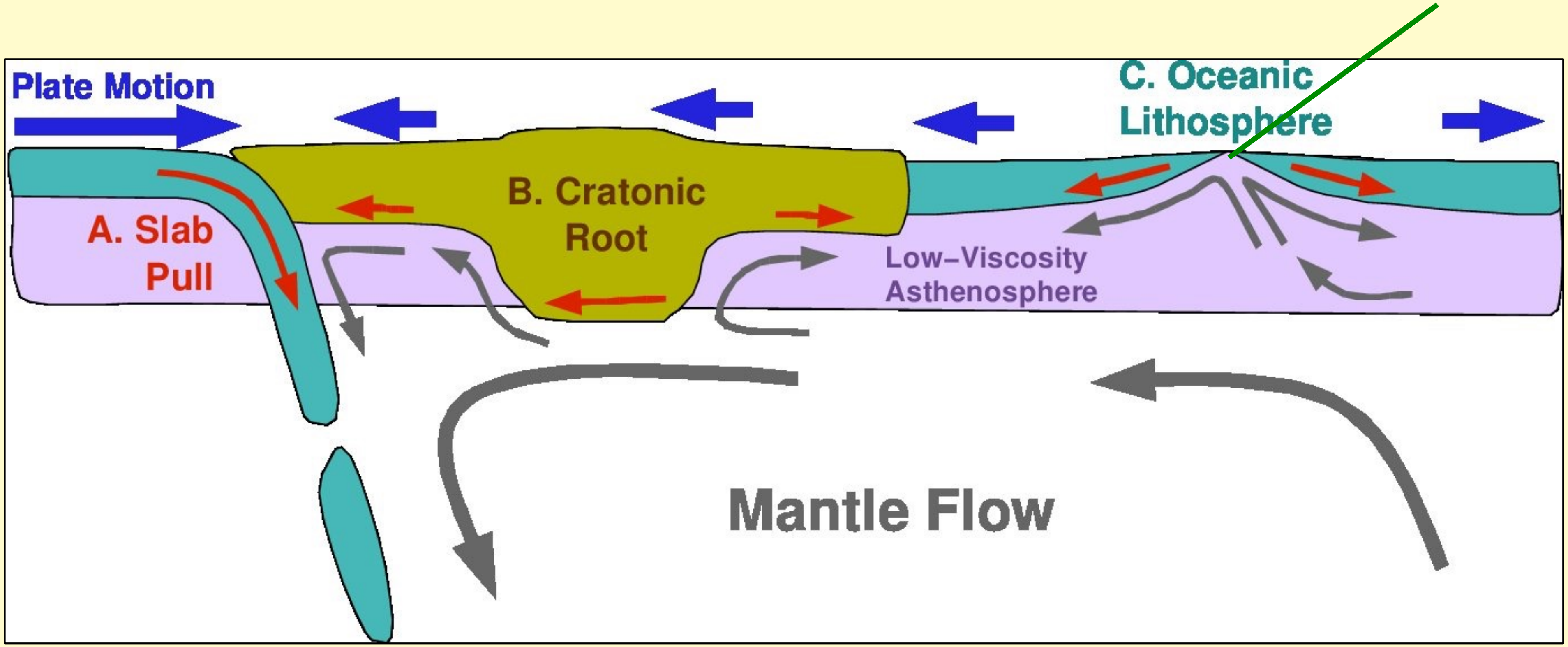
Lithosphere and Asthenosphere: Composition and Evolution

