Joint ICTP-EAIFR-IUGG Workshop on Computational Geodynamics: Towards Building a New Expertise Across Africa

PLATE TECTONICS

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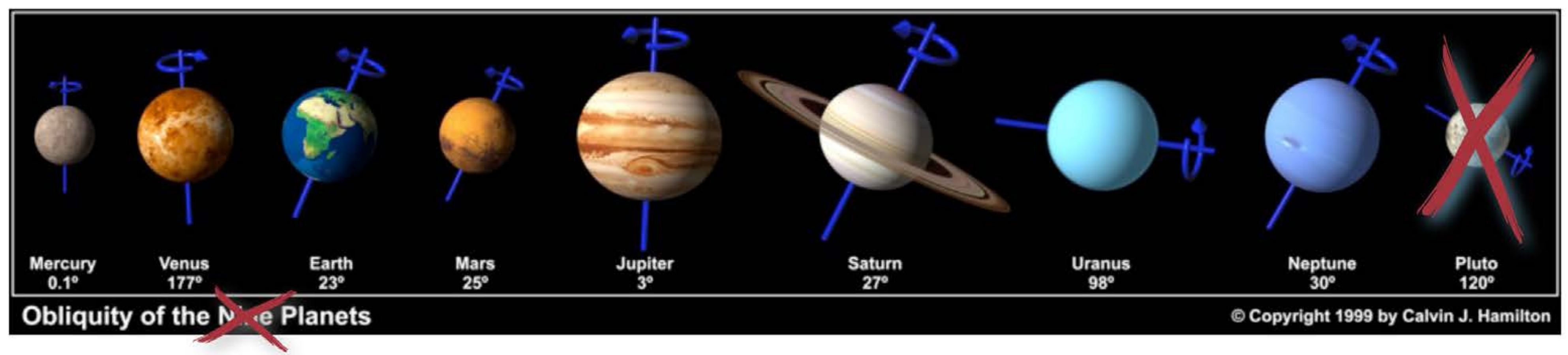
Outline of lecture

1. Rocky planets in the solar system.
2. Main surface features of planet Earth.
3. Viscous & petrological layering of the Earth.
4. Plate tectonics & mantle convection.
5. Plate and plate boundary kinematics.
6. Plate kinematics & reference frames.
7. Plate tectonics and geodynamics.

Eight planets in the solar system

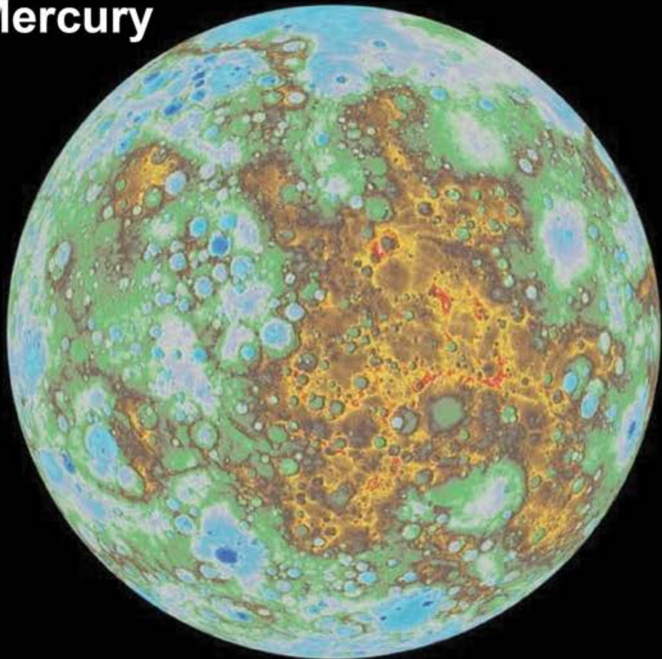


- 4 rocky planets (Mercury, Venus, Earth, Mars)
(metallic core + silicate mantle)
- *2 gas giants (Jupiter, Saturn)*
(mostly hydrogen & helium)
- *2 ice giants (Uranus, Neptune)*
(mostly heavy volatiles)
- *1 dwarf planet (Pluto) (and possibly many more)*

- *Several rocky satellites (e.g. Moon, Io)*

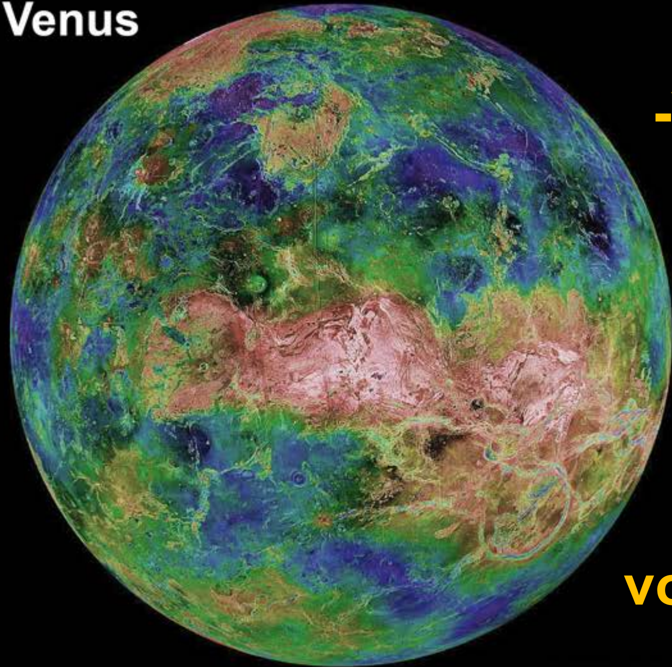
Topography of rocky planets: Mercury, Venus, Earth, Mars

Mercury



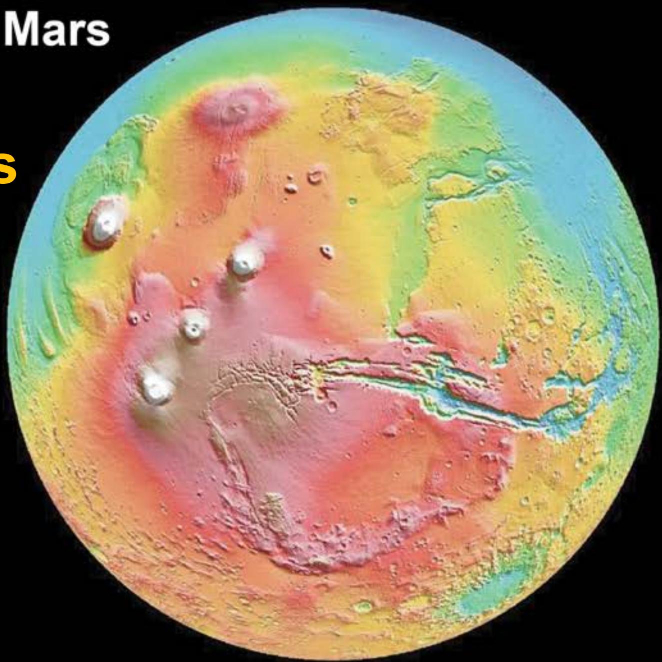
- -Many impact craters
- -Reverse faults

Venus



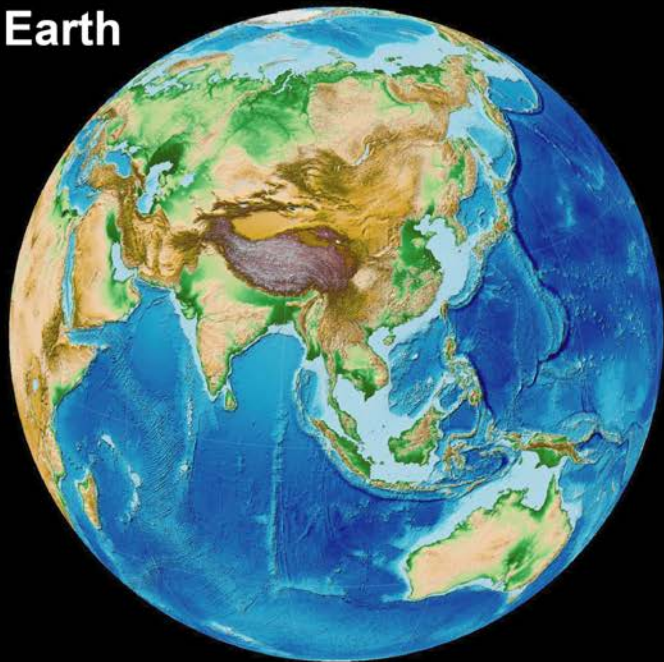
- -Volcanic features
- -Some impact craters
- -Faults due to volcanism

Mars



- -Volcanoes
- -Impact craters
- -Rift with normal faults

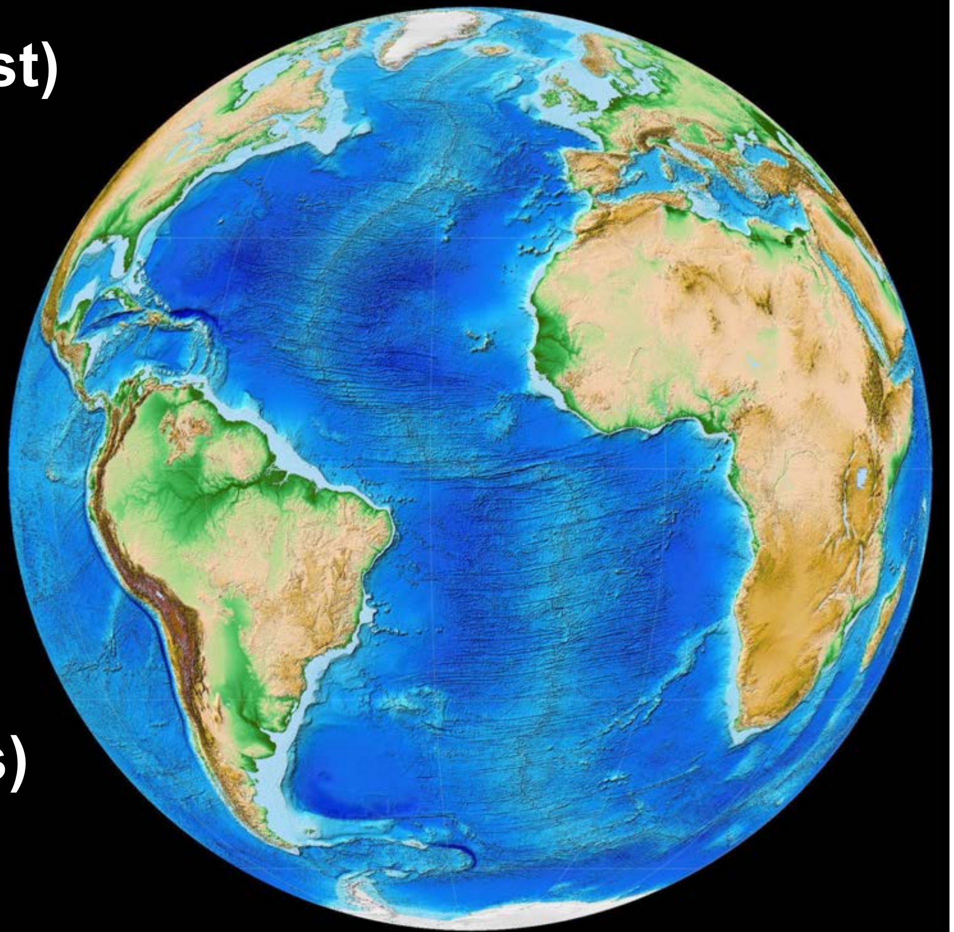
Earth



Rocky planet: Earth

Surface features

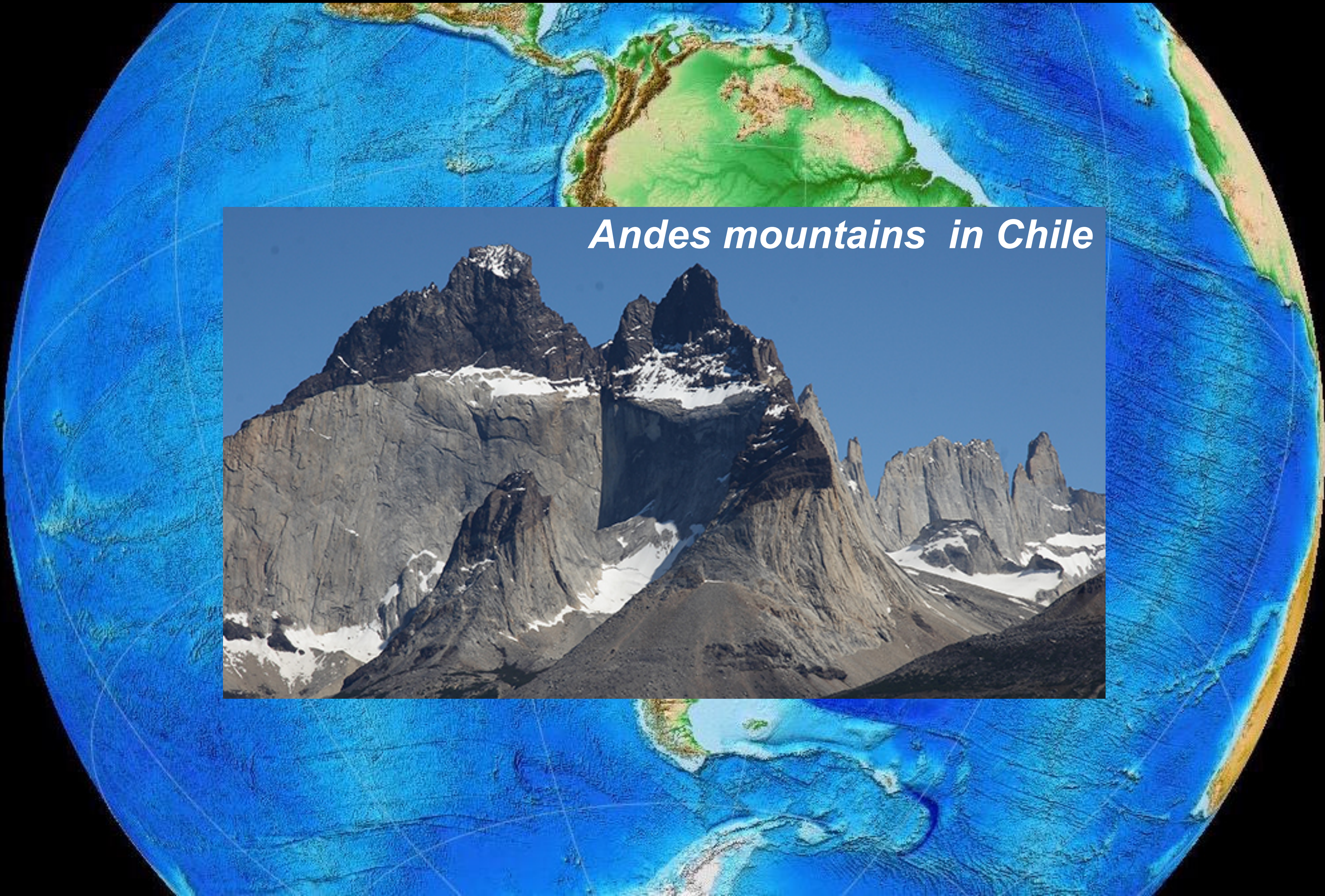
- Bimodal topography (deep ocean basins and high continents)
- Linear mountain ranges
- Linear deep sea trenches
- Faults (normal, strike-slip, thrust)
- Volcanoes (often aligned along linear zones)
- Only a few impact craters



