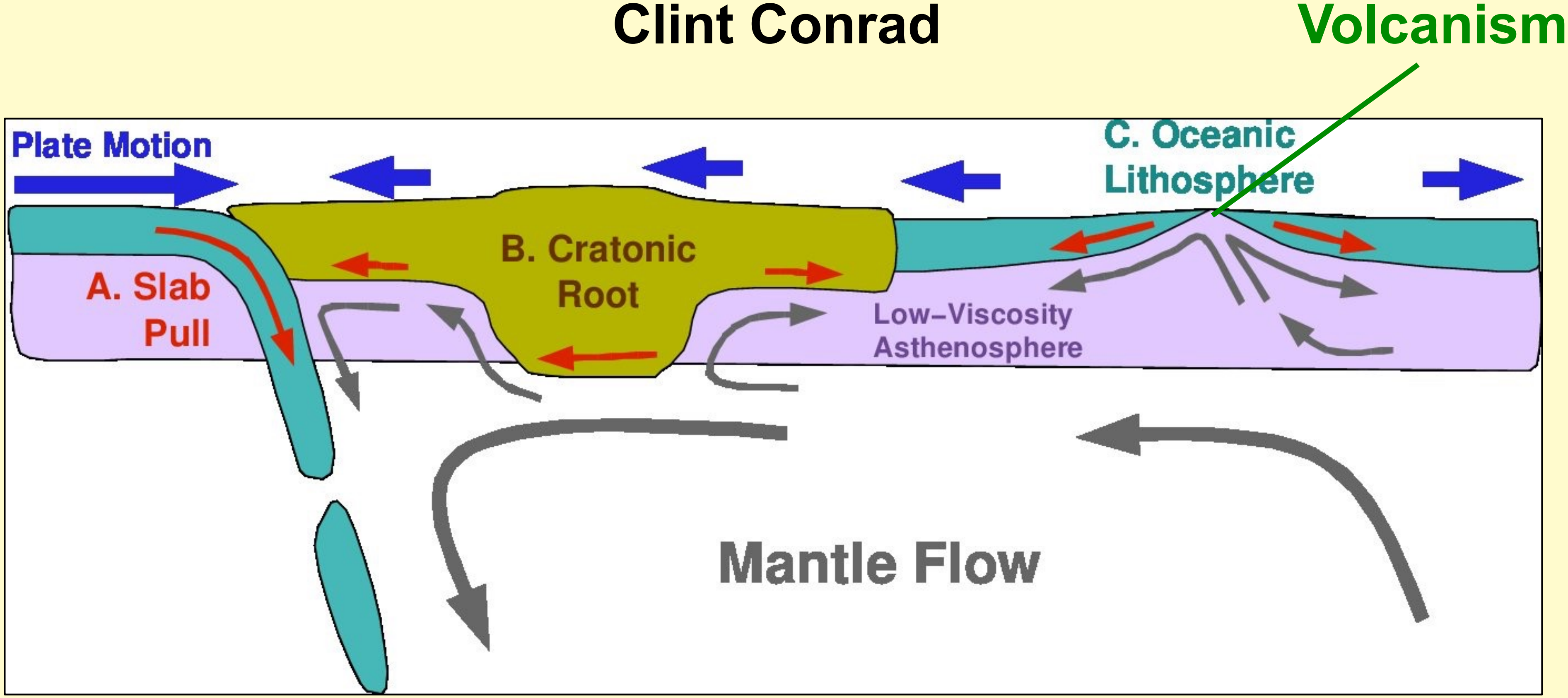
Lithosphere and Asthenosphere: Composition and Evolution

GEO-DEEP9300

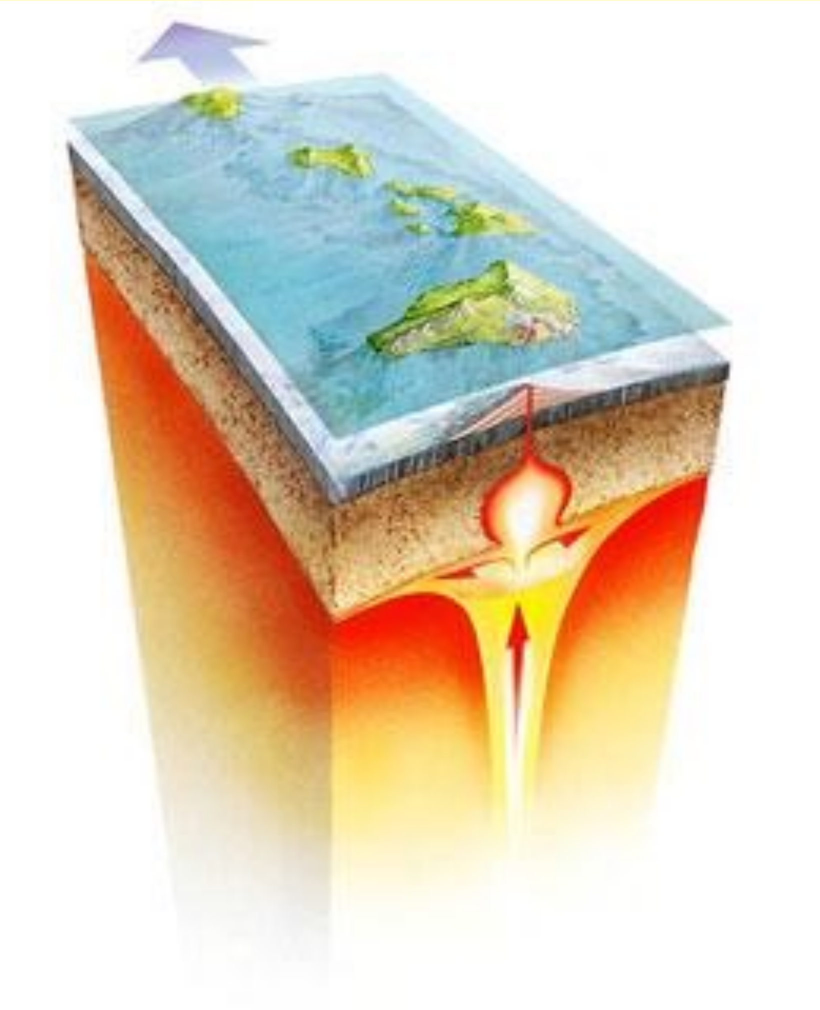
Valerie Maupin
Clint Conrad

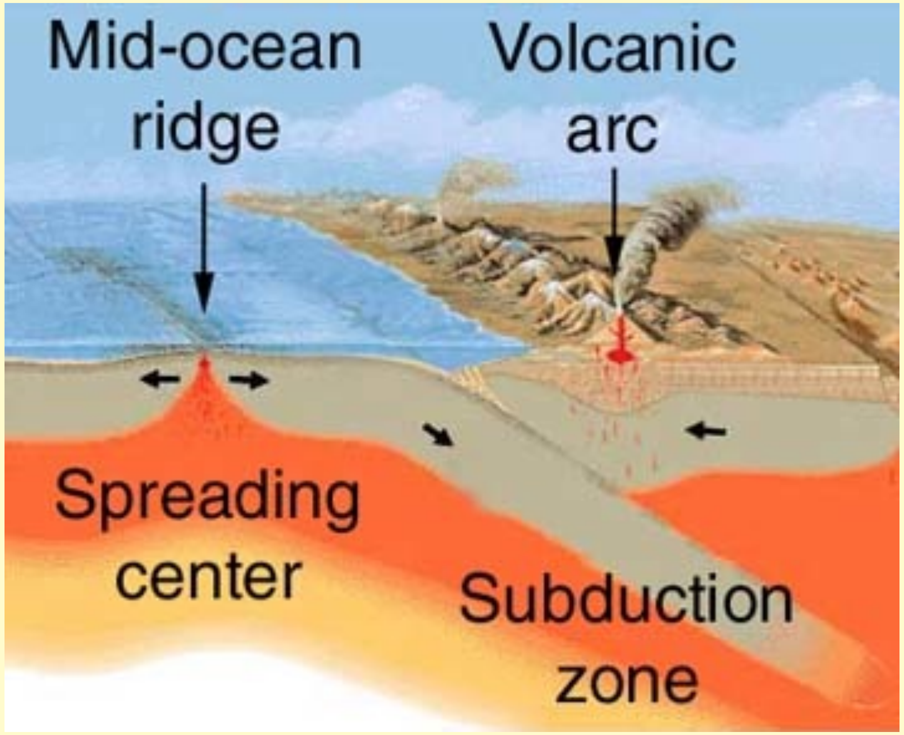


Global Volcanism

Most volcanism results from plumes bringing heat from the deep mantle …

… or by "shallow" processes at plate boundaries

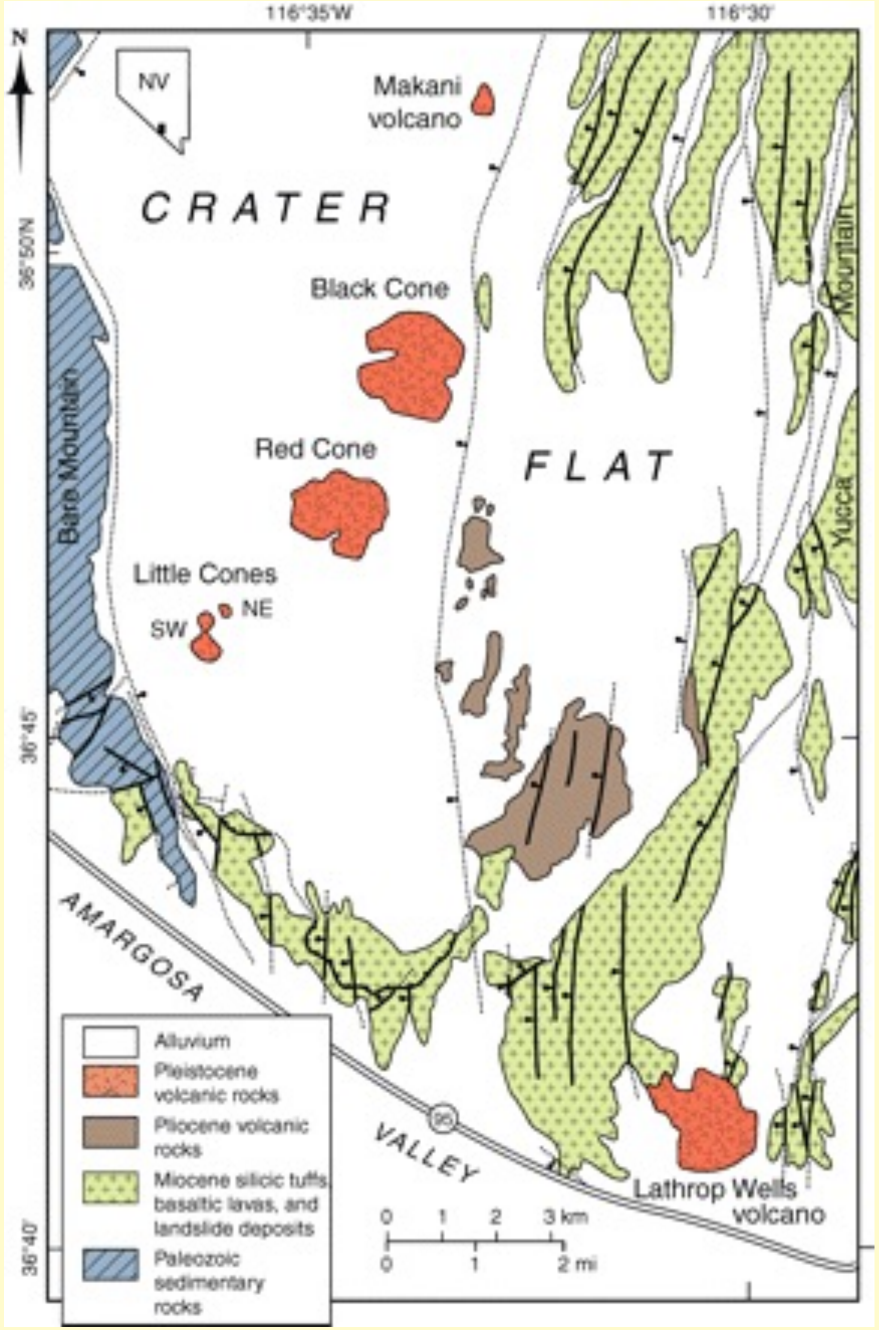




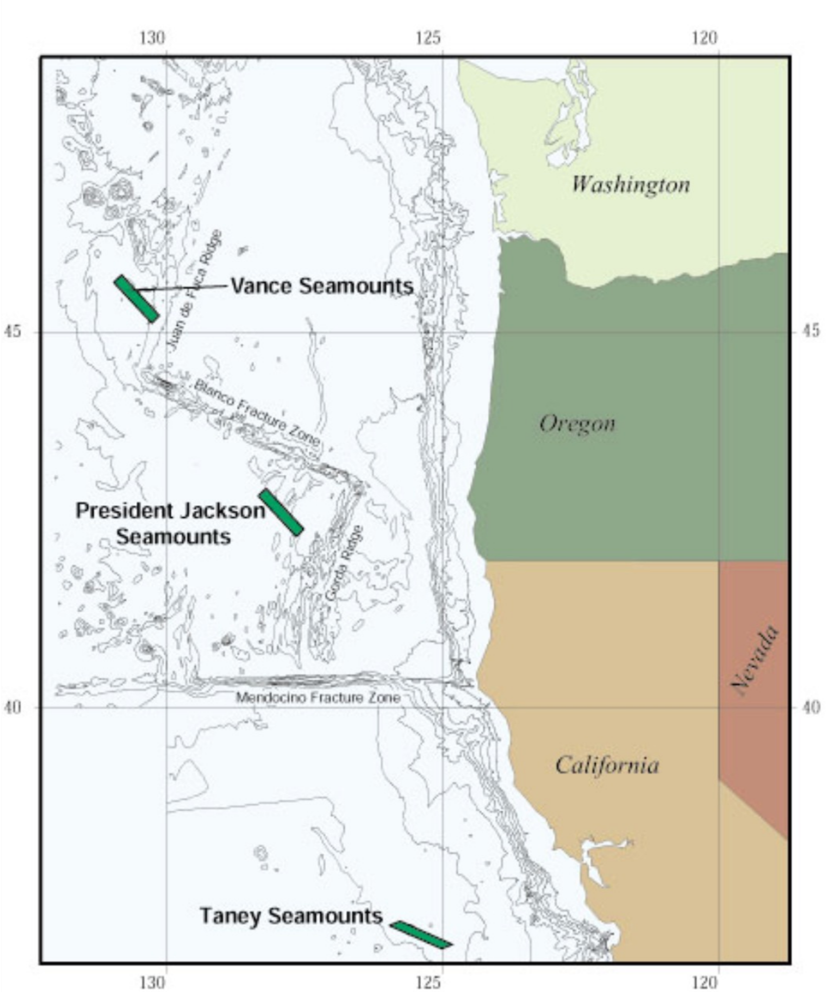
Volcanic History

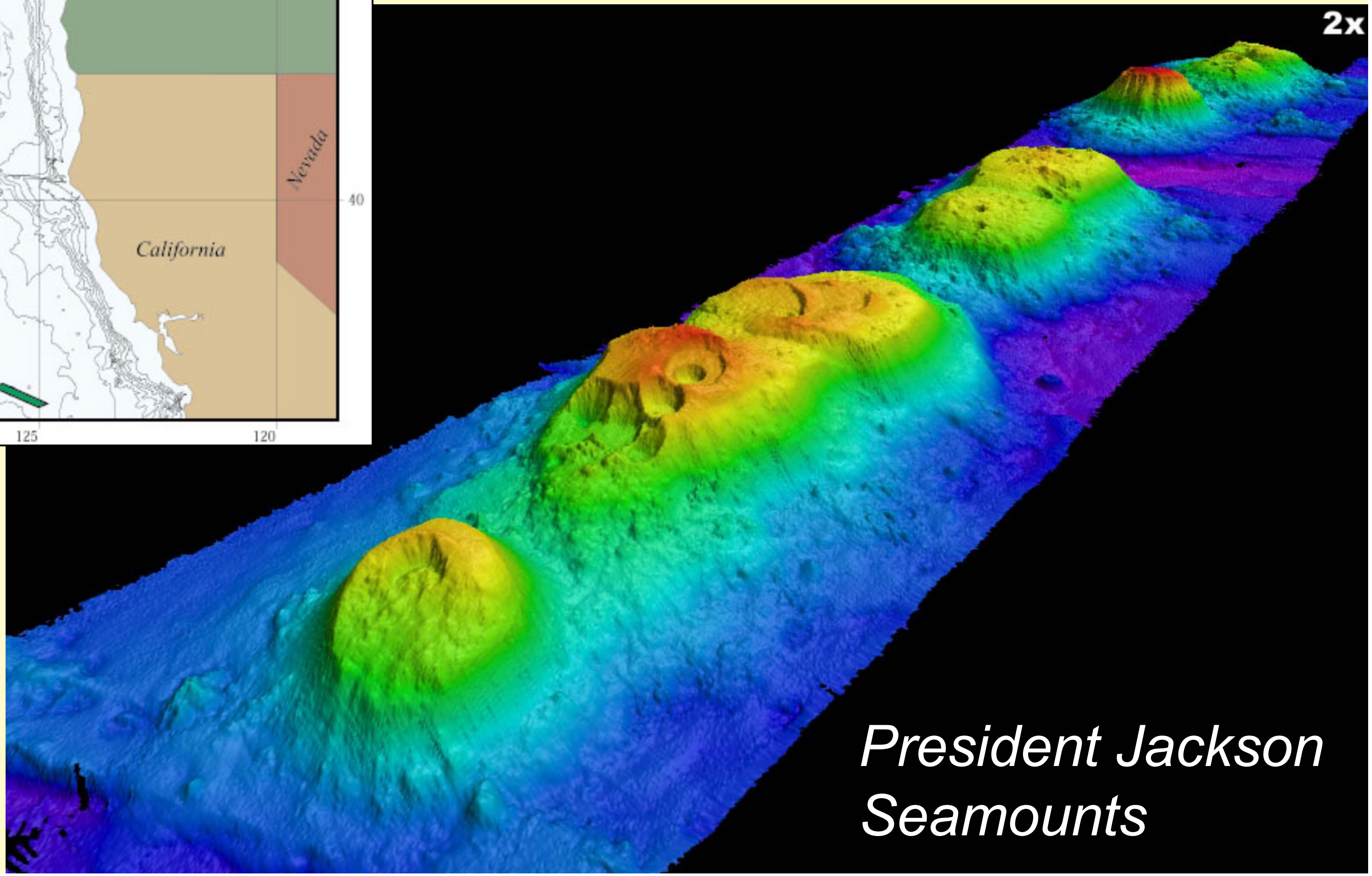
[*Valentine et al., GSA Bull.*, 2006]

10 Ma	1.5 Myr of basalt flows
4 Ma	smaller basalt flows
1 Ma	5 volcanoes
80 ka	Lanthrop Wells

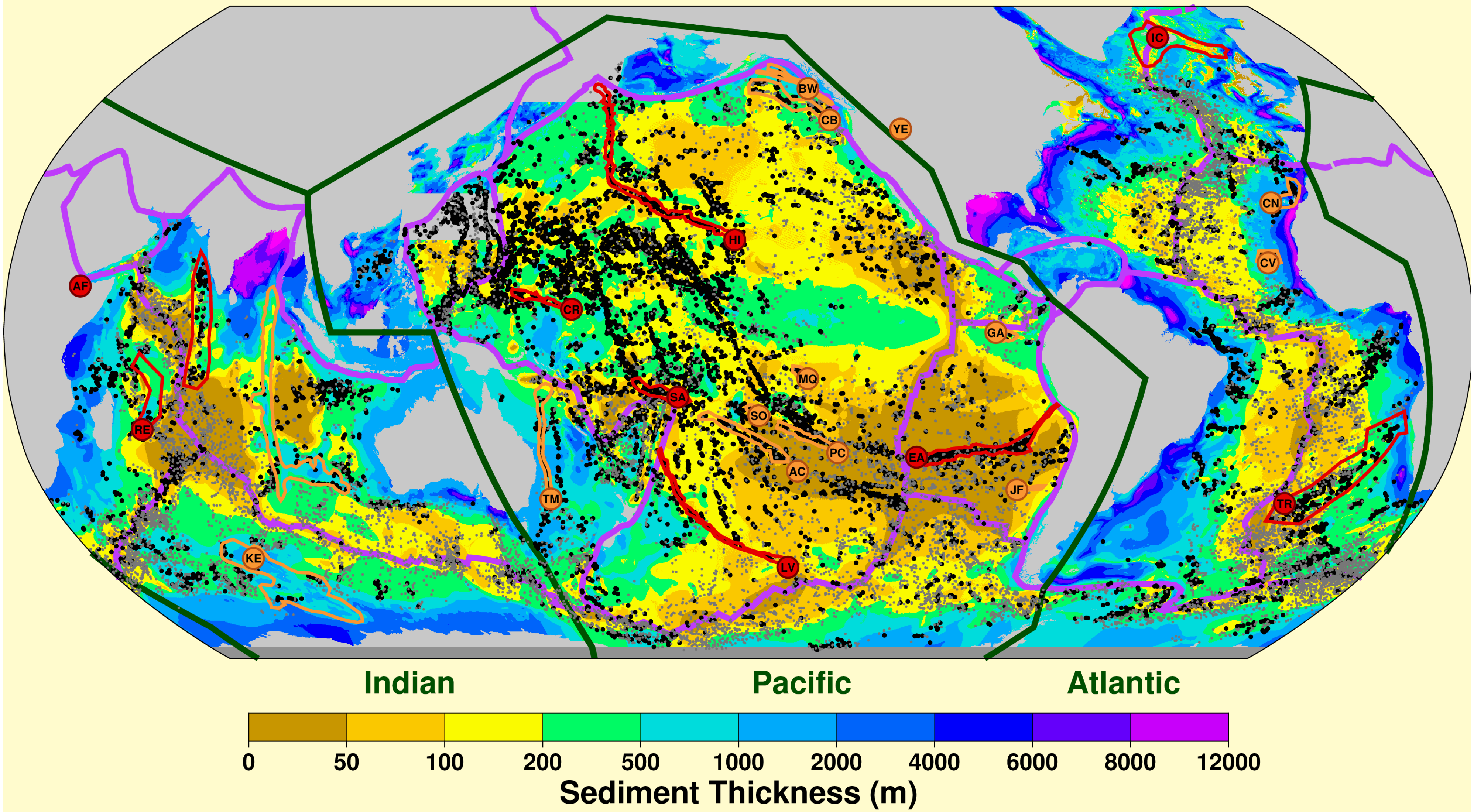


Seamounts represent past volcanism on the seafloor



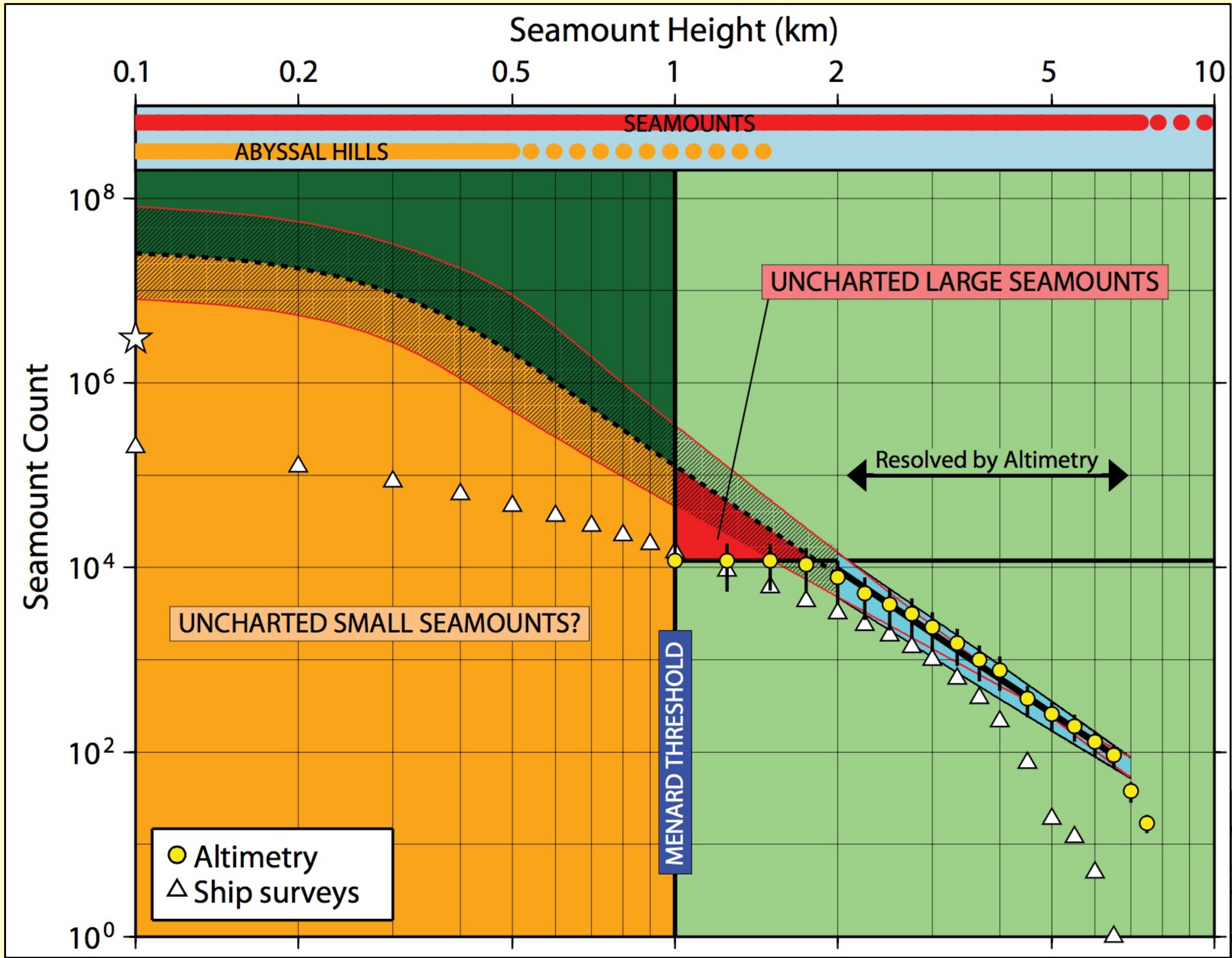


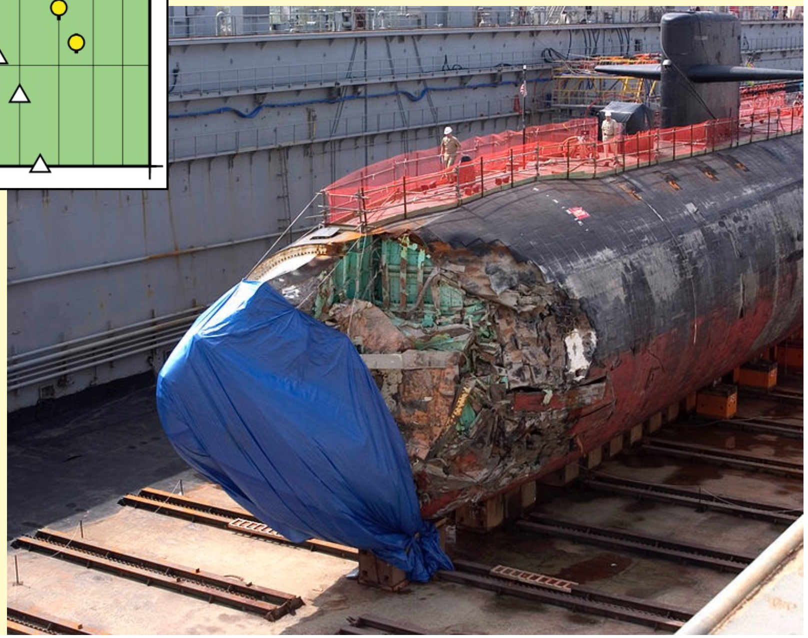
The *Kim & Wessel* [2011] Catalog
24,000+ seamounts detected using satellite gravity



Seamount Census: Height – Frequency Distribution

Wessel et al. [2010]