GEO-DEEP9300

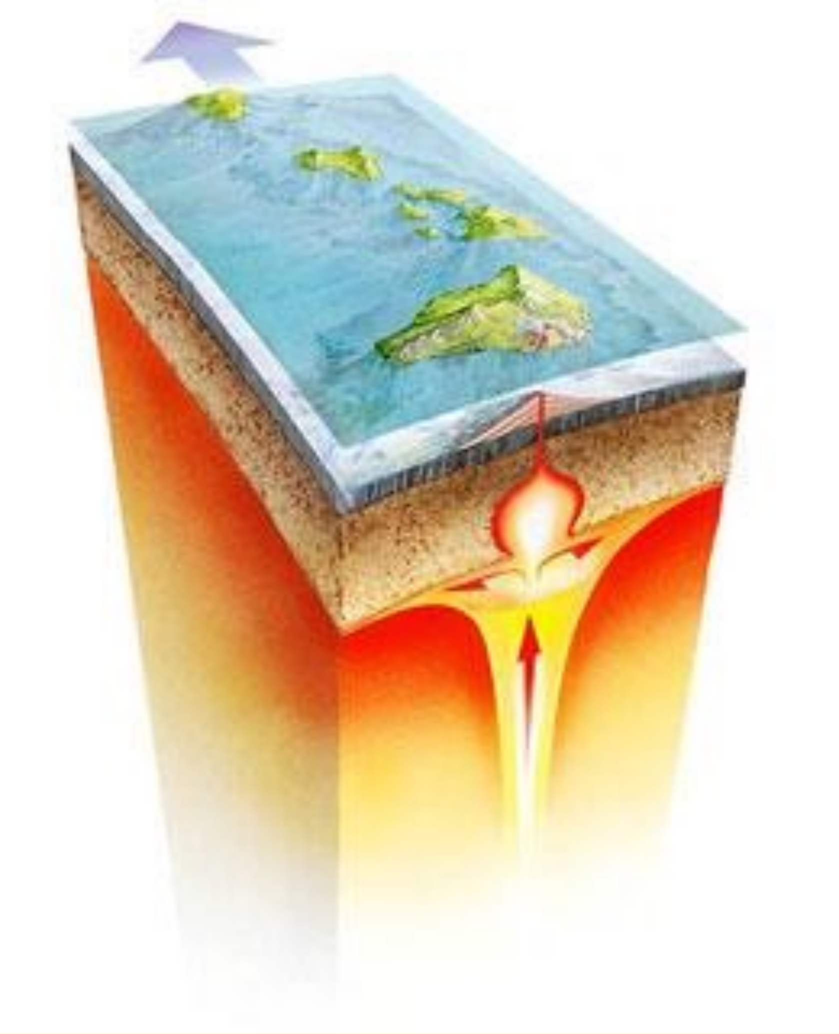
Valerie Maupin
Clint Conrad

Volcanism

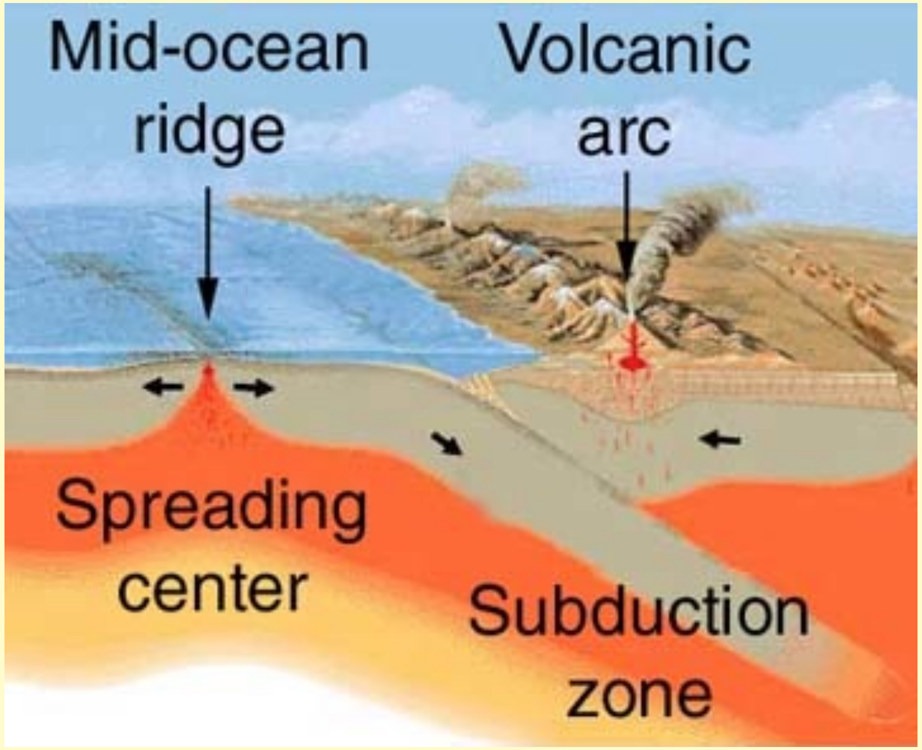


