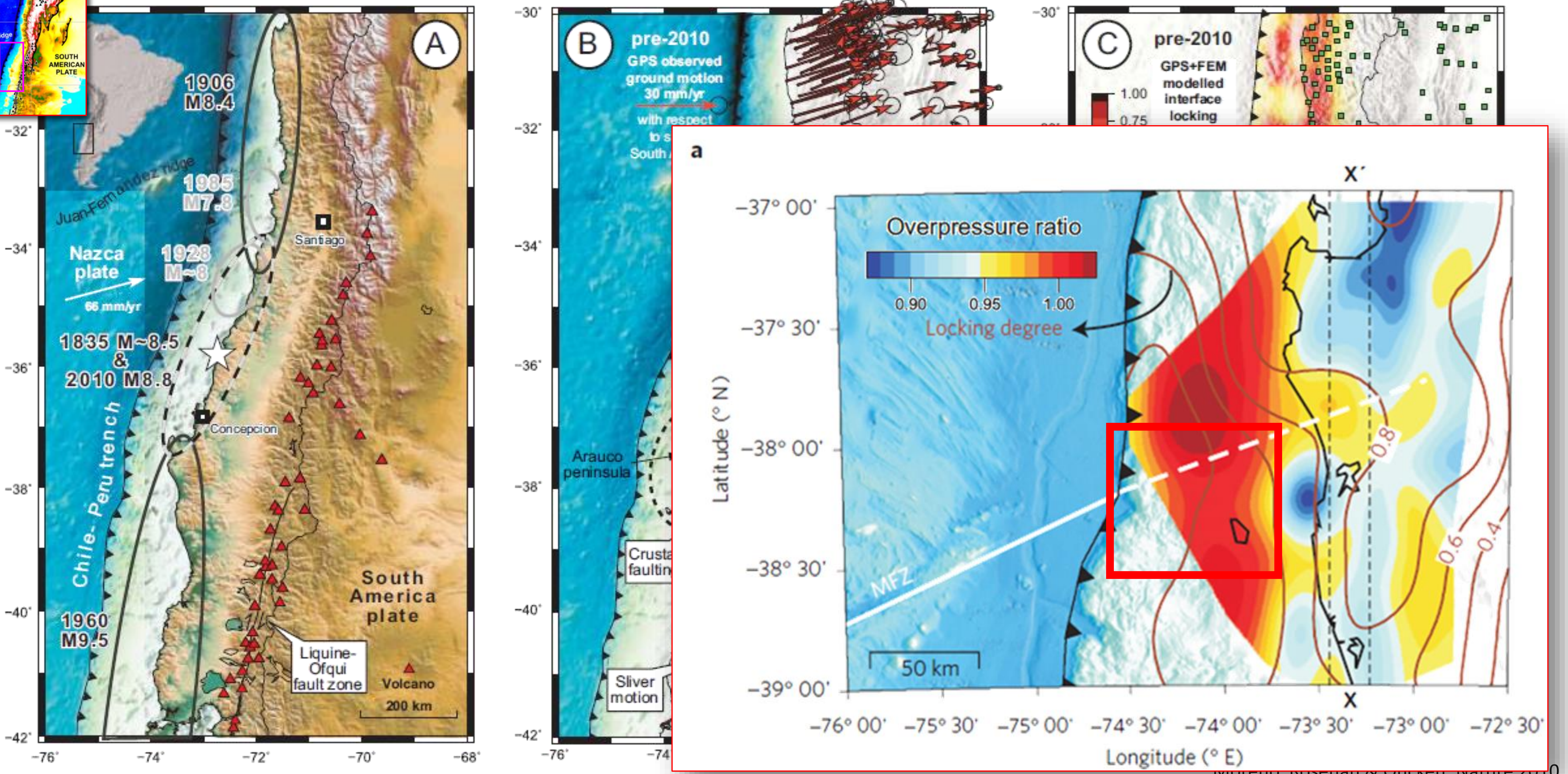
Those who see the sinking cold rind as the main driver are advocates of "slab pull" or perhaps better "plate slide"; those who see the rising hot mass as the main driver are advocates of "ridge push" or perhaps better "ridge rise"; those who see a circular flow of variably heated material as the main driver are advocates of "mantle convection".