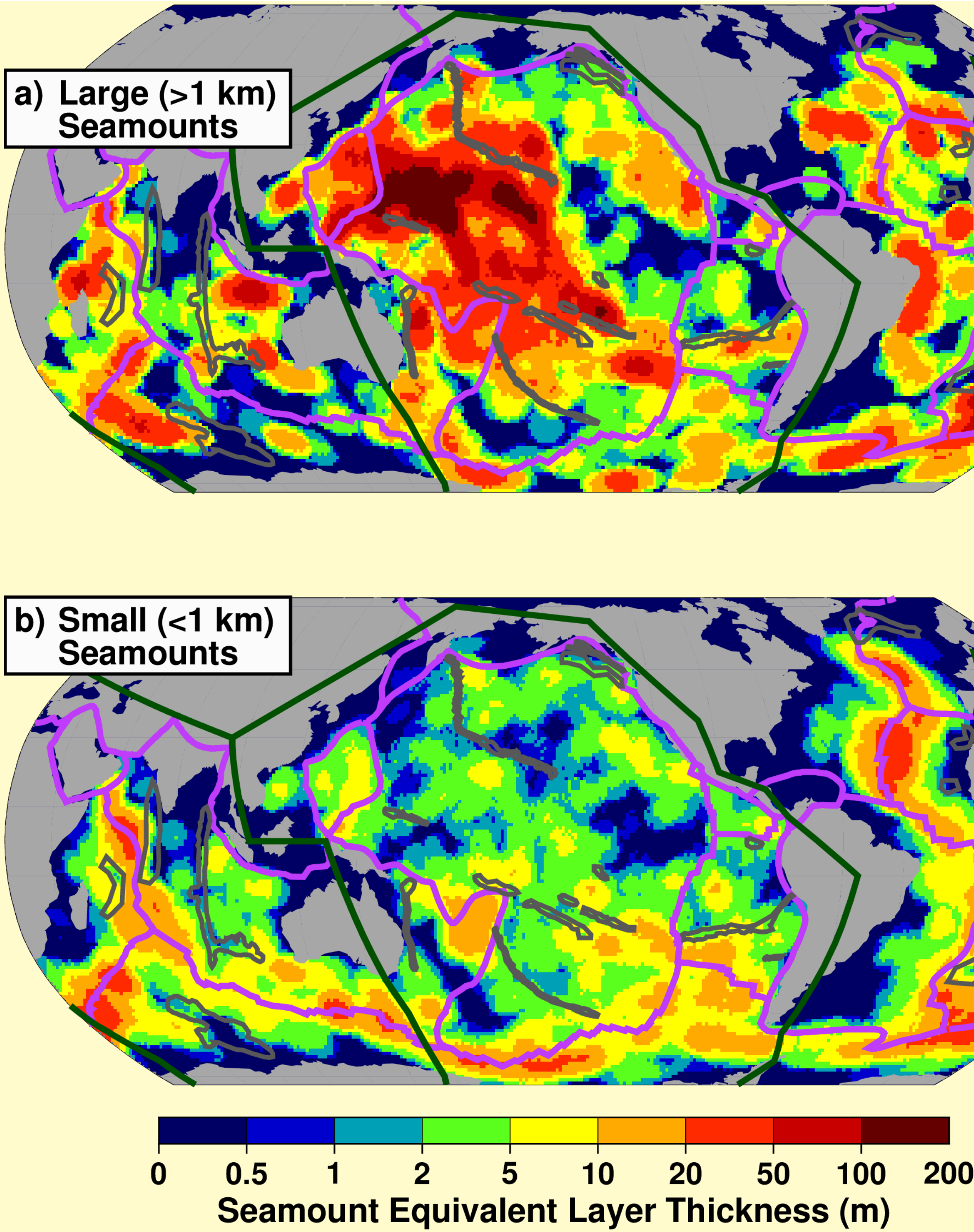


USS San Francisco
Crashed into a uncharted seamount (2005)

Seamount Equivalent Layer Thickness:

Thickness of a volcanic layer if all seamounts are spread evenly across nearby seafloor

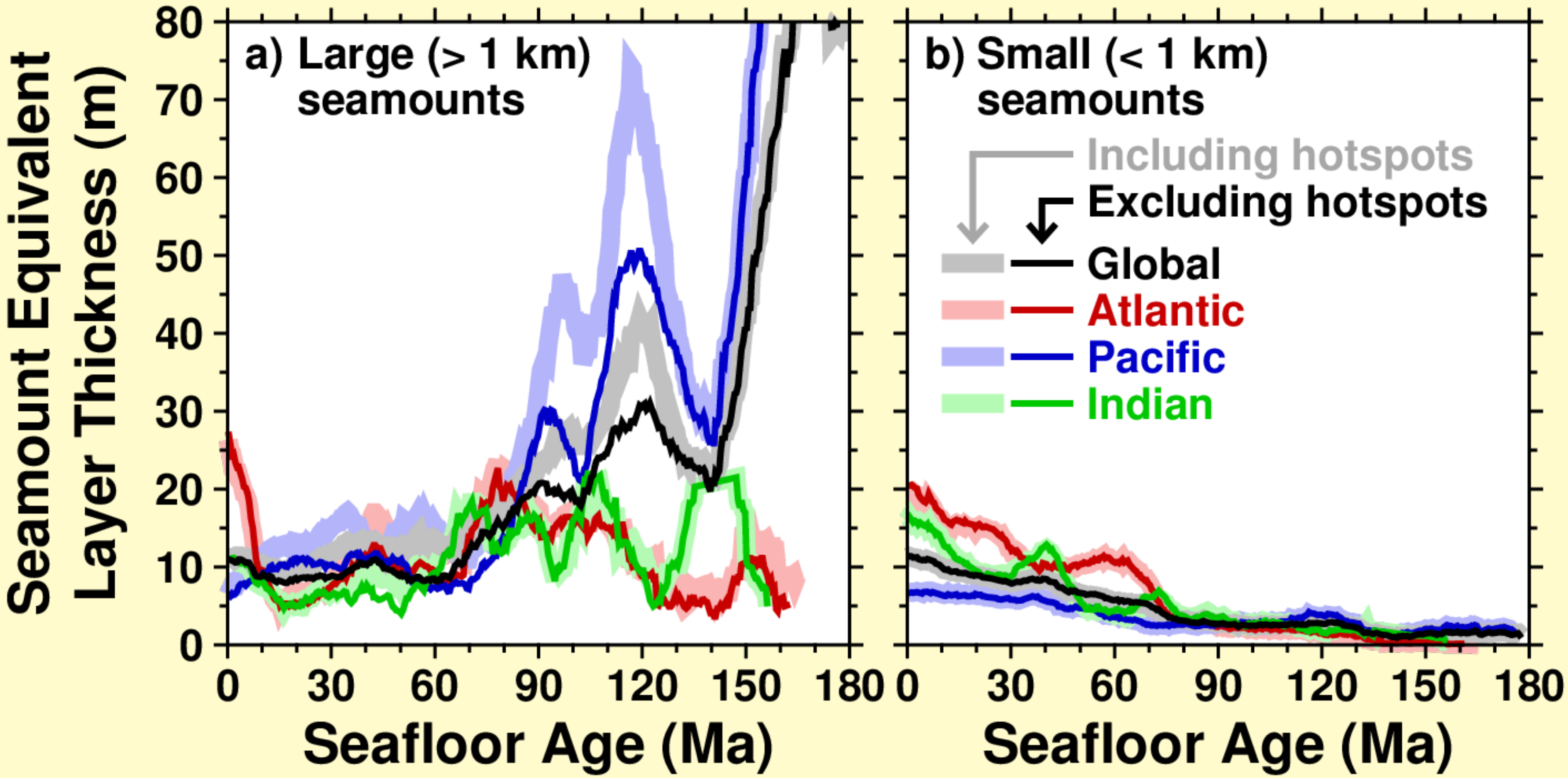
Conrad et al. [2017]



Seamount equivalent thickness vs. seafloor age

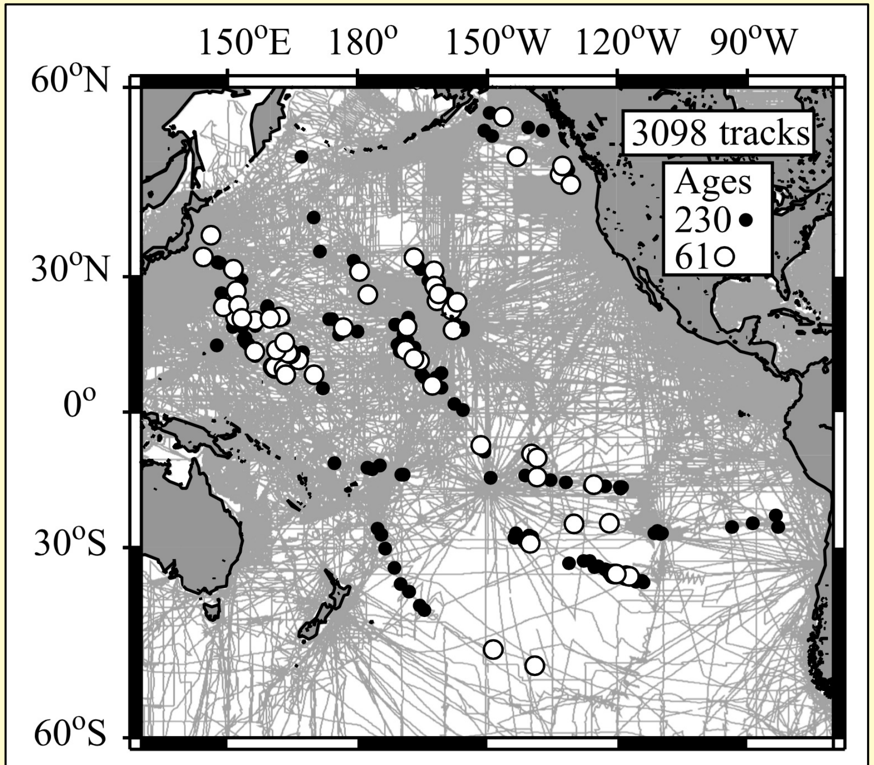
Large seamounts:
- 10 m until ~70 Myr
- Increases after 70 Myr (esp in Pacific)

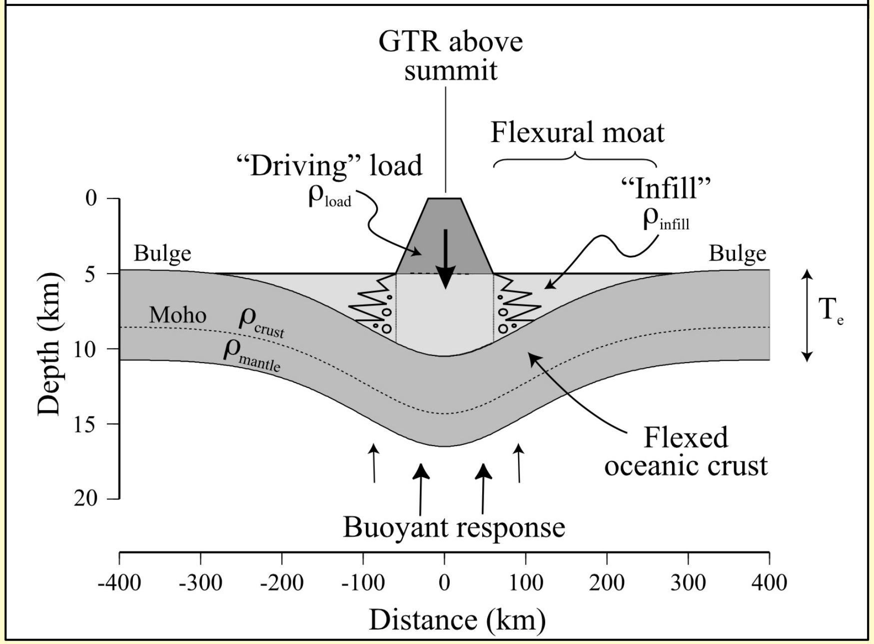
Small seamounts:
- Decreases away from the ridge due to sampling problems

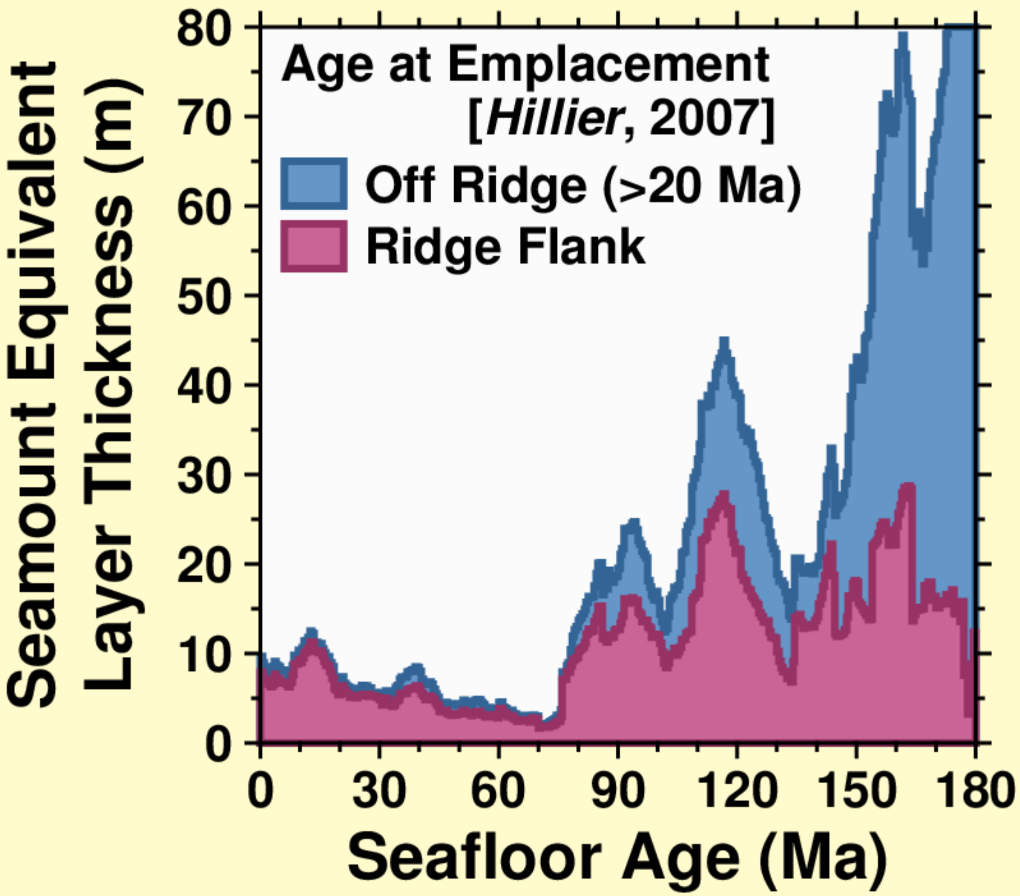


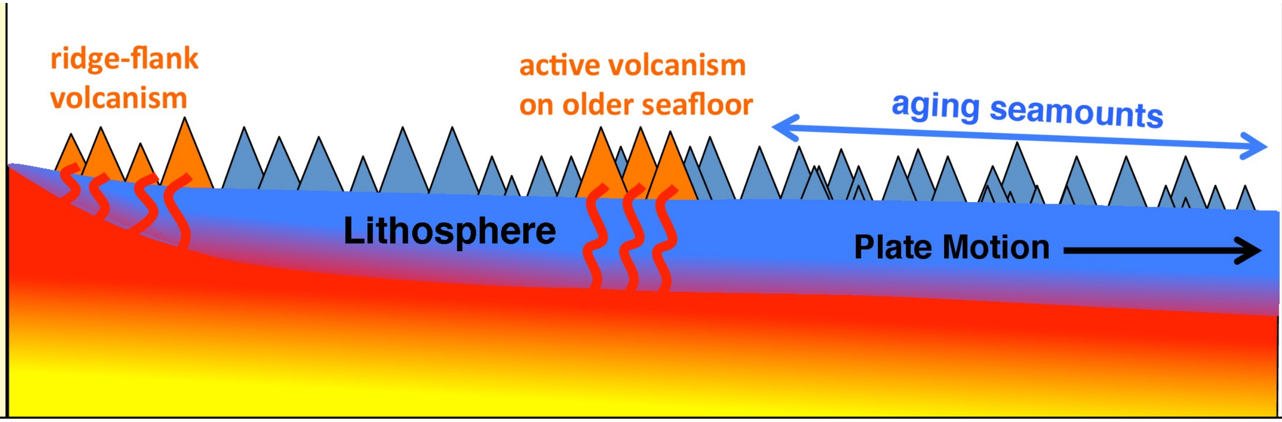
Age of the Seamounts:

- Poorly constrained!
- Must be younger than seafloor
- Constraints for some seamounts from plate flexure

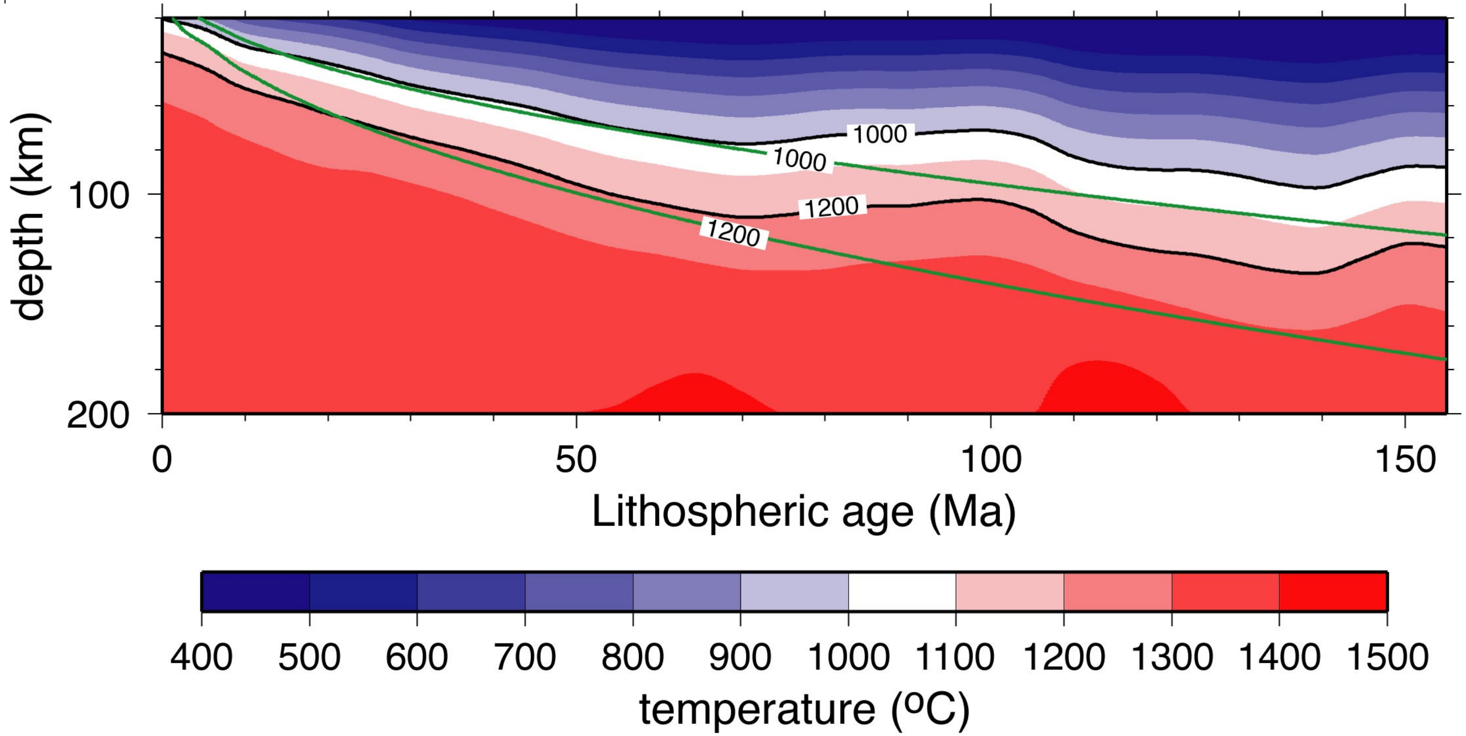








Model of Seamount Emplacement
Conrad et al. [2017]



Thermal Profile of the Pacific Lithosphere
Ritzwoller et al. [2004]

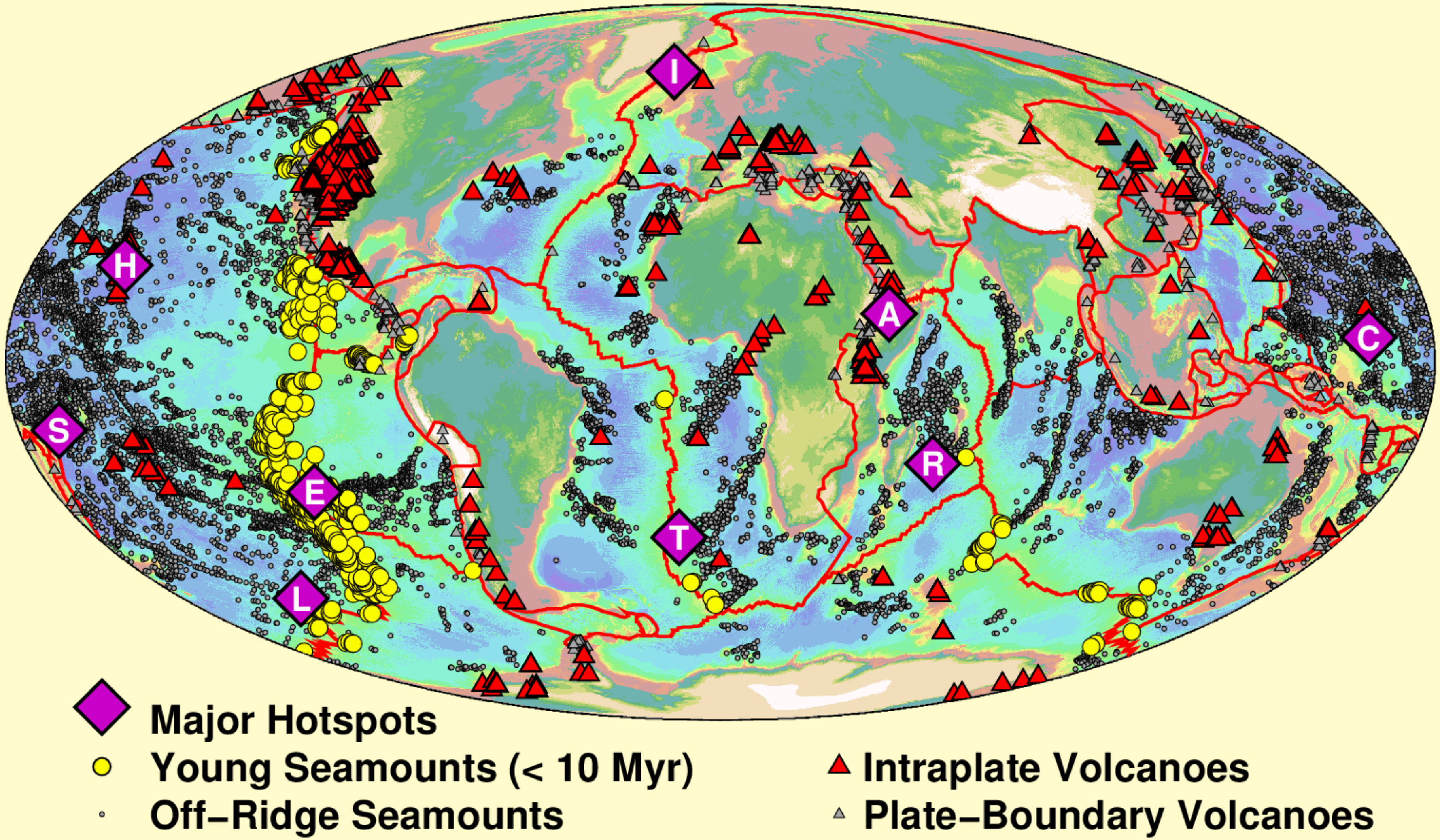
Model for Seamount formation:

- One population formed on the ridge flanks
- Another population formed on seafloor > 70 Myr old
- Pacific seamount production was faster in the Cretaceous

Intraplate Volcanism

- Mostly minor and mostly basaltic
- Sometimes exhibits age non-hotspot-like age progression

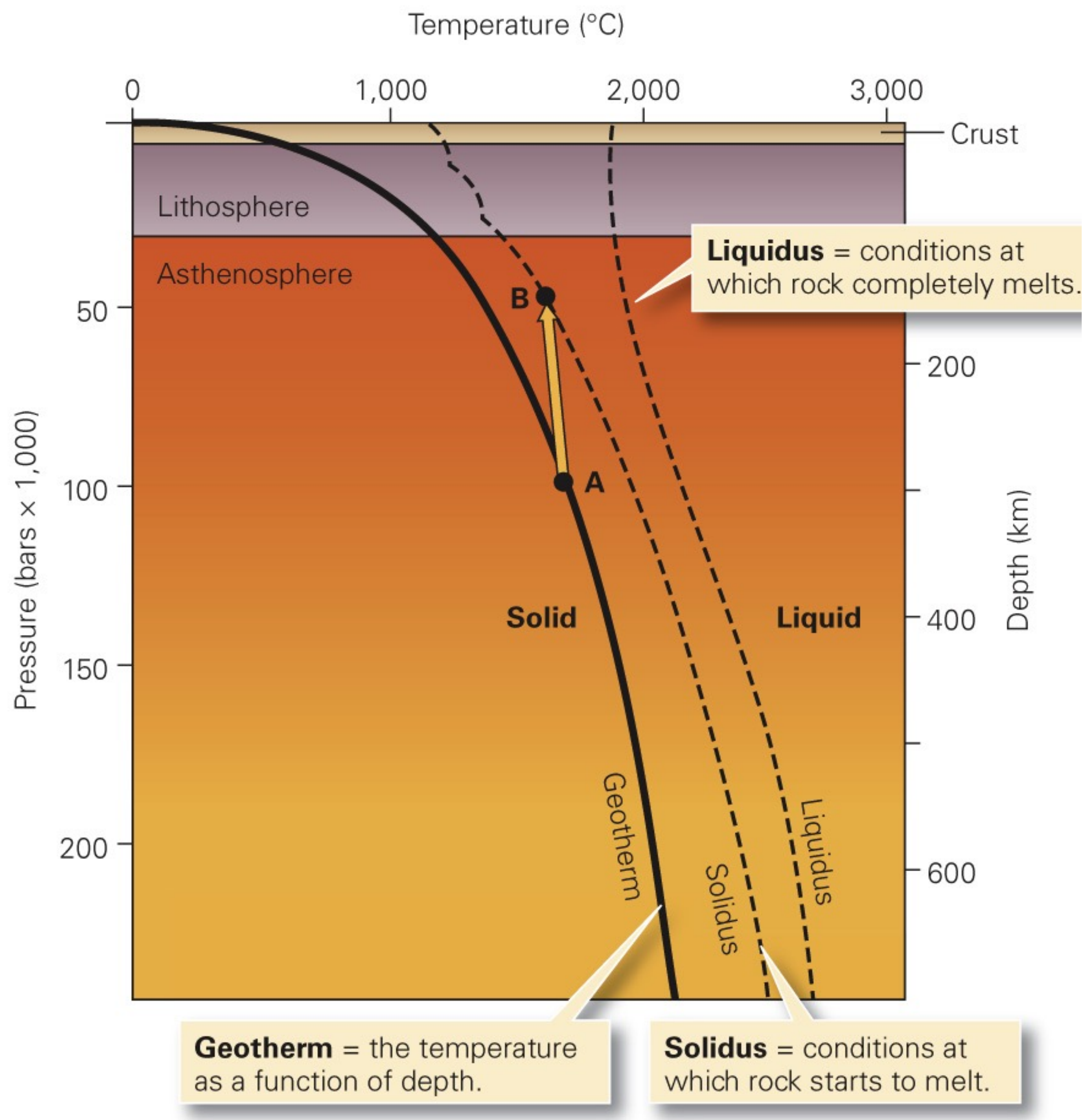
→ **How is the lithosphere and asthenosphere important?**
→ **What is the mechanism?**



The following can produce melting:

- Hot Mantle Temperatures
- Reduced Mantle Solidus (e.g., due to volatiles)
- Mantle upwelling

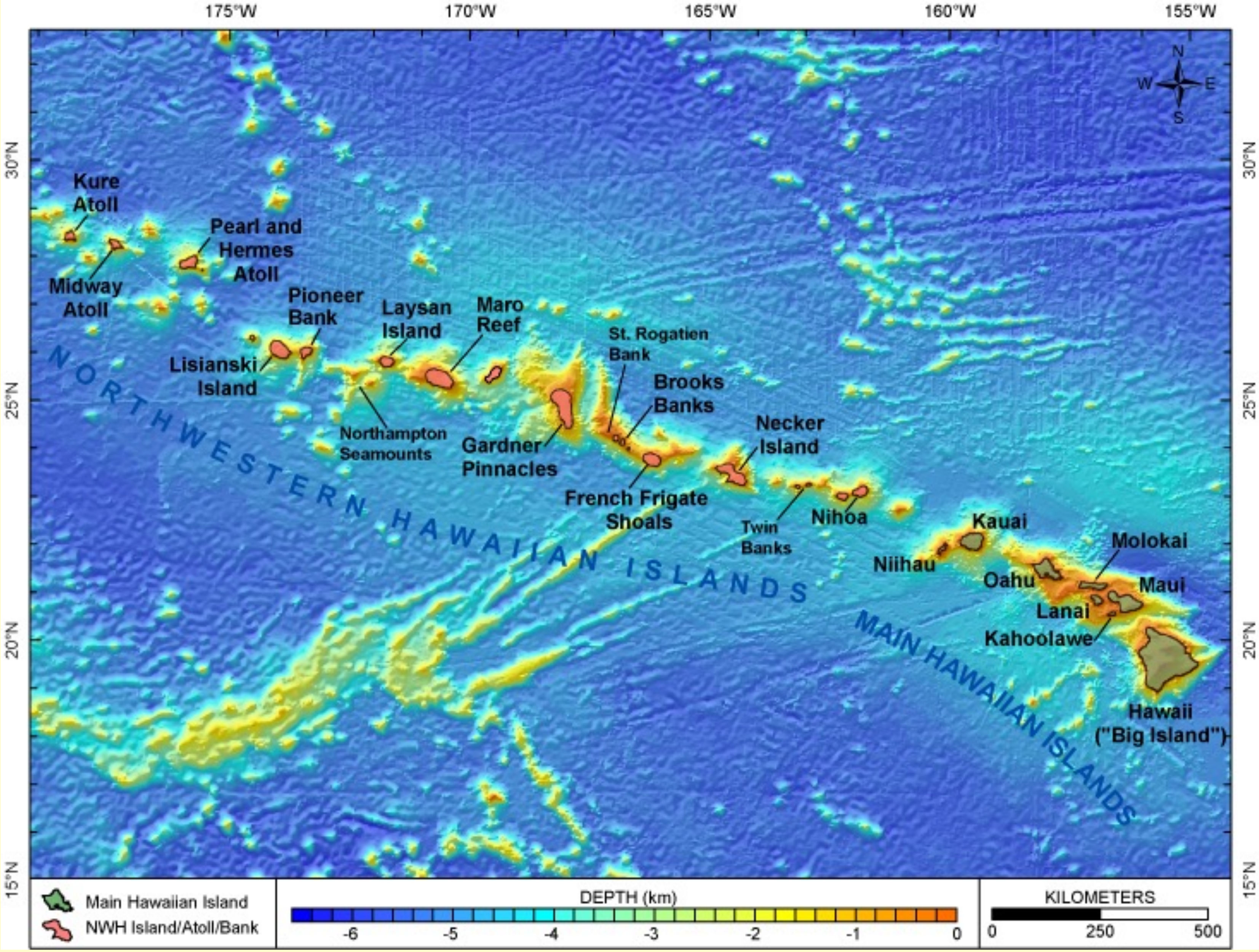
→ **Which mechanisms can cause localized mantle upwelling?**