Global Volcanism

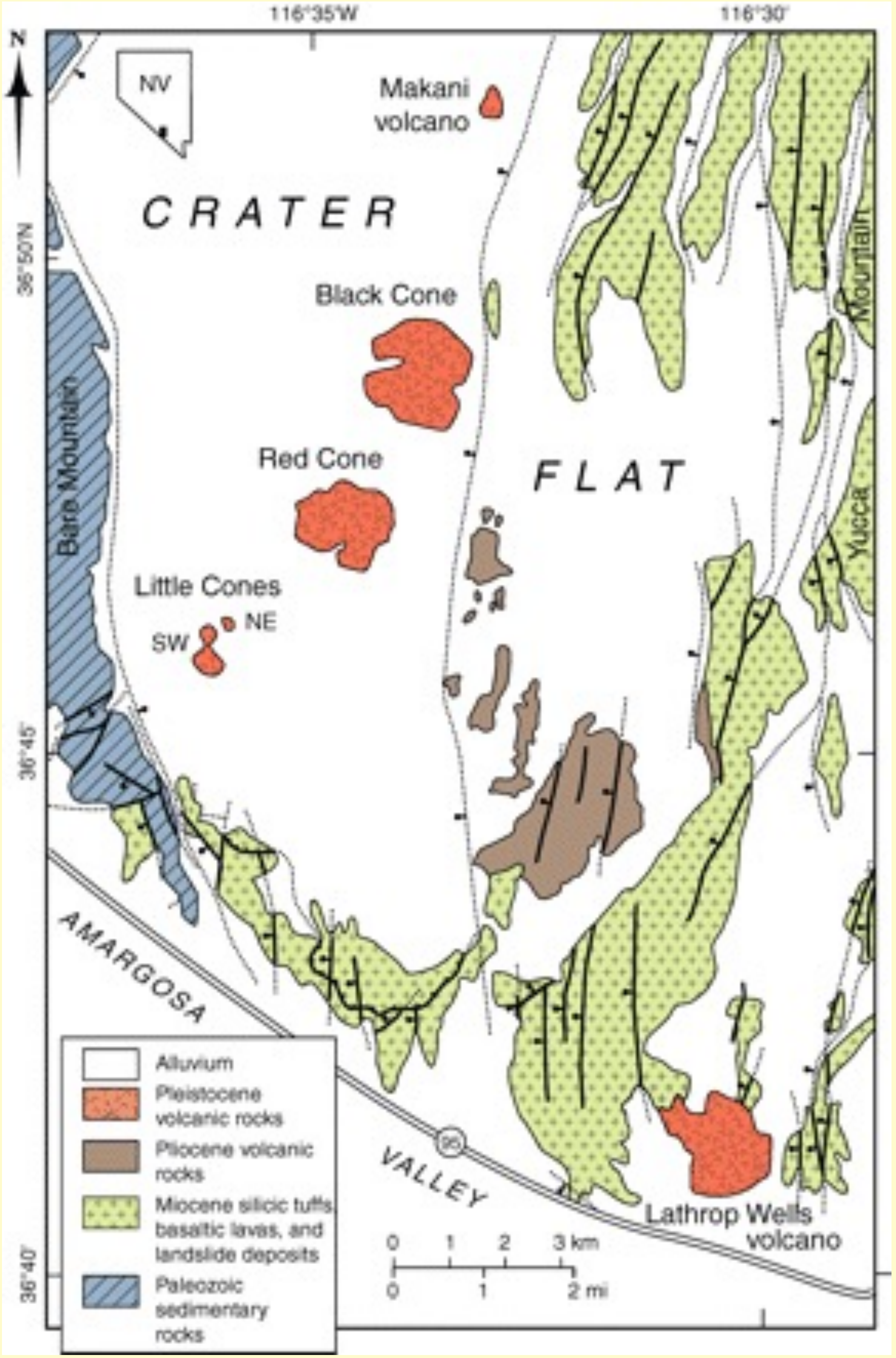
Most volcanism results from plumes bringing heat from the deep mantle …