Peculiarities

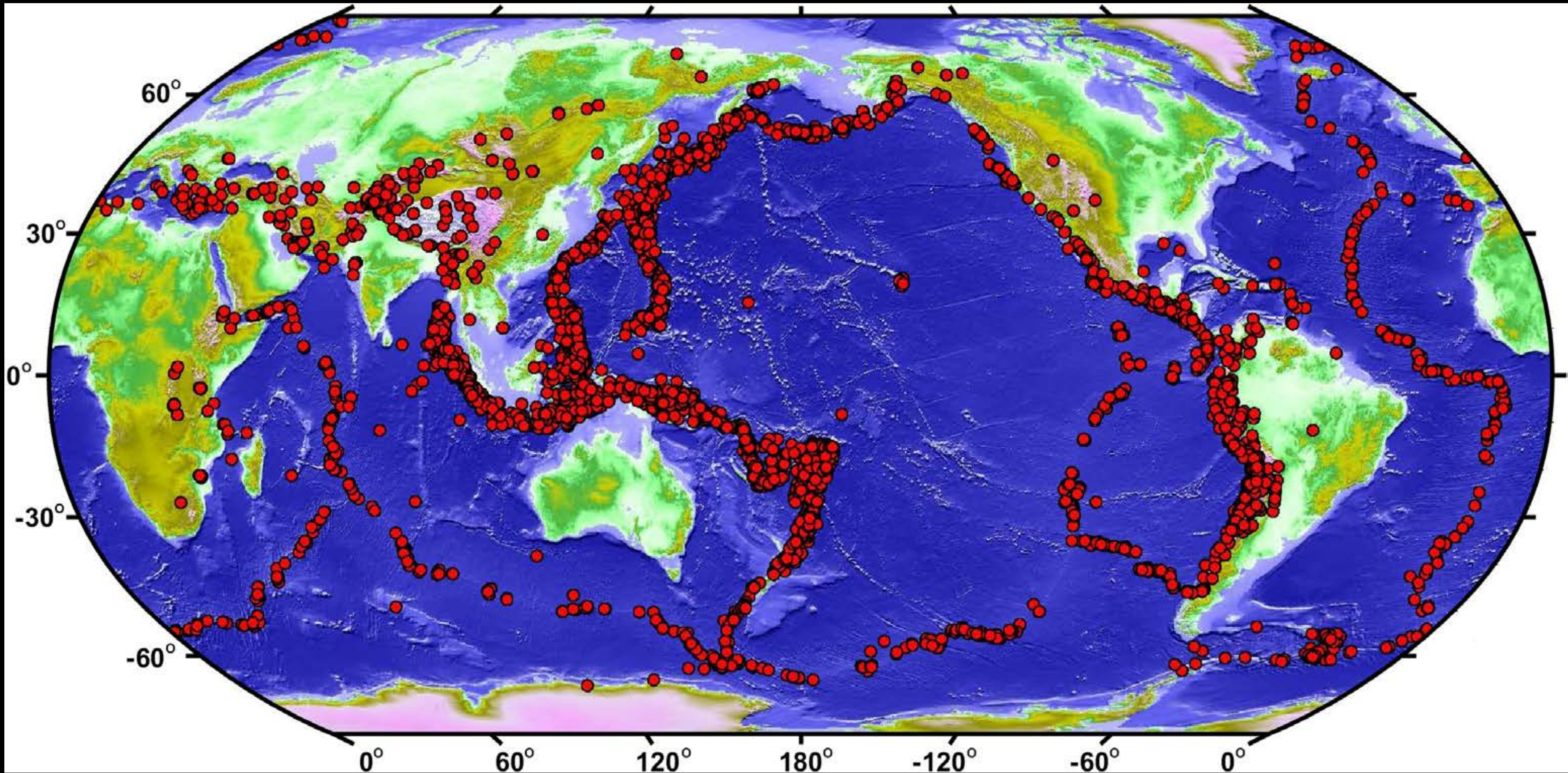
- Linear zones of seismicity
- Biosphere (life)
- Abundant water (liquid, ice, gas)

Topography on Earth



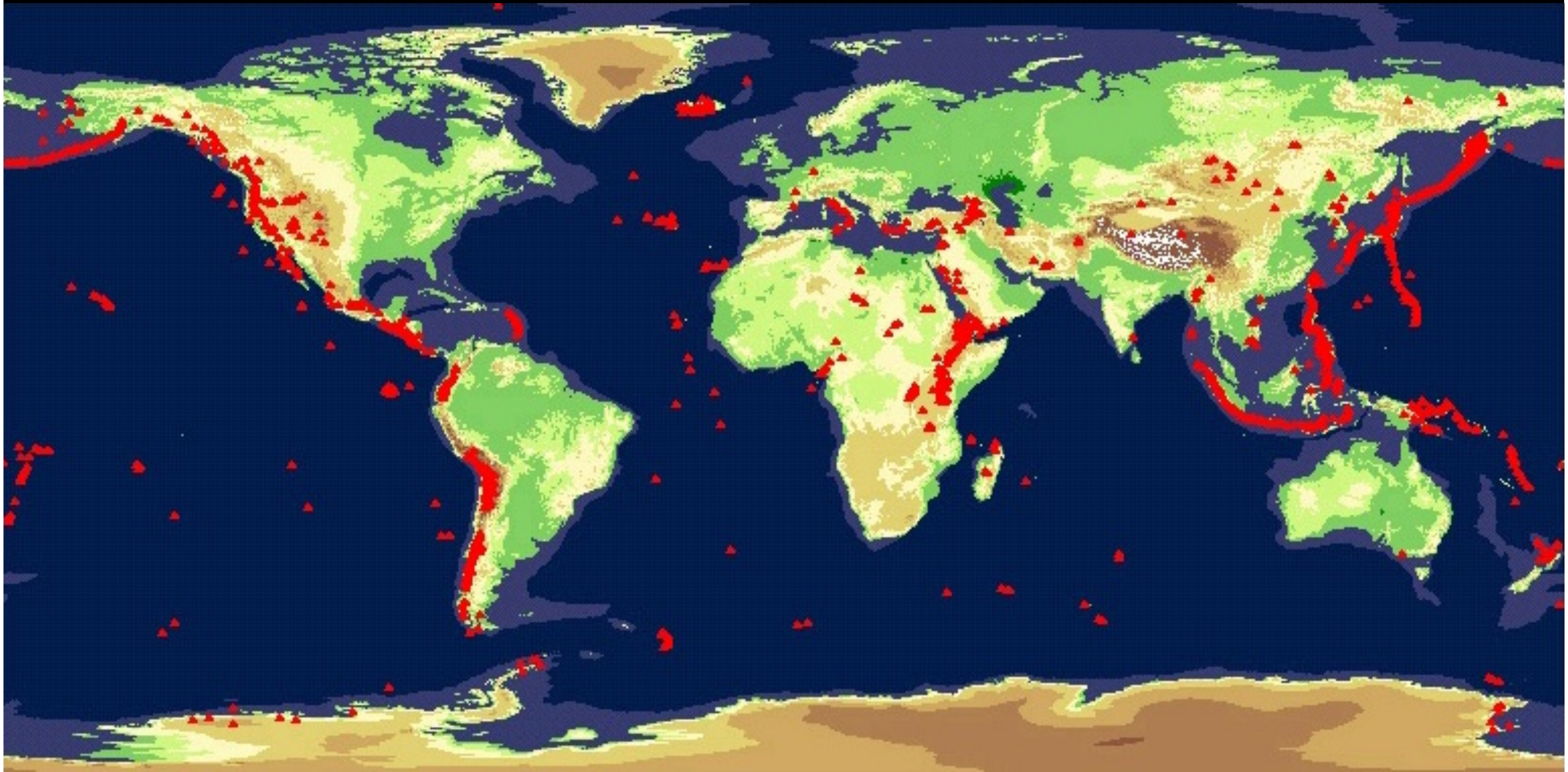
Linear mountain ranges & deep sea trenches, bimodal topography.

Rocky planet: Earth (earthquakes)



Linear belts of seismicity (earthquakes with moment magnitude ≥ 5.0 during the period 2005-2007). [*Schellart & Rawlinson*, Tectonophysics 2010]

Rocky planet: Earth (volcanoes)



Linear belts of volcanoes [D. Prentiss, U. California, Santa Barbara]

Faults on Earth (normal, strike-slip, reverse)

Earth & Plate Tectonics

Surface features

- Bimodal topography (deep ocean basins and high continents)
- Linear mountain ranges
- Linear deep sea trenches
- Faults (normal, strike-slip, reverse)
- Volcanoes (often aligned along linear zones)
- Only a few impact craters

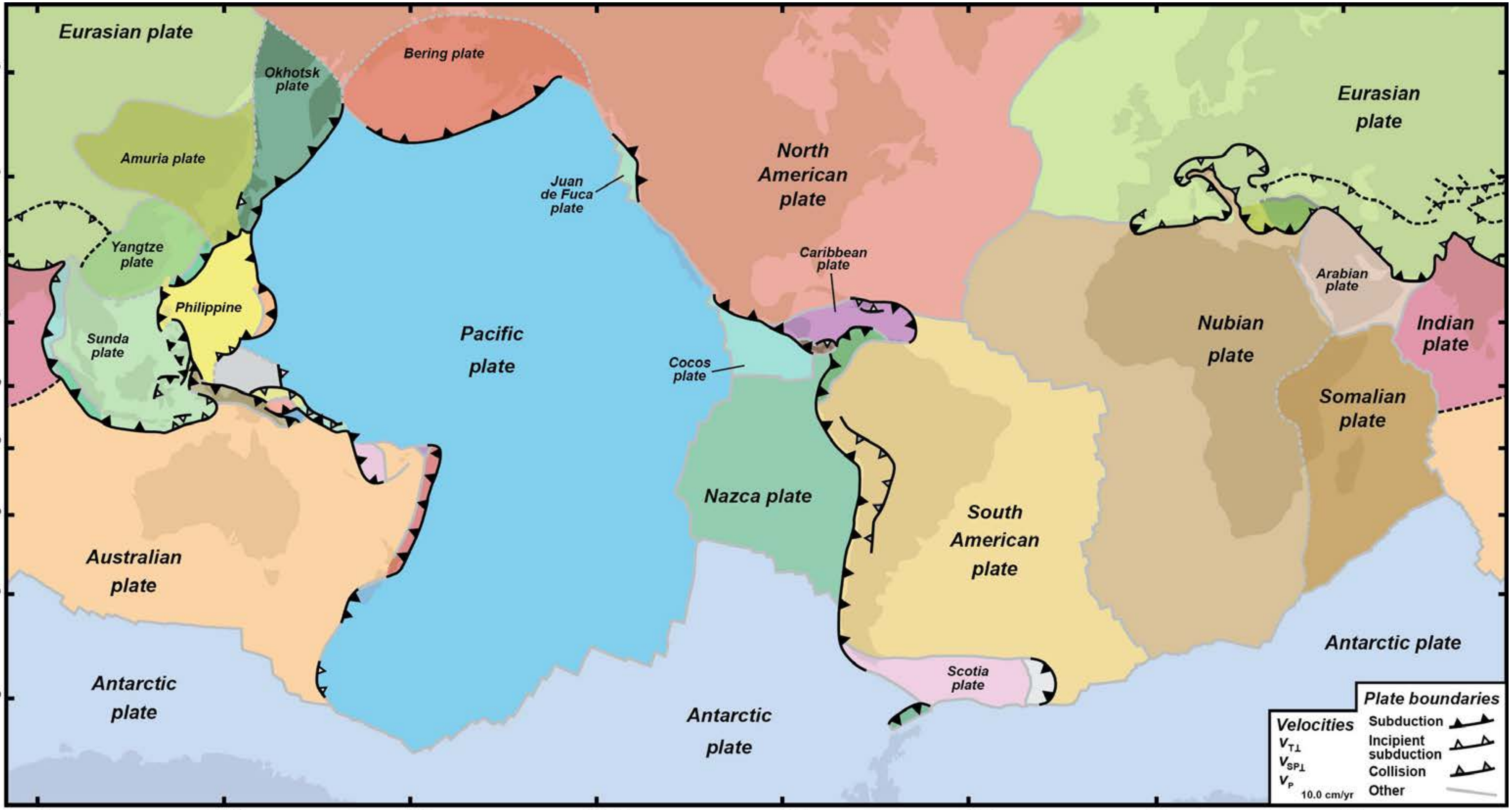
} Result of plate tectonics

Peculiarities

- Linear zones of seismicity → Result of plate tectonics
- Abundant water → Requirement for plate tectonics
- Biosphere (life) → Plate tectonics required?

Theory of plate tectonics

The outer shell (lithosphere) of the Earth is broken up into "plates", on average some 100 km thick, that move across the globe over a lower viscosity sub-lithospheric mantle at cm/year.



4 rocky planets: Surface activity & mantle convection

Inactive planet
(Mercury)

Active planets
-volcanism, volcano-tectonics (Mars)

→ **Stagnant-lid convection**

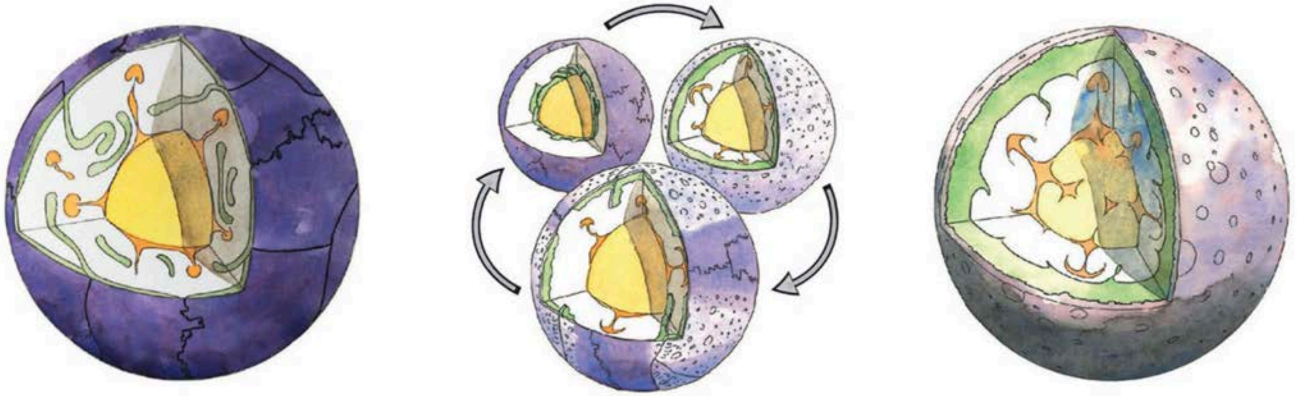
-volcanism, volcano-tectonics, resurfacing (Venus)

→ **Episodic overturn**

-Tectonics, volcanism (Earth)