Source: Davies, 2013

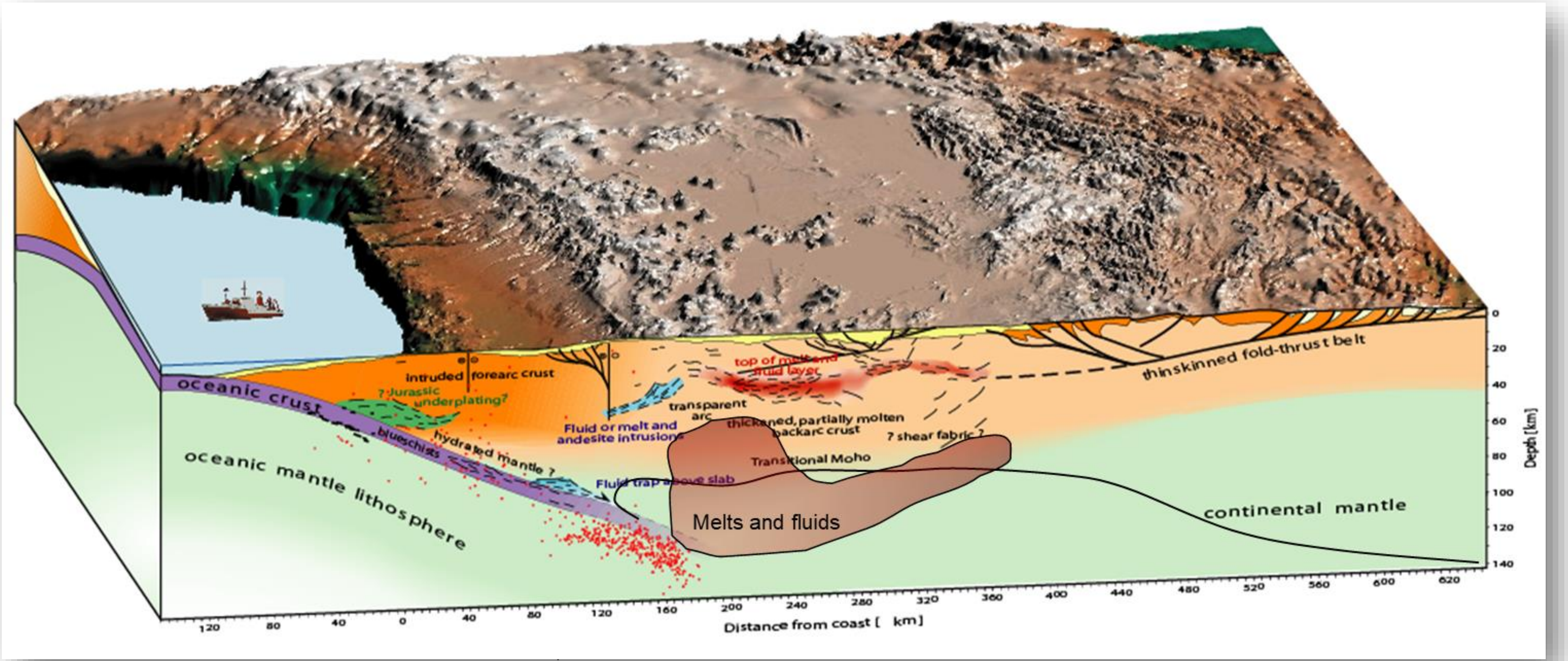


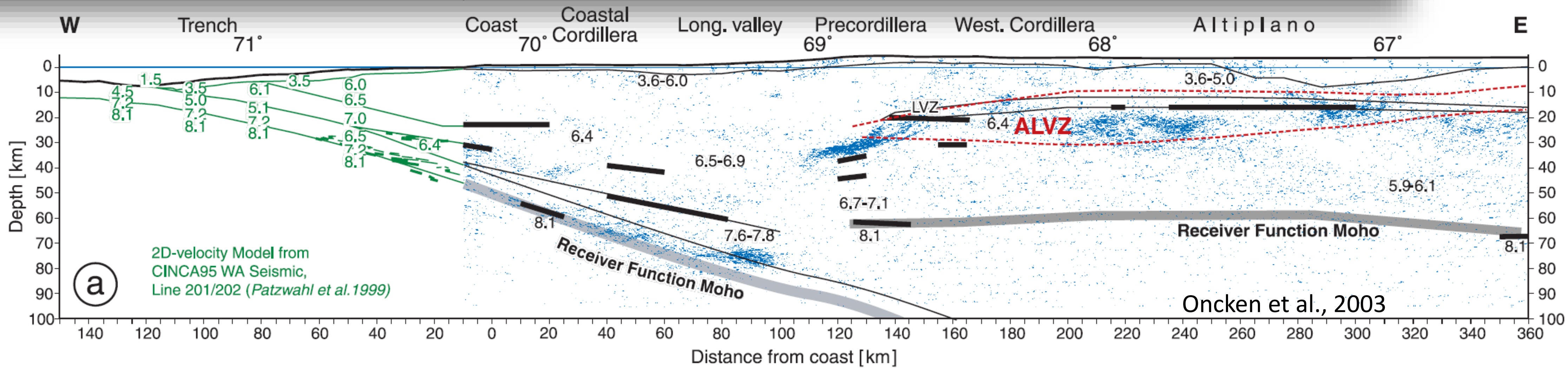
Kinematic locking prior to the Mw=8.8 Maule earthquake of 27.2.2010