… or by "shallow" processes at plate boundaries



Crater Flat, Southern Nevada

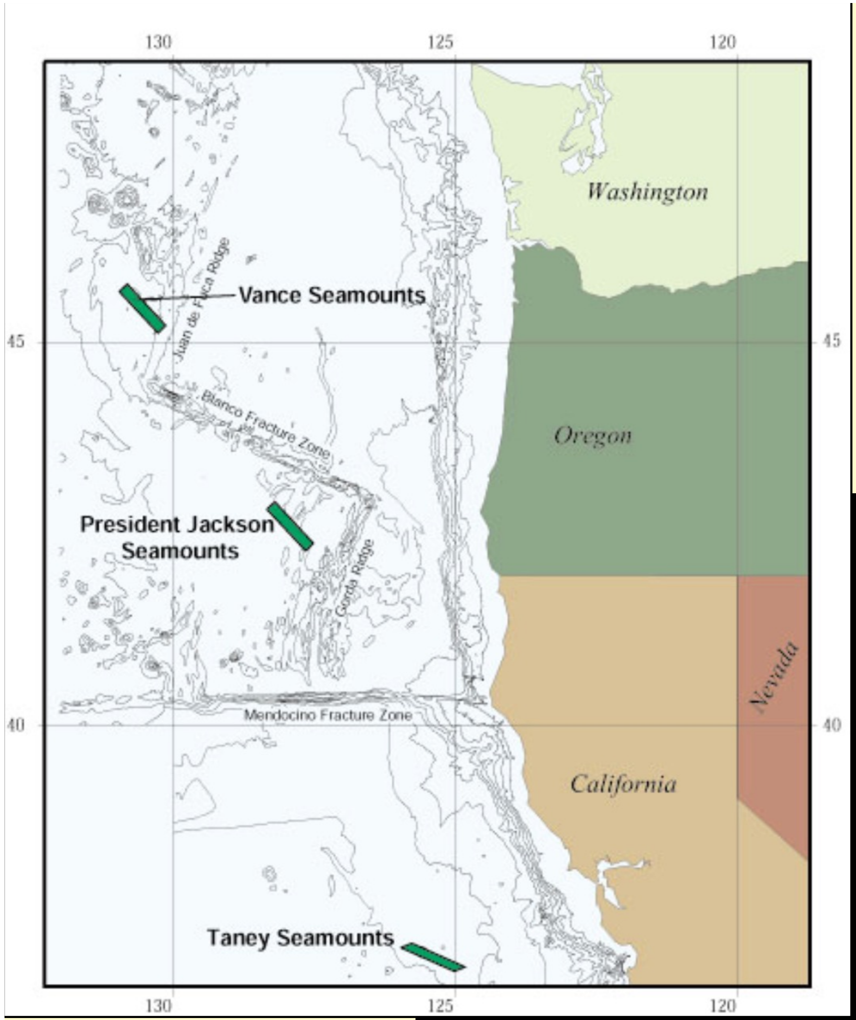


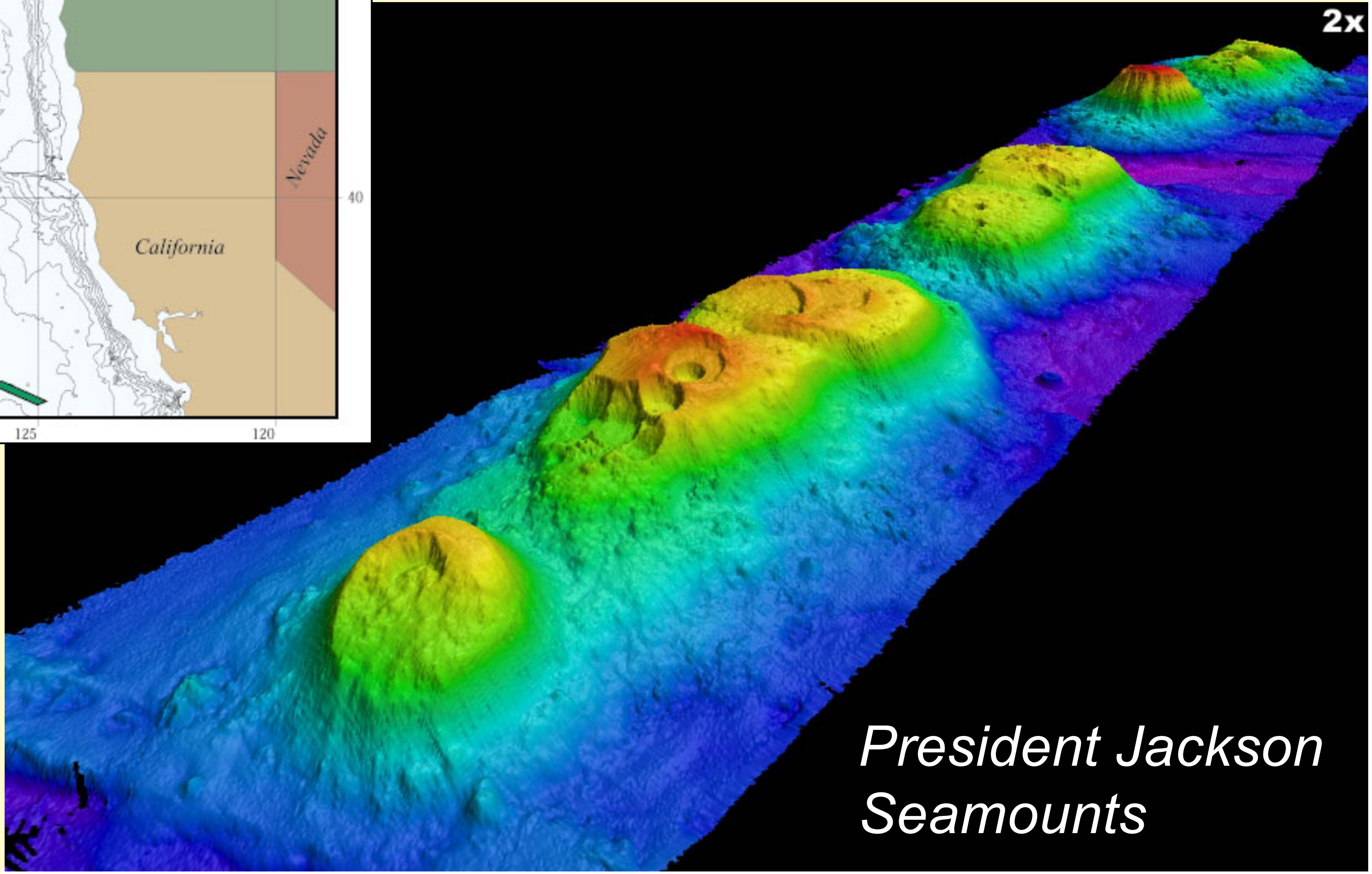