→ **Mobile-lid convection (plate tectonics)**

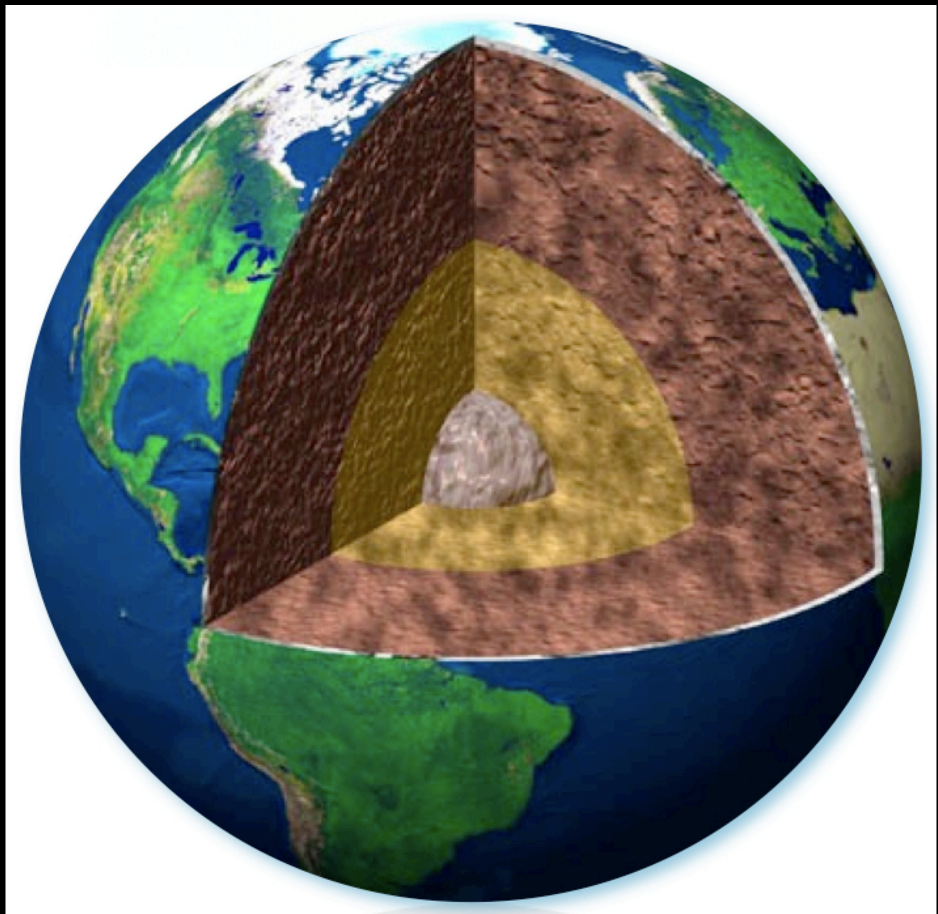
Mobile *Episodic* *Stagnant*



[Laurenço & Rozel, 2023]

Rocky planet: Earth

Physical layering of the Earth: Viscosity



Inner core (solid) (iron-nickel)
(η = 10^{14}-10^{15} Pa·s, 1220 km)

Outer core (liquid) (iron-nickel)
(η = 10^{-2}-10^{2} Pa·s, 2250 km)

Sub-lithospheric mantle
(peridotite) (s.l. upper mantle η = 10^{19}-10^{20} Pa·s, ~560 km, lower mantle η = 10^{21}-10^{22} Pa·s, 2230 km)

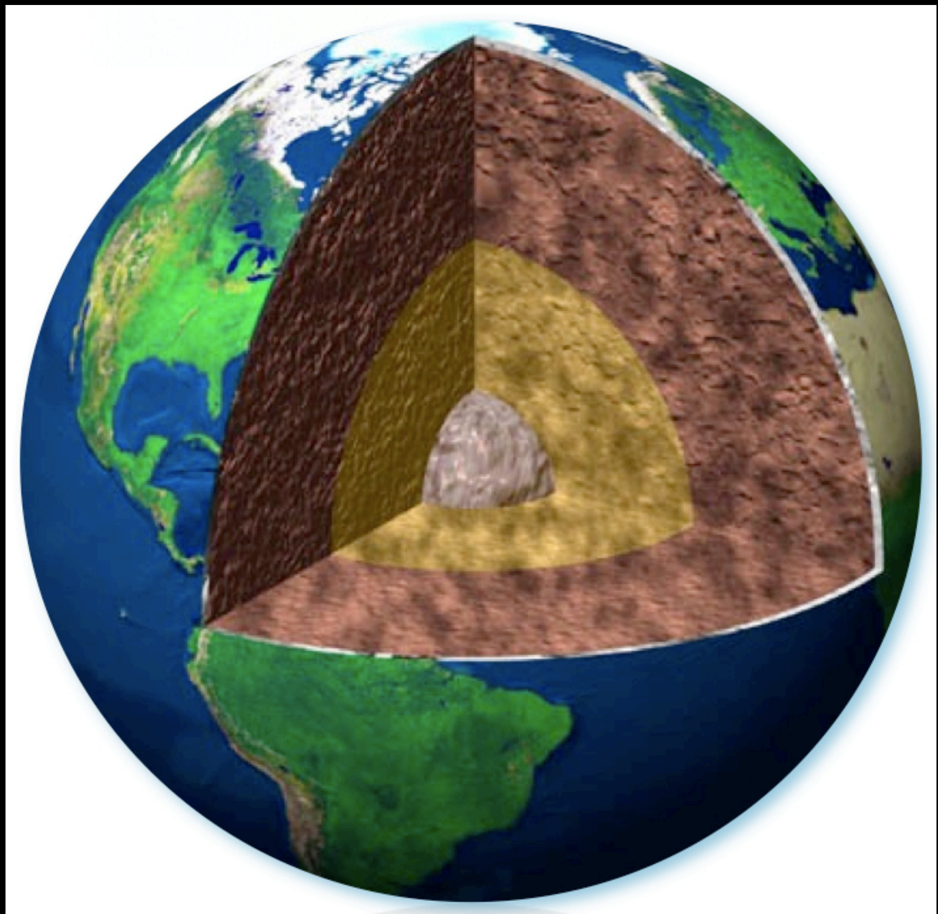
Lithosphere (plates)
(crust + uppermost mantle)
(η = 10^{22}-10^{25} Pa·s, ~100 km)

Hydrosphere (water)
(η = 10^{-3} Pa·s)

Atmosphere (air)
(η = 10^{-5} Pa·s)

Rocky planet: Earth

Petrological/chemical layering of the Earth



Core *(iron-nickel)

(10-13 g/cm^3, ~3470 km)

Mantle *(peridotite)

(3.3-5.7 g/cm^3, ~2890 km)

****Crust:***

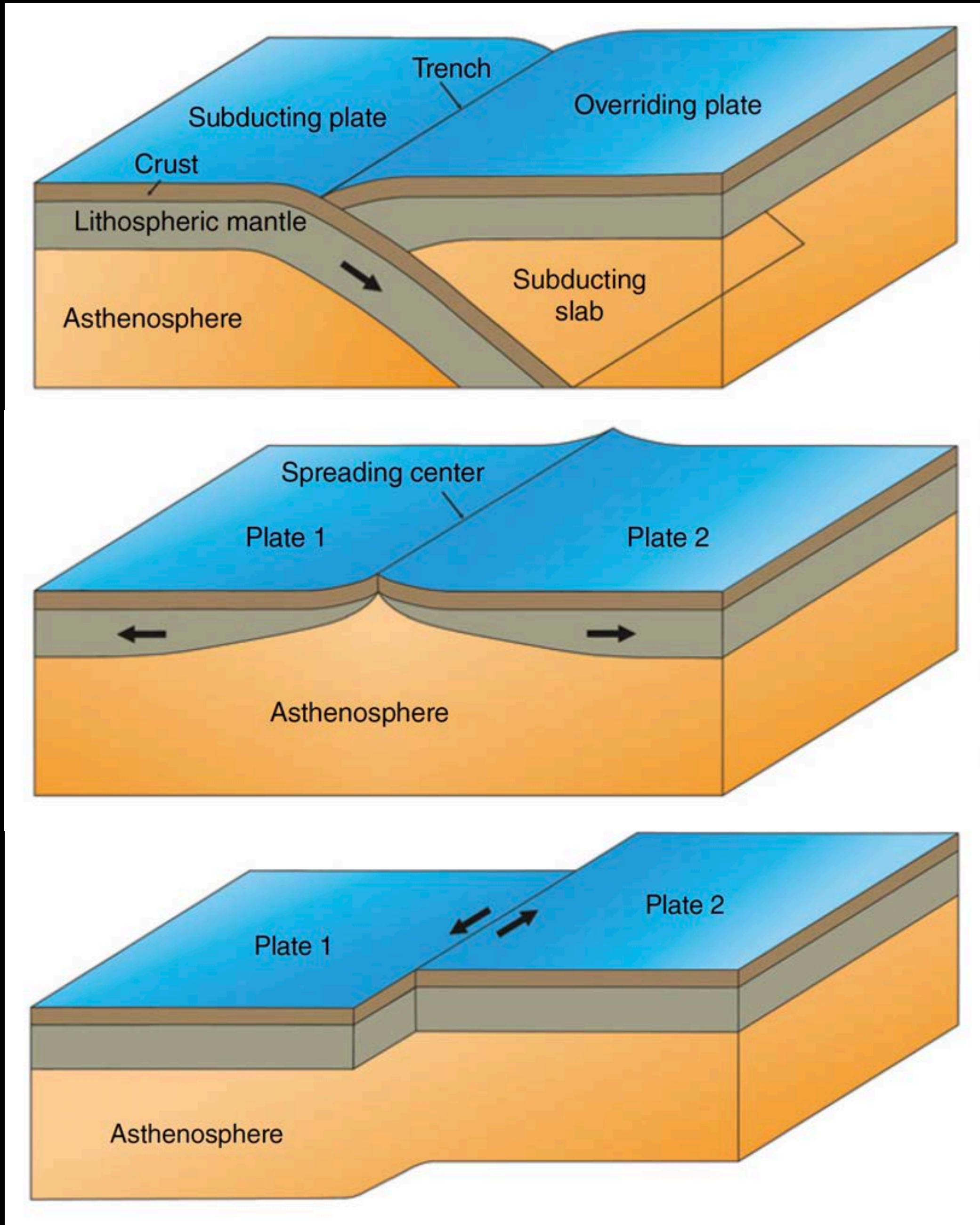
-Continental (granite)
(2.7 g/cm^3, ~35 km)

-Oceanic (basalt)
(2.9 g/cm^3, ~7 km)

***Hydrosphere (H_2O)**

***Atmosphere (N_2, O_2)**

Plate tectonics & plate boundaries



Convergent *plate boundary*

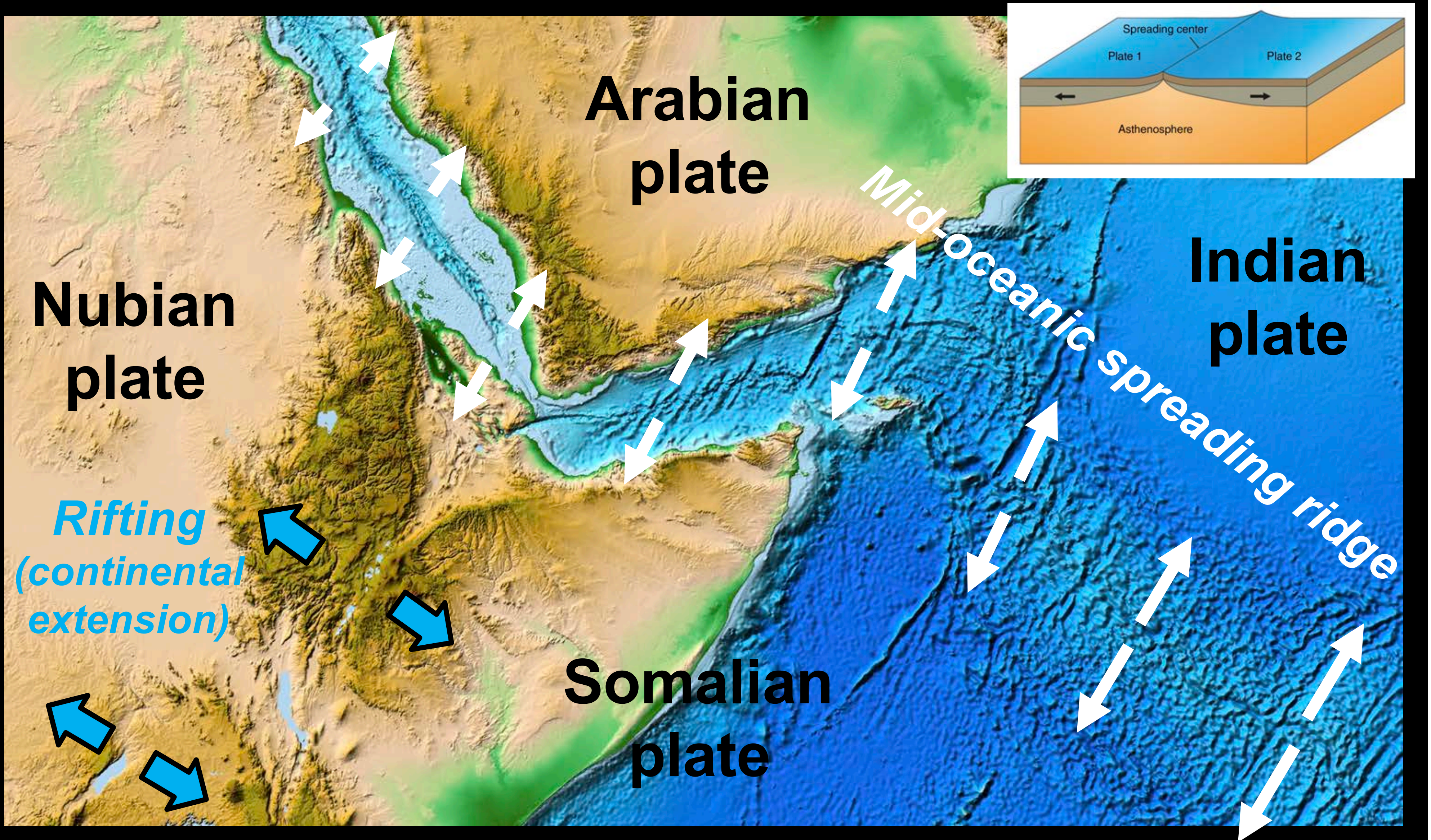
Divergent *plate boundary*

Transform *plate boundary*

[Duarte and Schellart, Geoph. Monograph 219, 2016]