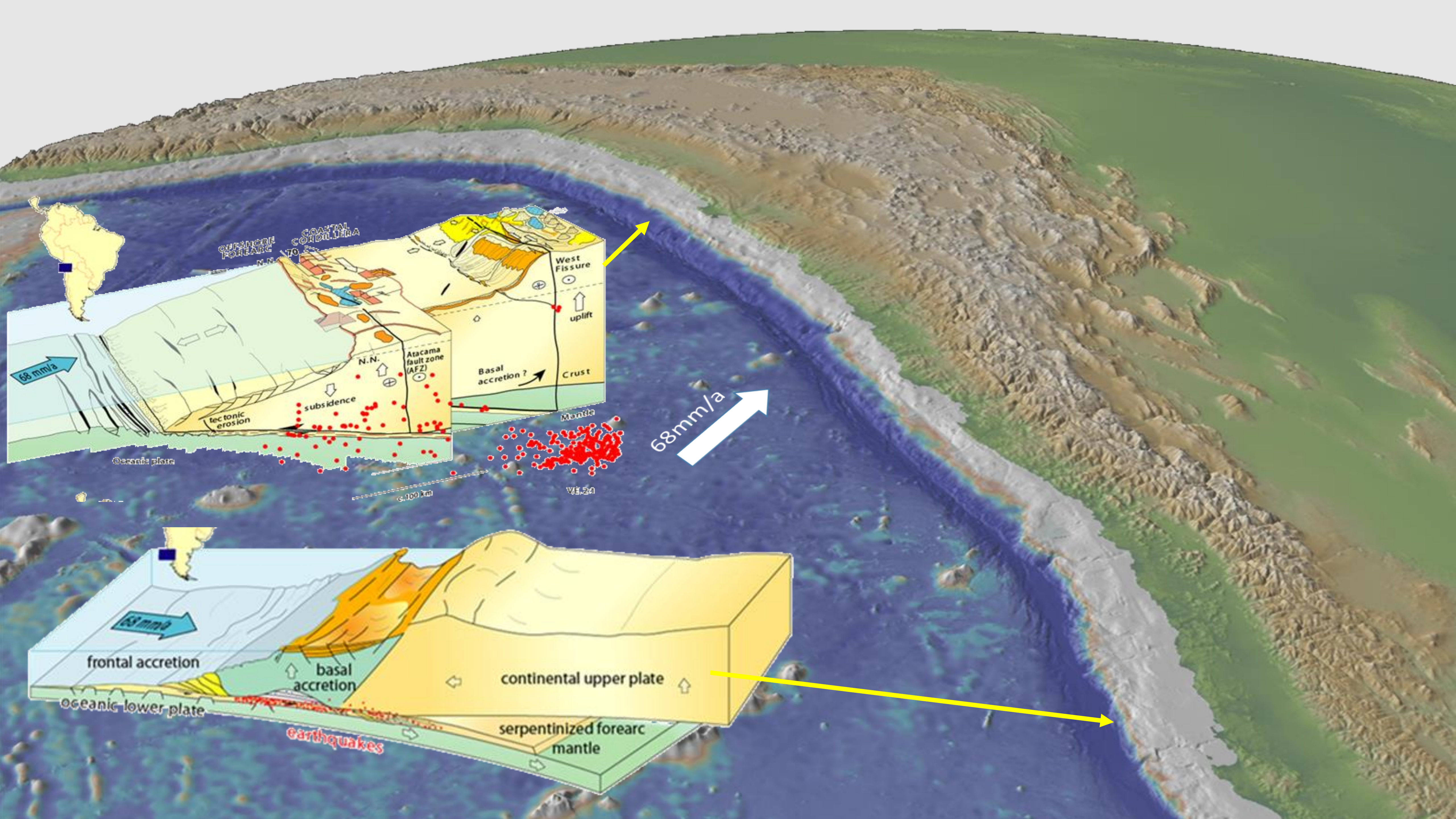


Moreno, Rosenau & Oncken, Nature 2010

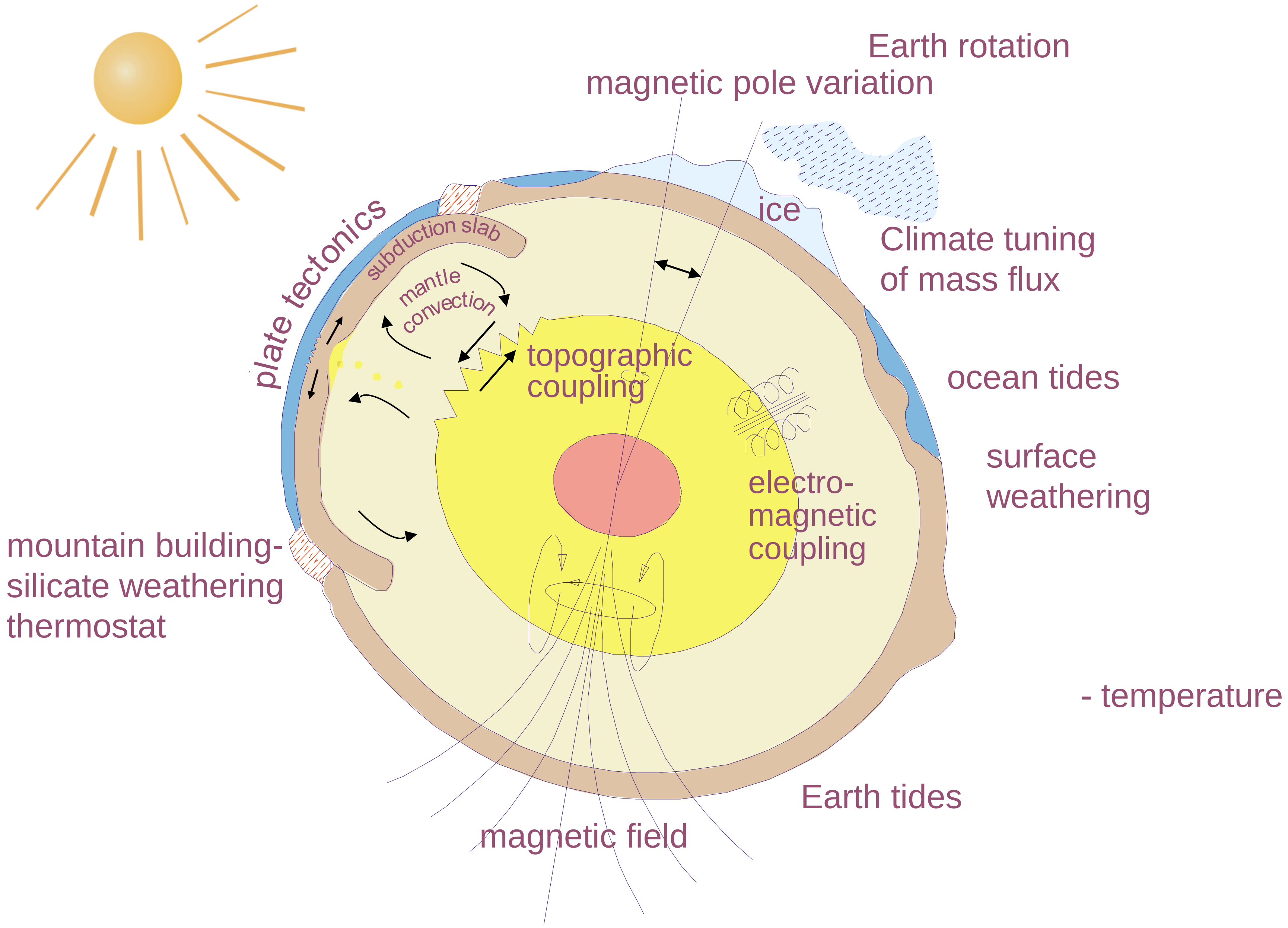
Andean archi-tecture



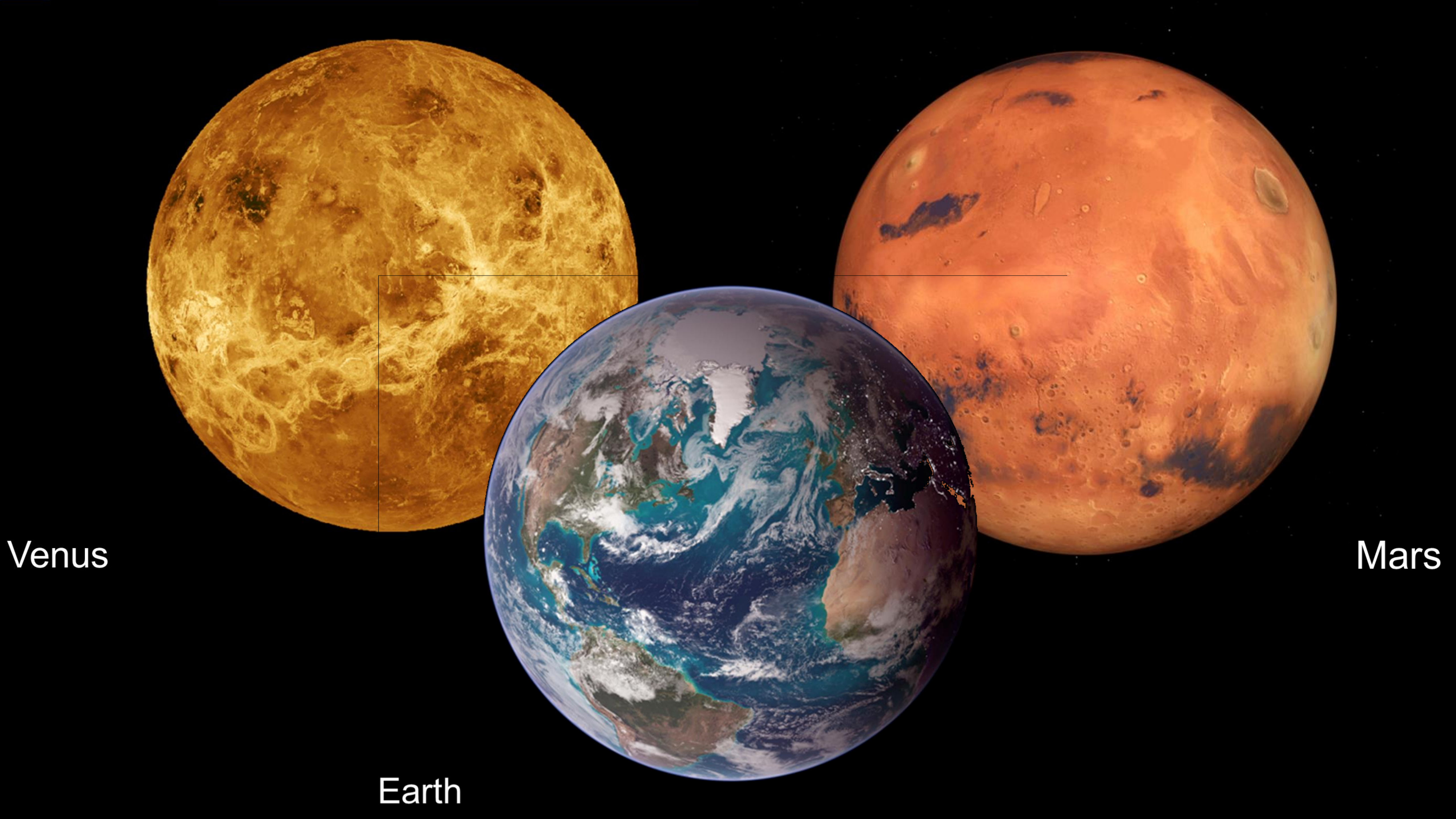