Volcanic History

[*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

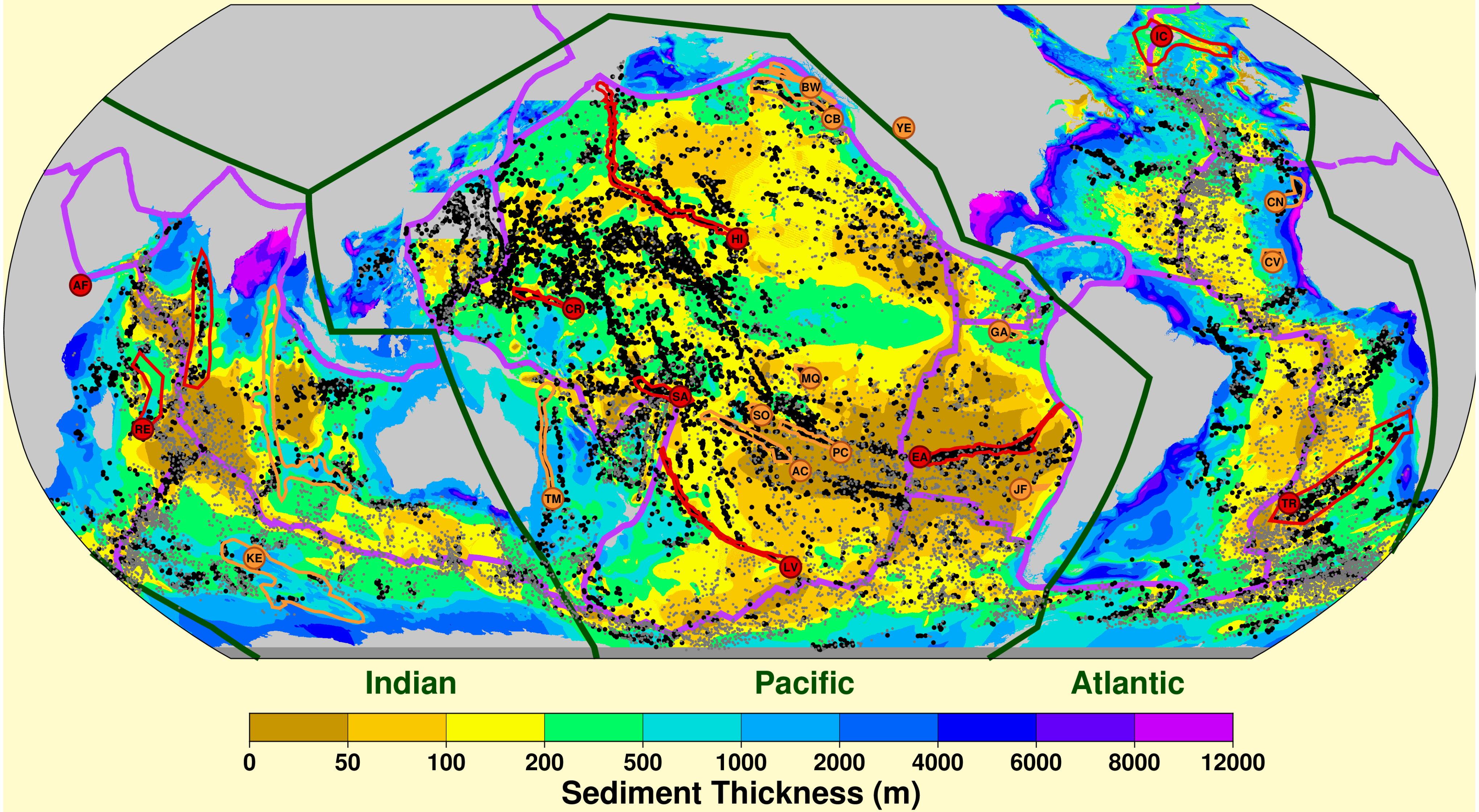
Seamounts represent past volcanism on the seafloor