Divergent plate boundaries

Creation of new tectonic plate material

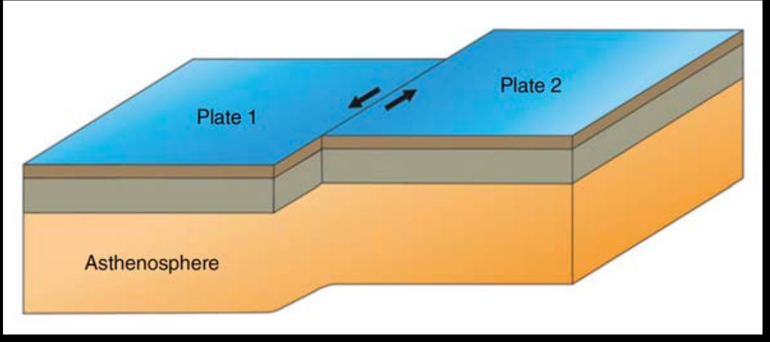


Transform plate boundaries

Conservation of tectonic plate material

Transform fault connecting two spreading ridges

Transform fault connecting spreading ridge & subduction zone



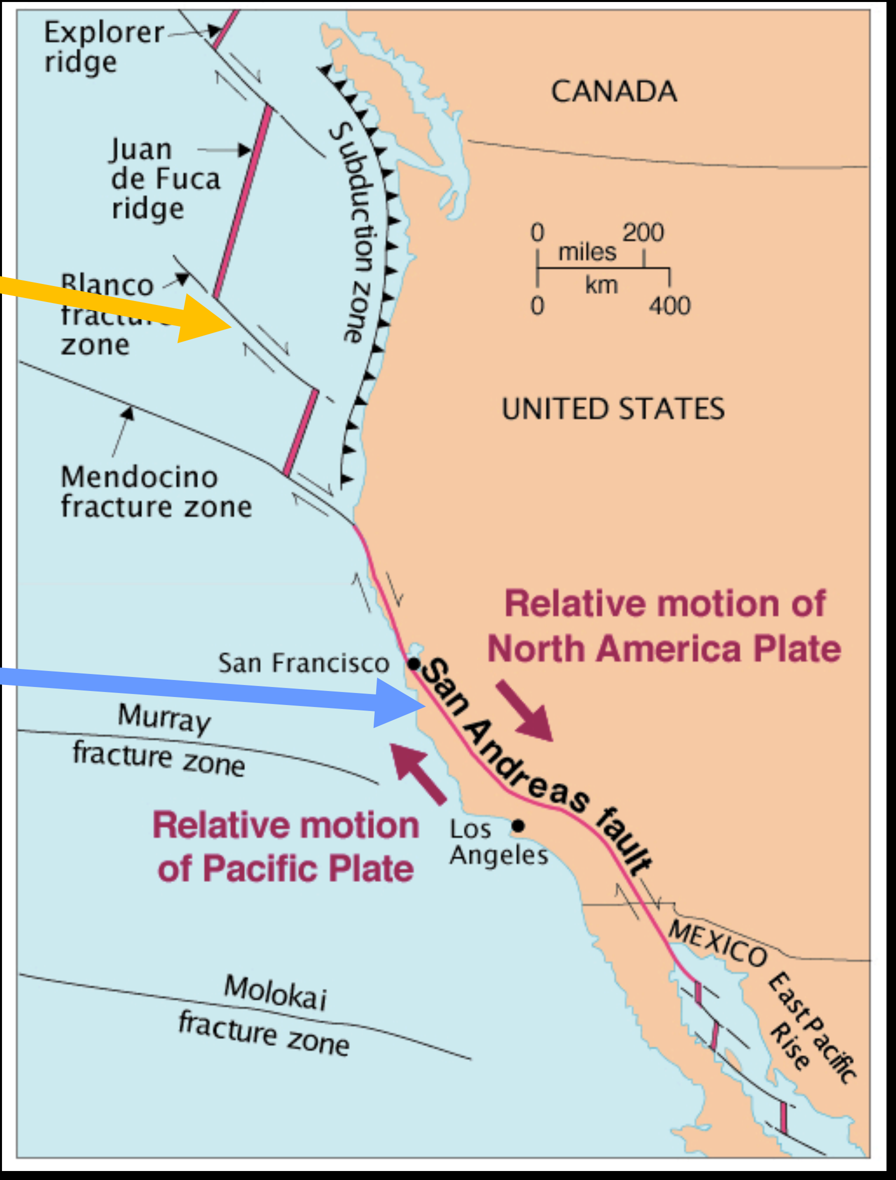
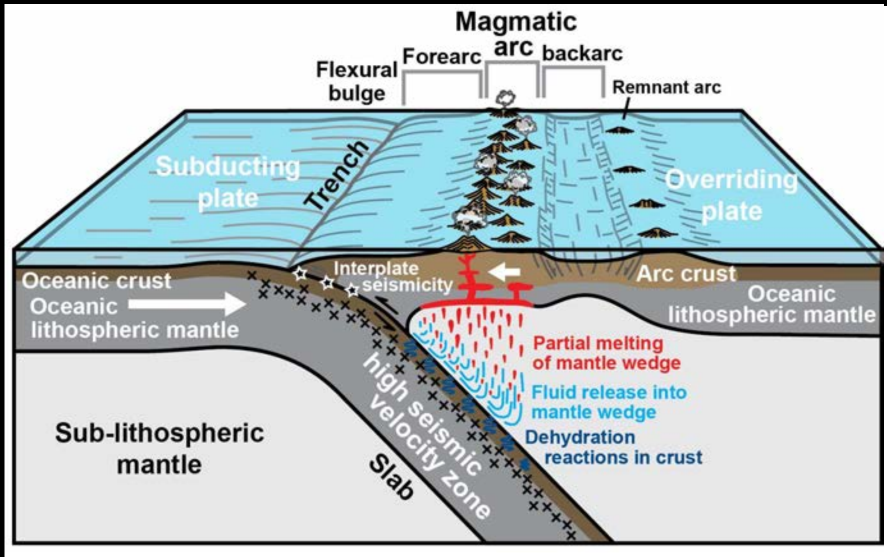


Image credit USGS

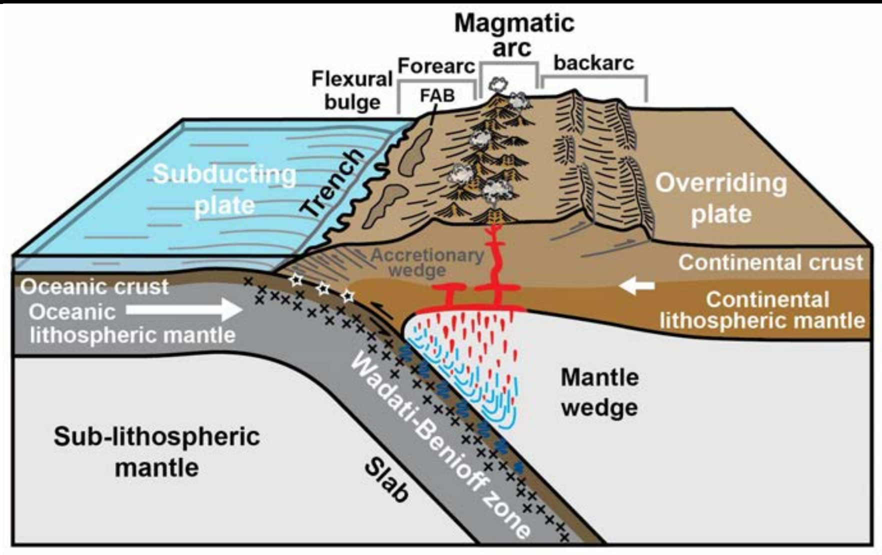
Convergent plate boundaries

Destruction of tectonic plate material

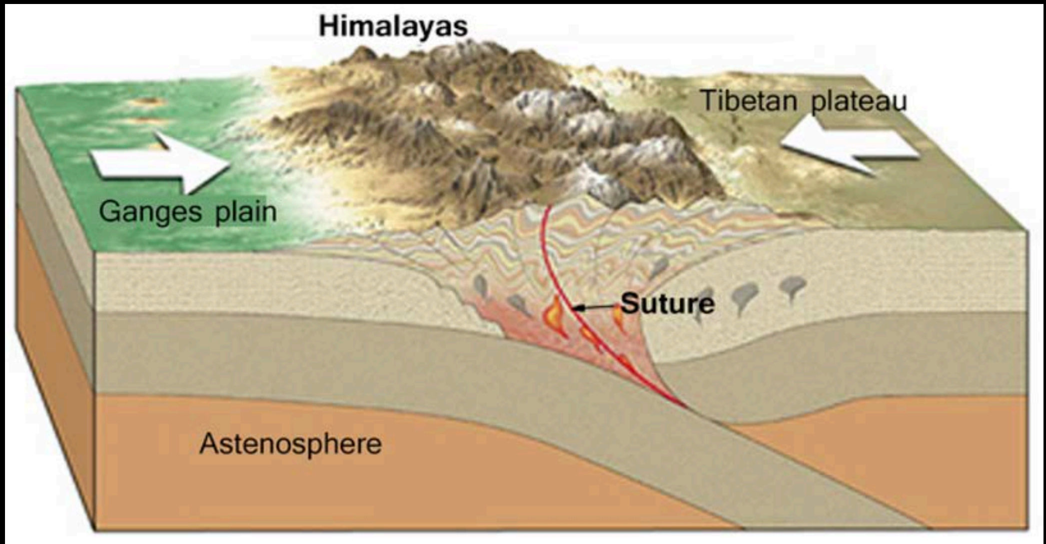


Ocean-ocean subduction

[*Schellart*, 2023]



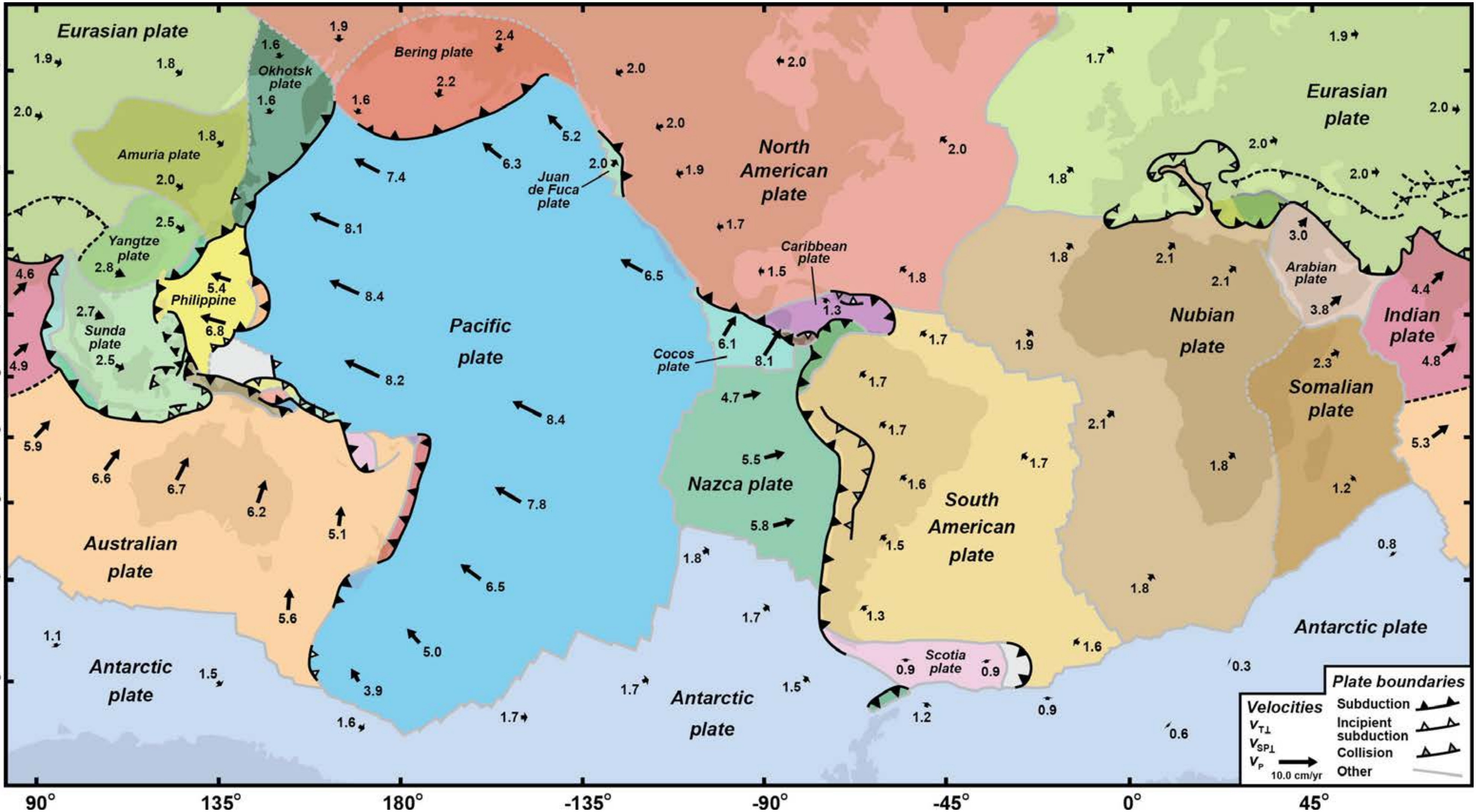
Ocean-continent subduction



Continent-continent collision

[Hovland et al., MPG 2023]

Tectonic plates and their velocities



Indo-Atlantic hotspot reference frame

Modified from *Schellart* [Dynamics of plate tectonics and mantle convection, Chapter 14, 2023]

Plate velocities on a sphere

***Are described with Euler poles (rotation poles) and rotation rates. An Euler pole can be thought of as the intersection of a rotation axis (that goes through the centre of the Earth) and the Earth's surface.**

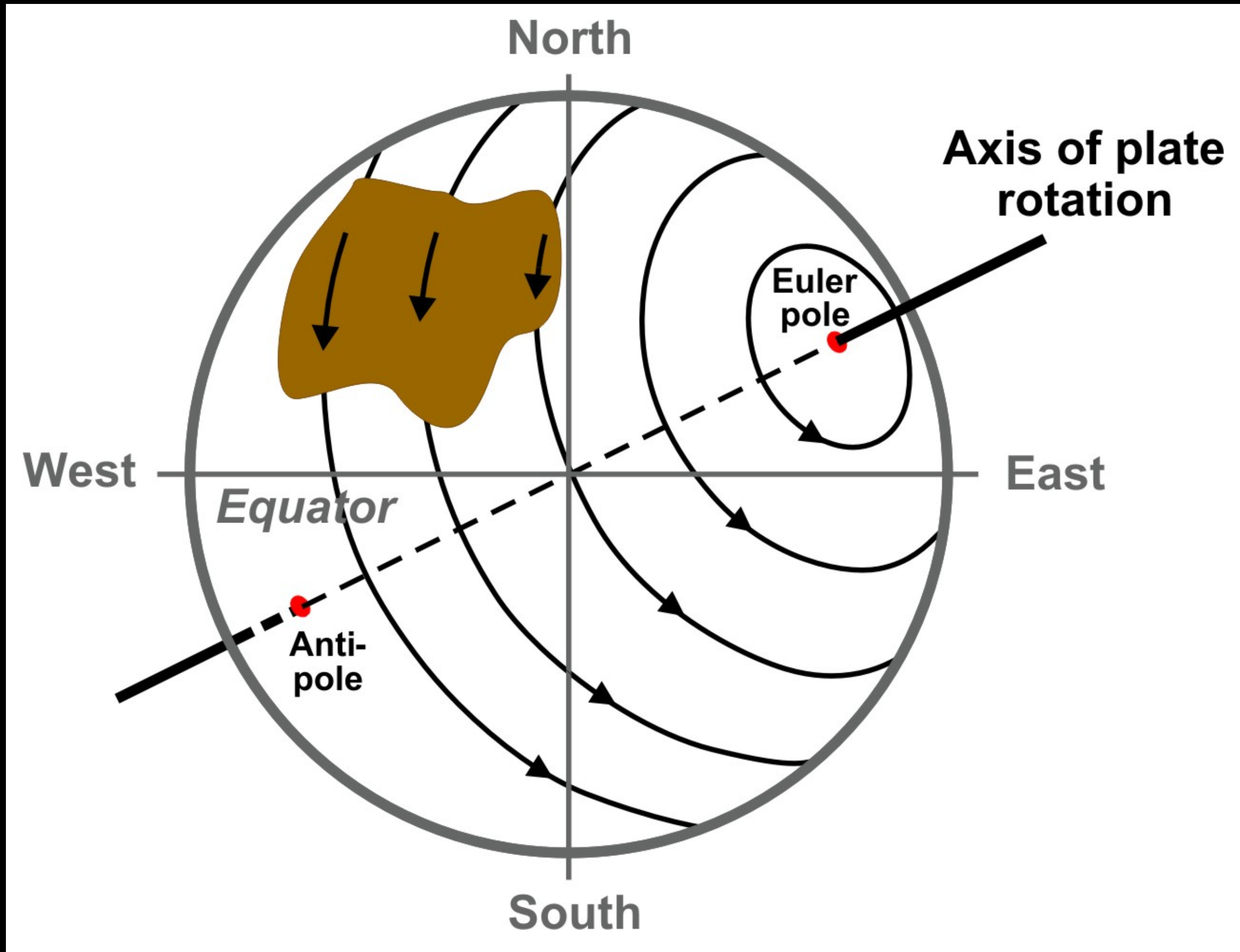


Plate velocities on a sphere

*Plate velocities maximum at 90º from Euler pole (great circle).
*Plate velocity = 0 at Euler pole and anti-pole.
*Velocity trajectories along small circles (great circle at 90º).