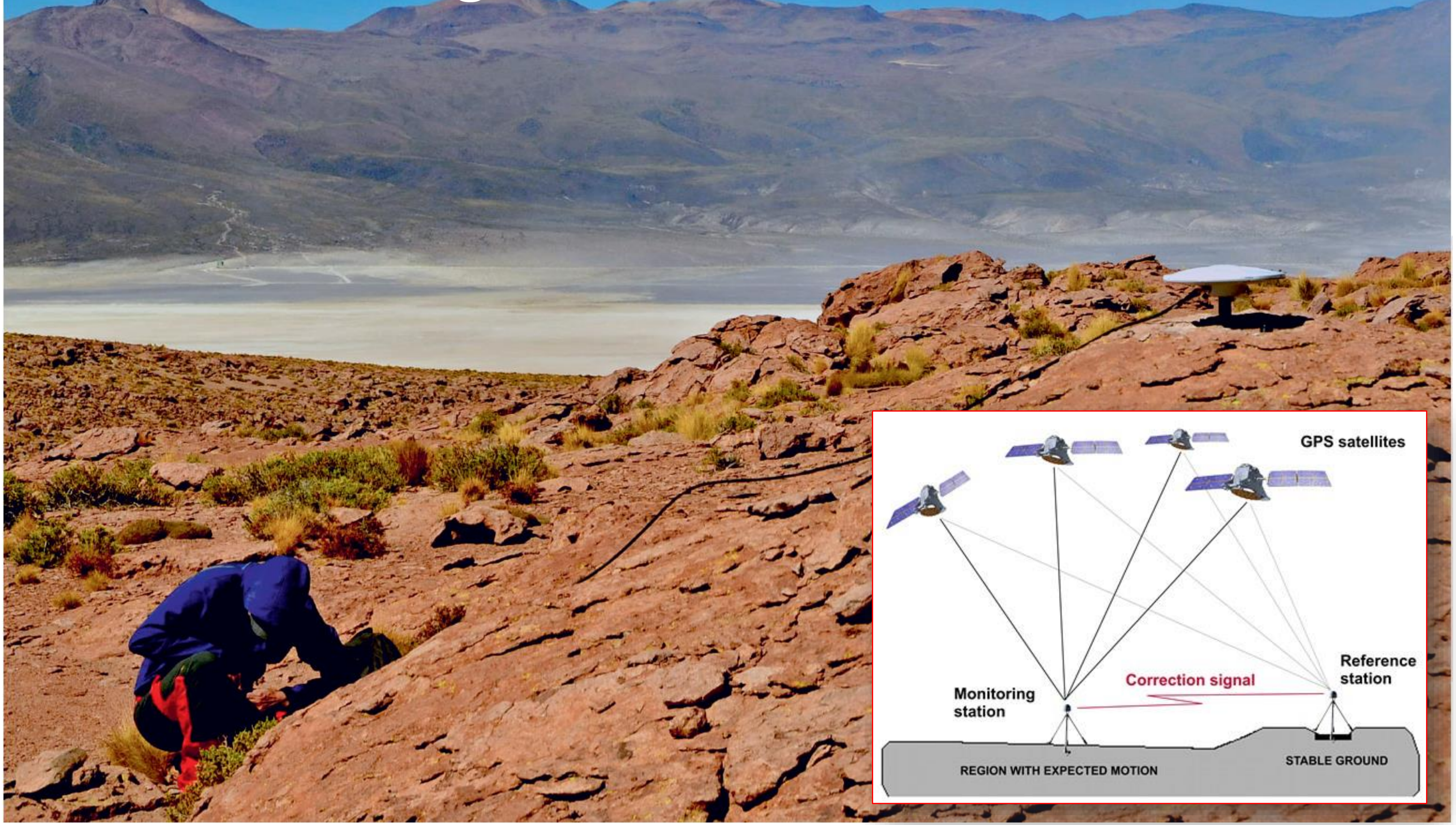
OFFSHORE FOREARC
COASTAL CORDILLERA
West Fissure
uplift
68 mm/a
Atacama fault zone (AFZ)
N.N.
Basal accretion ?
Crust
subsidence
tectonic erosion
Mantle
Oceanic plate
c.100 km
V.E.2:1
68mm/a
68 mm/a
frontal accretion
basal accretion
continental upper plate
oceanic lower plate
earthquakes
serpentinized forearc mantle