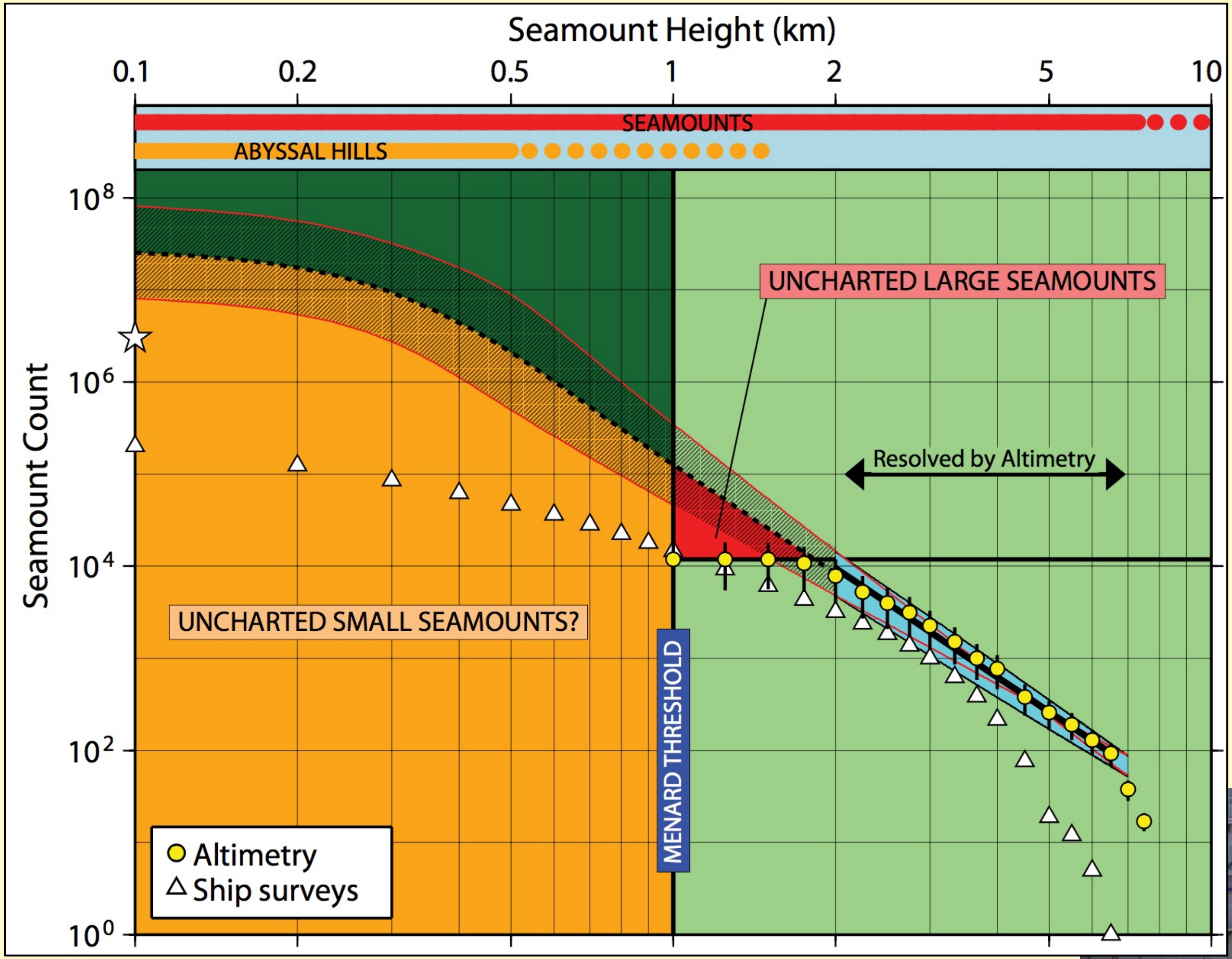
President Jackson Seamounts

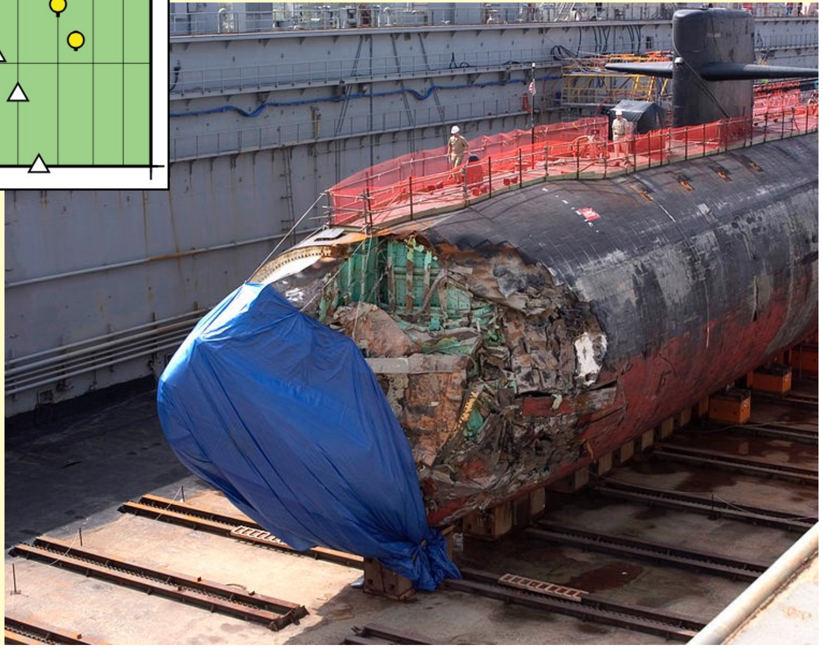
The *Kim & Wessel* [2011] Catalog
24,000+ seamounts detected using satellite gravity



Seamount Census: Height – Frequency Distribution

Wessel et al. [2010]