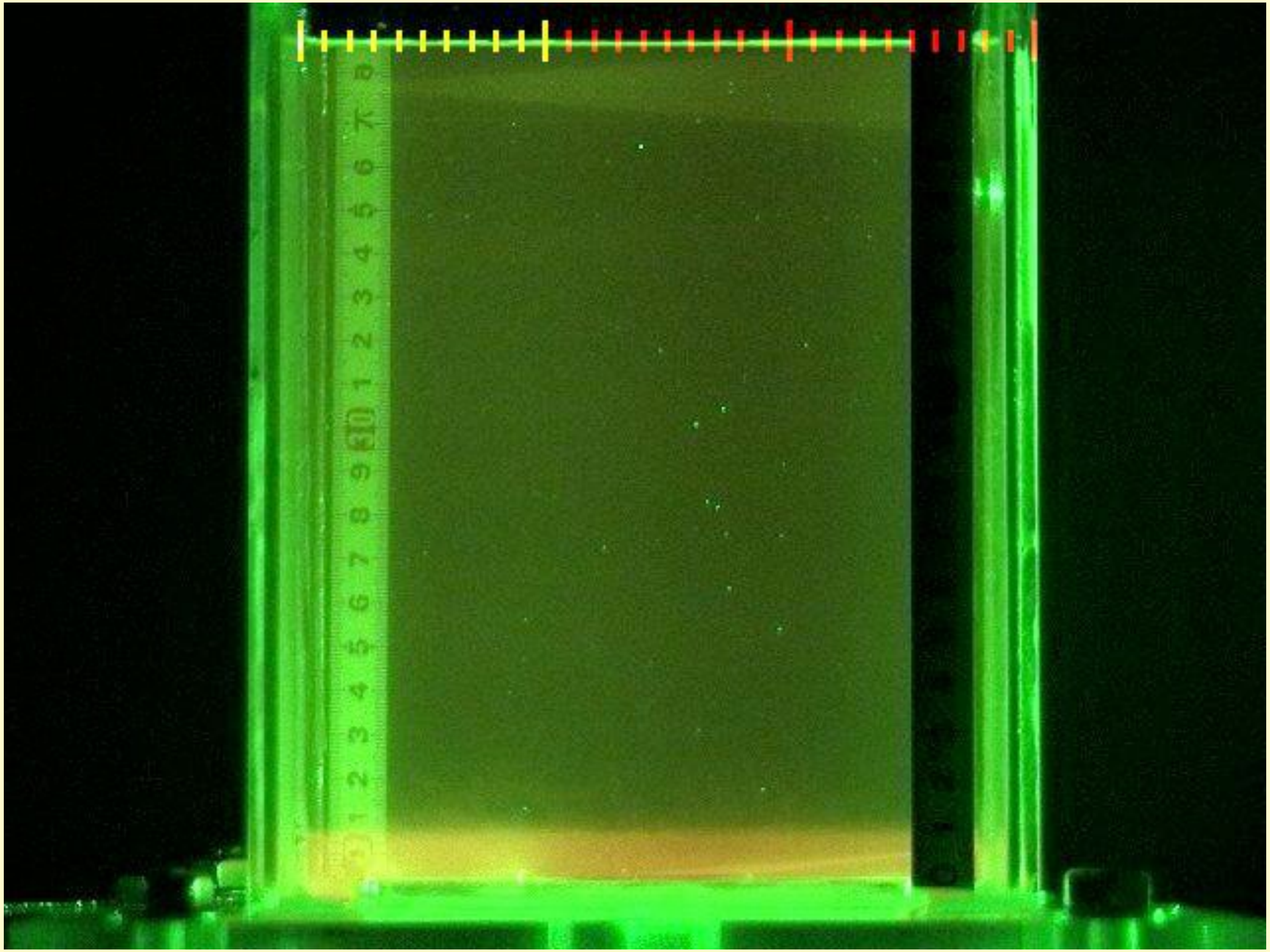


4 Mechanisms:

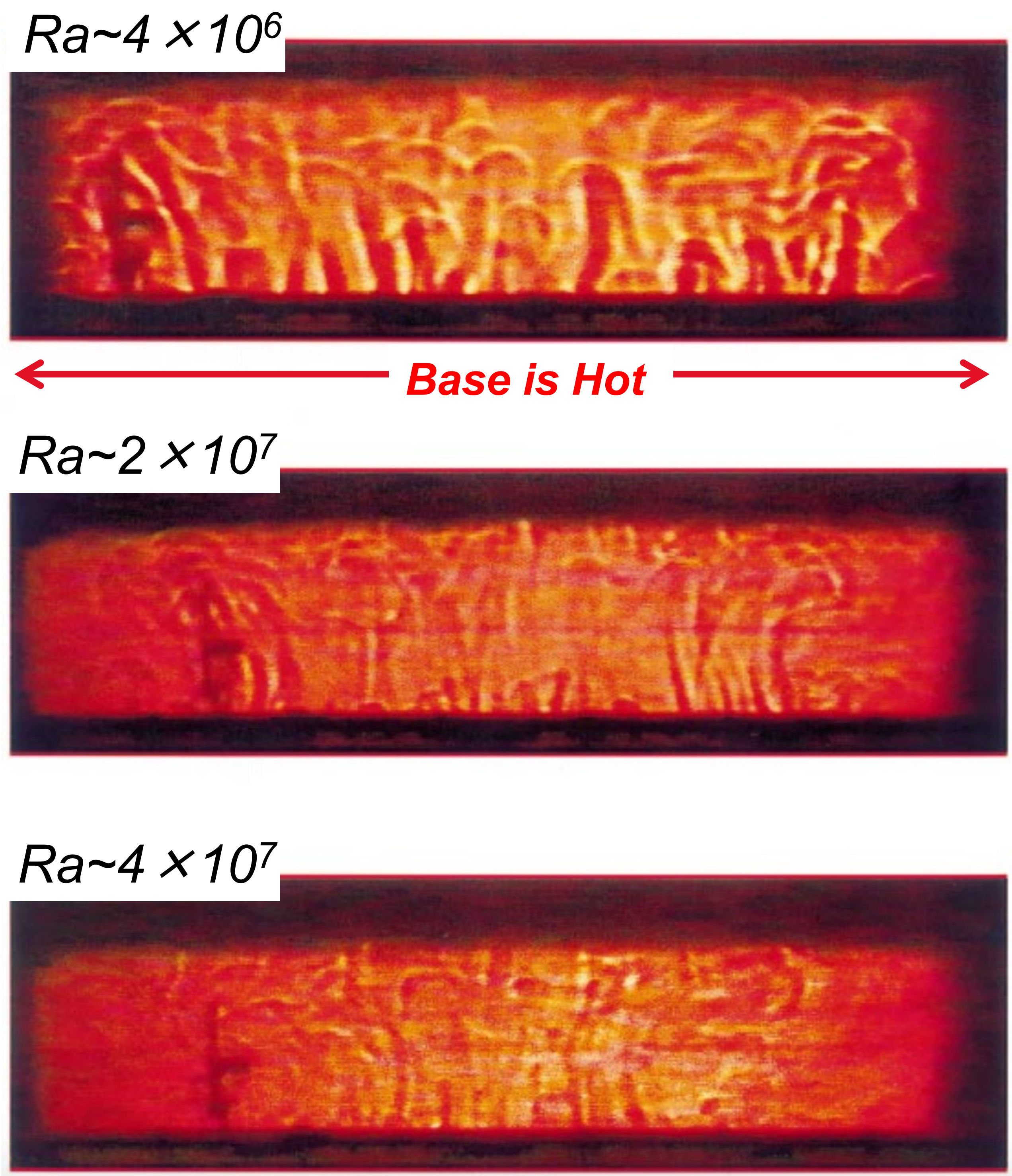
- Plumes
- Small-Scale Convection
- Shear-Driven Upwelling
- Petit-Spots

1. Mantle Plumes





A Plume Experiment in Corn Syrup:
Plumes have heads and tails

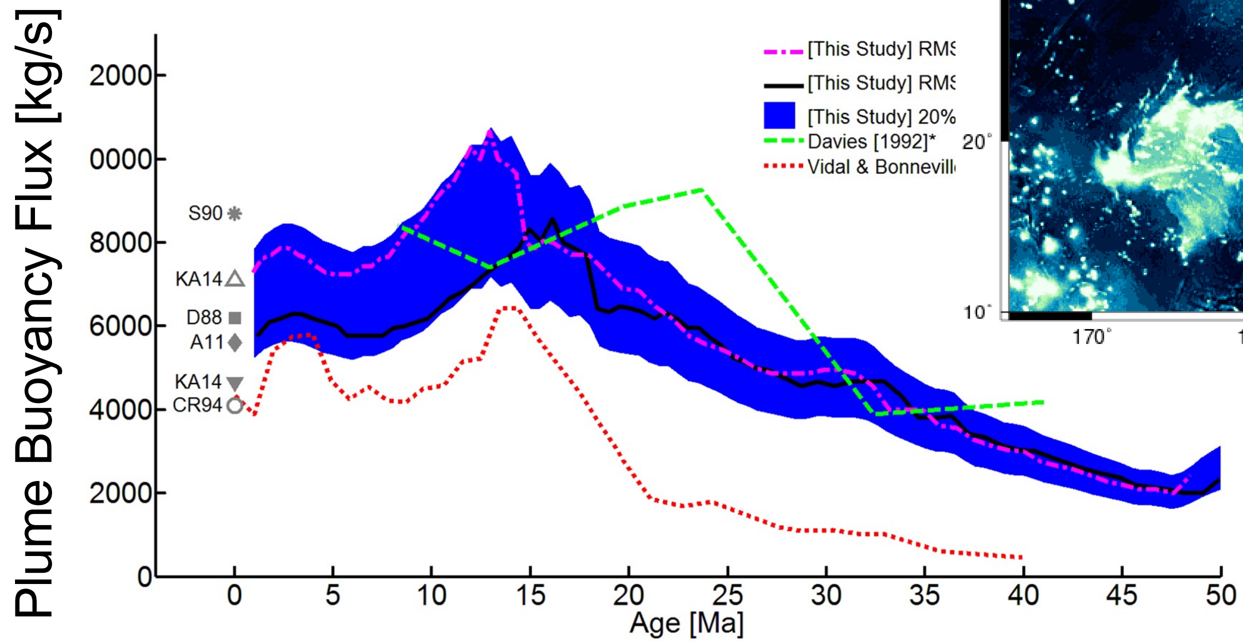


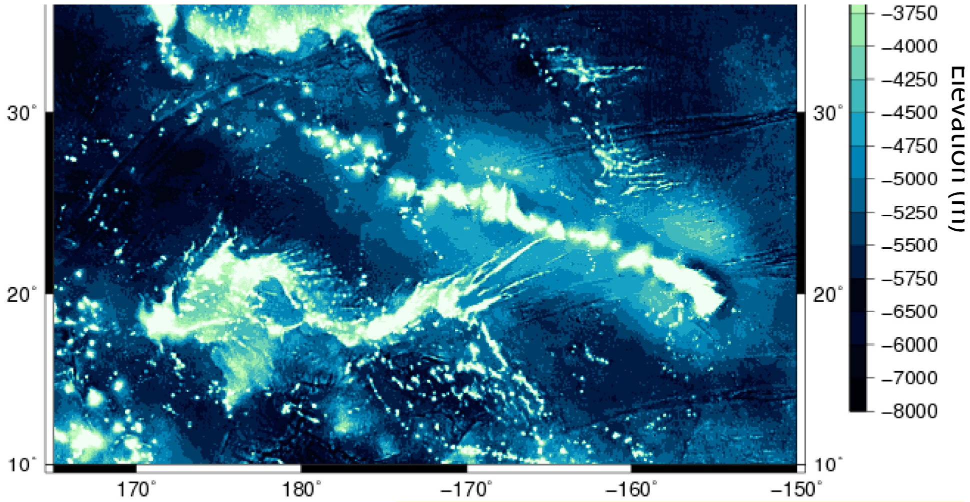
Laboratory experiment of convection in a tank of corn syrup.

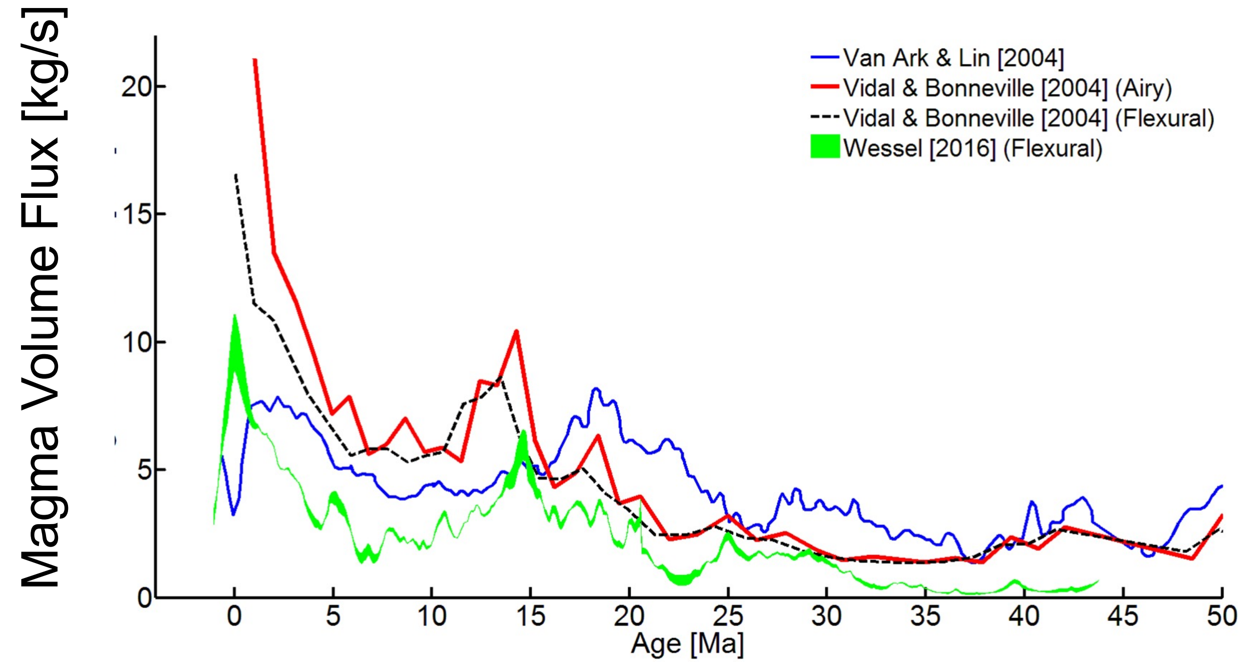
Lithgow-Bertelloni et al. [2001]

More vigorous convection (hotter) makes for:
smaller heads
and
thinner tails

Plumes uplift the lithosphere







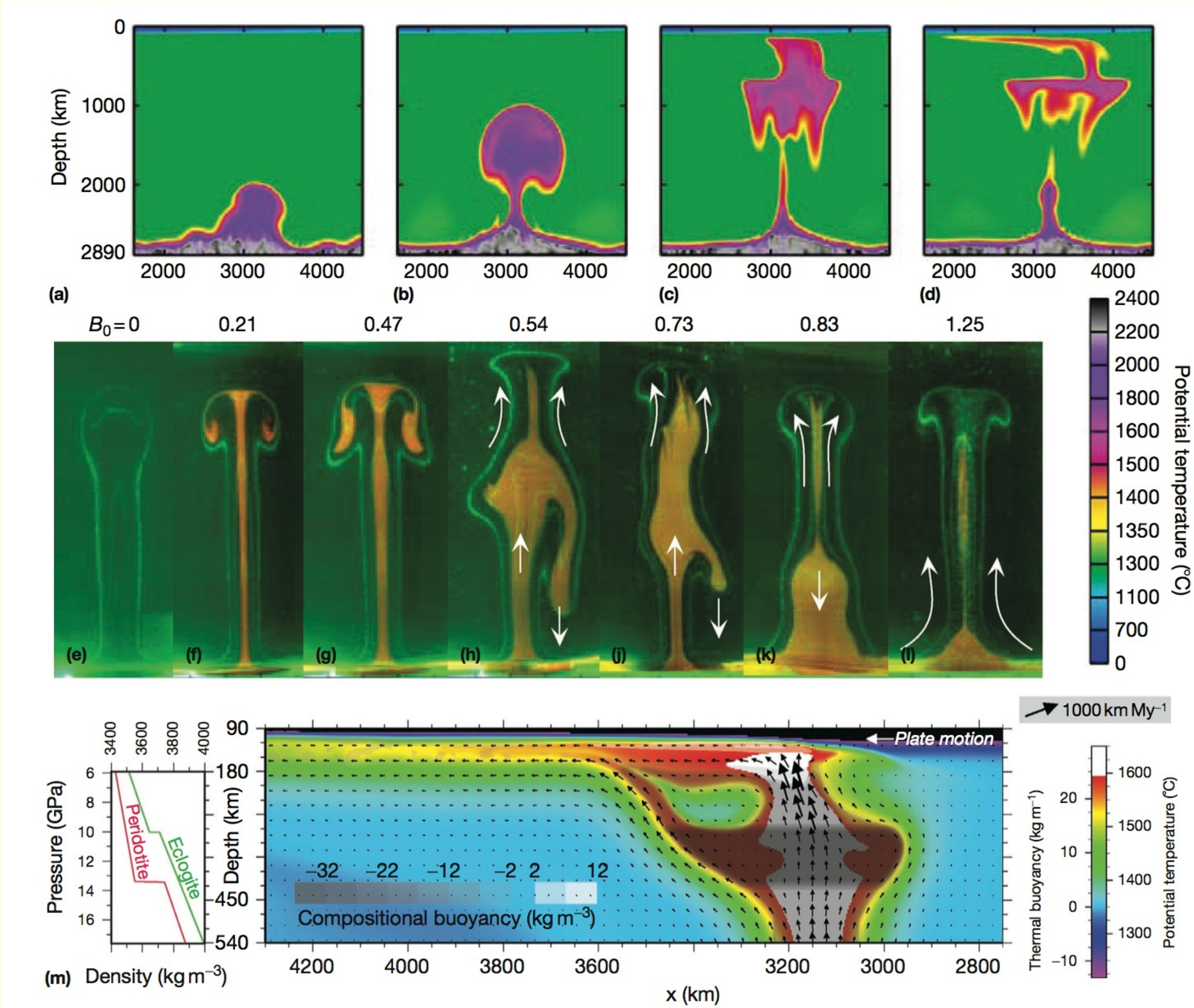
Hawaiian plume buoyancy flux has been growing with time

Togia, MS thesis [2015]

Plumes can exhibit interesting behavior!

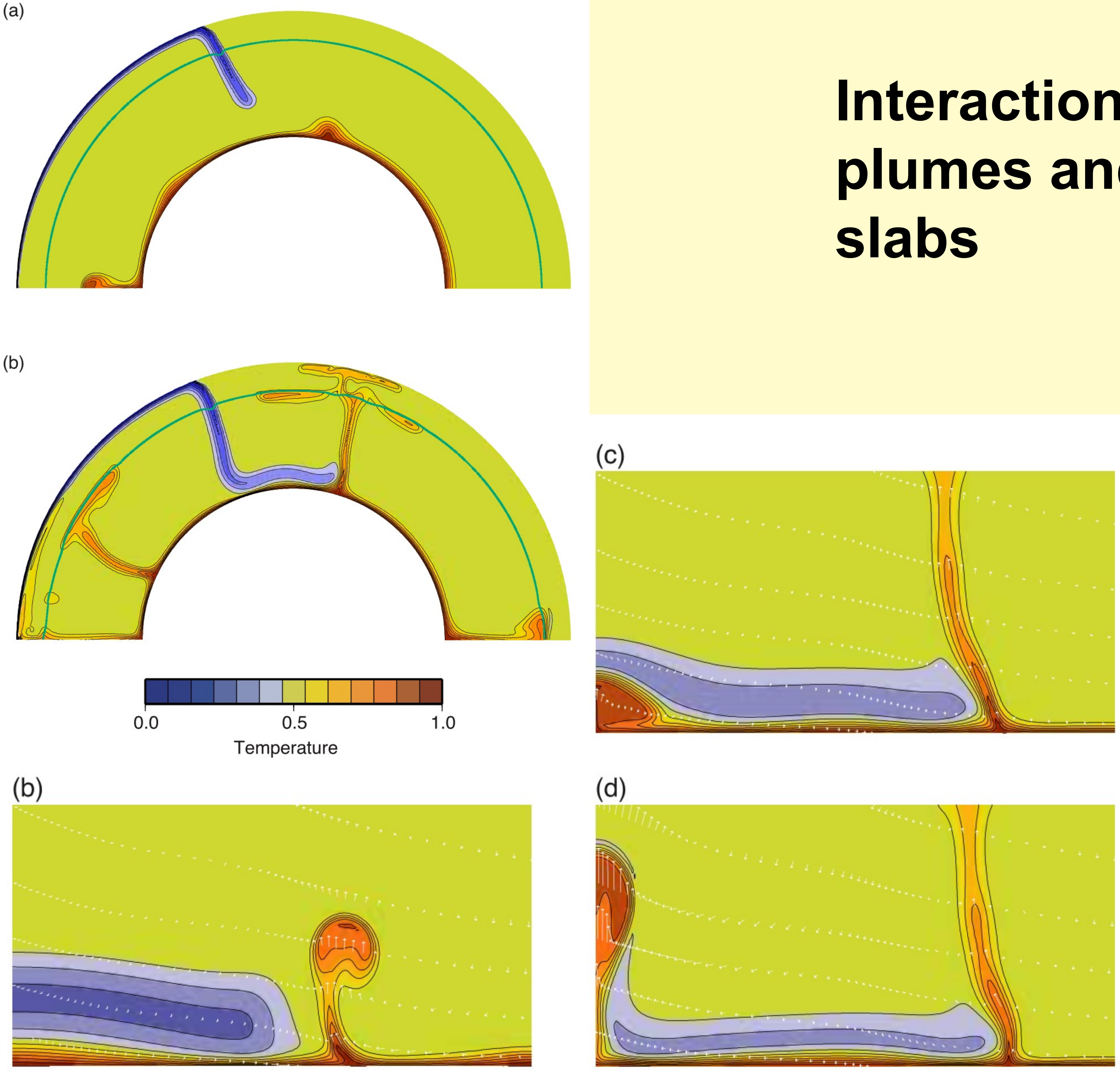
410 km:
Plume
Accelerated

610 km:
Plume
Impeded



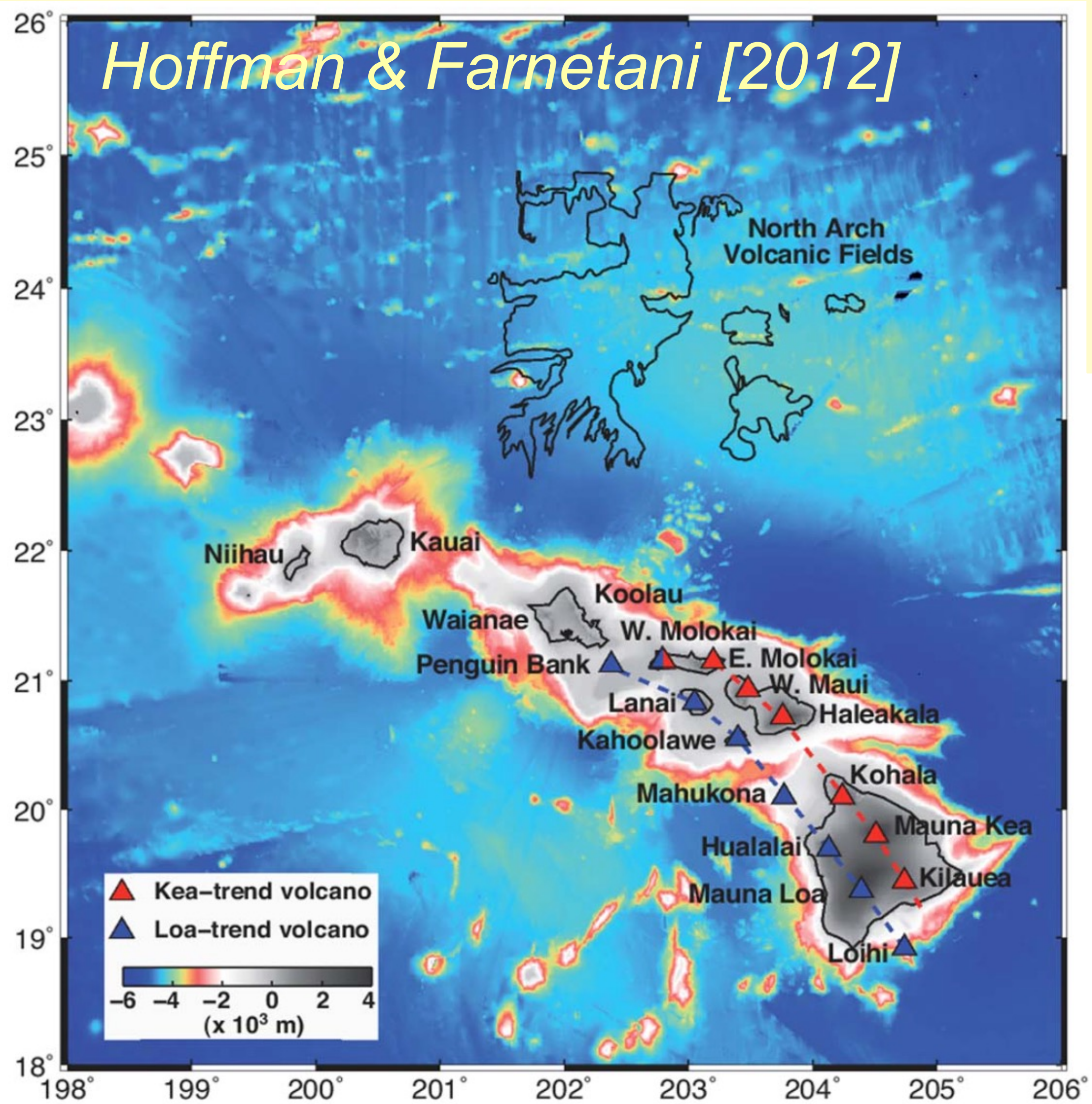
Ballmer et al. [2015]