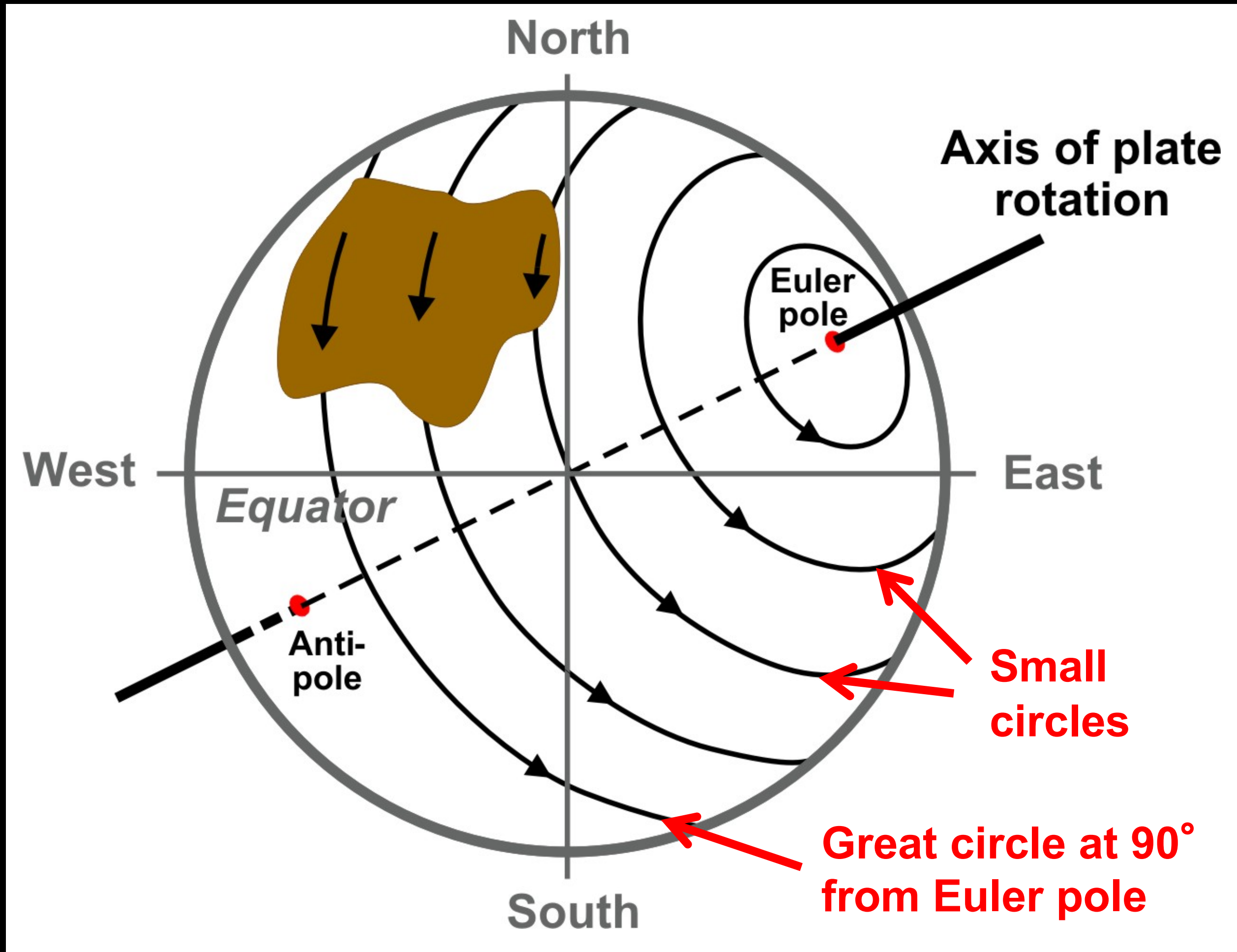
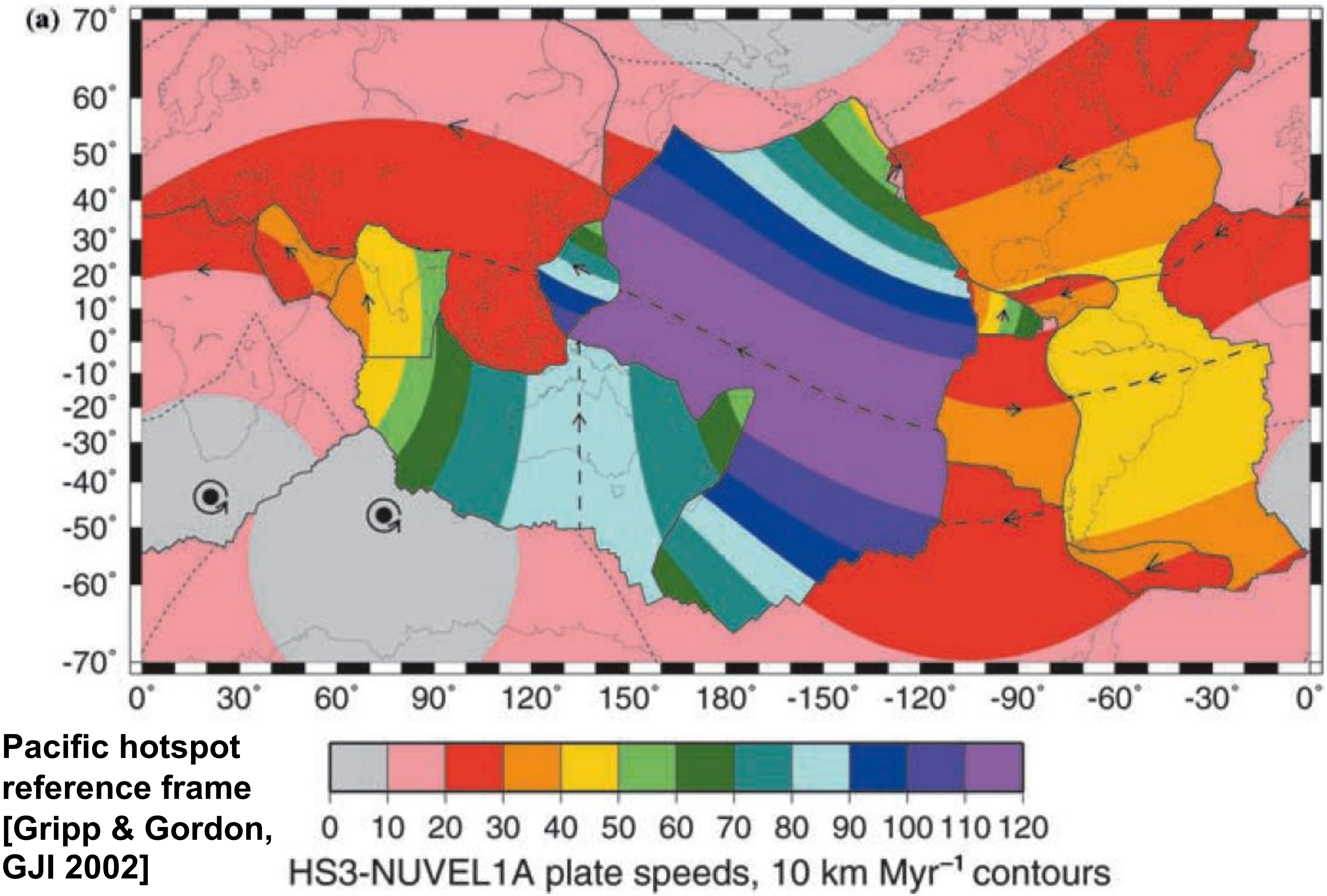
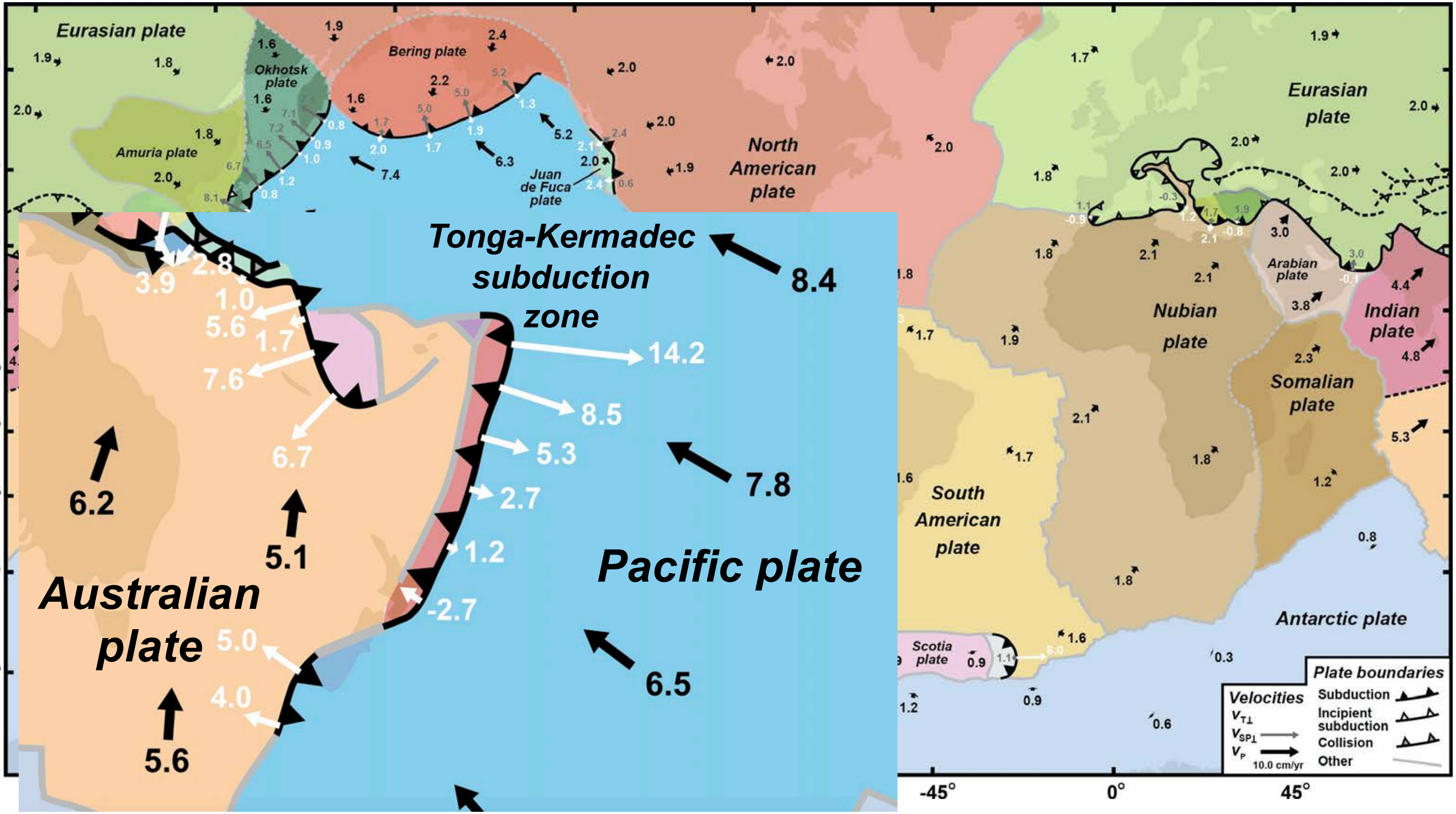


Plate velocities on a sphere



Pacific hotspot reference frame [Gripp & Gordon, GJI 2002]

Plate & plate boundary velocities on Earth



Indo-Atlantic hotspot reference frame

Modified from *Schellart* [Dynamics of plate tectonics and mantle convection, Chapter 14, 2023]

Plate boundary velocities: trench migration [Elsasser, JGR 1971]