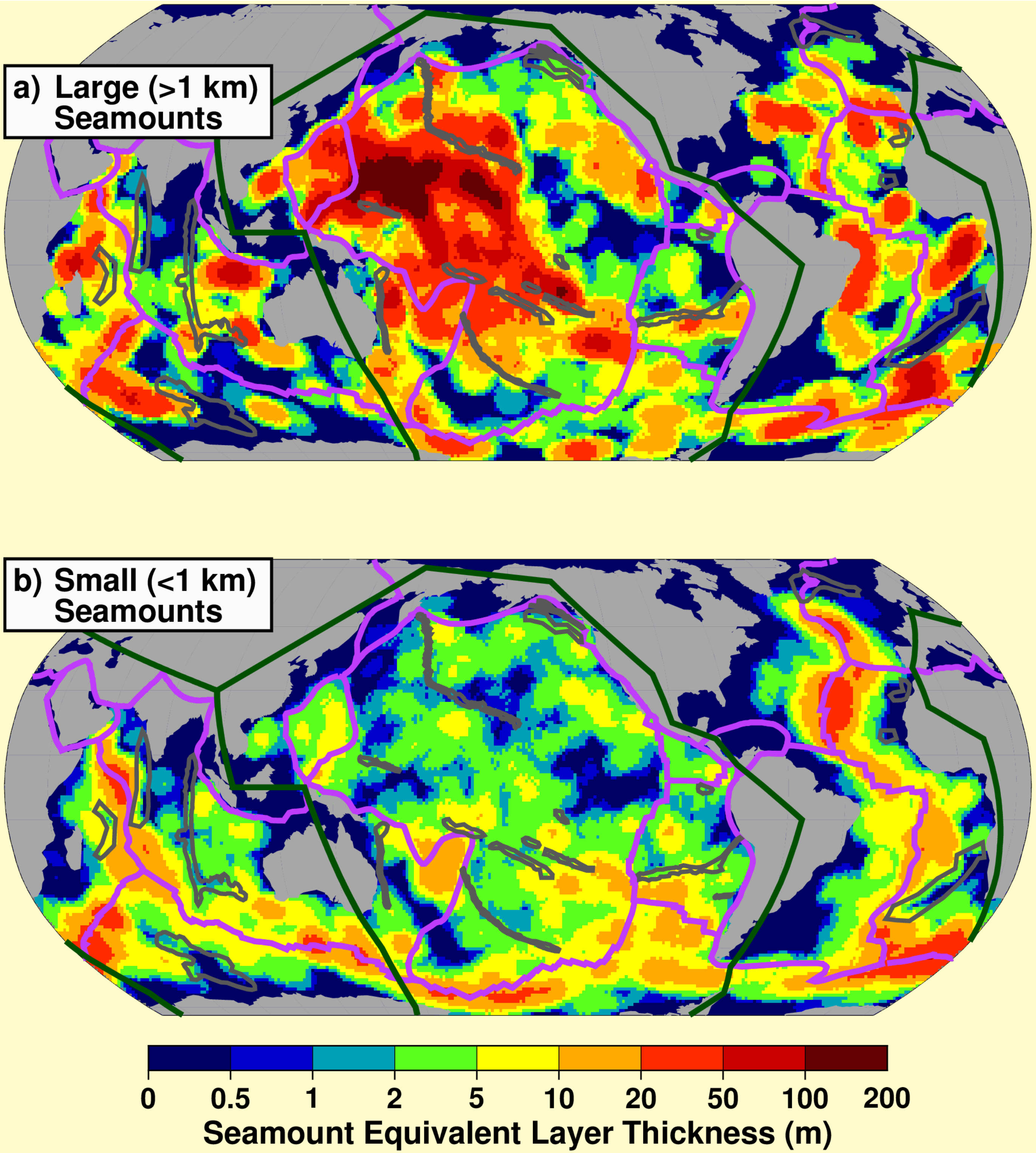


USS San Francisco
Crashed into a uncharted seamount (2005)

Seamount Equivalent Layer Thickness:

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

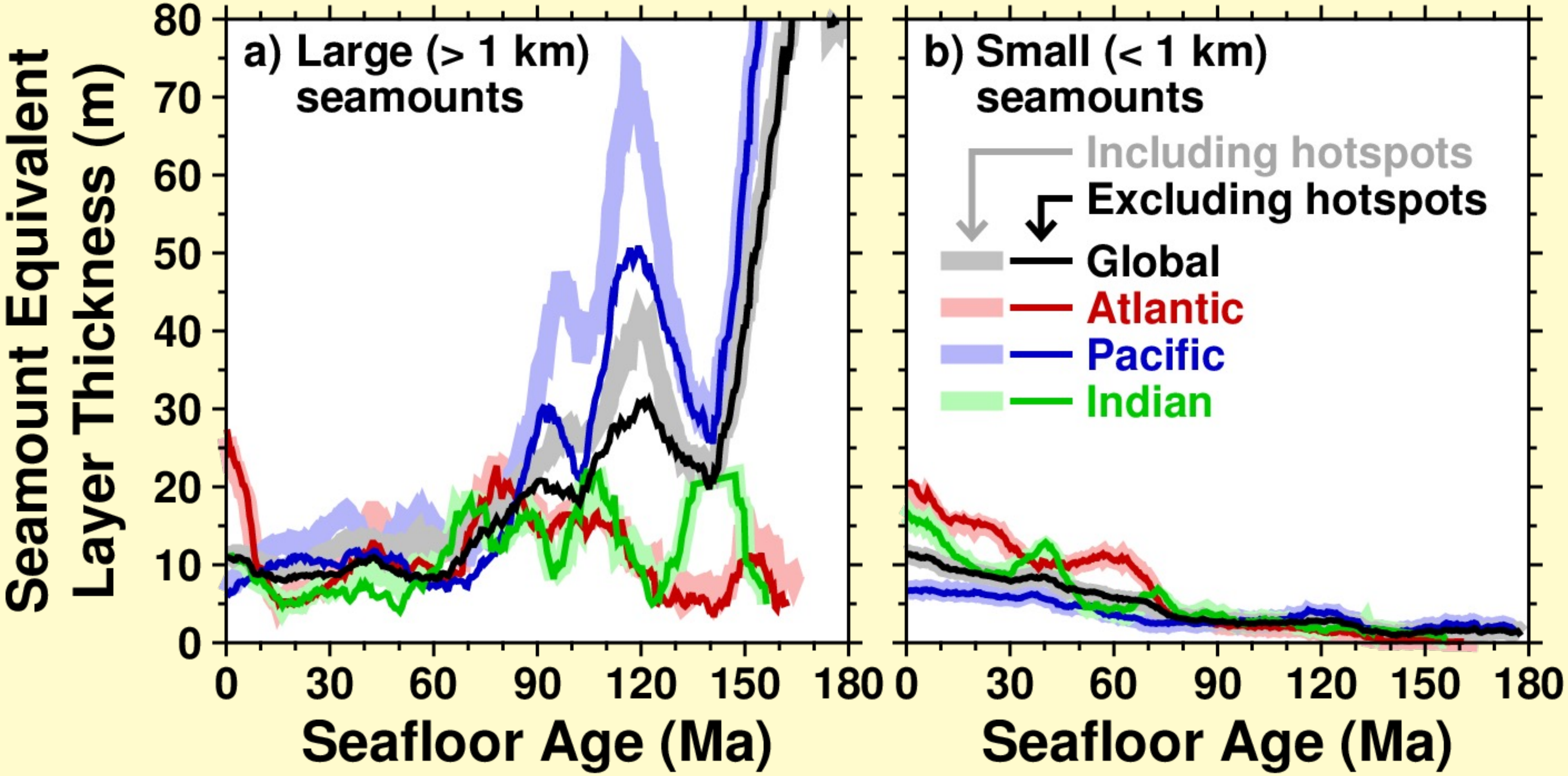
Conrad et al. [2017]