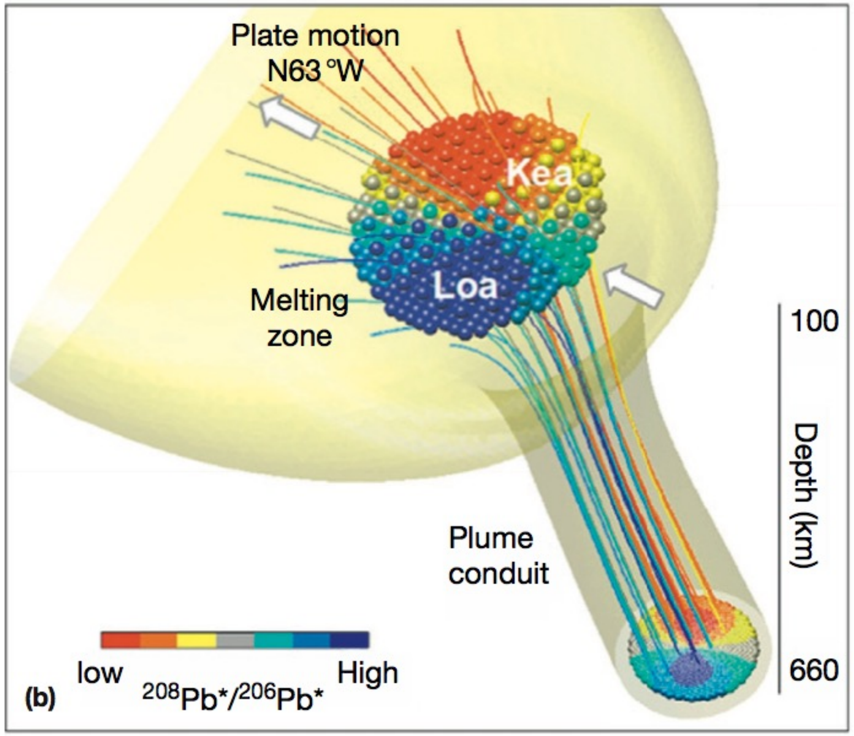
Interaction of plumes and slabs



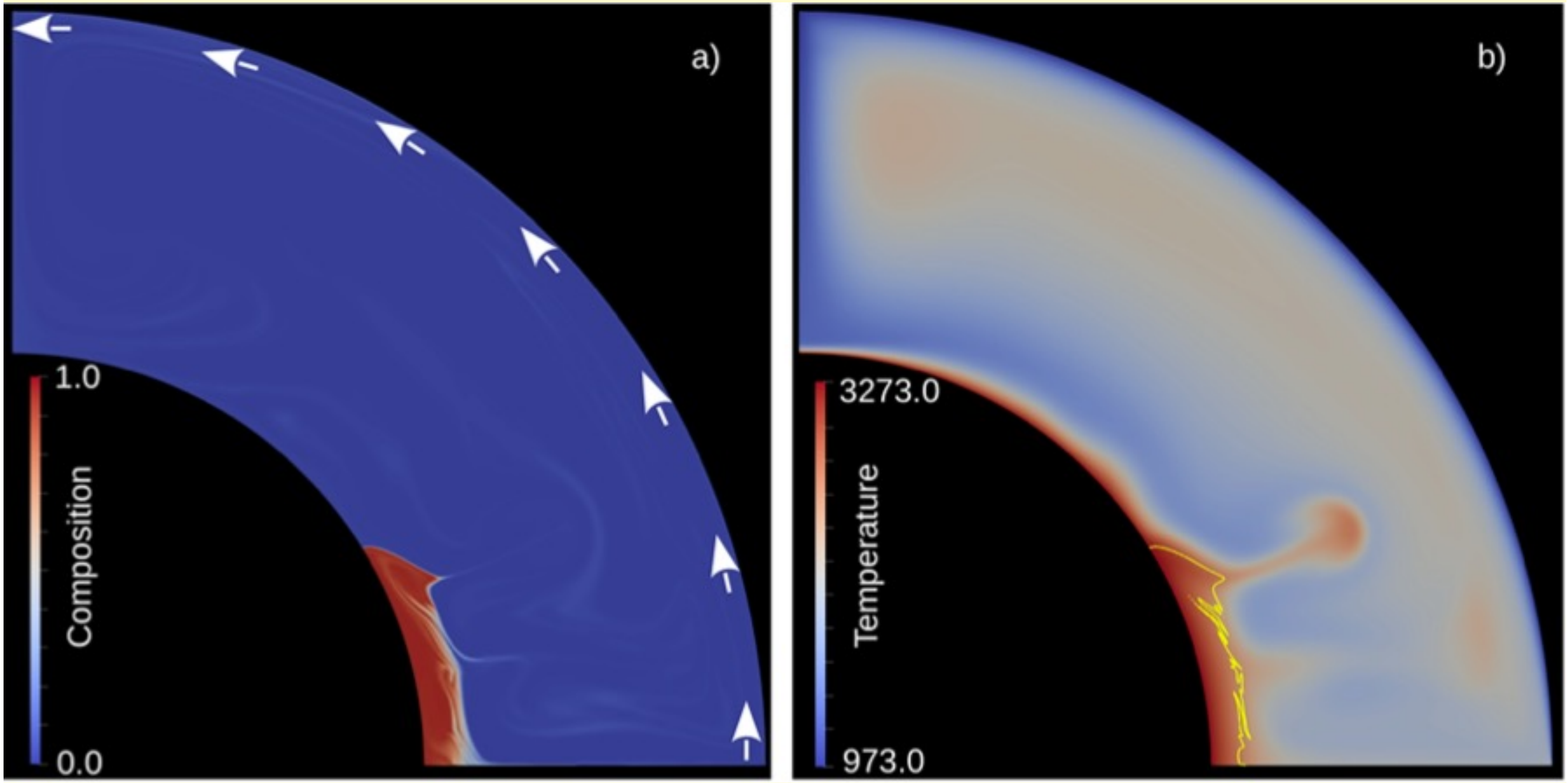
Tan & Gurnis [2002]

Bisected plumes may sample preserved geochemical gradients from the deep mantle



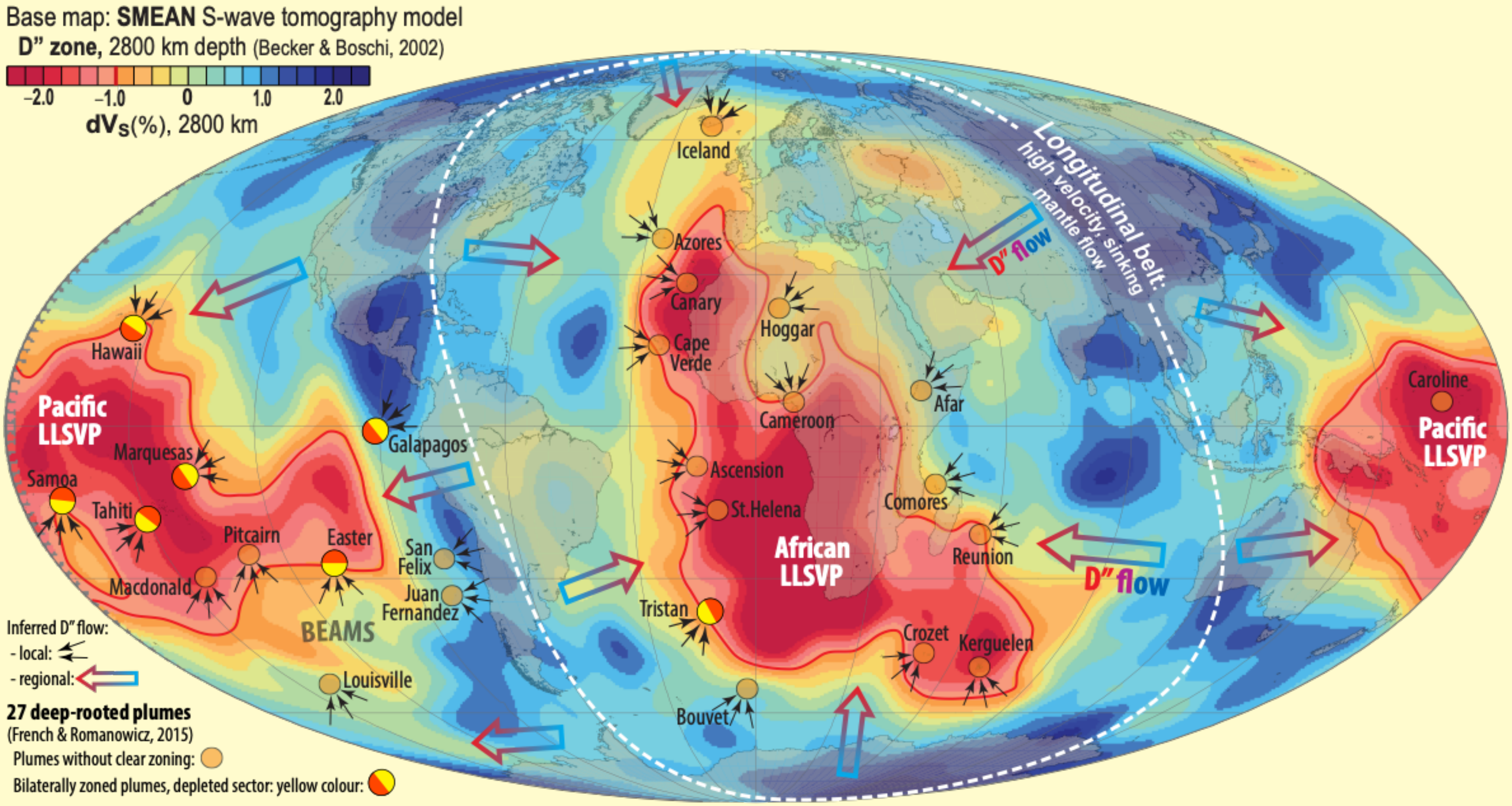


Bisected plumes may sample preserved geochemical gradients from the deep mantle

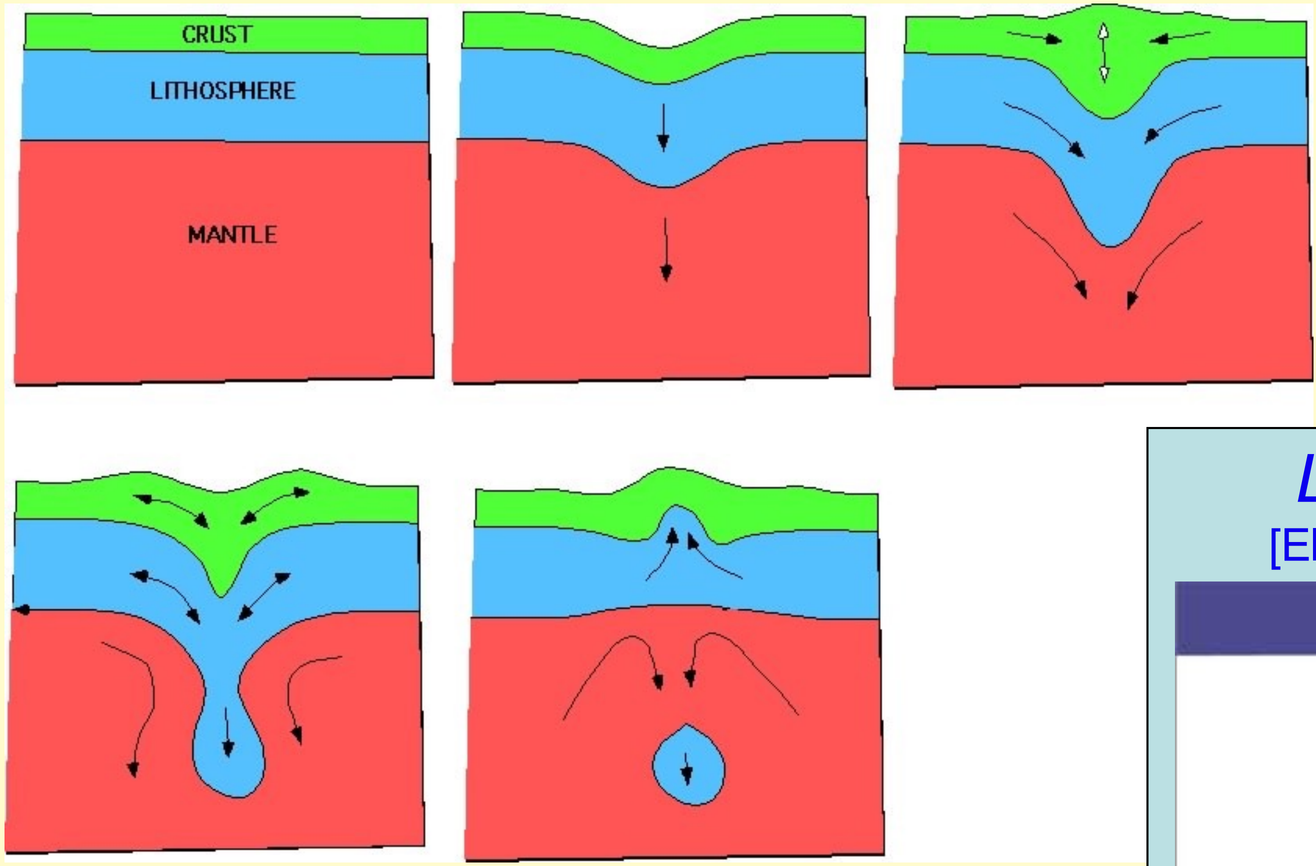


Plumes rise from the edges of the LLSVPs in the lower mantle [*Heyn et al., 2020*]

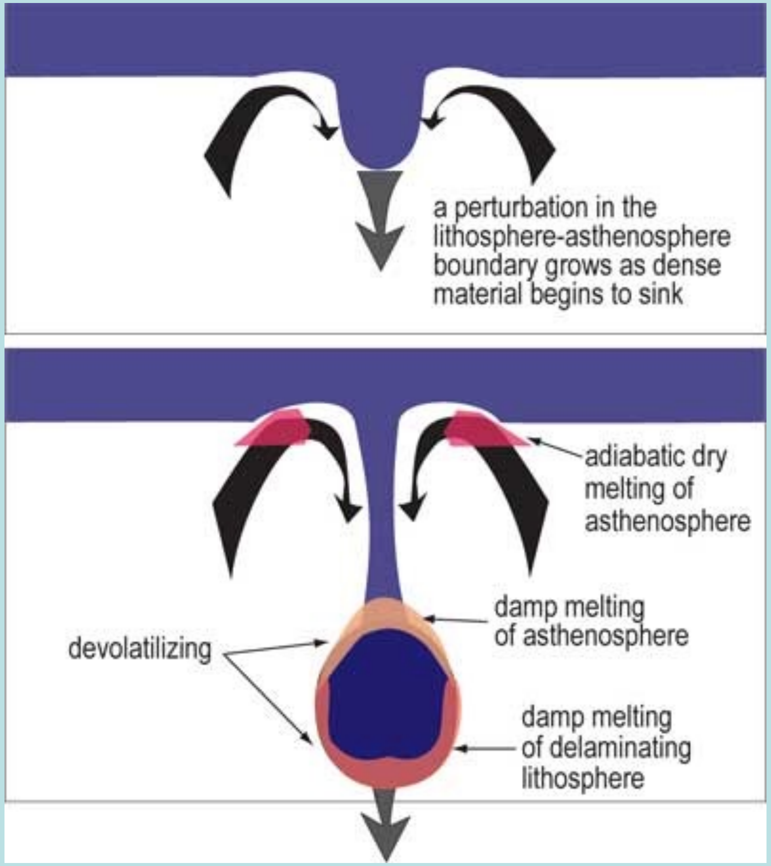
Bisected plumes may sample preserved geochemical gradients from the deep mantle



2. Small-Scale Convection

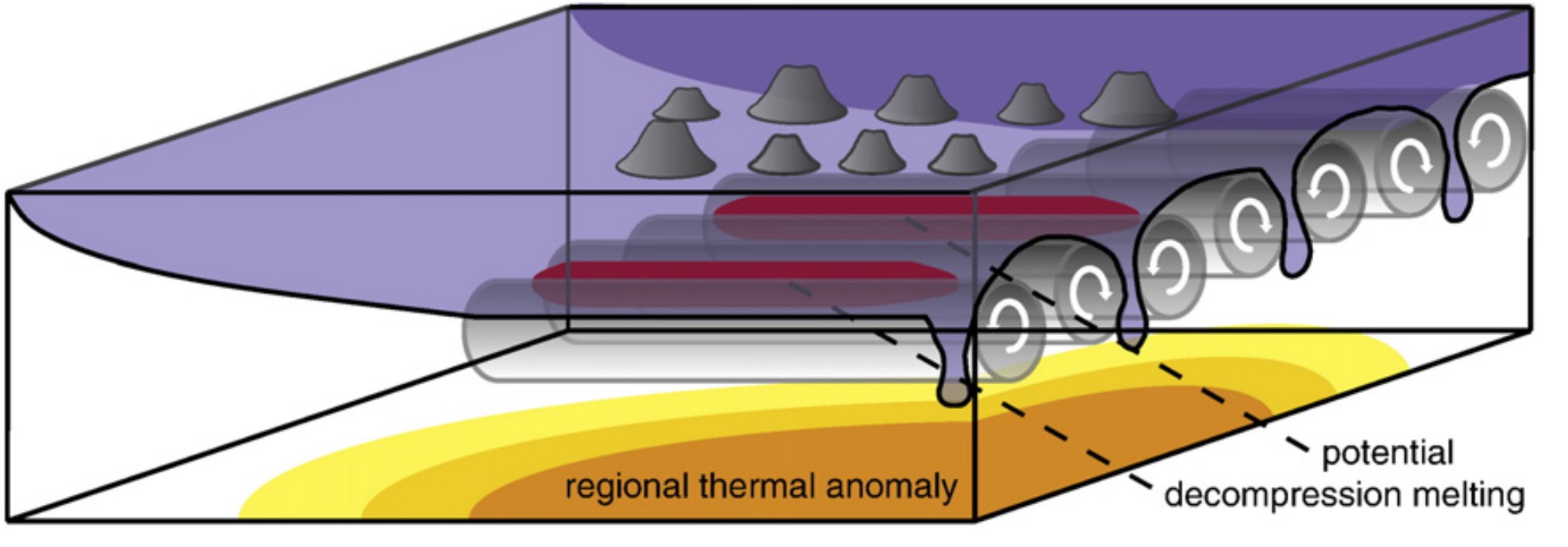


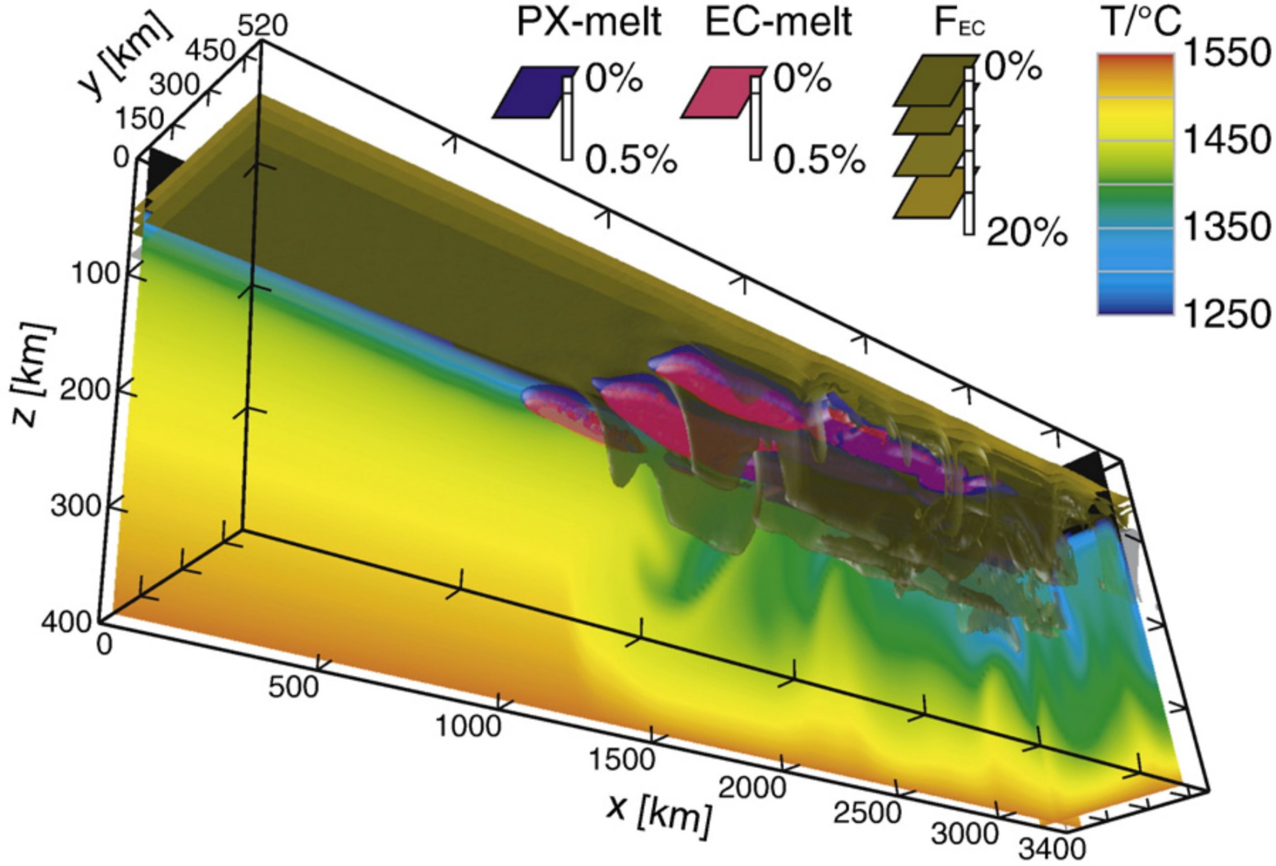
Lithospheric Drips
[Elkins-Tanton & Hager, 2000]



- Like an upside-down plume:
- Cold “drips” sink into the mantle.
- Return flow involves upwelling → produces melting.

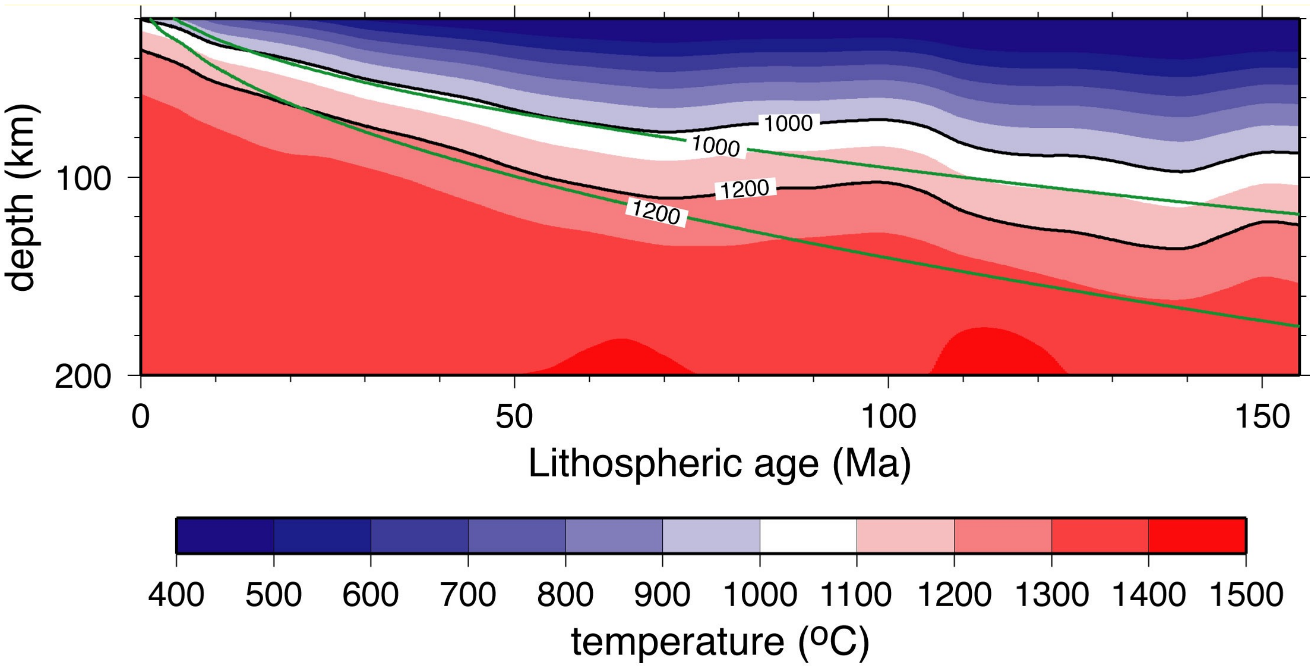
→ Explains some intraplate volcanism (continents & oceans)





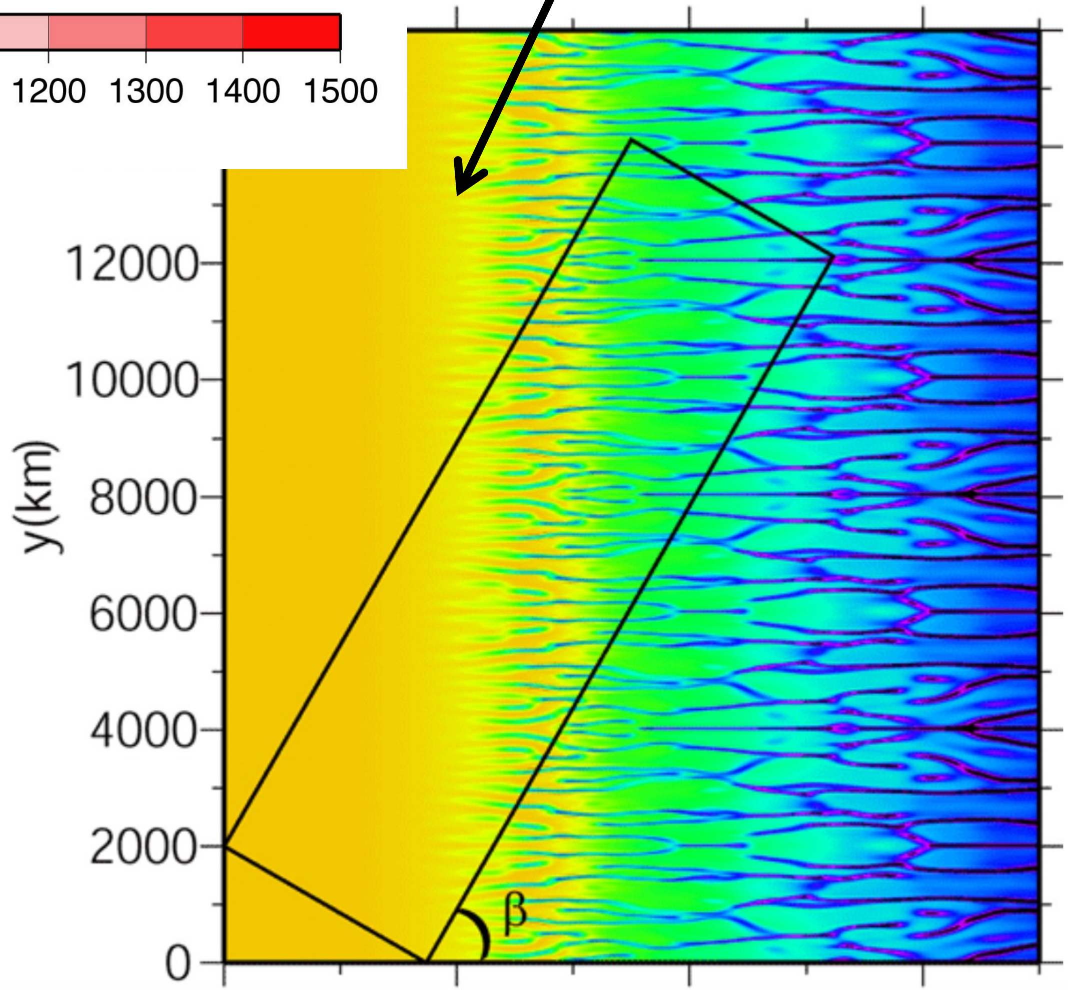
Small-Scale Convection (SSC) beneath the oceanic plates.
[*Ballmer et al.*, 2010]