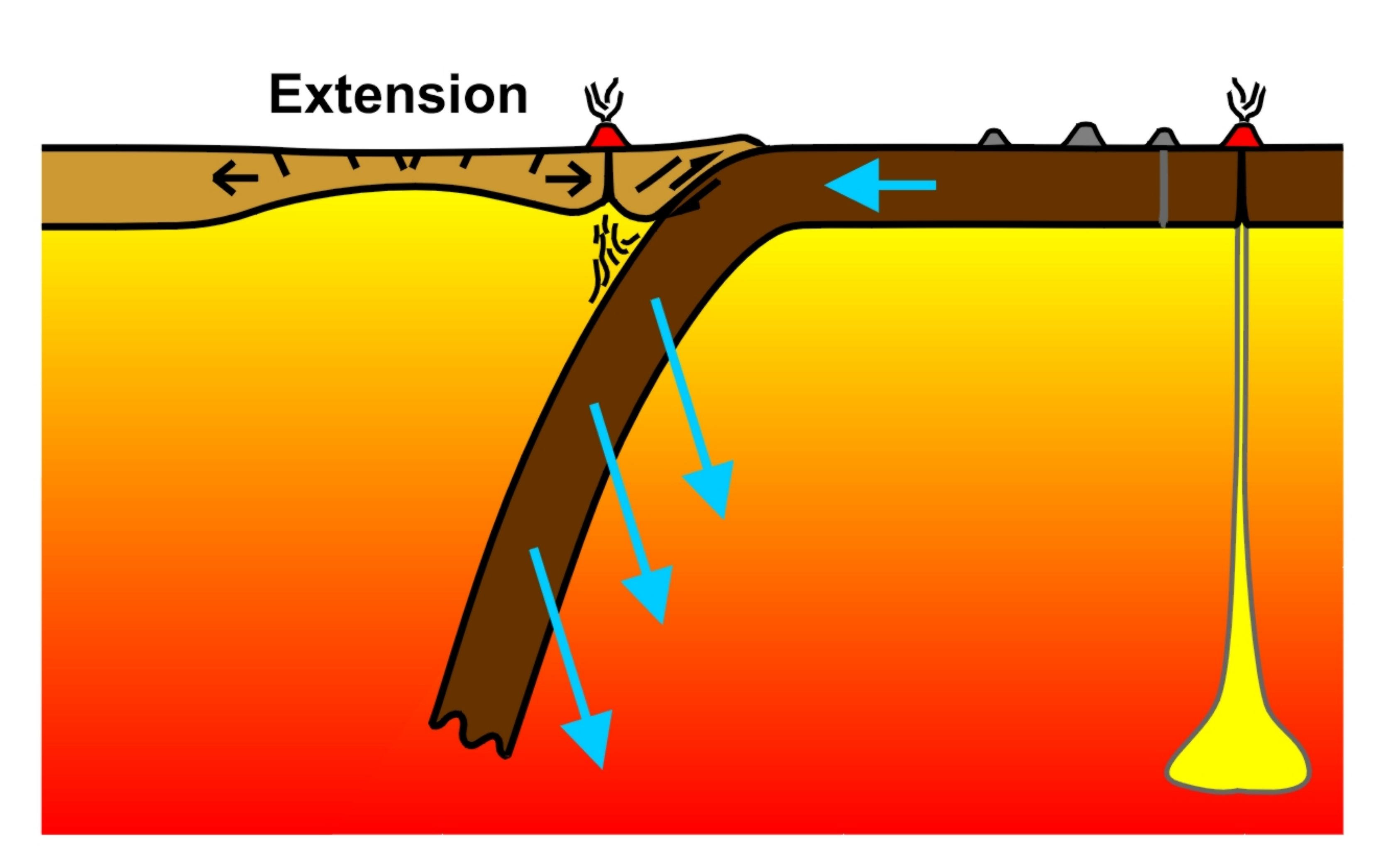
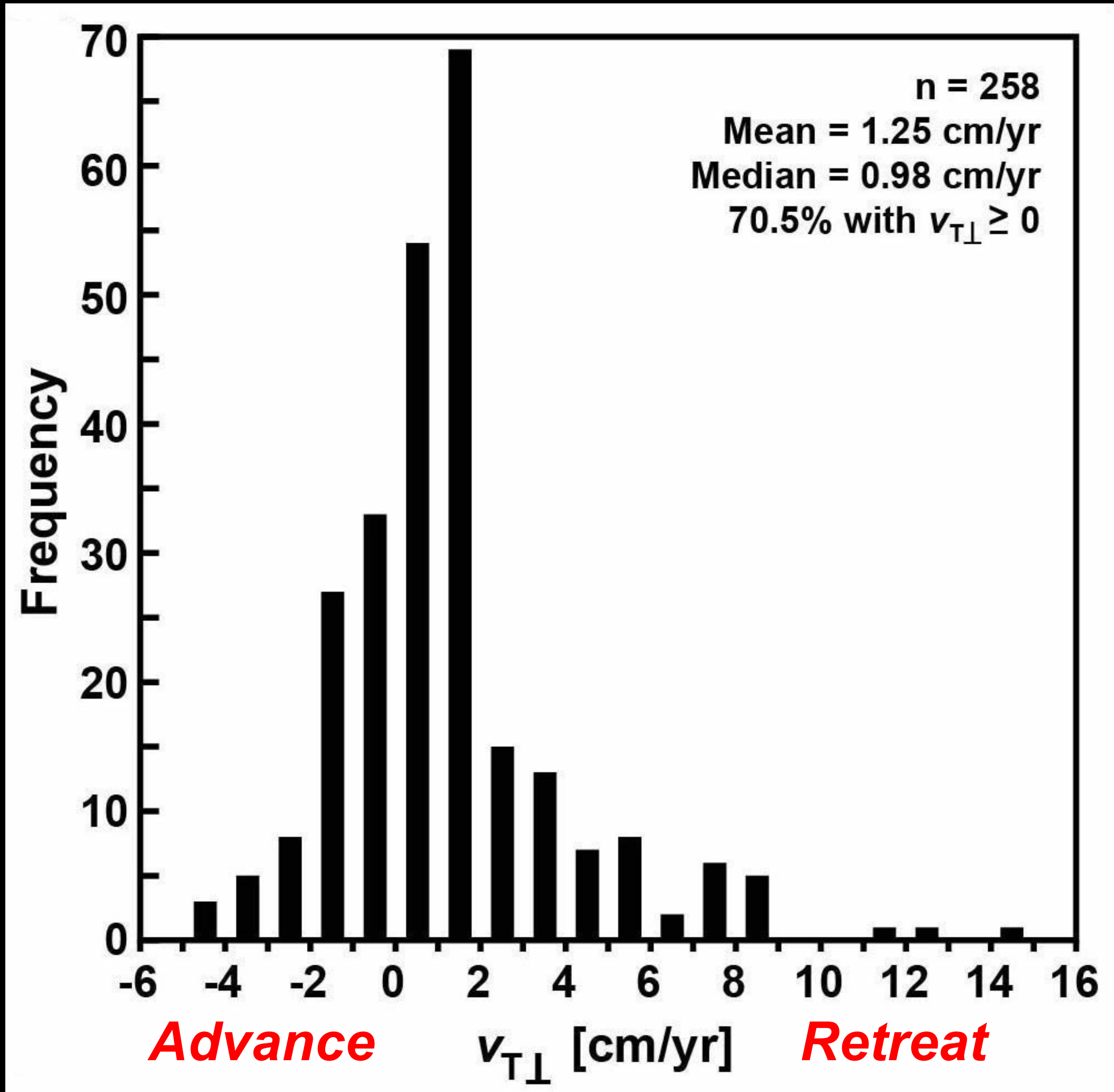


Plate boundary velocities: trench migration

for all active subduction zones (total of 51,600 km)

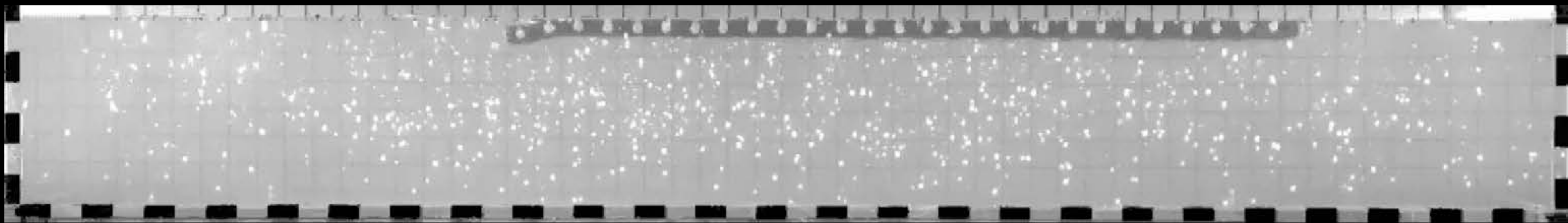
Indo-Atlantic moving hotspot reference frame



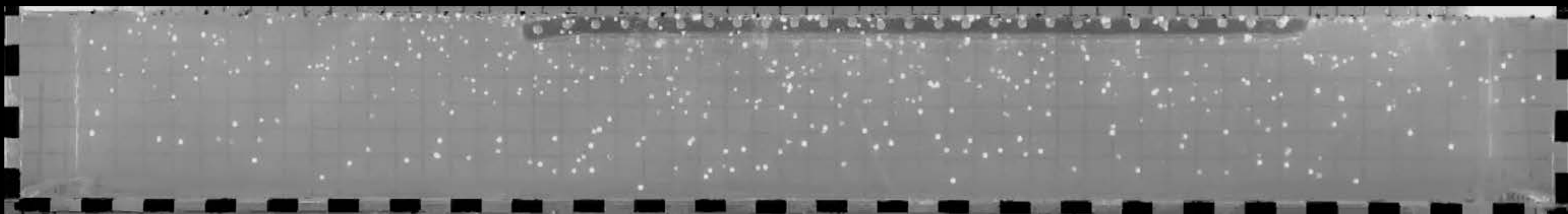
[*Schellart*, 2023]

About 70.5% of trenches retreat, ~29.5% advance

Subduction zone trench migration



Trench retreat and slab rollback (η_{SLAB} / η_{MANTLE} = 66)

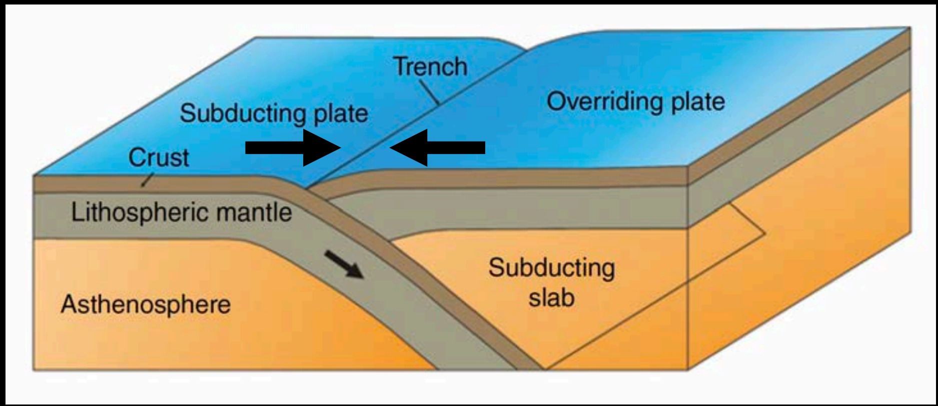


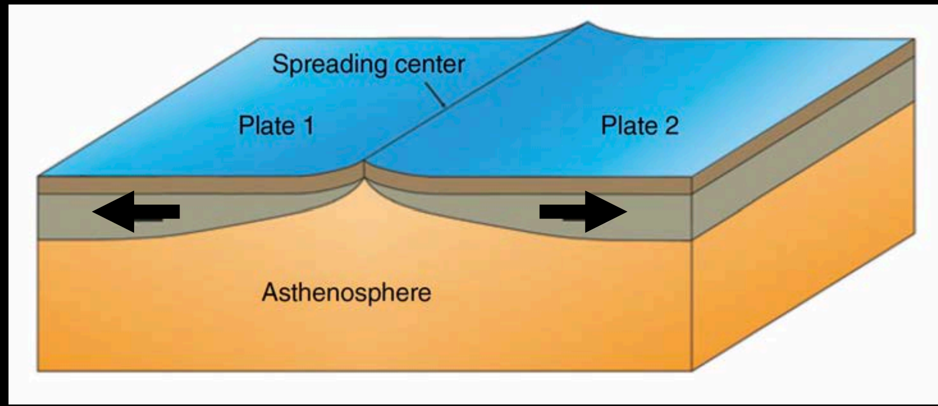
Trench advance and slab roll forward (η_{SLAB} / η_{MANTLE} = 1375)

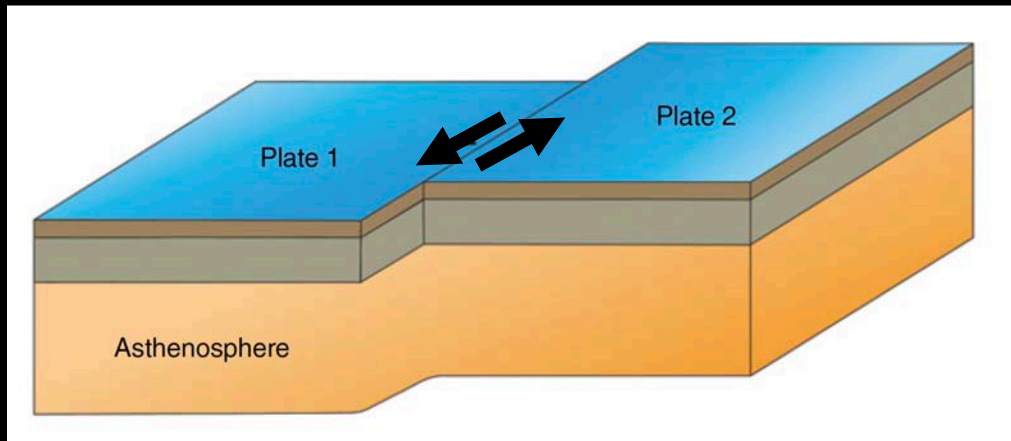
scaled laboratory models of subduction

Schellart [G^3, *2008*]

Relative and absolute velocities in plate tectonics



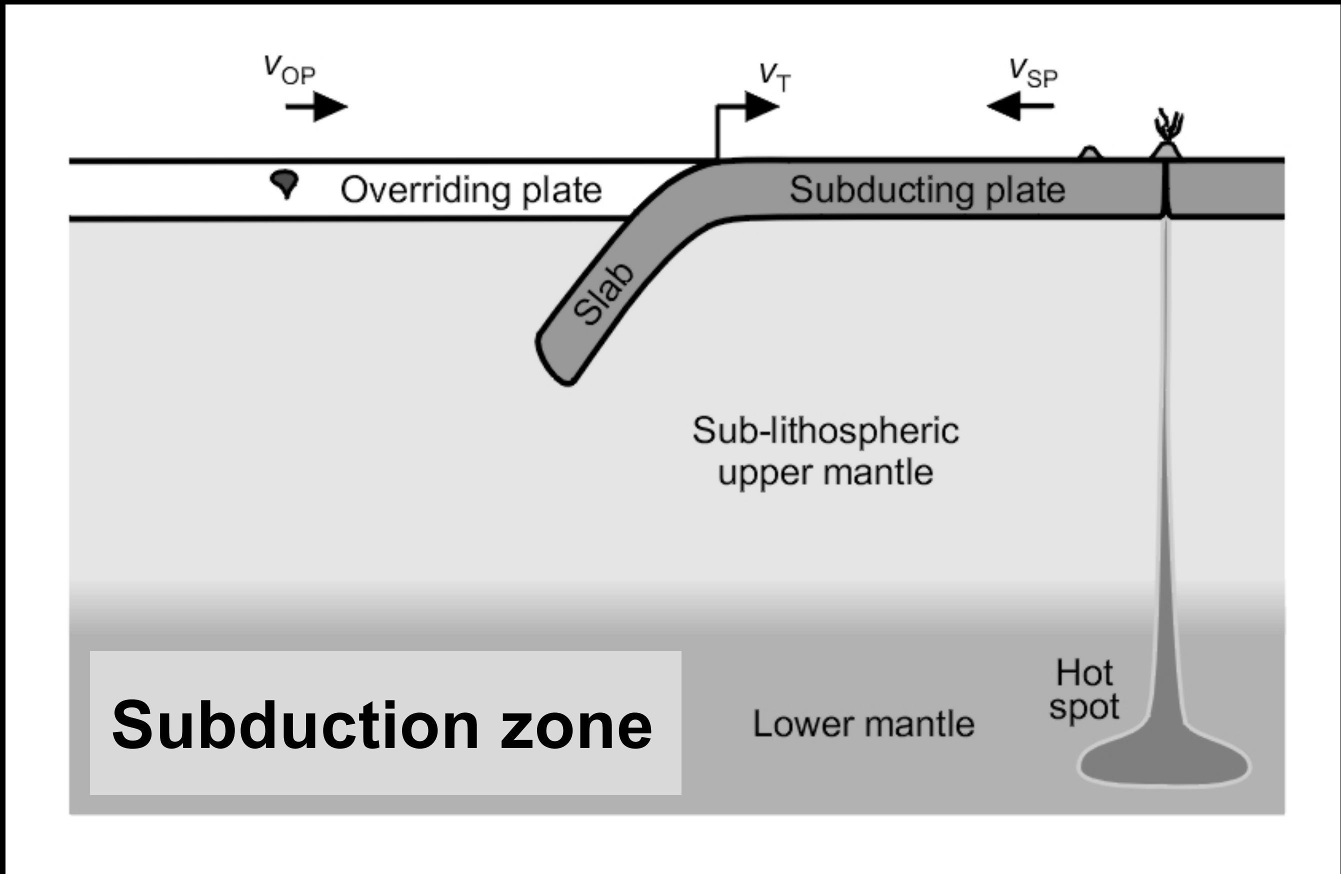




Convergence velocity
Divergence velocity
Transform velocity

Relative velocities
(between two plates)
(independent of reference frame)