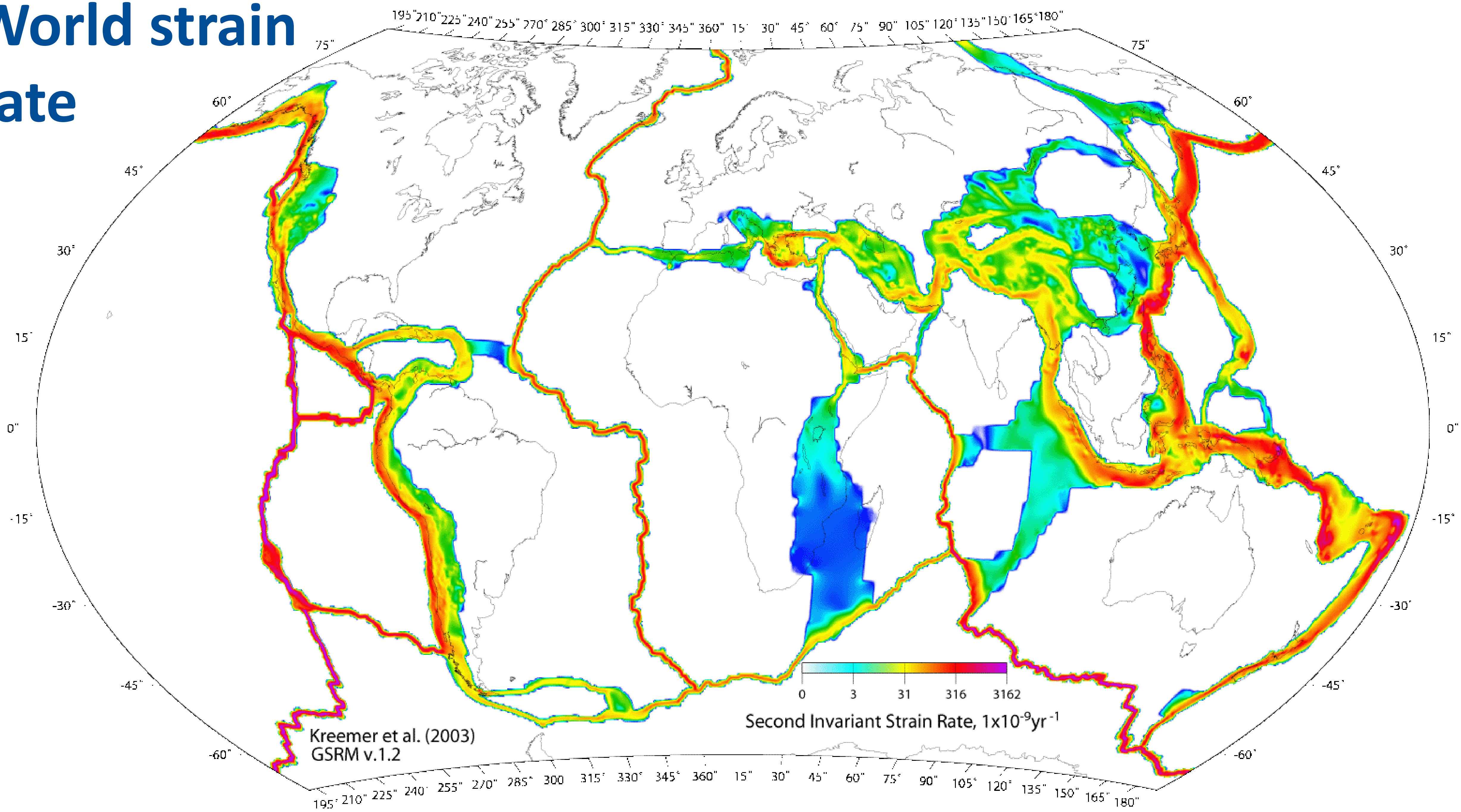
Earth rotation
magnetic pole variation
ice
Climate tuning
of mass flux
plate tectonics
subduction slab
mantle
convection
topographic
coupling
ocean tides
surface
weathering
electro-
magnetic
coupling
mountain building-
silicate weathering
thermostat
- temperature
Earth tides
magnetic field