"Richter Rolls" organize the volcanism into linear trends

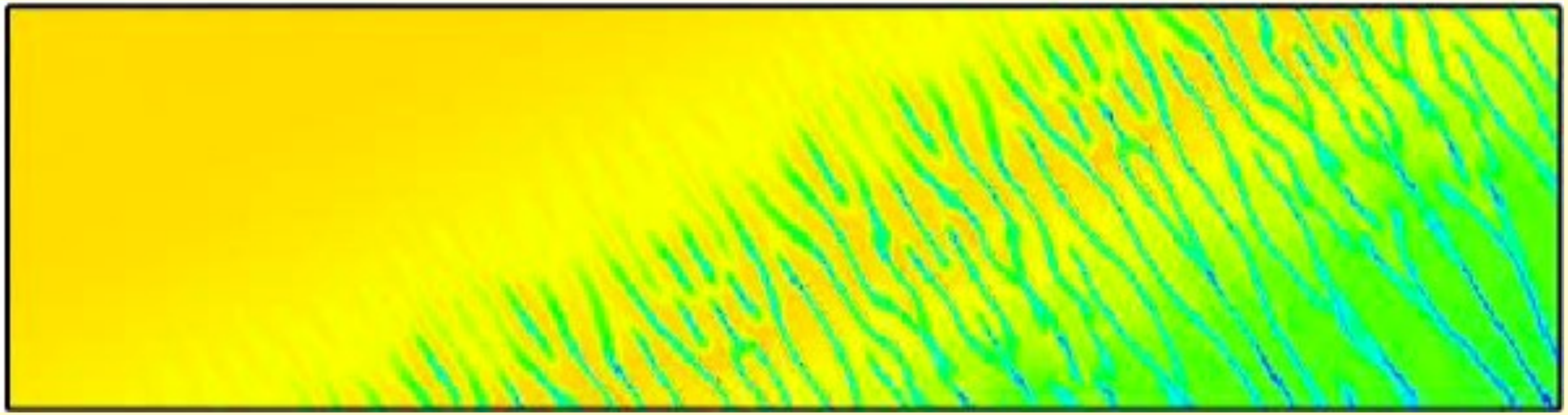


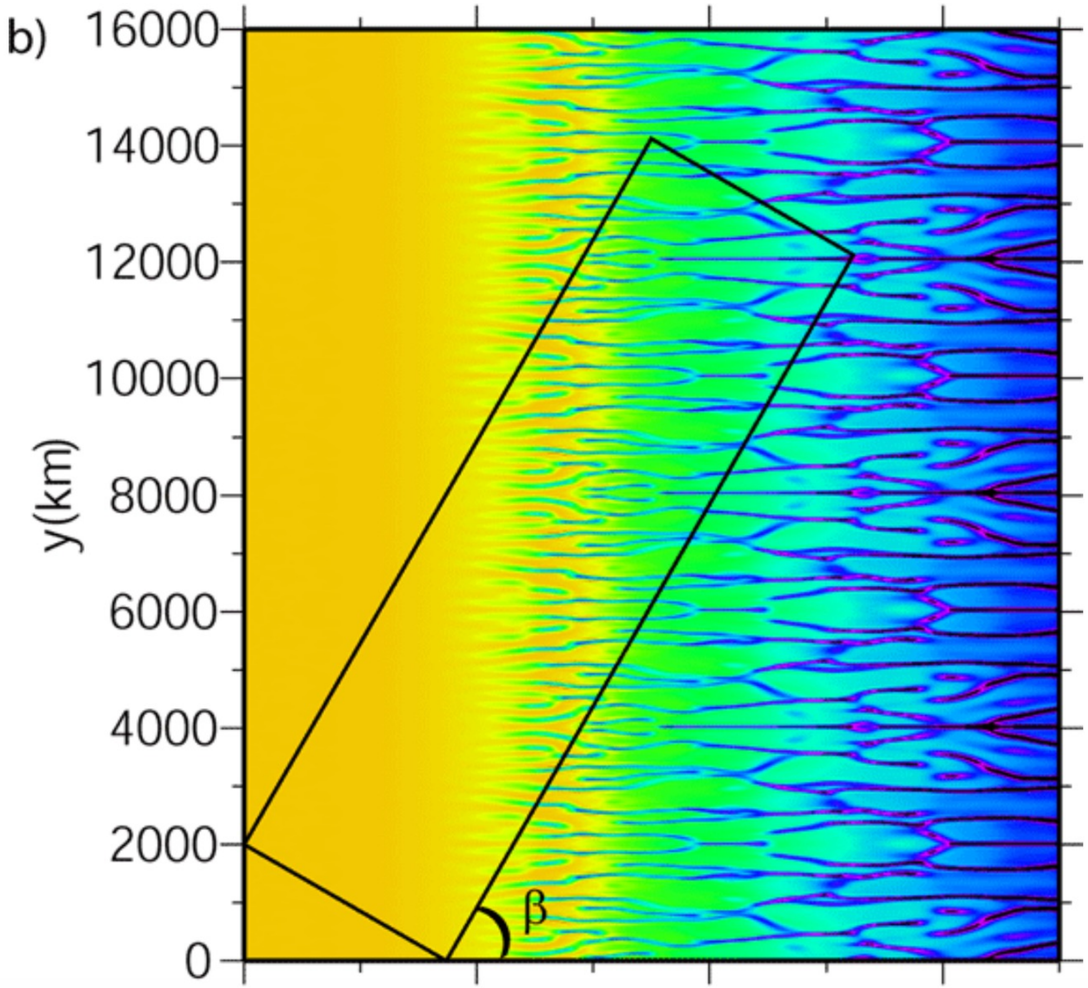
Onset of small-scale convection
→ Occurs at a critical plate age

Thermal Profile of the Pacific Lithosphere
→ Onset at ~70 Myr (?)
[*Ritzwoller et al.*, 2004]



van Hunen & Zhong [2006]

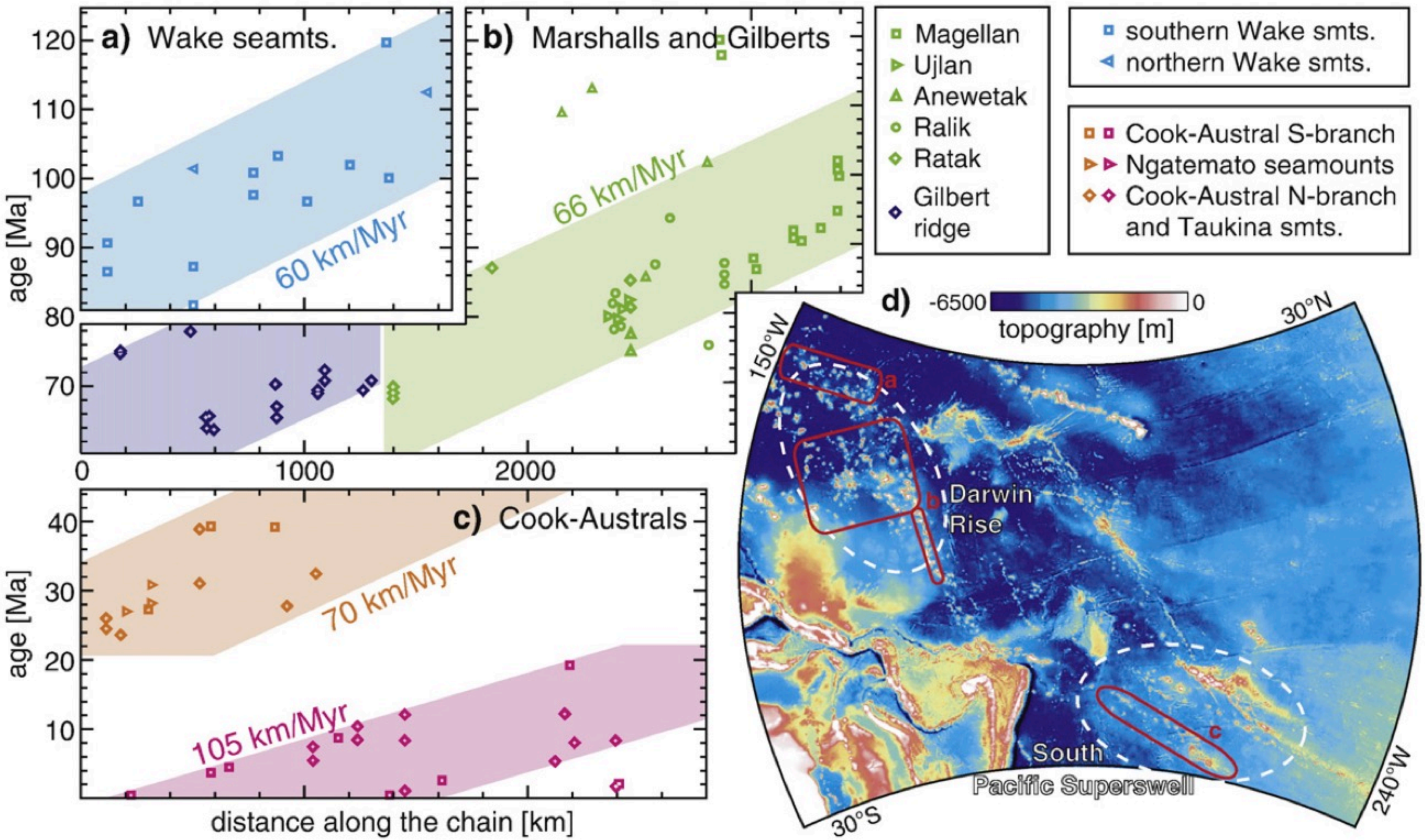




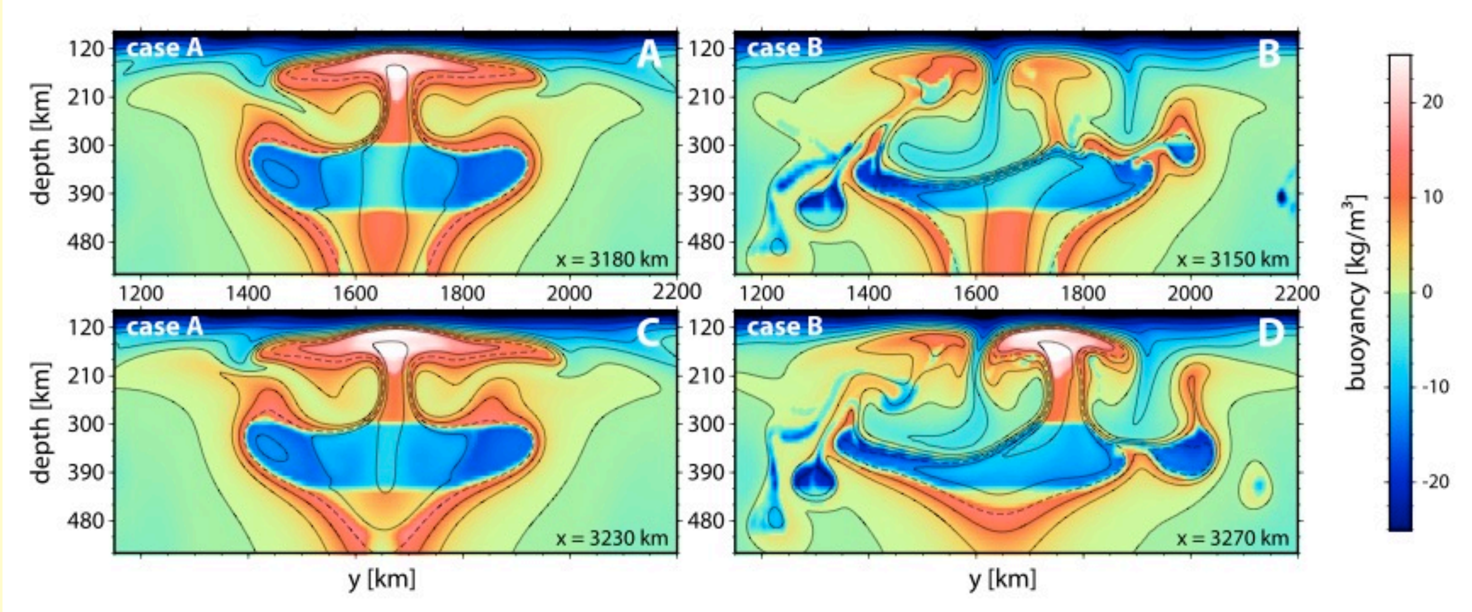
Richter Rolls organize into the direction of plate motion

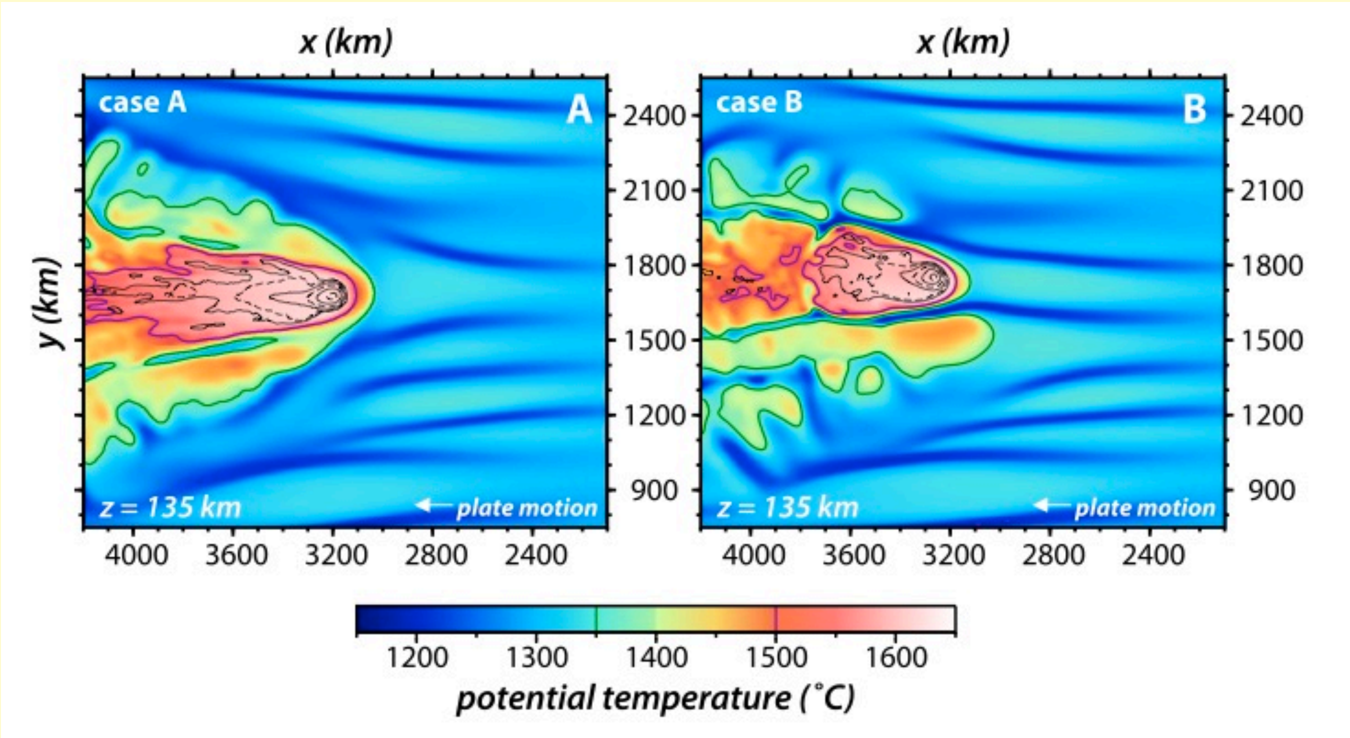
van Hunen & Zhong [2006]

SSC may explain some mountains and minor volcanism.



Ballmer et al., 2010





Interaction of a plume with small-scale convection

Ballmer et al., 2013

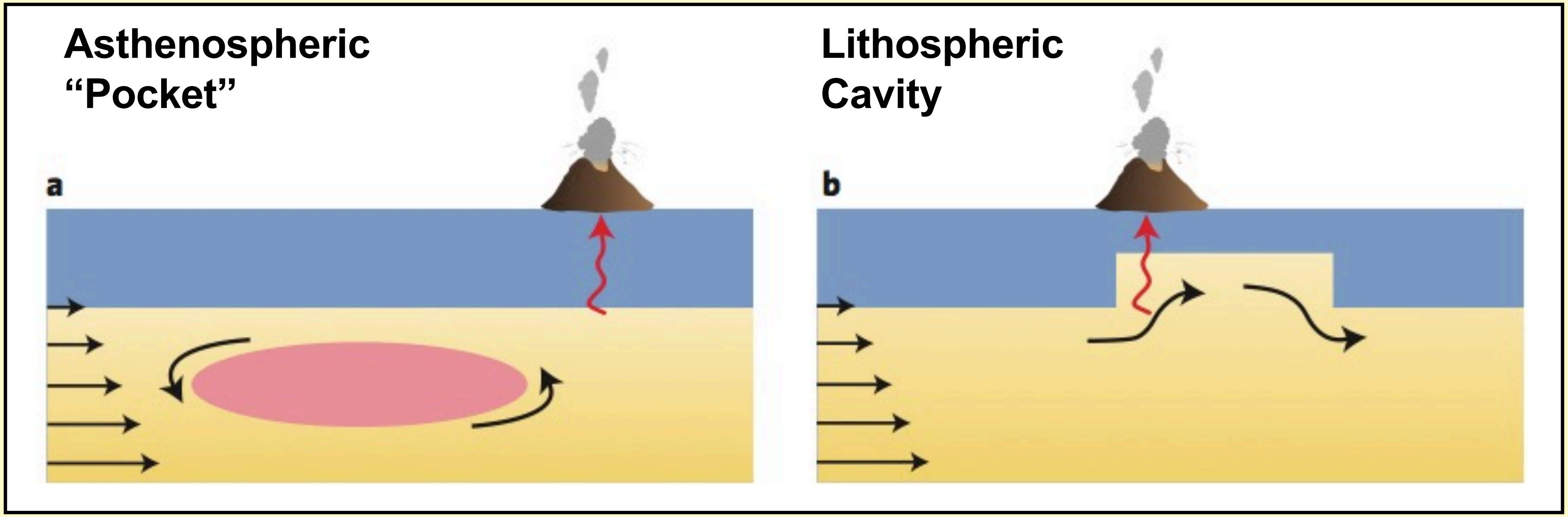
3. Shear-Driven Upwelling (SDU)

Ingredients:

- Near-Solidus Asthenosphere
- Viscosity Heterogeneity
- Rapid Asthenospheric Shear

Conrad et al. [*PEPI*, 2010]
Conrad et al. [*Nat. Geosci.*, 2011]
Bianco et al. [*JGR*, 2011]

Density Heterogeneity not required



King [*News & Views*, *Nature Geoscience*,2011]

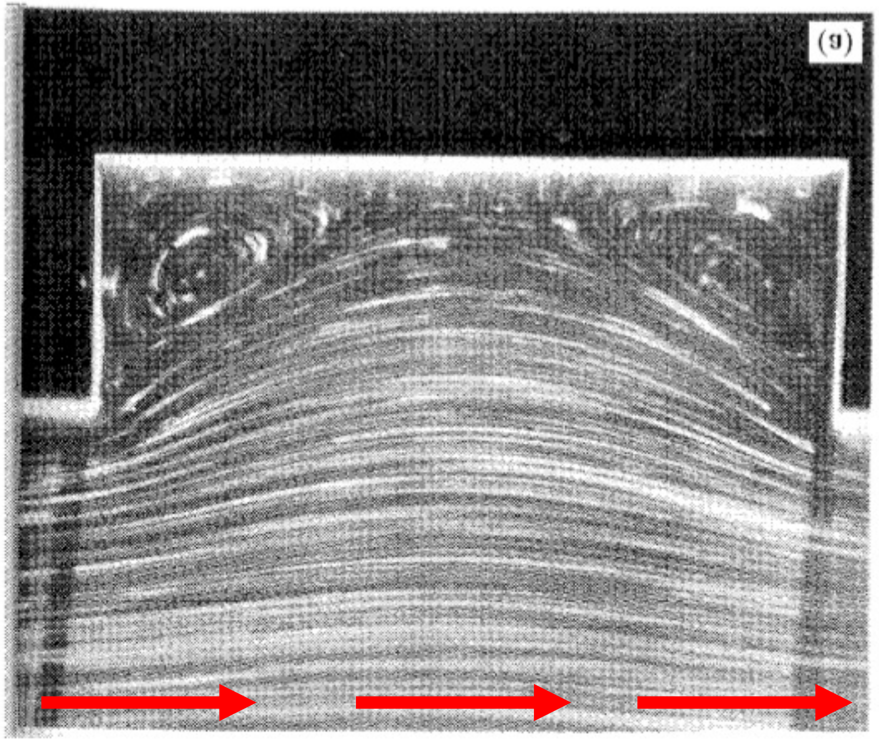
Shear-Driven Cavity Flow

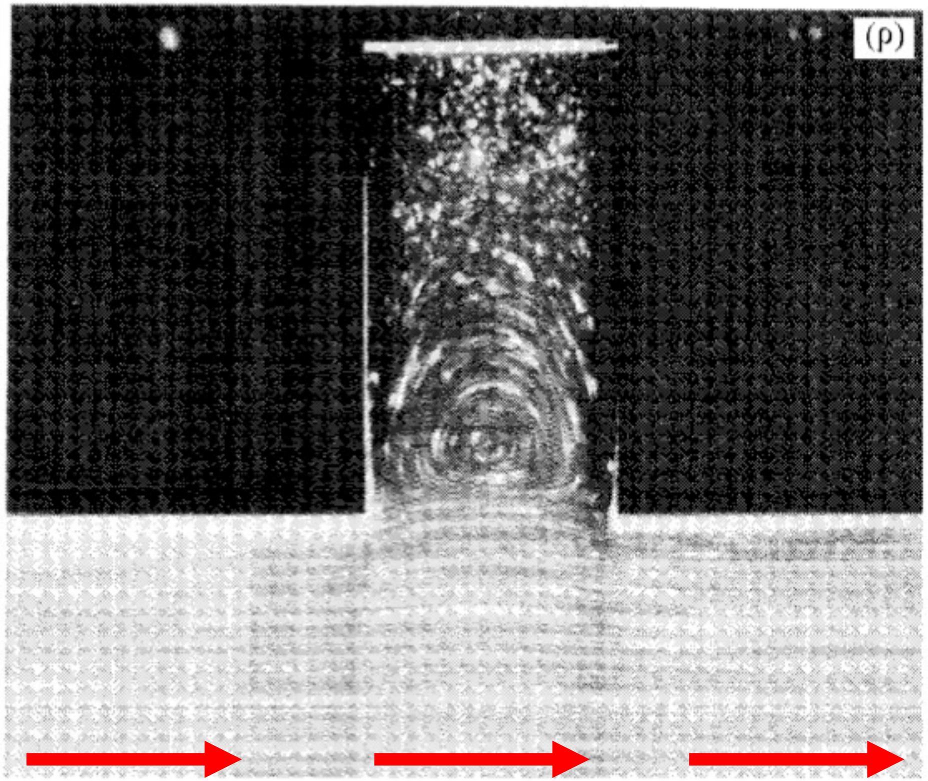
A classic engineering problem

Industrial Applications:

- Spin Coating
- Mixing Processes
- Liquid cooling by melt spinning
- Benchmark for computational schemes

Shear-Driven Cavity Flow

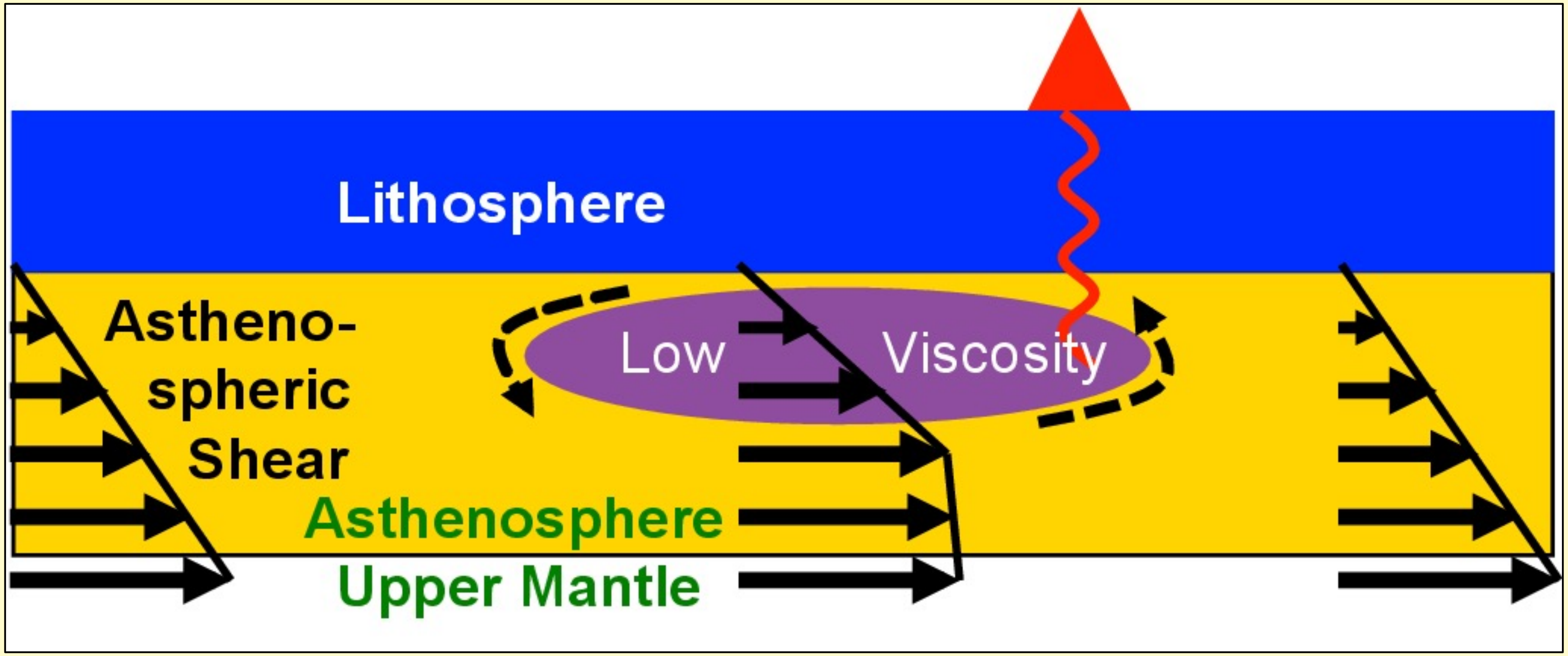




[*Taneda*,1979]

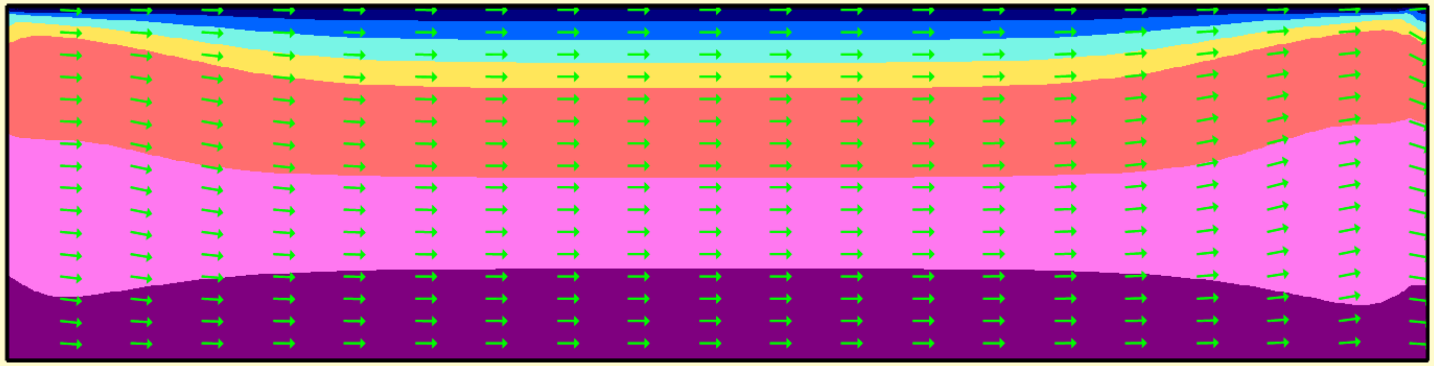
Shear-Driven Upwelling within an Low-Viscosity Pocket

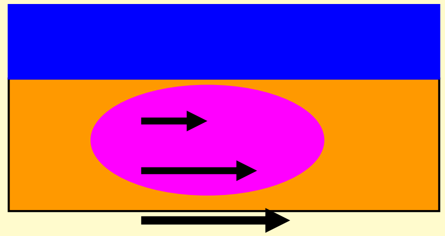
- A previously unstudied variation of shear-driven cavity flow: Flow within a low-viscosity "pocket"



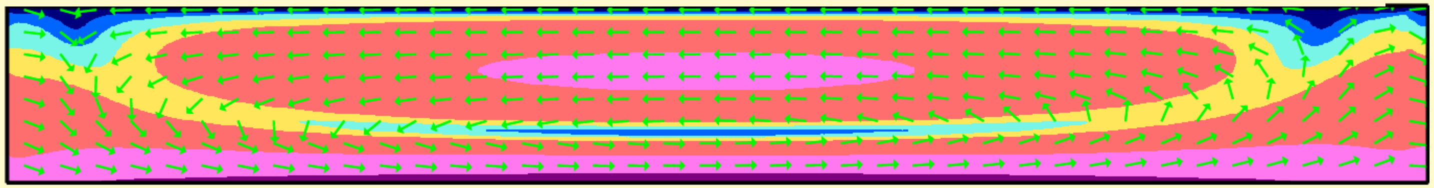
Flow patterns within a low-viscosity "pocket"

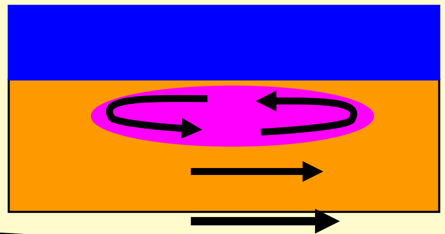
A) Thick pocket: Shear develops within the pocket



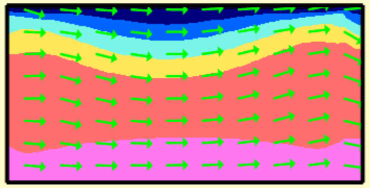


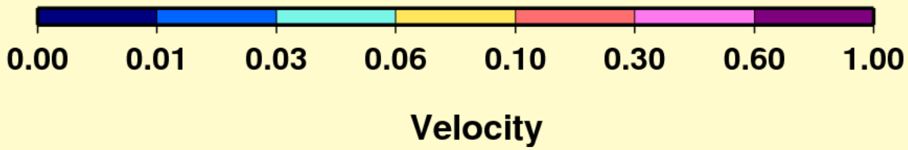
B) Shallow & wide pocket: Circulation within the pocket