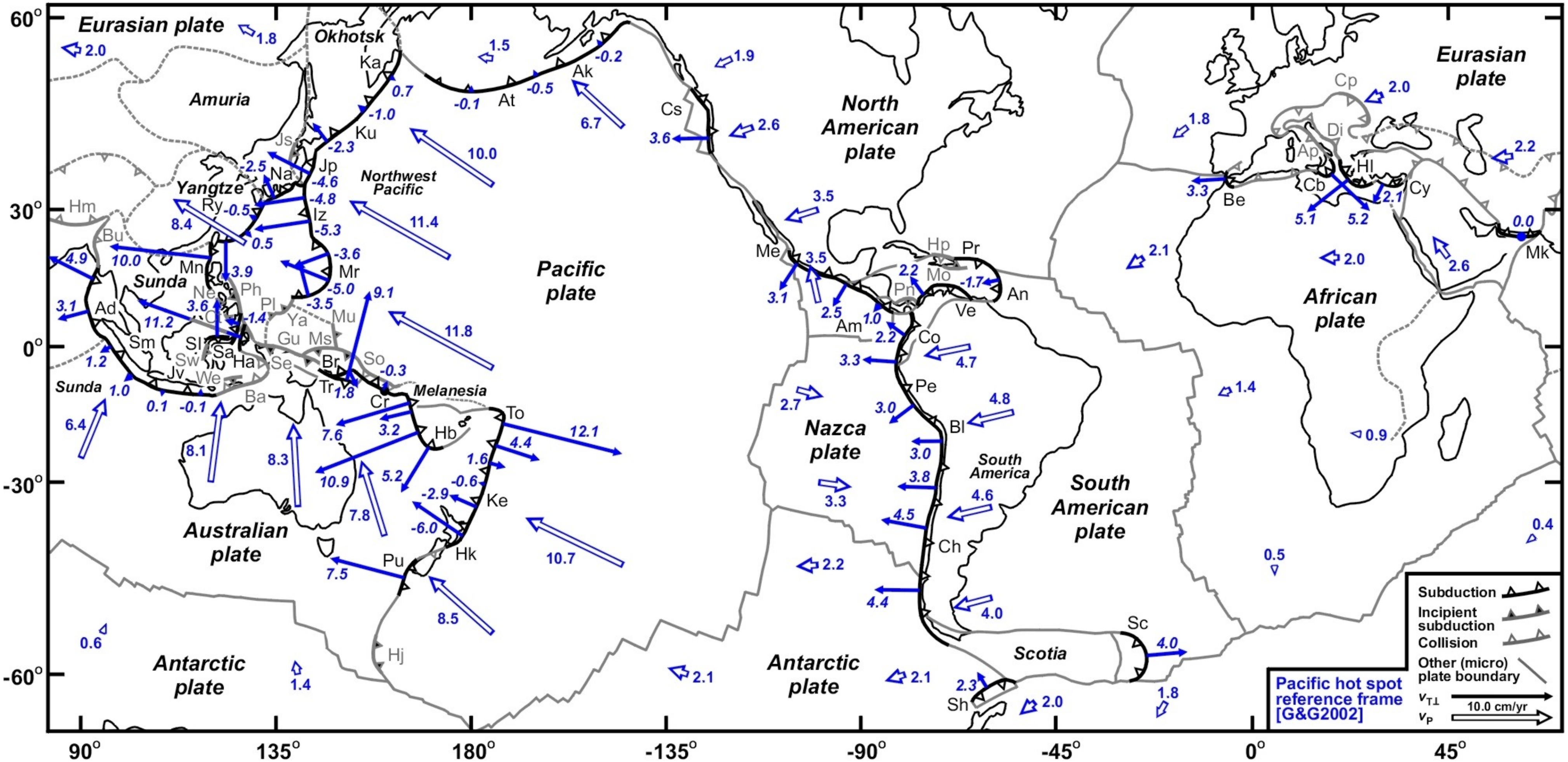
Relative and absolute velocities in plate tectonics



Overriding plate velocity (v_{OP})
Subducting plate velocity (v_{SP})
Trench velocity (v_T)
Plate velocity

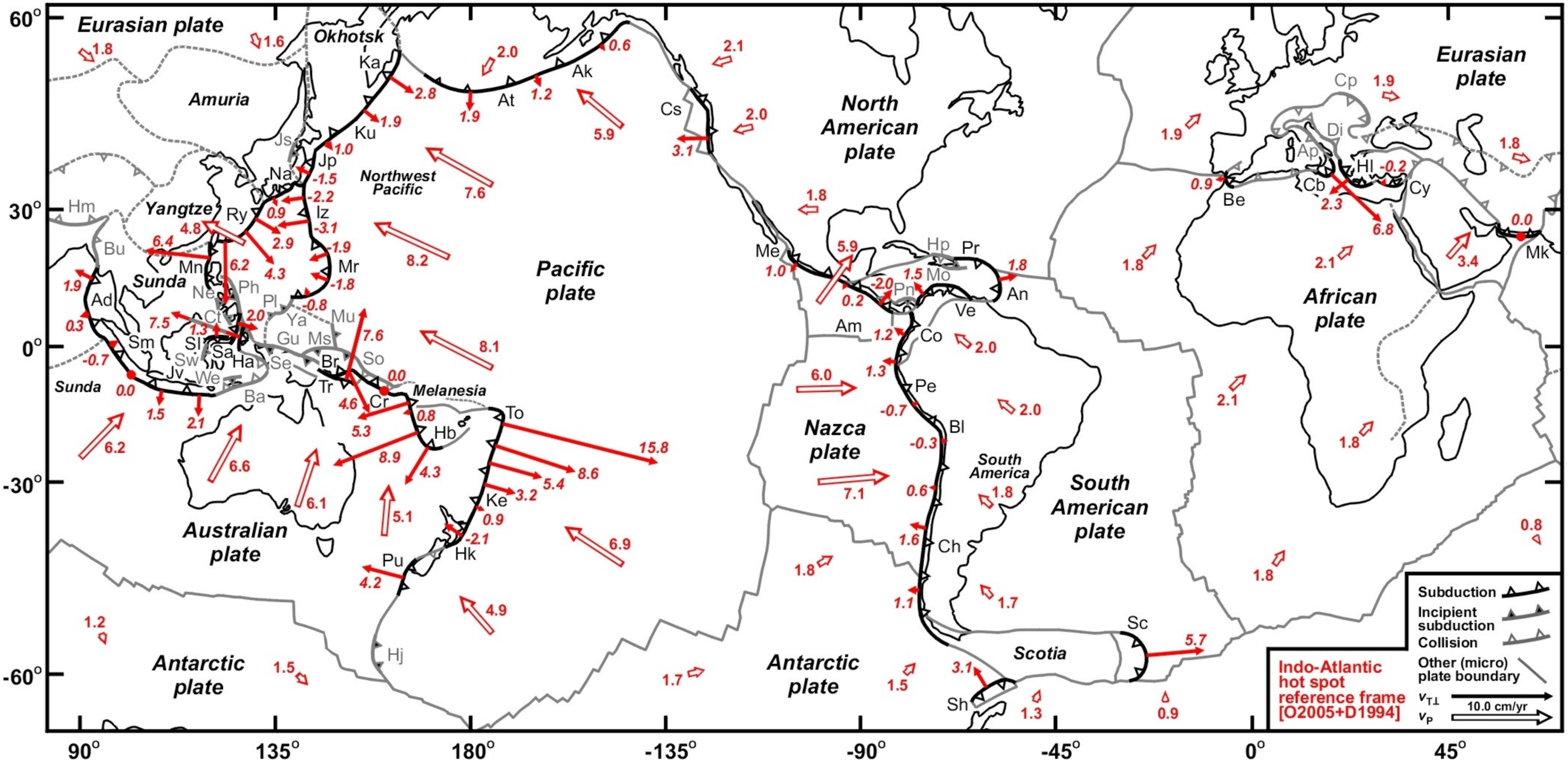
"Absolute velocities"
(depend on reference frame)

Plate velocities and trench velocities (in different "absolute" global reference frames)



[Schellart et al., ESR 2008]

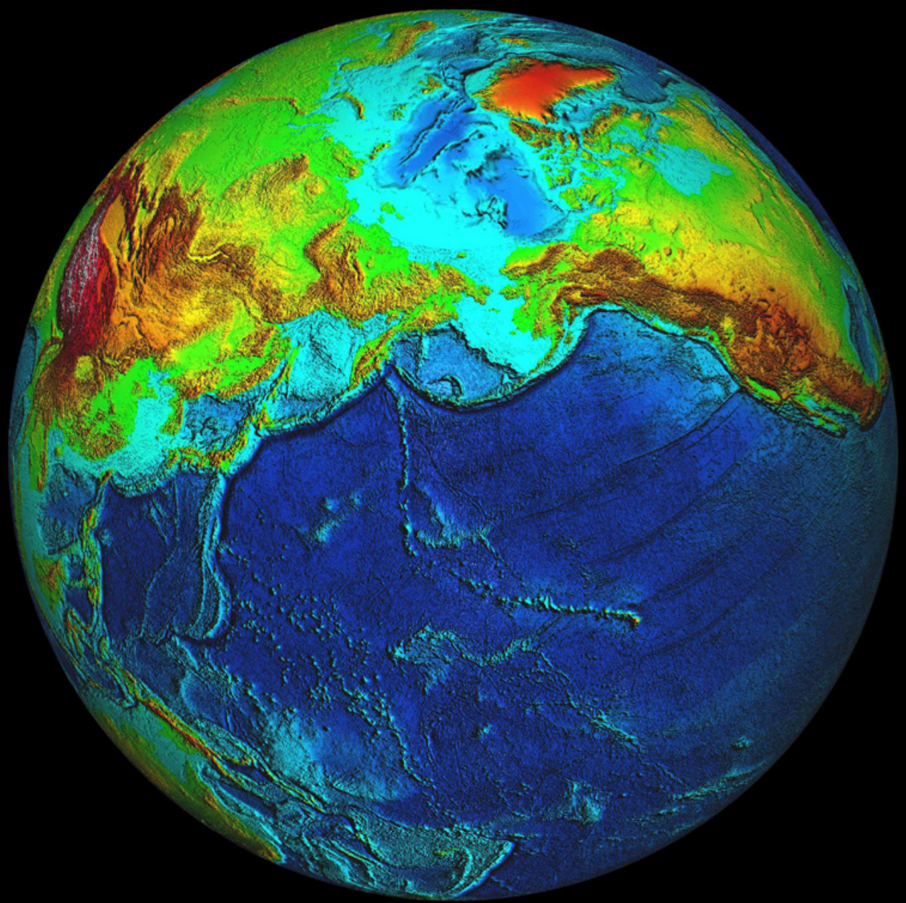
Plate velocities and trench velocities (in different "absolute" global reference frames)

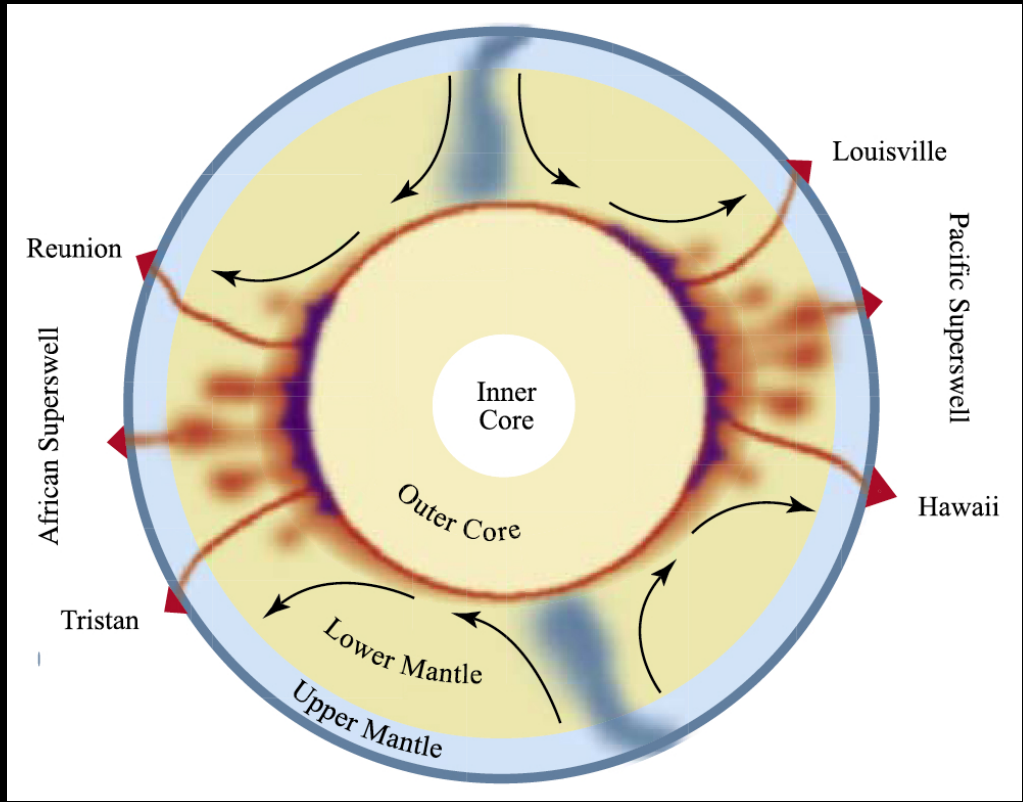


[Schellart et al., ESR 2008]

Different "absolute" global reference frames

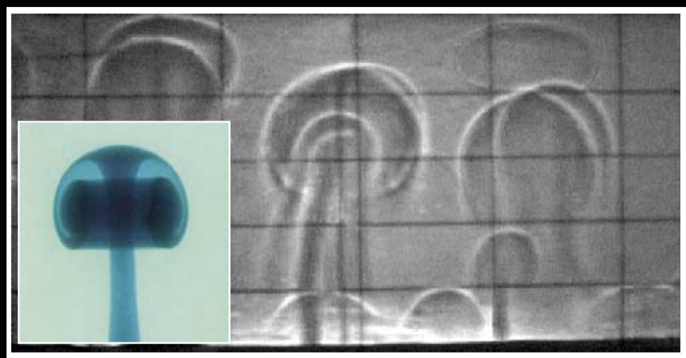
1. **Pacific hotspot**
2. **Indo-Atlantic hotspot**
3. **Global hotspot**





Jellinek & Manga [RG, 2004]

Experimental mantle plume



Different “absolute” global reference frames

1. Pacific hotspot 2. Indo-Atlantic hotspot 3. Global hotspot	Plumes / hotspots move in a convecting mantle
4. No-net-rotation	Not the same as no-net-torque
5. Antarctic plate	Not only spreading ridges along boundaries, variable basal drag
6. Minimum dissipation	Difficult to constrain
7. Paleomagnetic	No constraint on longitude
8. Subduction / slab	Assumes vertical sinking of slabs

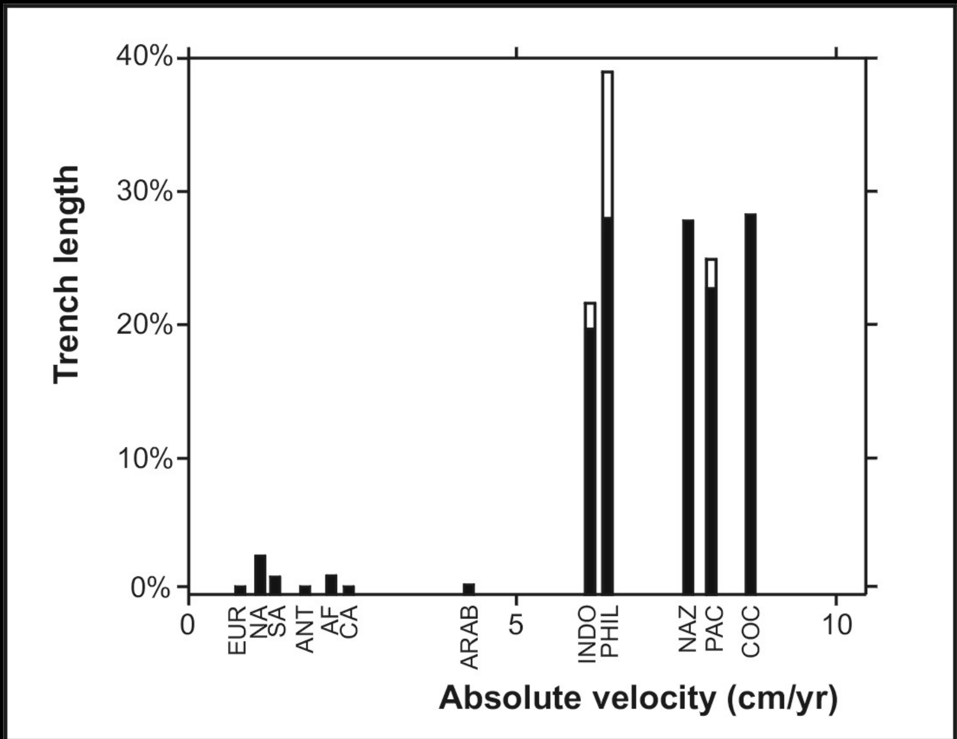
All have limitations / problems!