Venus
Earth
Mars

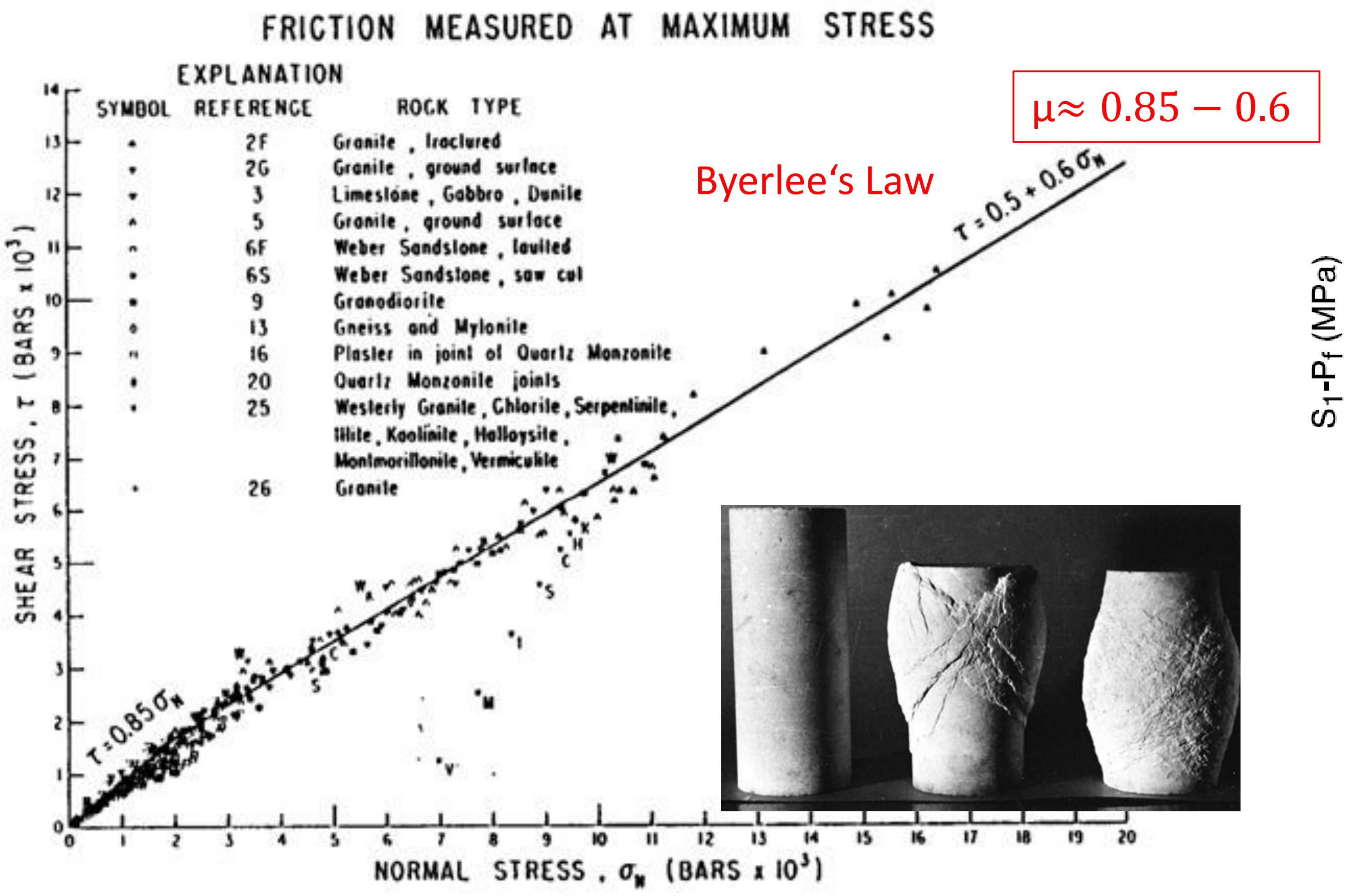
Measuring active deformation with GPS



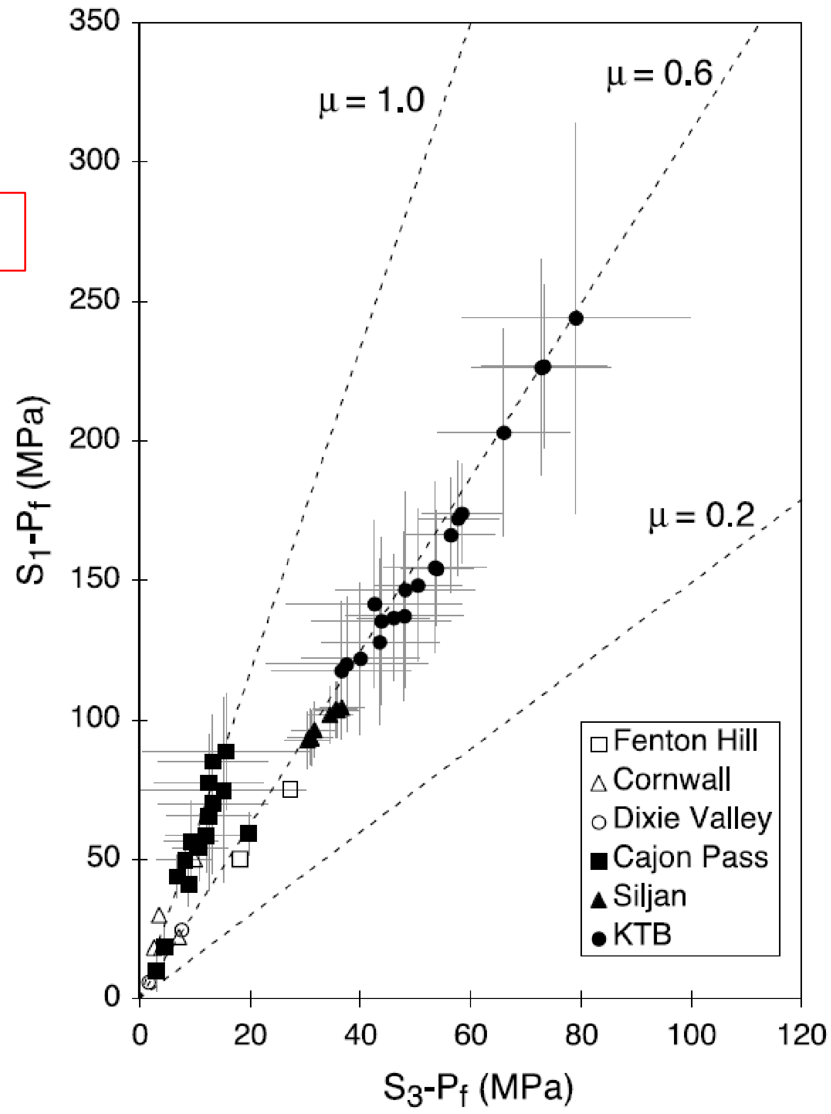
World strain rate



Earth‘s crust is in failure equilibrium globally !



Rock strength in experiments …



… and stress state in deep wells.