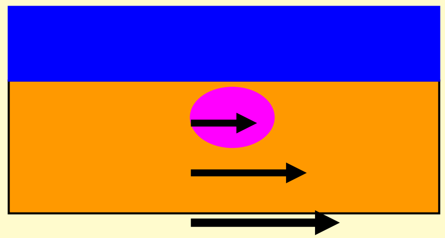




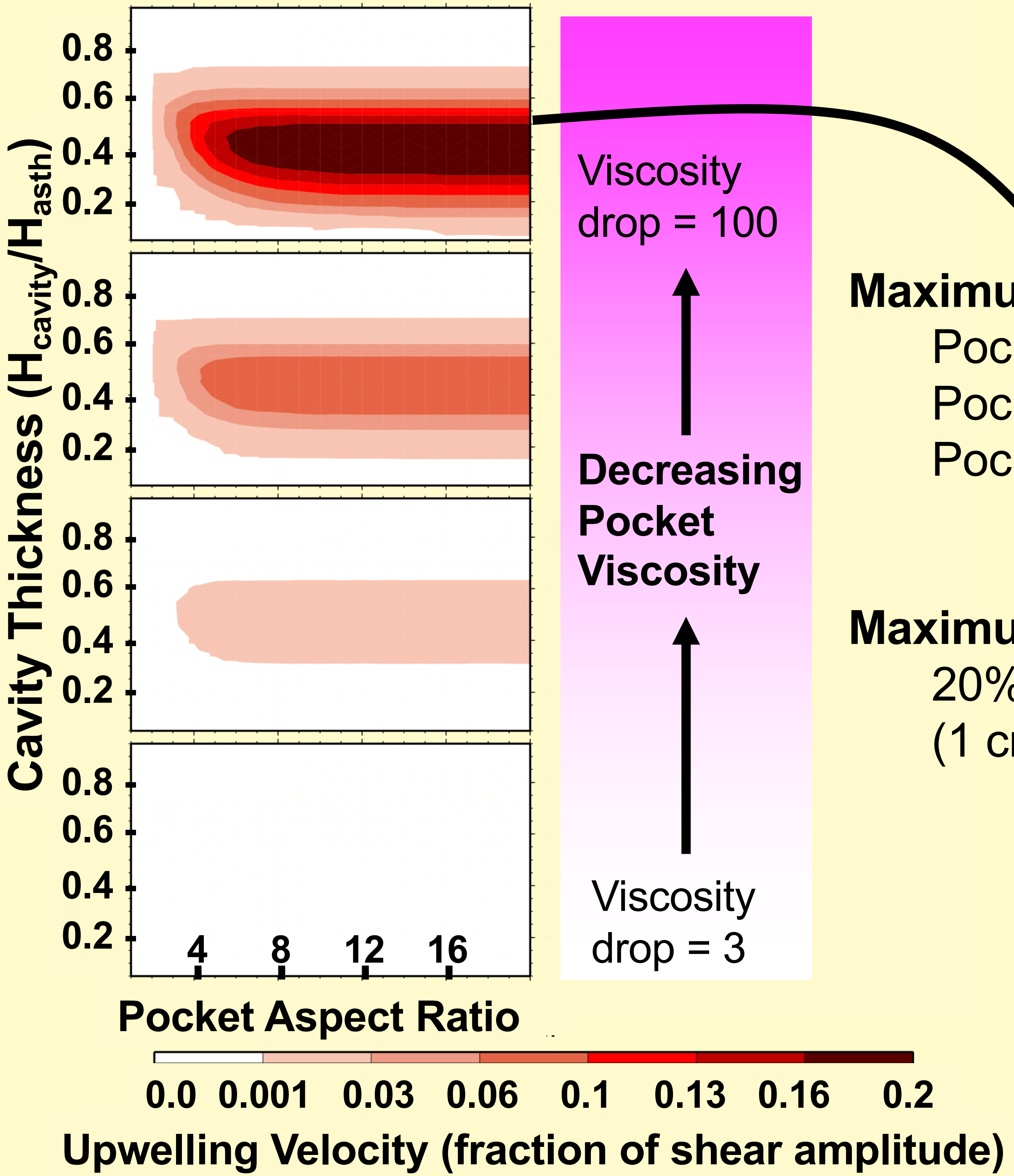
C) Shallow & narrow pocket: Pocket rides along with flow







Conrad et al. [PEPI, 2010]



Maximum upwelling occurs for:

Pocket viscosity drop of 100

Pocket aspect ratio > 5

Pocket occupies the upper 20-60% of asthenosphere

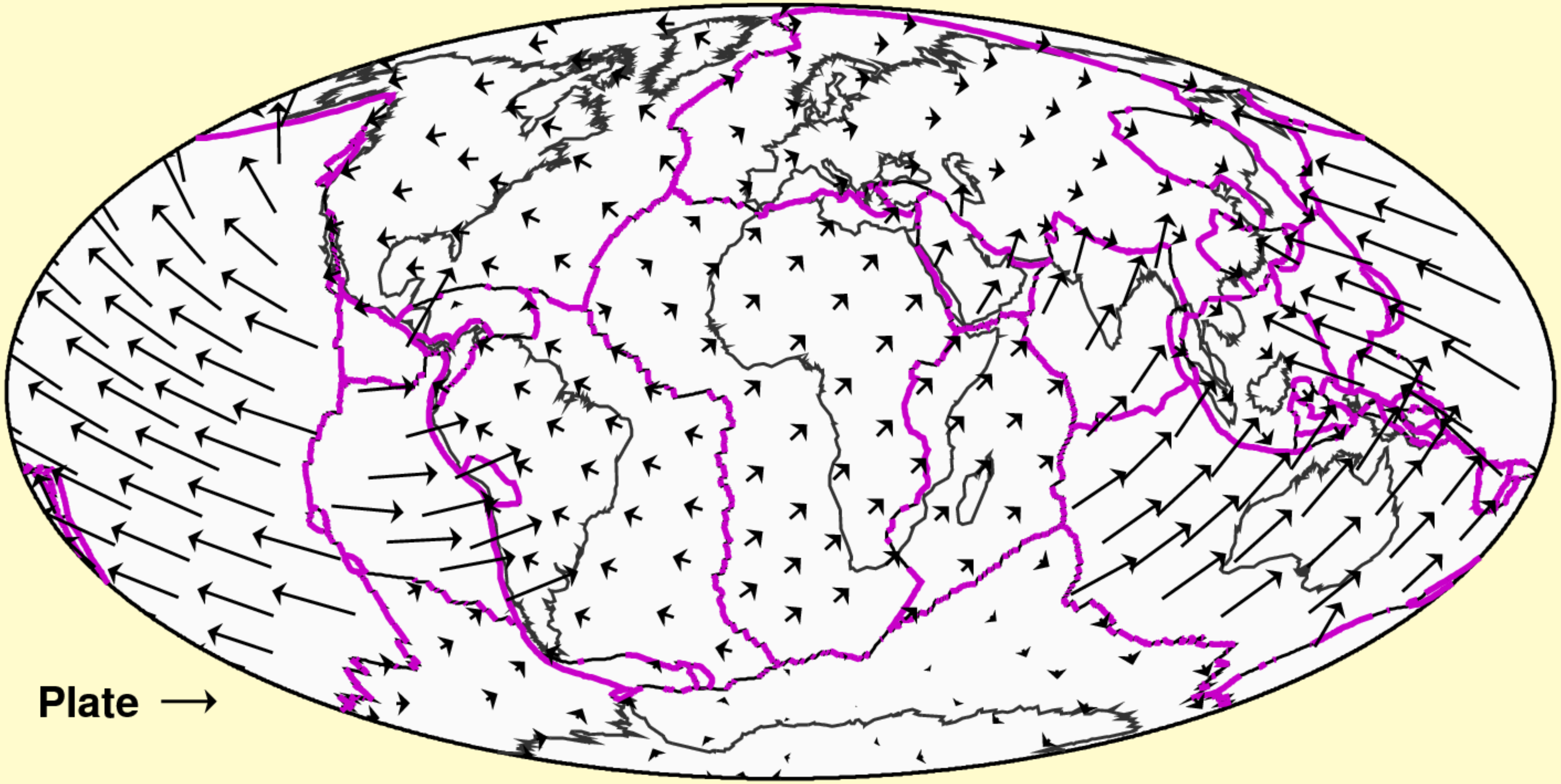
Maximum rate of upwelling:

20% of *V*

(1 cm/yr)

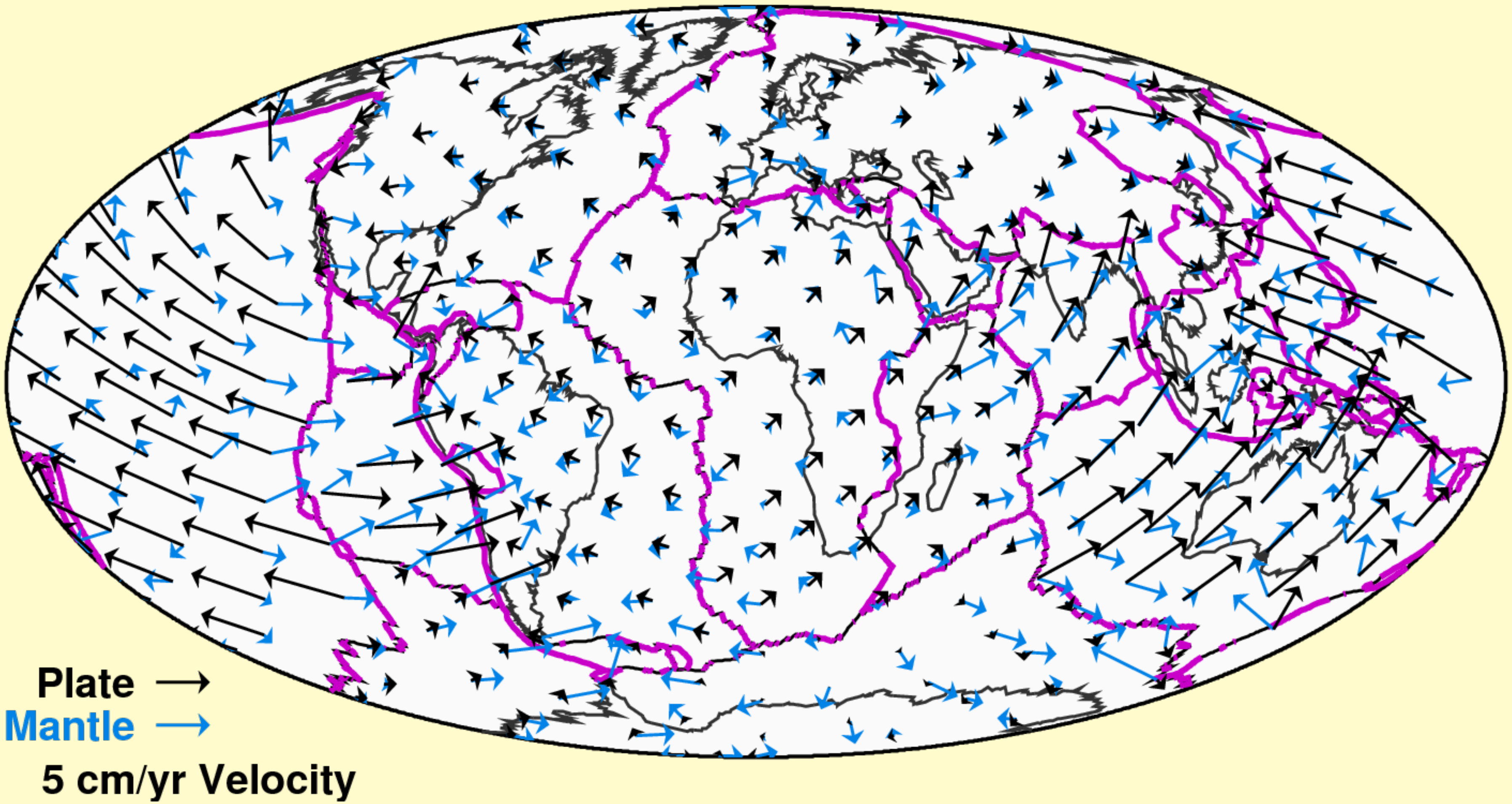
Conrad et al. [PEPI, 2010]

Where is asthenospheric shear largest?



Surface Plate Motions

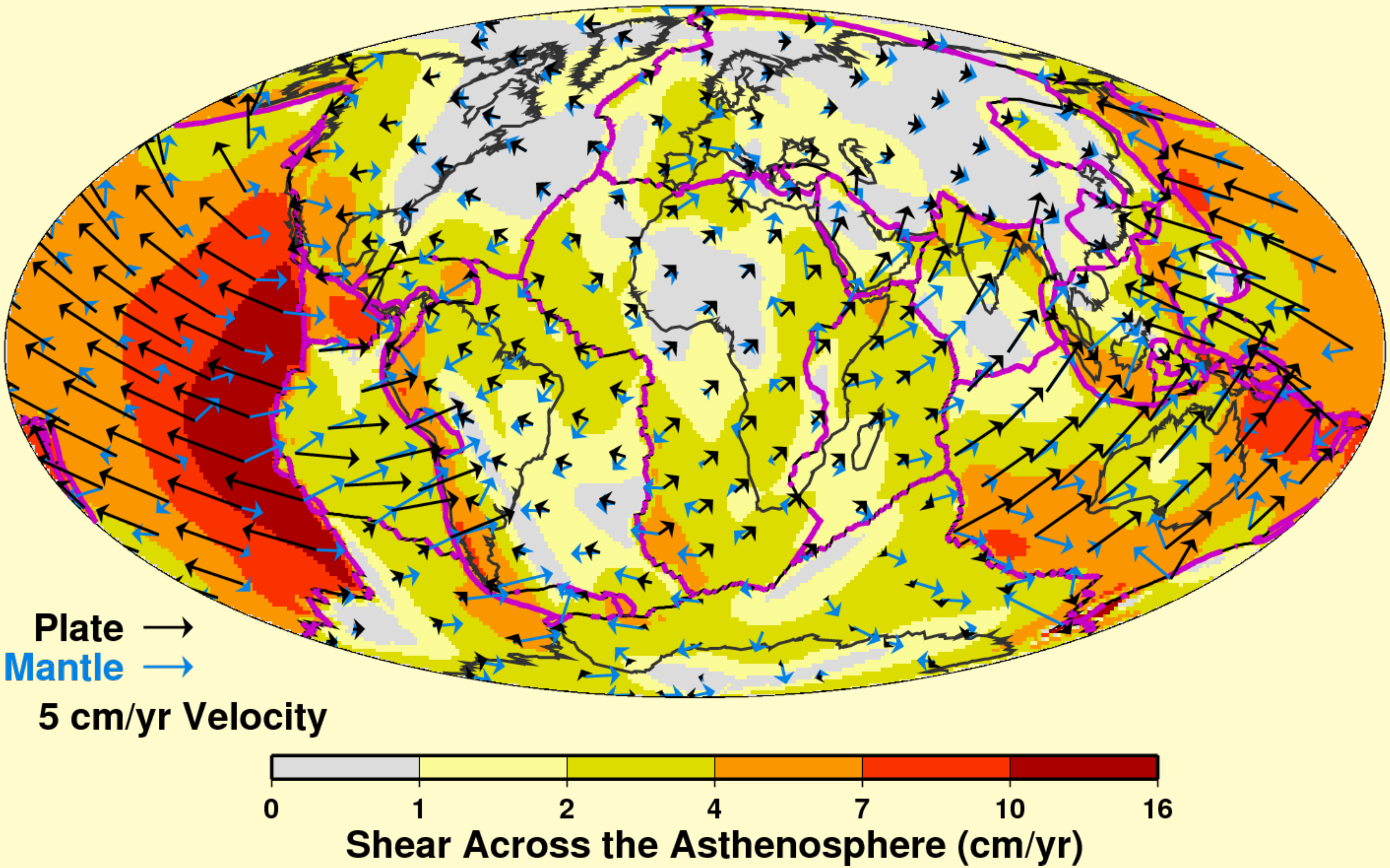
Where is asthenospheric shear largest?



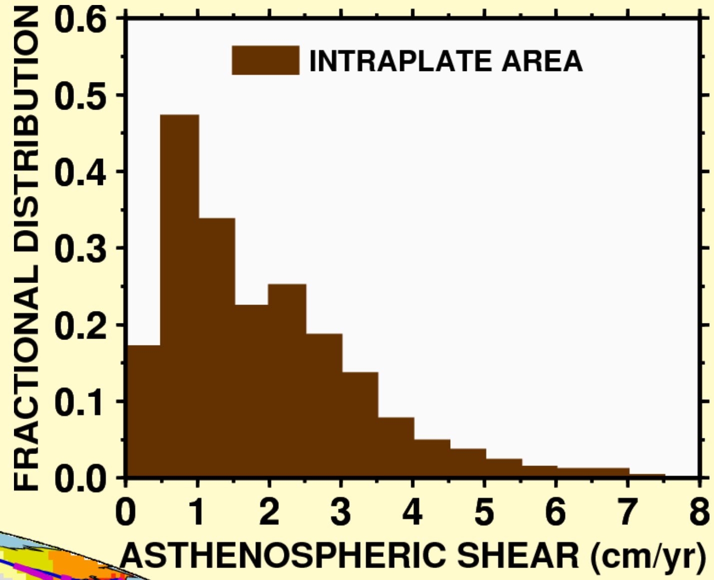
Surface Plate Motions and Mantle Flow at 300 km

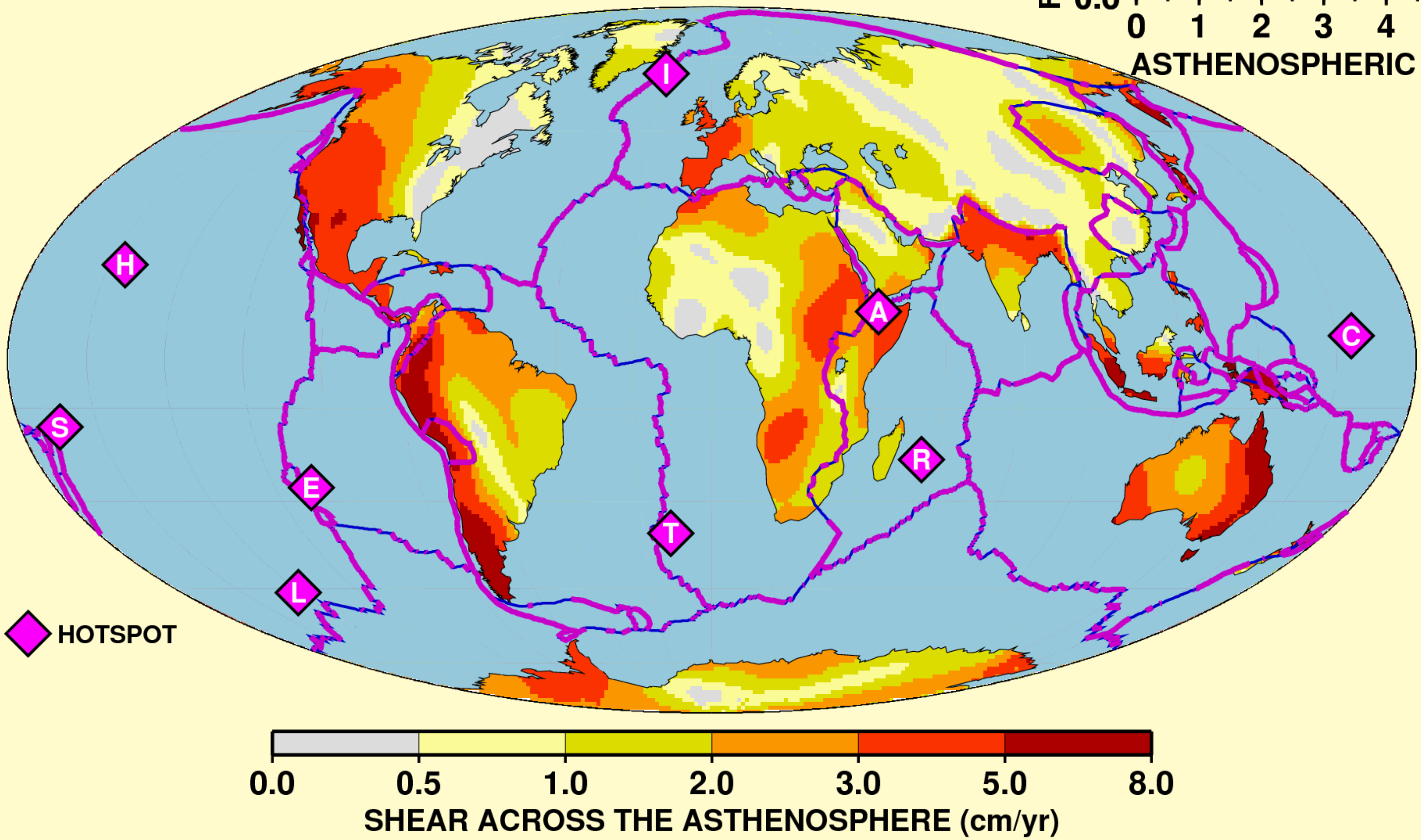
Mantle flow field from *Conrad and Behn* [2010]

Where is asthenospheric shear largest?

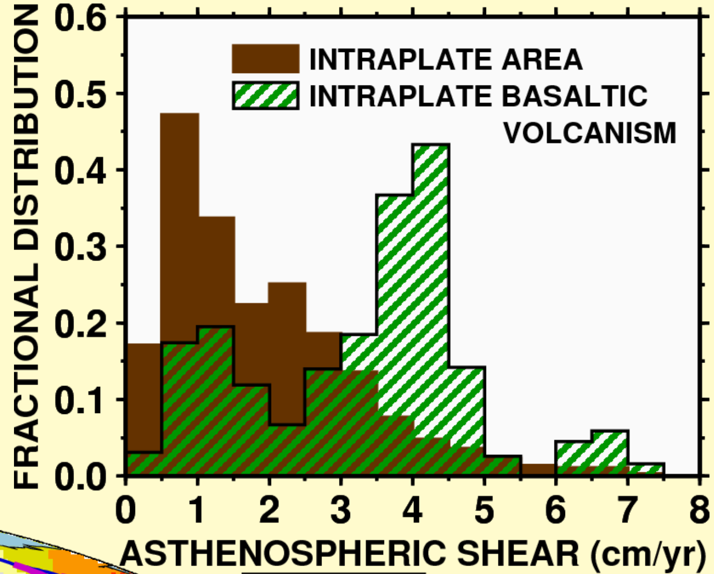


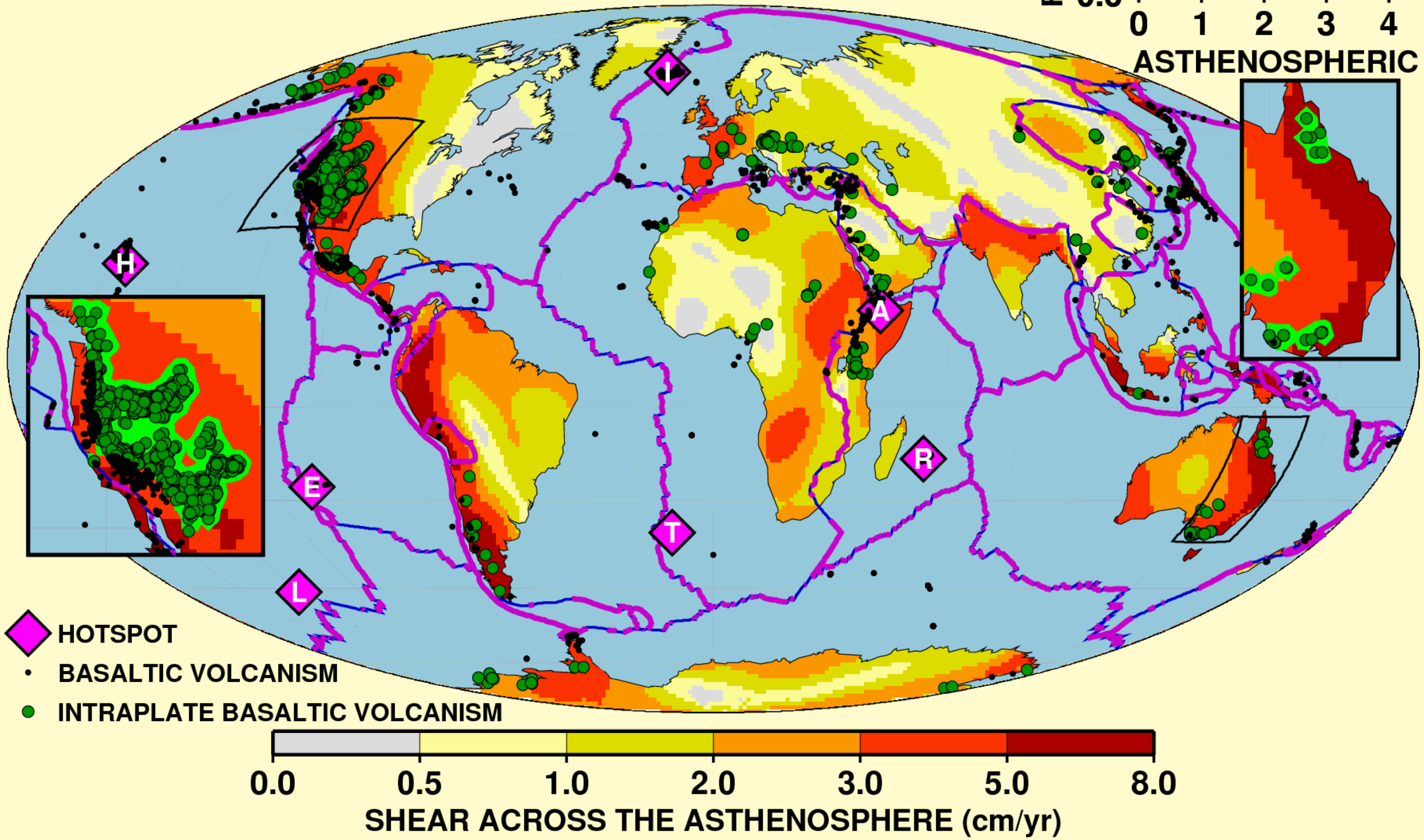
Asthenospheric Shear Beneath Continents



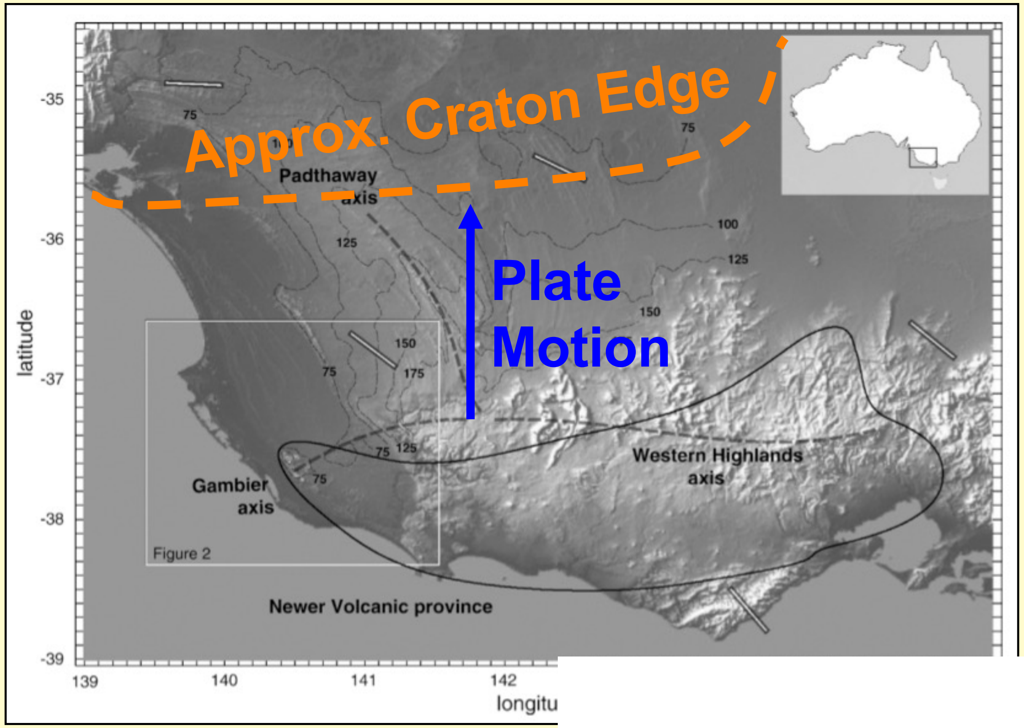


Asthenospheric Shear
and
Continental Volcanism



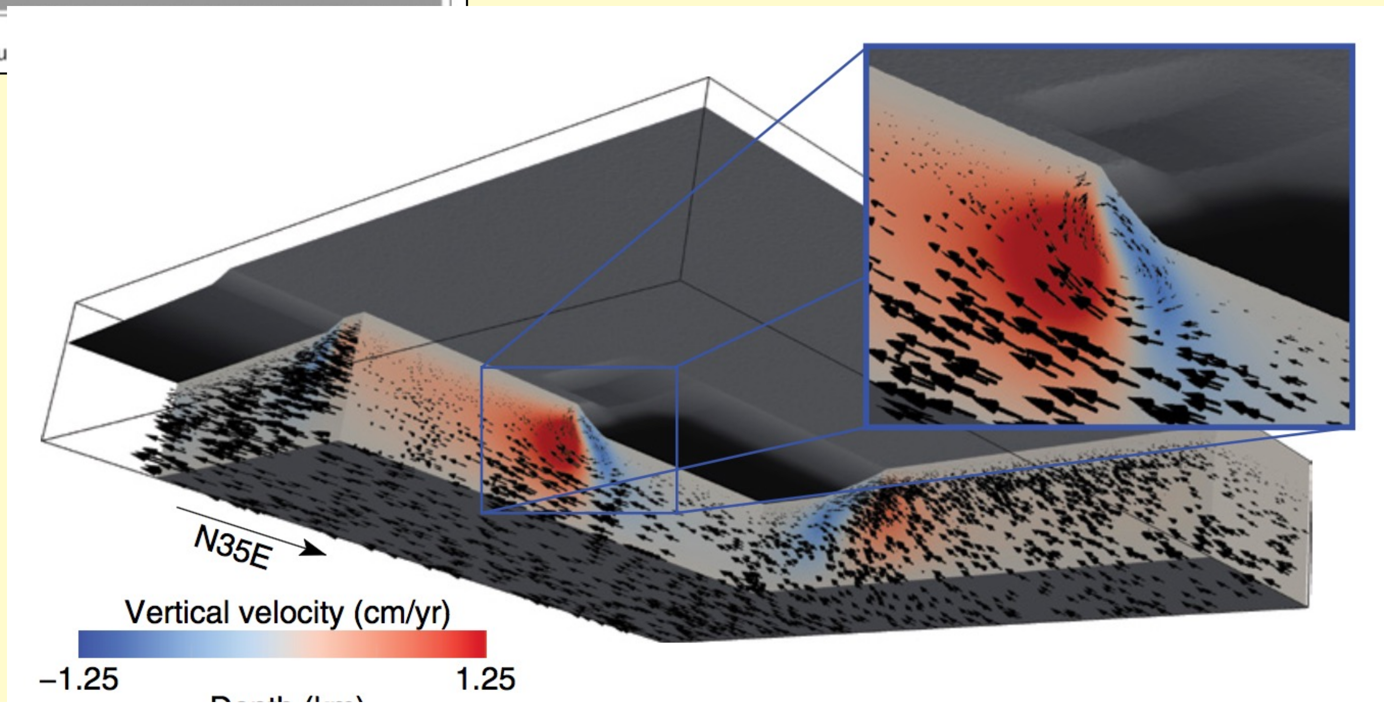


The Newer Volcanic Province (South Australia)