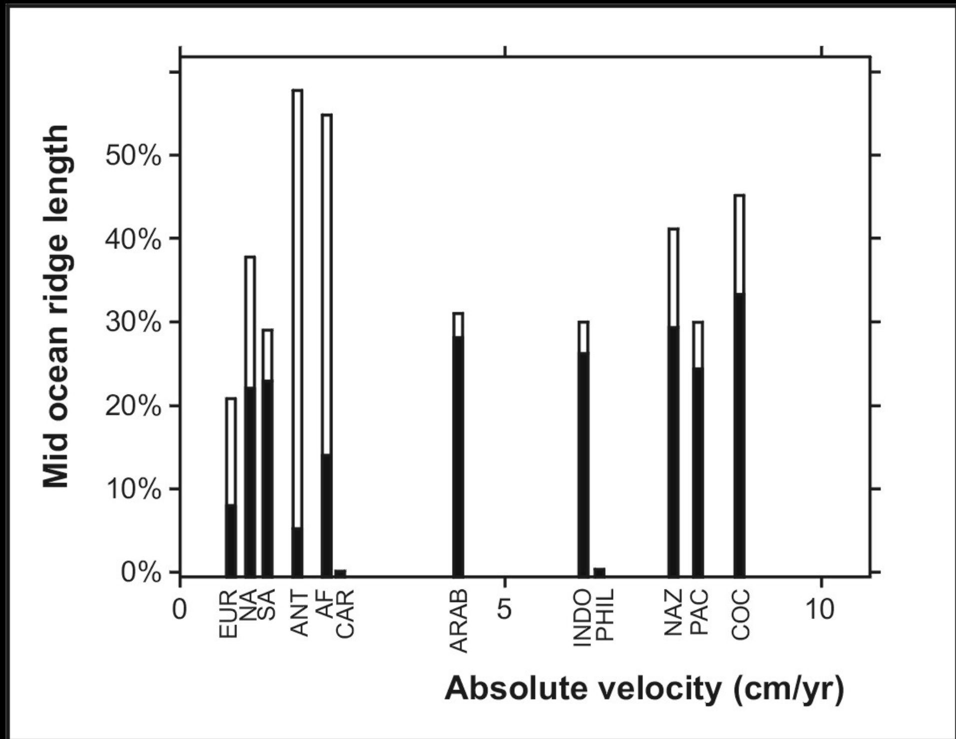
Plate kinematics & Geodynamics

Slabs as the major driver of plate tectonics

[*Forsyth and Uyeda*, GJRAS, 1975]

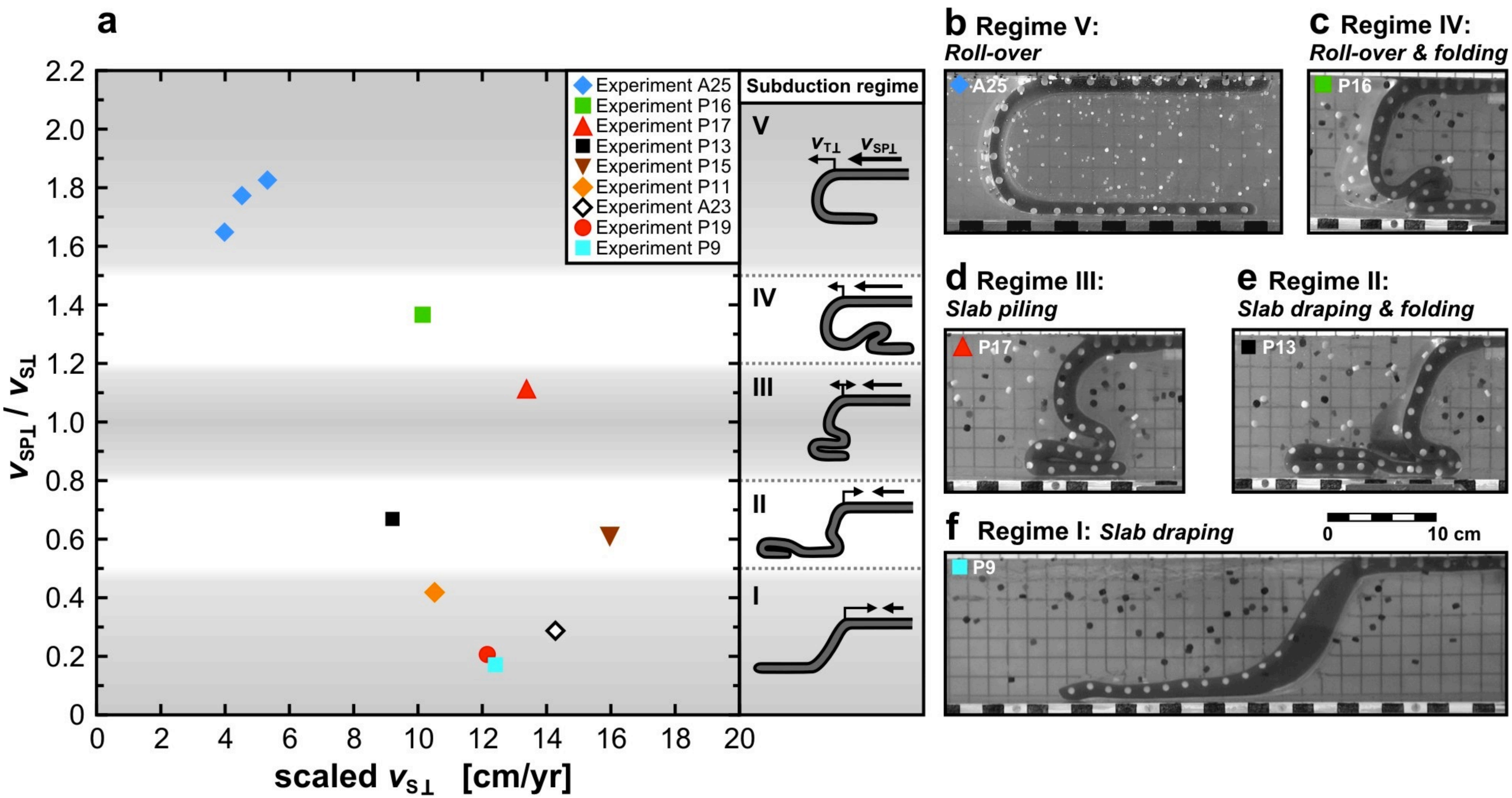
Potential limitation with diagrams?





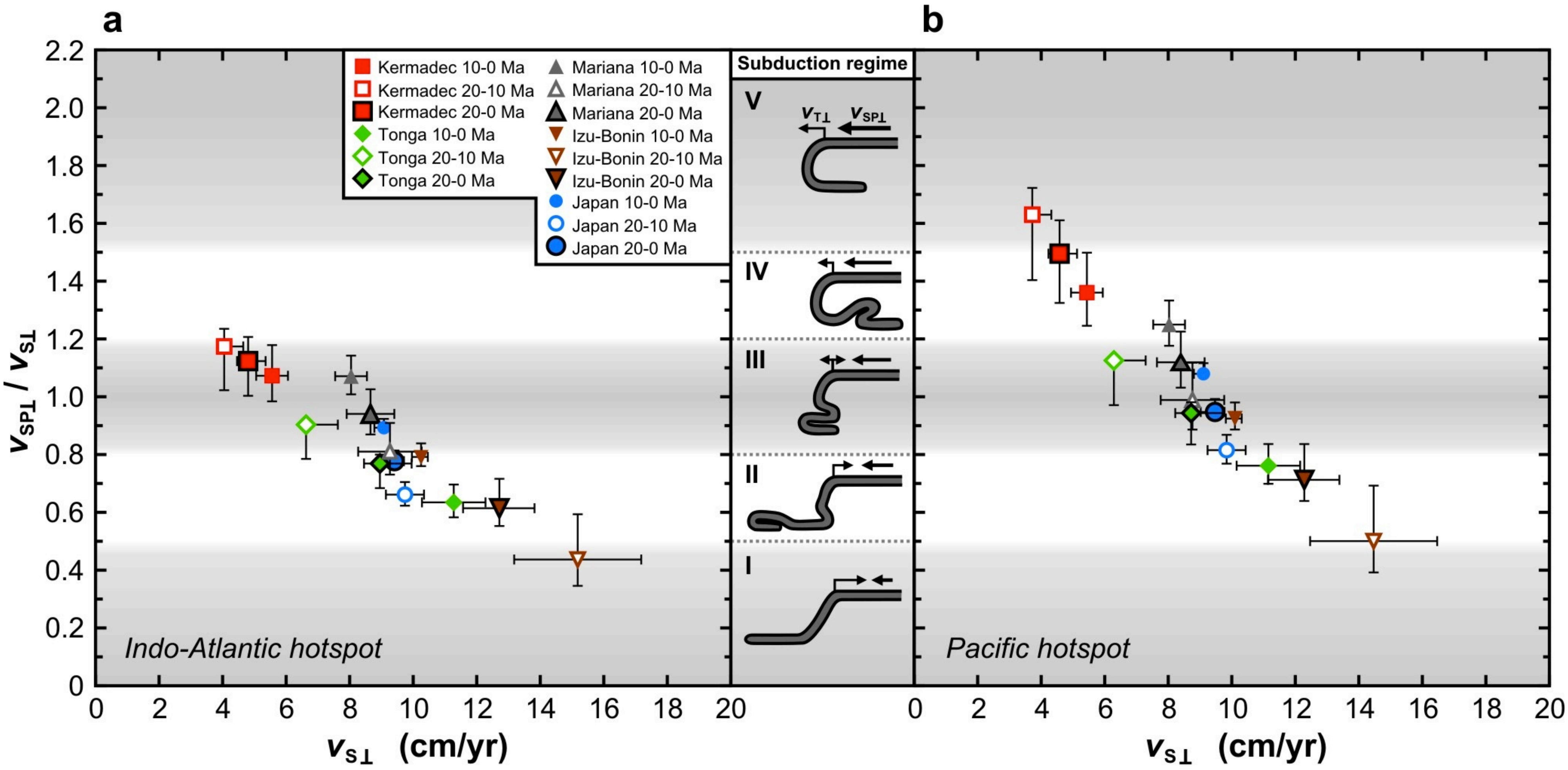
[*Forsyth and Uyeda*, GJRAS, 1975]

Subduction kinematics and slab geometry in buoyancy-driven geodynamic models



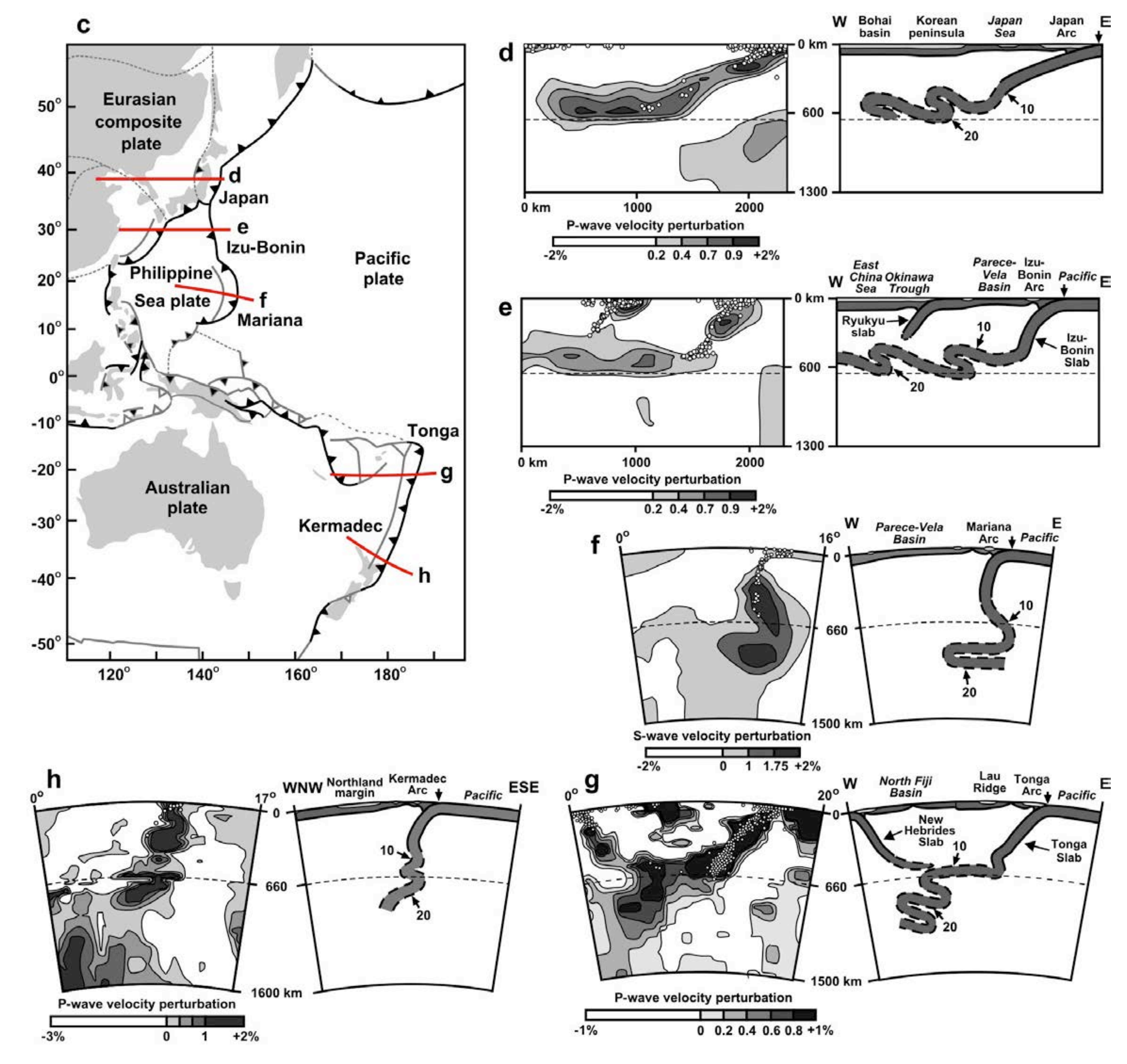
Schellart [GRL, 2011]

Subduction kinematics in nature



Schellart [GRL, 2011]

Slab geometry in nature



Schellart [GRL, 2011]

Take home points

- Earth is the only planet in the solar system that is characterised by *plate tectonics-style mantle convection*.
- In plate tectonics, the outer shell (lithosphere) of the Earth is broken up into “plates”, on average some 100 km thick.
- The plates move across the globe over a lower viscosity sub-lithospheric mantle at several cm/yr .
- Plate boundaries also move across the globe at several cm/yr.
- Plate & plate boundary velocities are dependent on the choice of “absolute” global reference frame.
- Plate kinematics can help us to inform the debate on plate driving forces and geodynamics!
- Geodynamics & geodynamic modelling can inform us on plate kinematics and different “absolute” global reference frames!

Thank you!