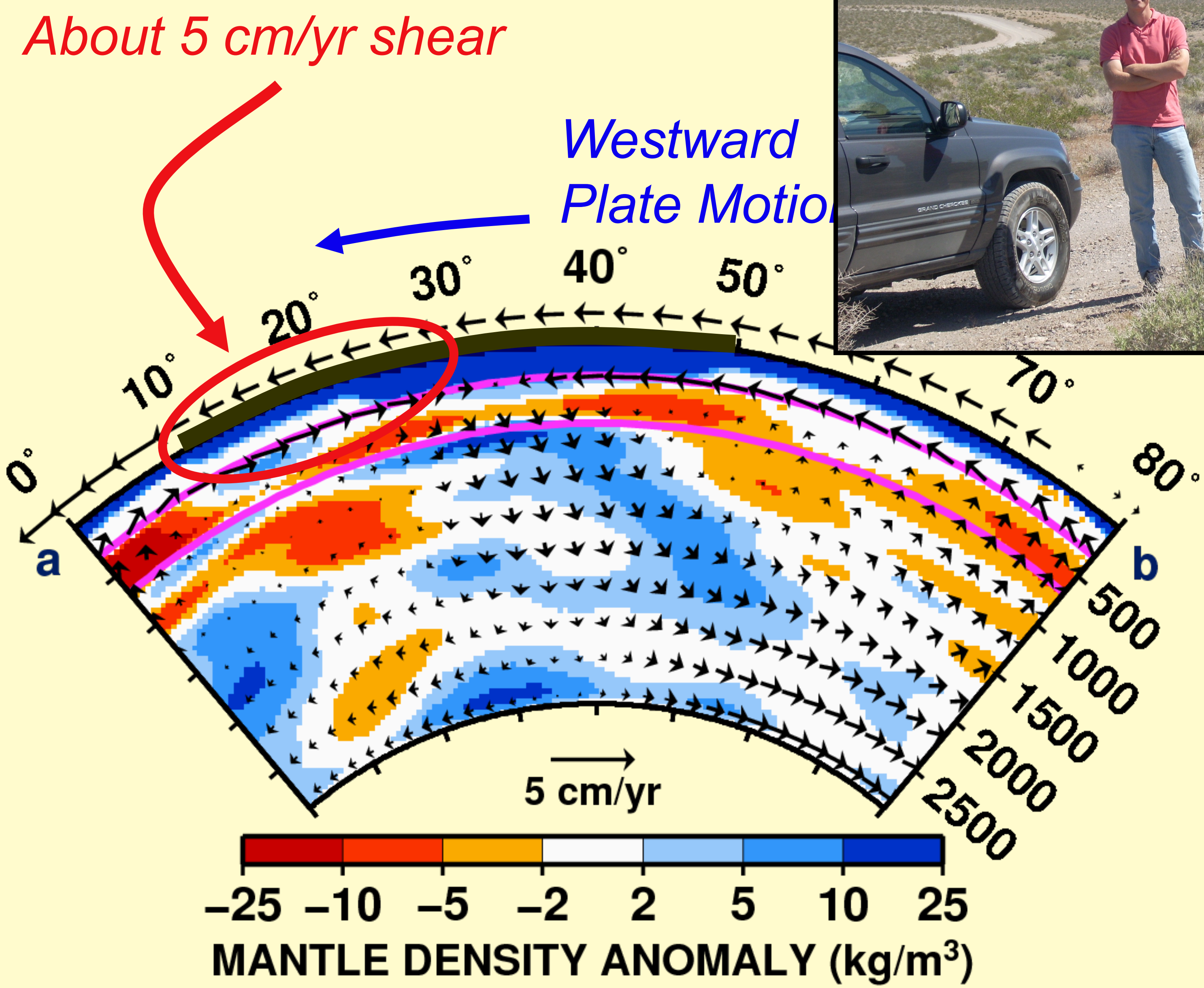
Mt. Gambier, Erupted 4500 yrs ago

SDU-like model →

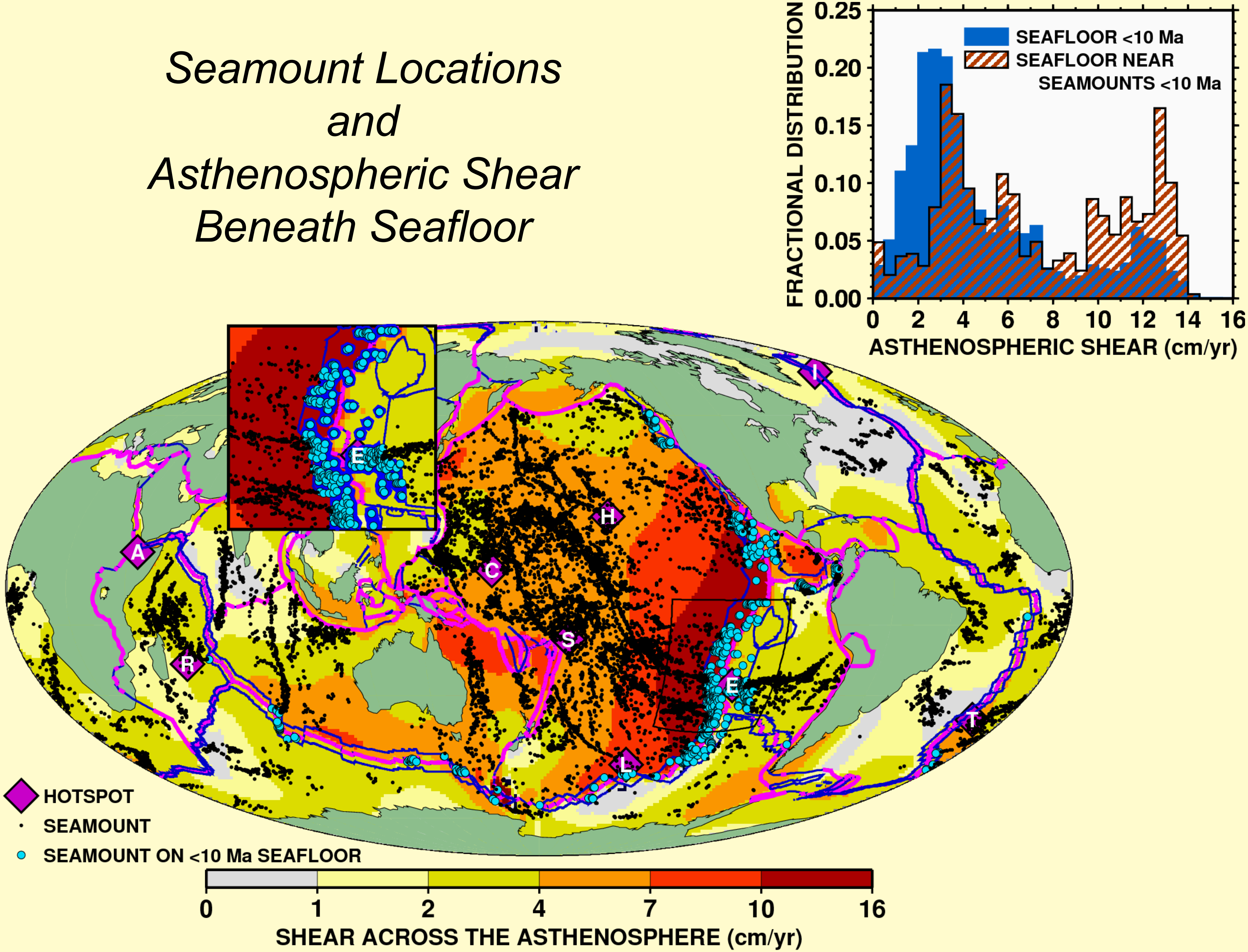


Davies & Rawlinson [2014]

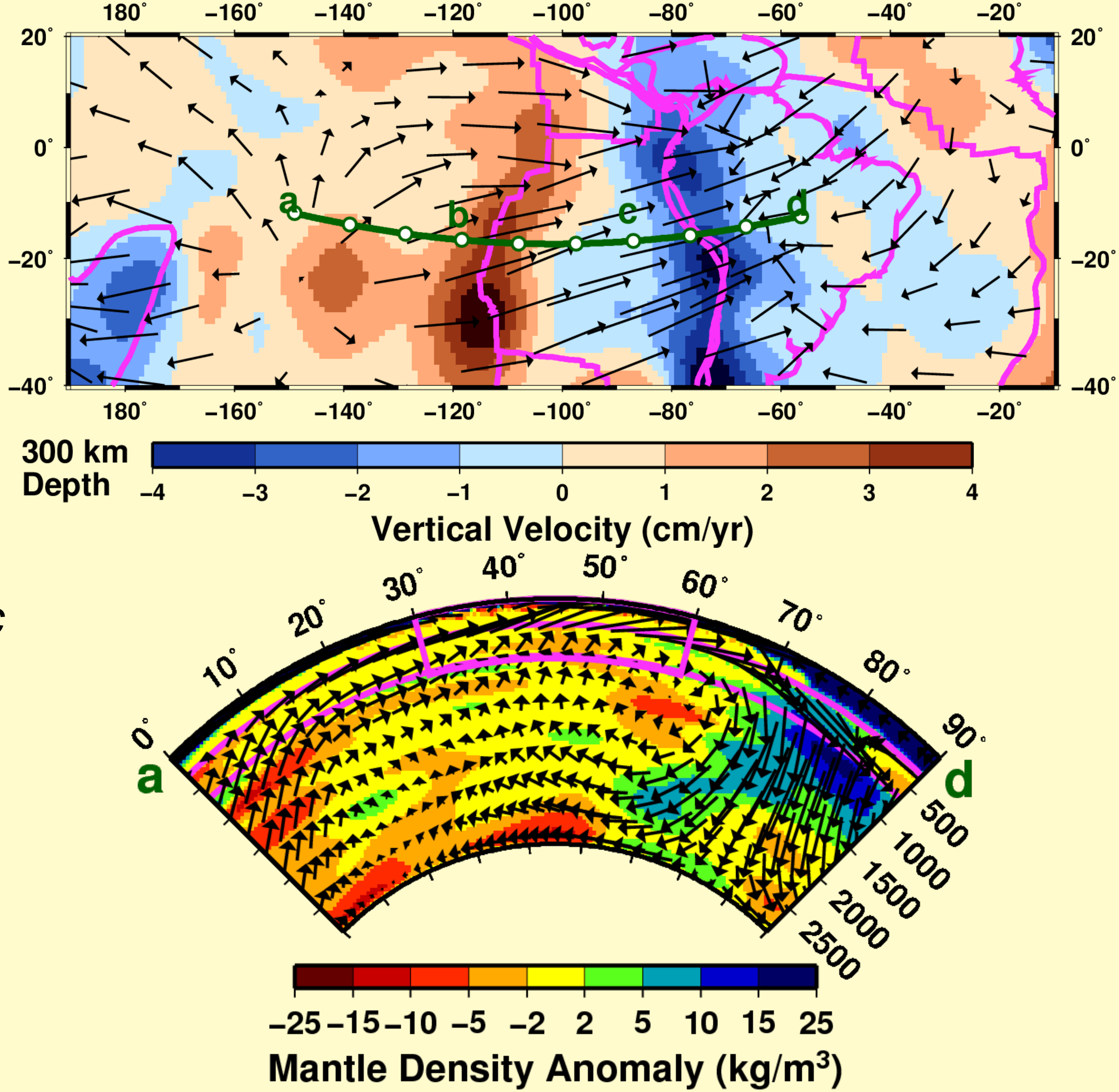
Asthenospheric Shear beneath the Western US



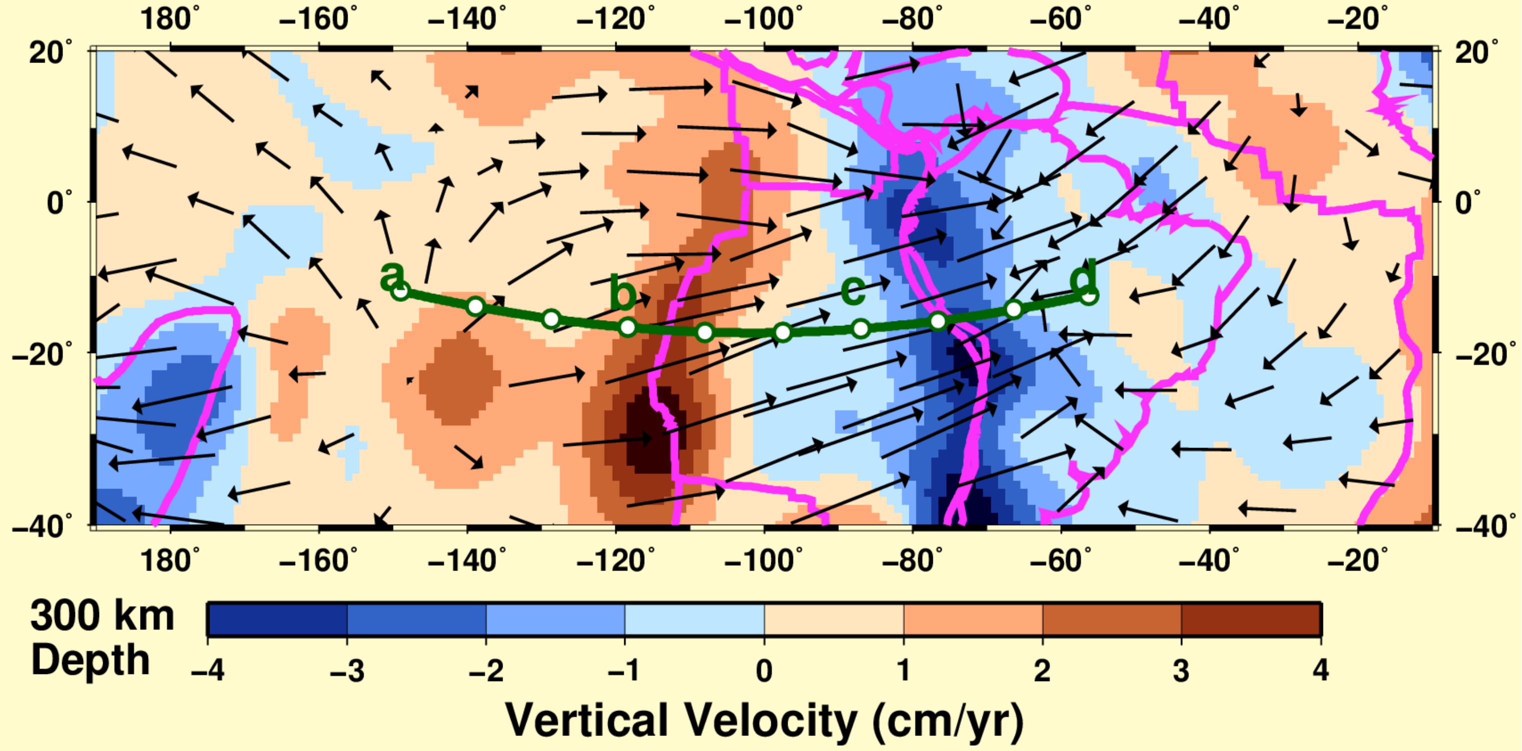
Seamount Locations and Asthenospheric Shear Beneath Seafloor

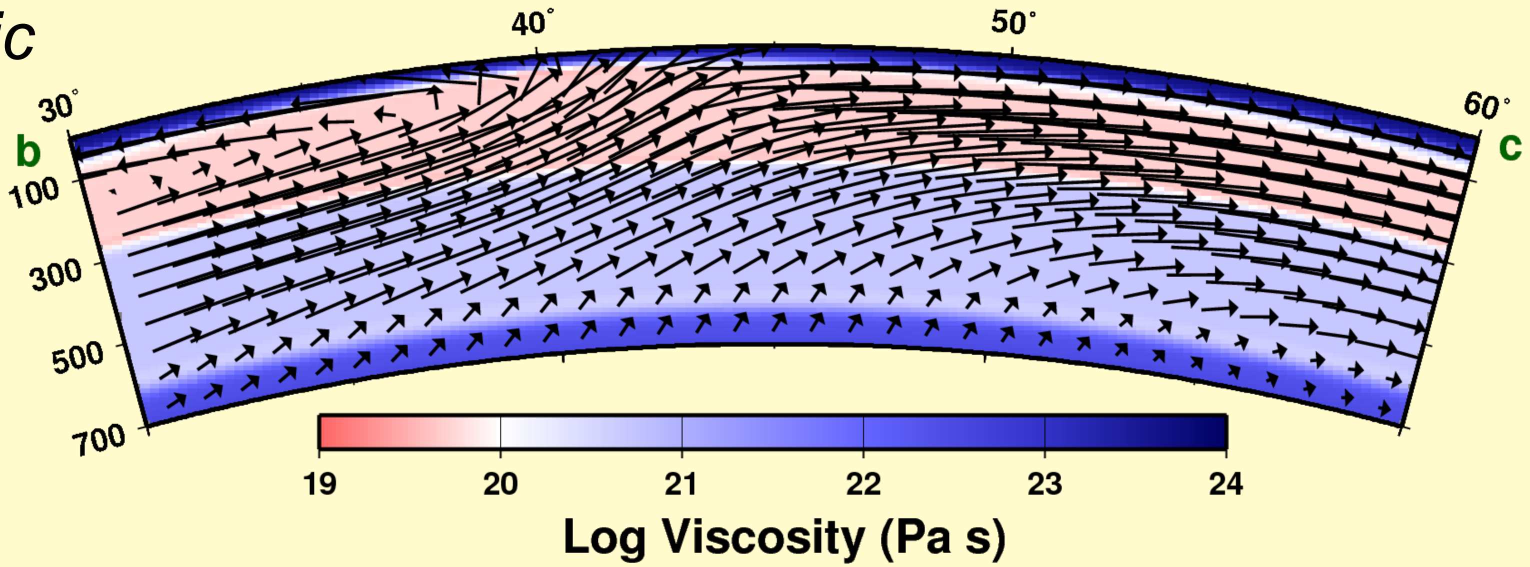


Mantle Flow beneath the South Pacific

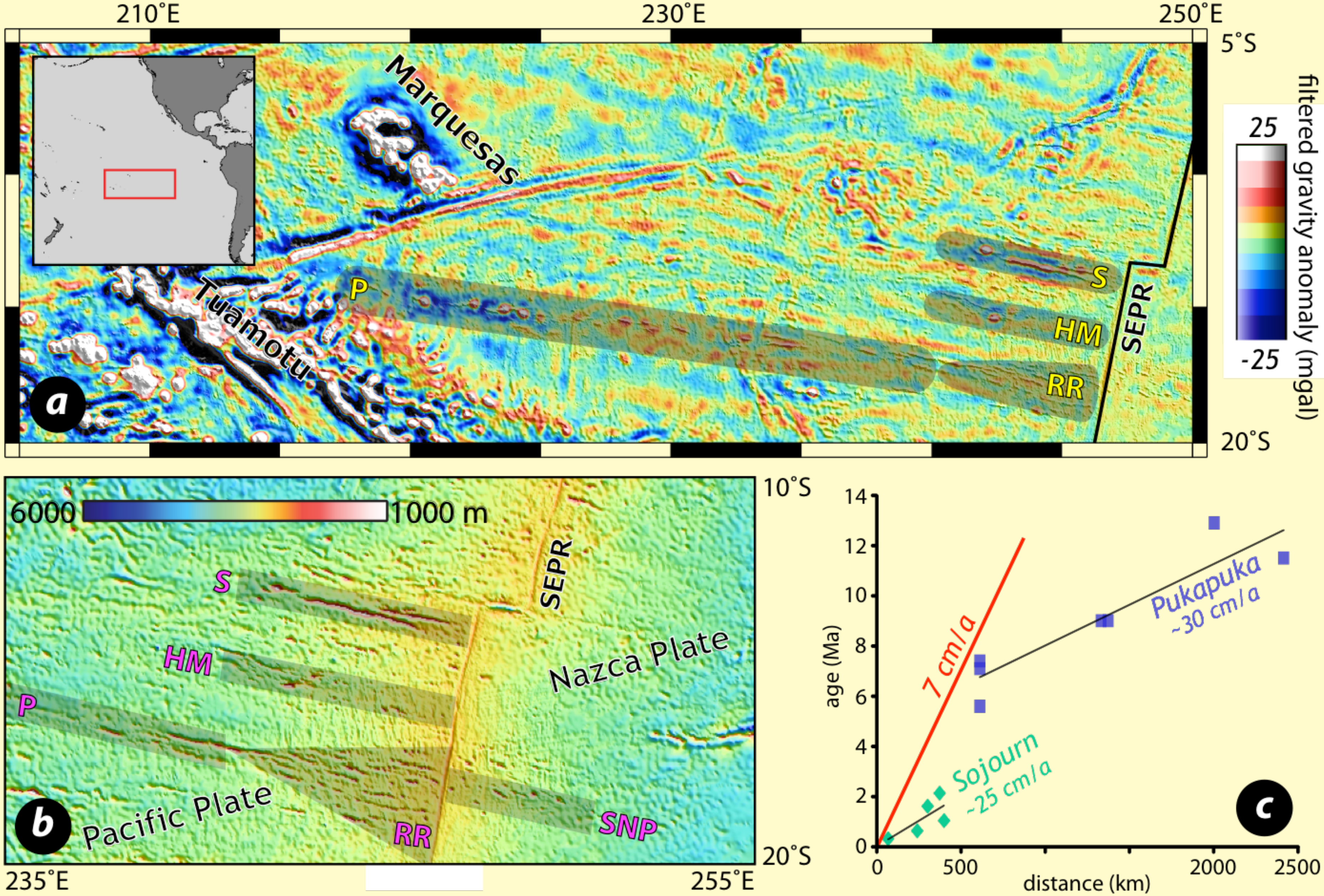


Mantle Flow beneath the South Pacific





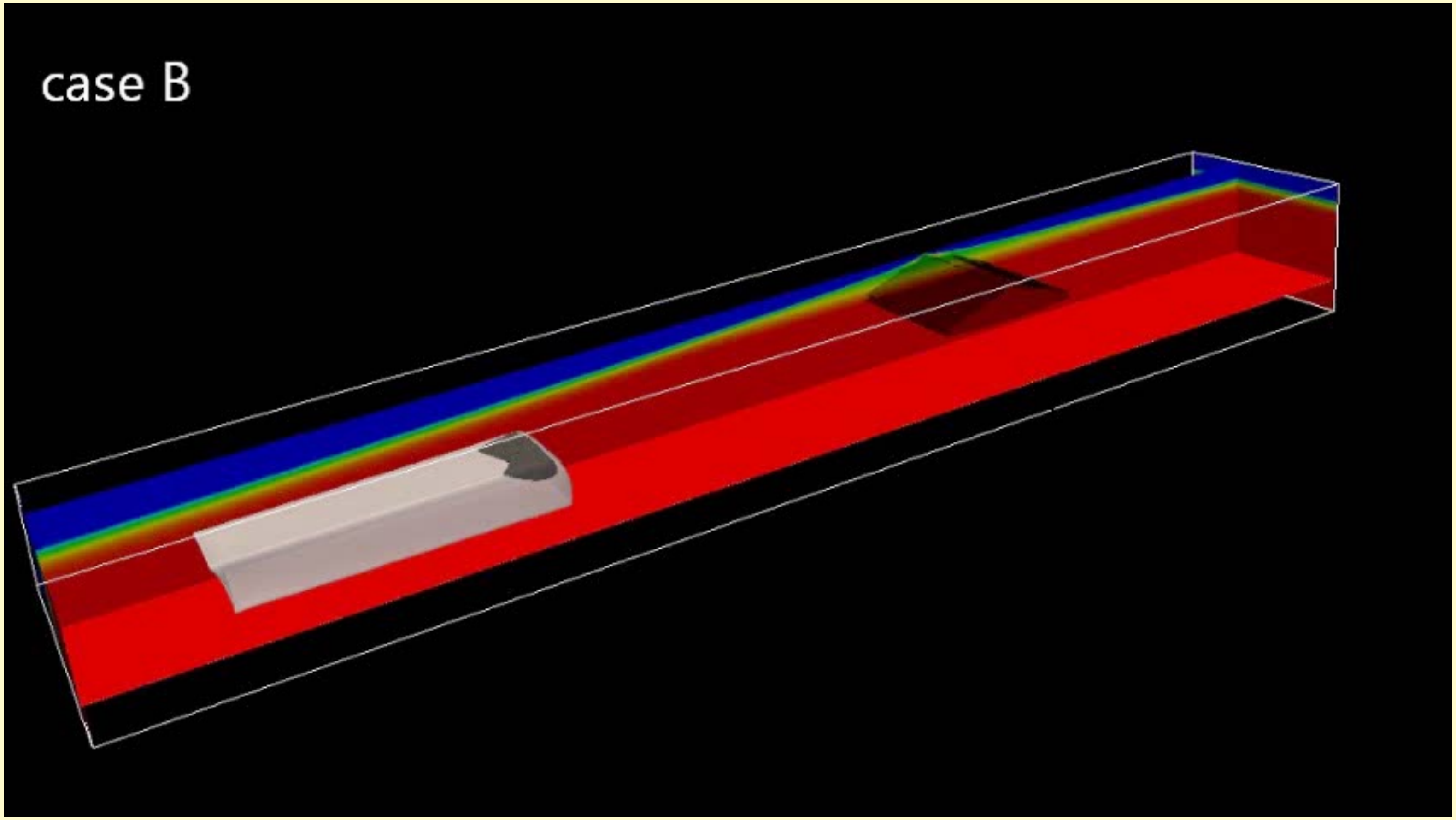
Volcano chains in the South Pacific



S = Sojourn
HM = Hoto-Matua
RR = Rano Rahi
P = Pukapuka
SNP = Seamounts on Nazca Plate

Ballmer et al. [*Geology*, 2013]

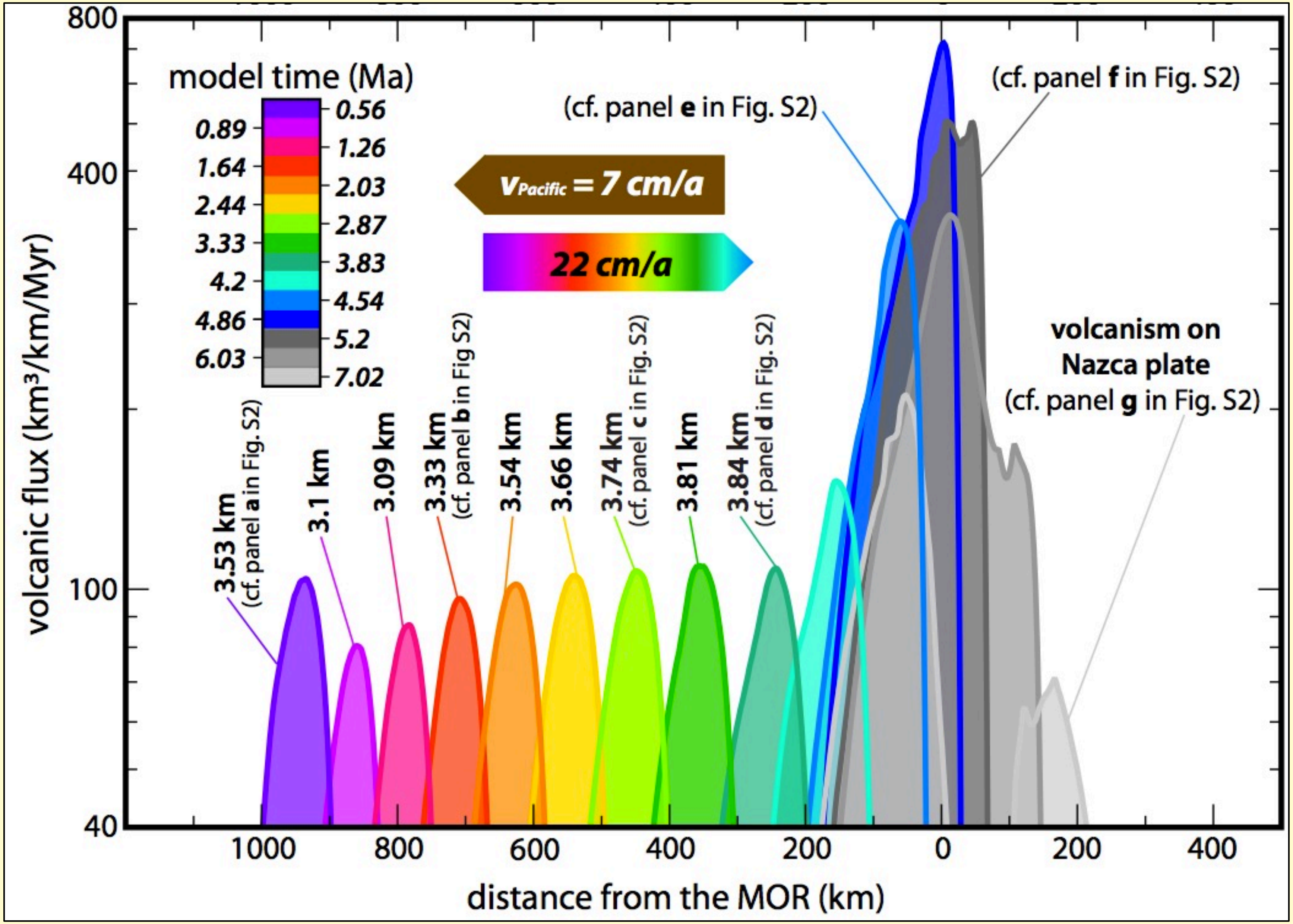
Hot and Wet Anomaly being pushed toward the East Pacific Rise



Like a “sideways” plume

Ballmer et al. [2013]

Case B: Hot and Wet Anomaly (Pukapuka)

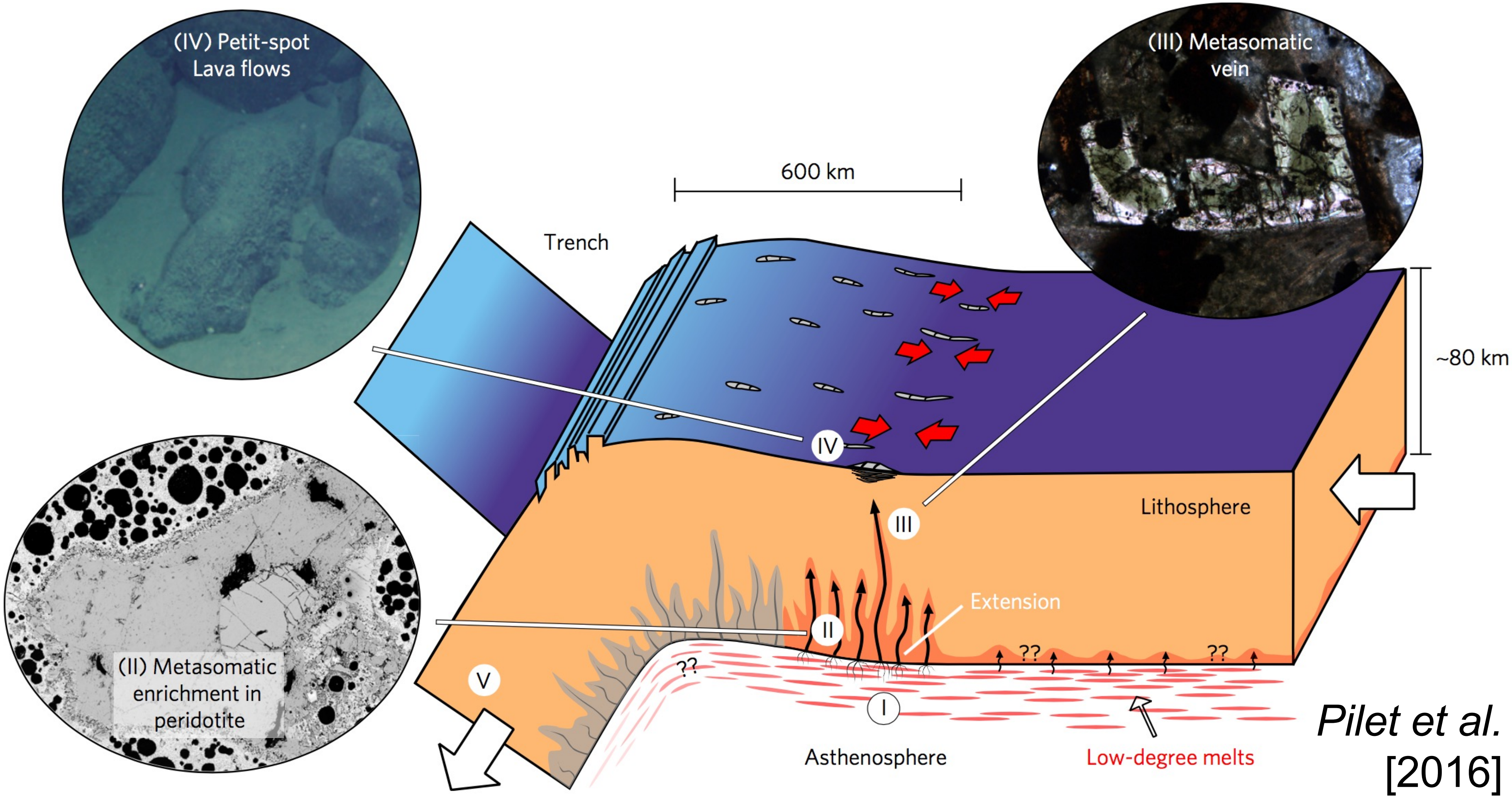


Ballmer et al. [Geology, 2013]

4. Petit Spots

- Very minor volcanism
- Happens near trenches
- Due to plate flexure

Implies that low-degree melt is prevalent in the upper asthenosphere



Pilet et al. [2016]

4. Petit Spots

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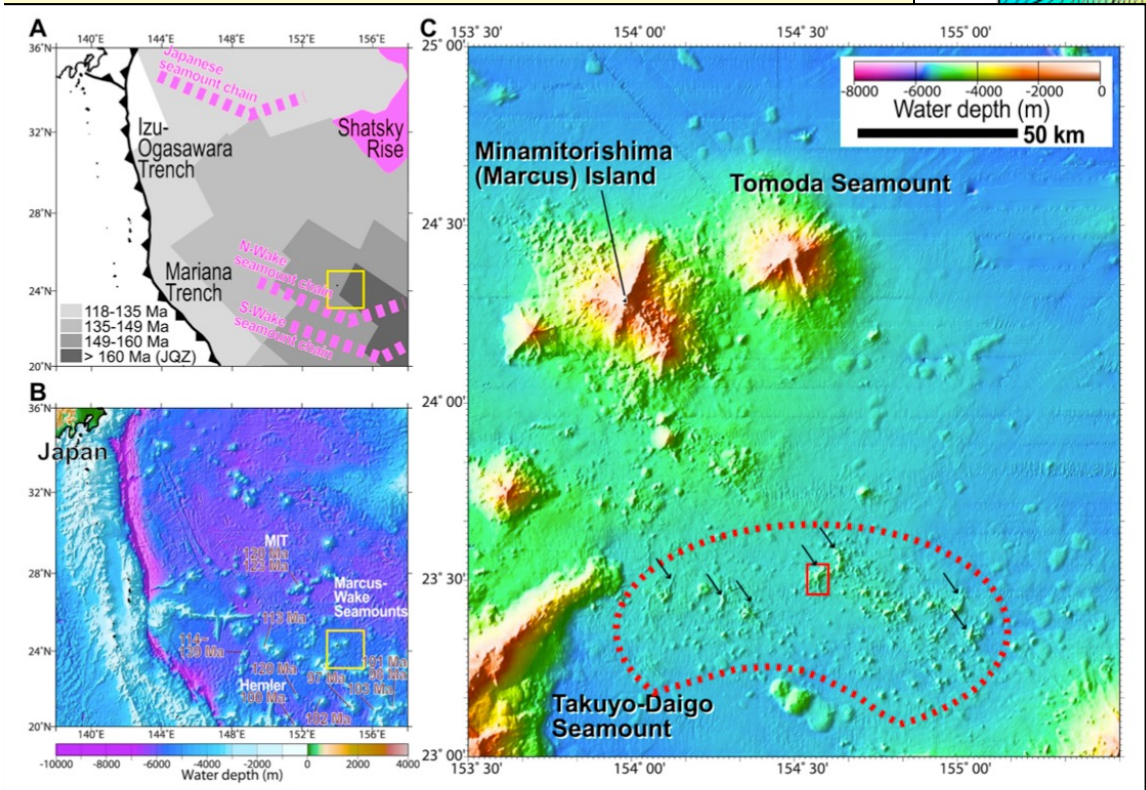
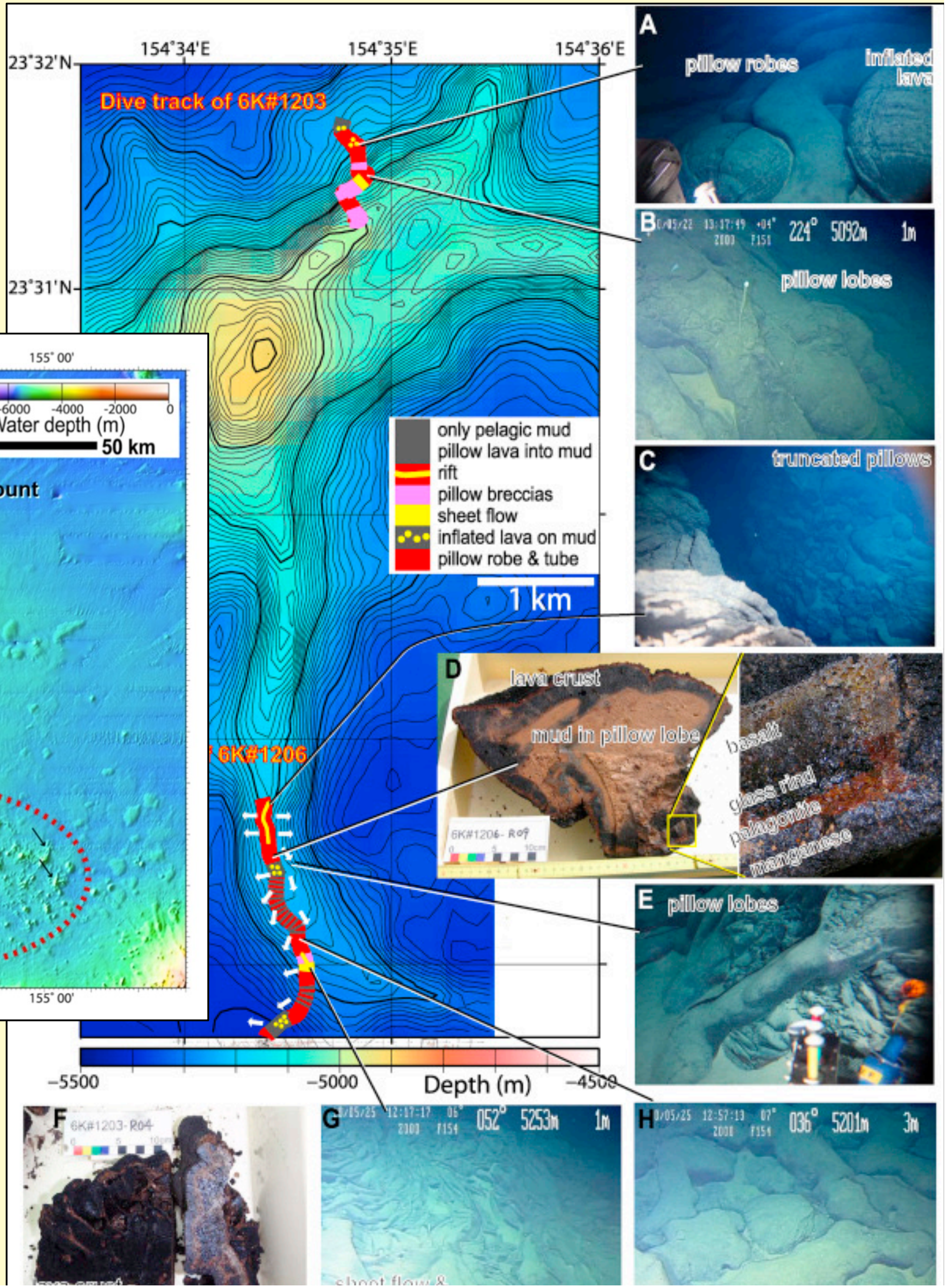
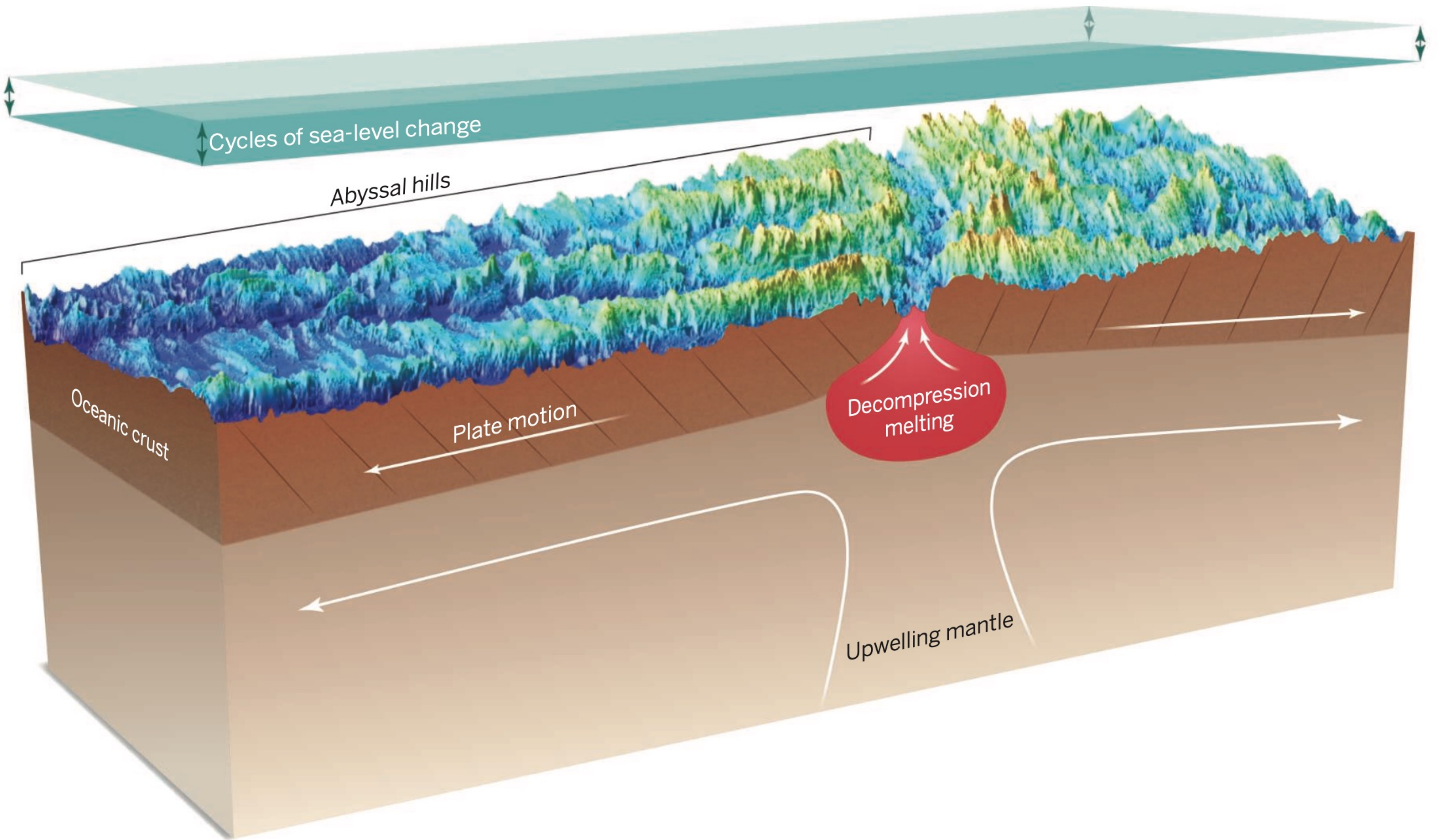




Hirano et al. [2019]

Surface Loading Affects on Volcanism



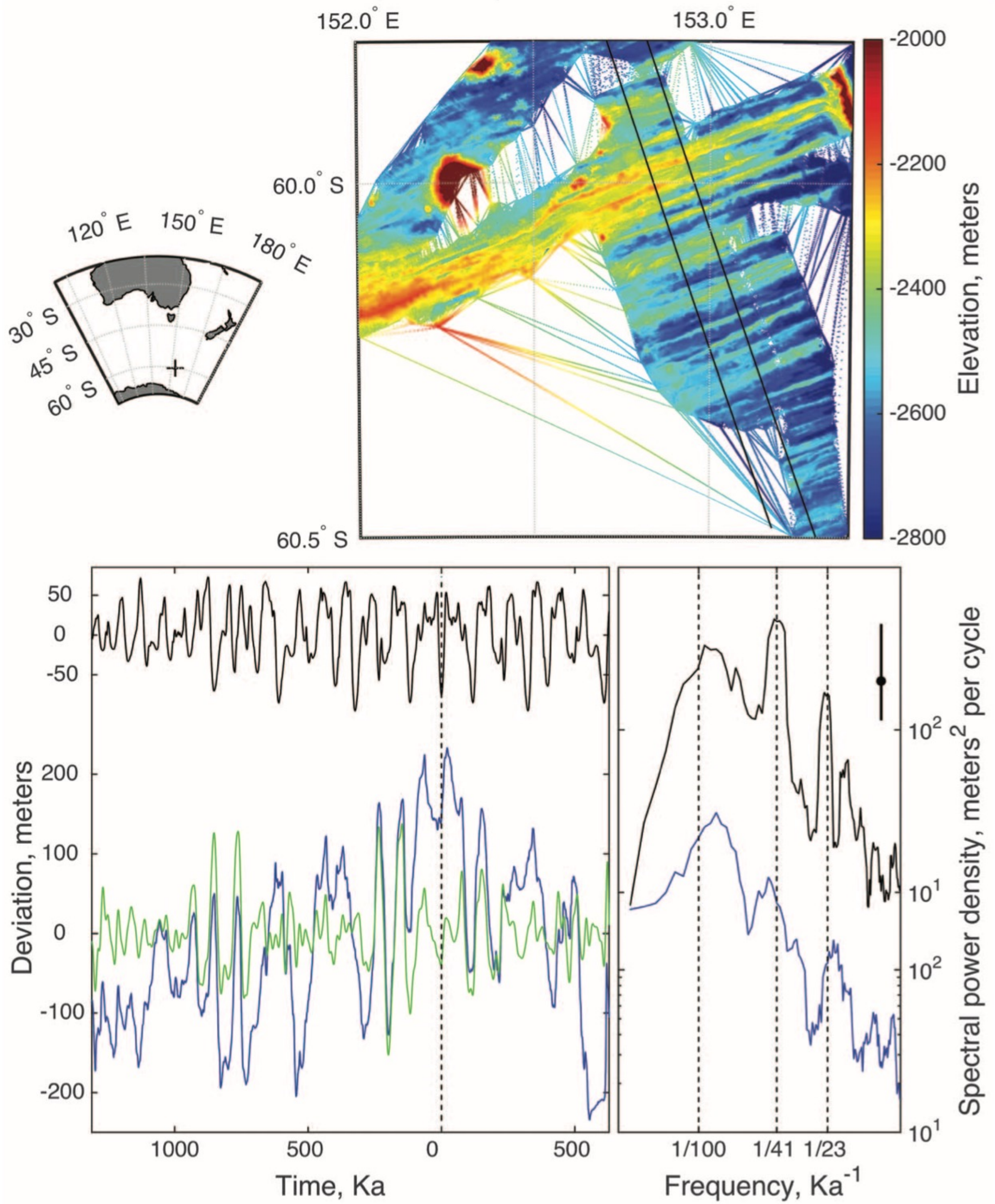
Conrad [2015]

Are the abyssal hills caused by sea level changes?

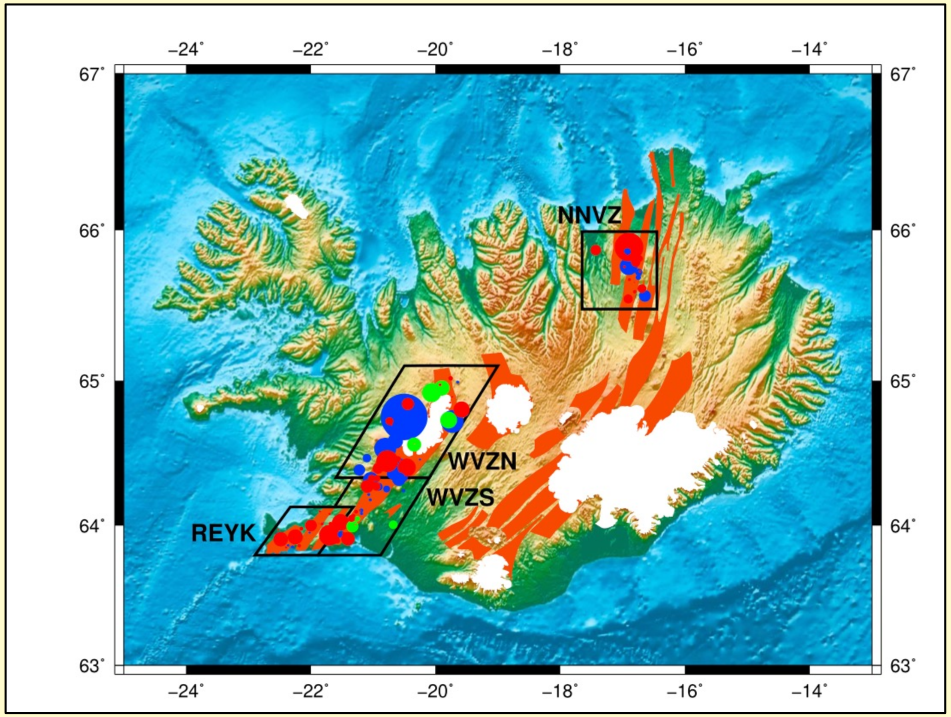
Valleys → rising sea level

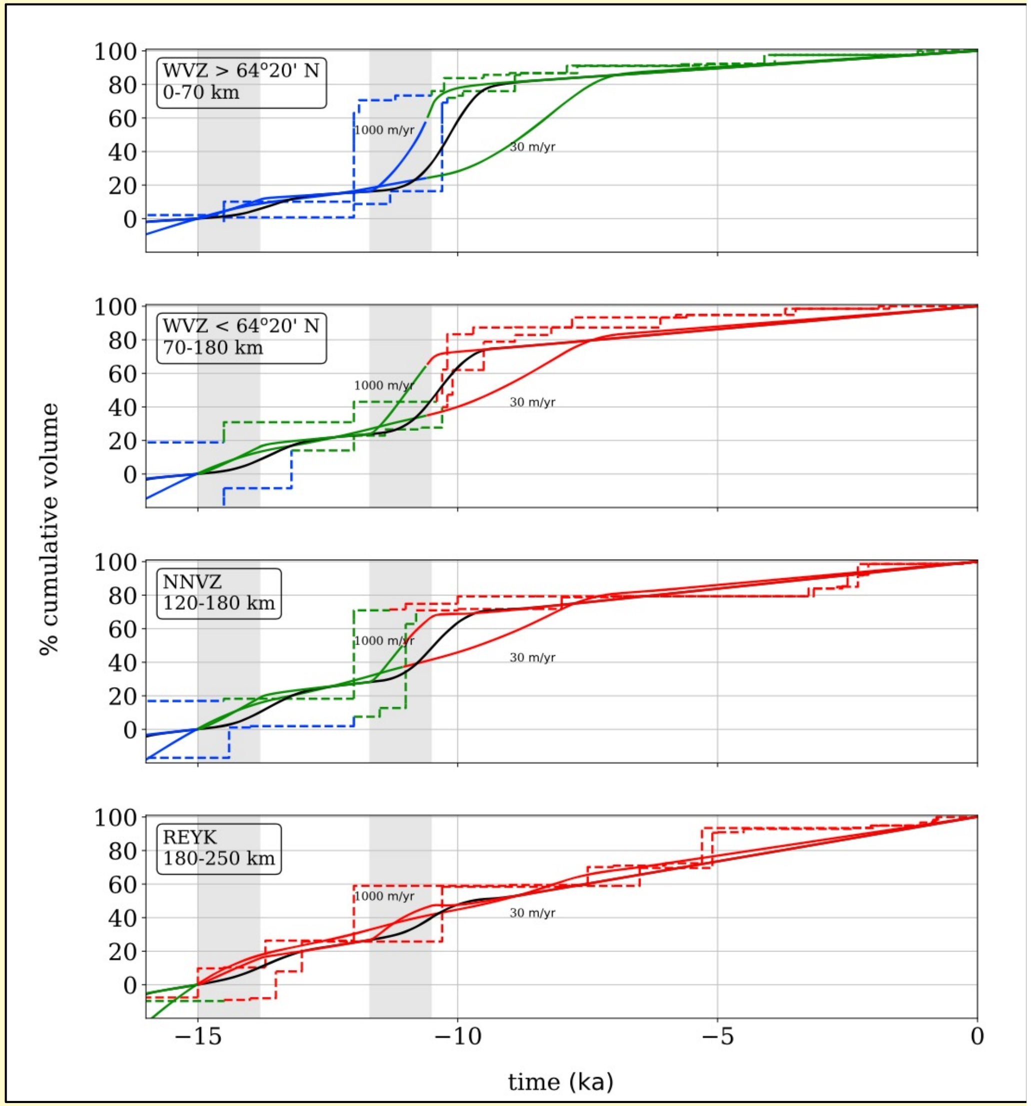
Hills → falling sea level

Crowley et al. [2015]



Amplification of Icelandic volcanism during deglaciation





Eksinchol et al. [2019]

Intraplate Volcanism in the Oceans

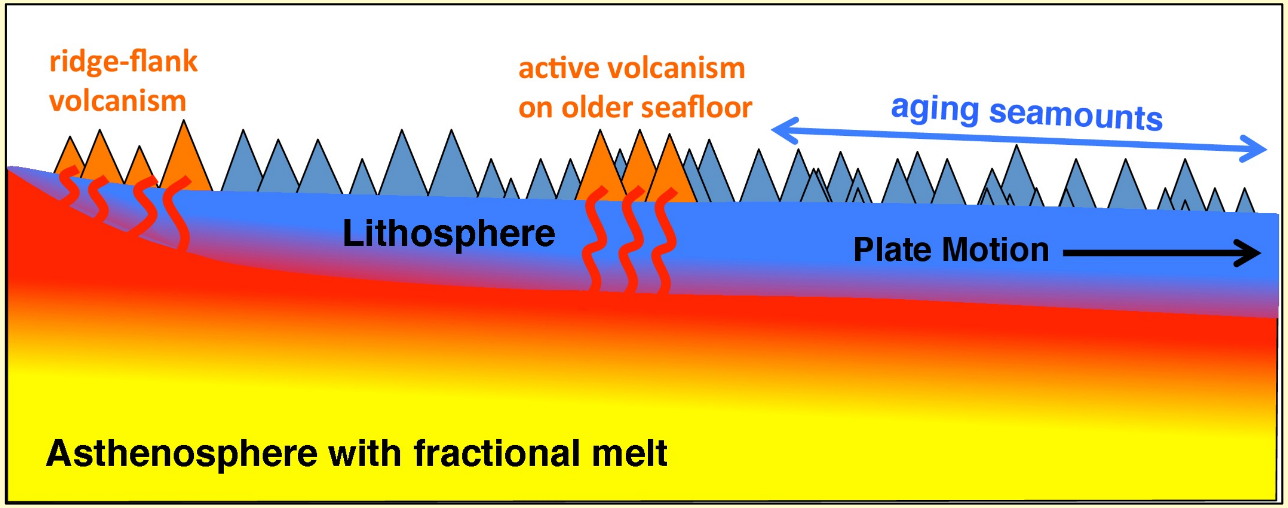
- More than 24,000 seamounts on the seafloor
- Many are still undiscovered
- We don't know ages for most of them

Melting can be caused by:

- **Plumes** rising from the LLSVP edges
- **Small-scale convection** on older lithosphere
- **Shear-driven upwelling** (especially in the Pacific)
- **Petit-spot volcanism** near trenches

Implications:

→ **The upper asthenosphere is close to melting or is already partially melted**



→ **Climate change can cause volcanism**