Seamount equivalent thickness vs. seafloor age

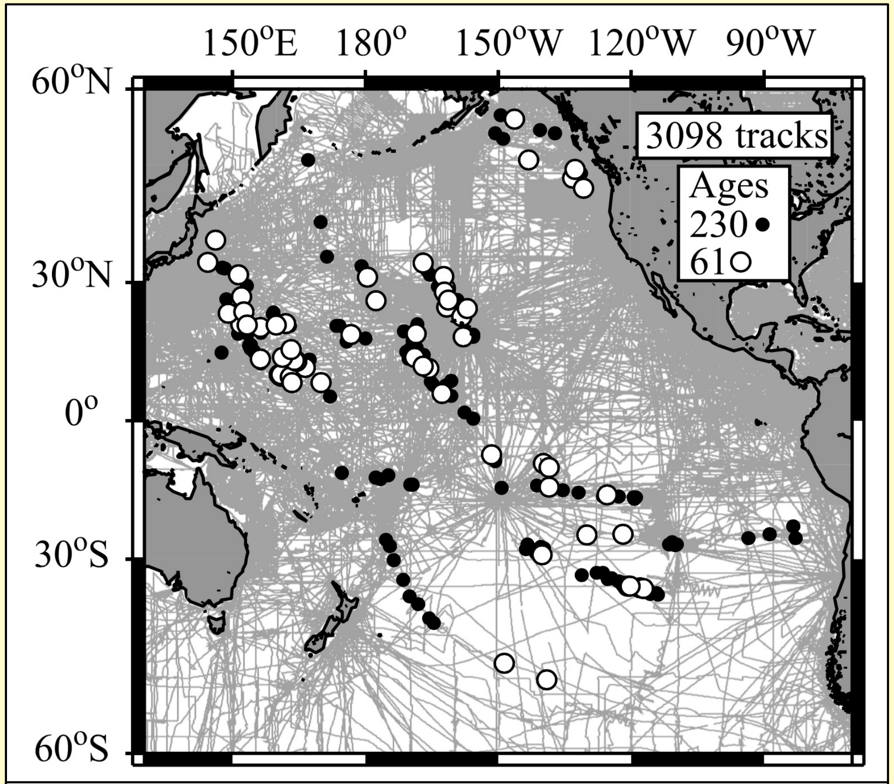
Large seamounts:
- 10 m until ~70 Myr
- Increases after 70 Myr (esp in Pacific)

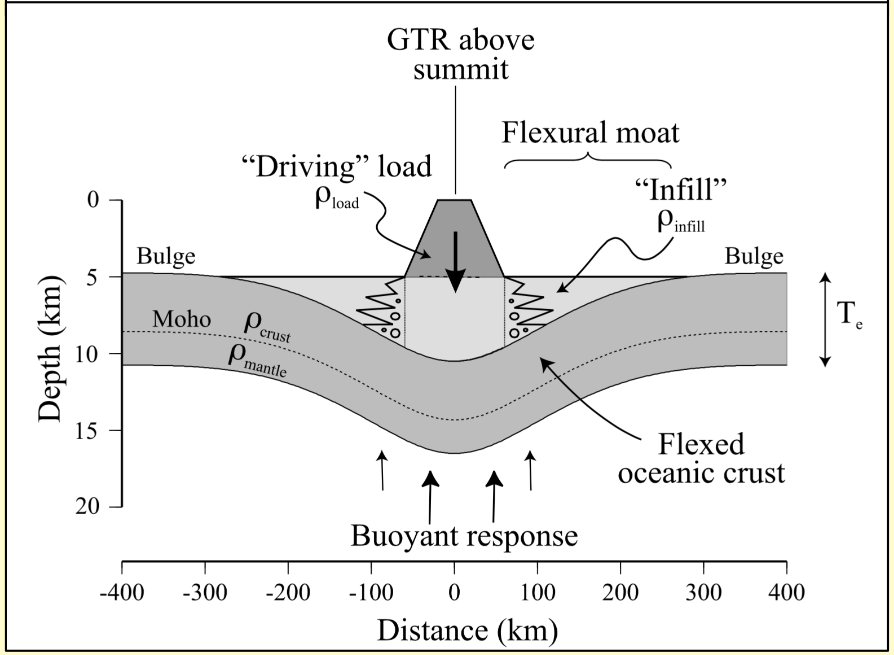
Small seamounts:
- Decreases away from the ridge due to sampling problems

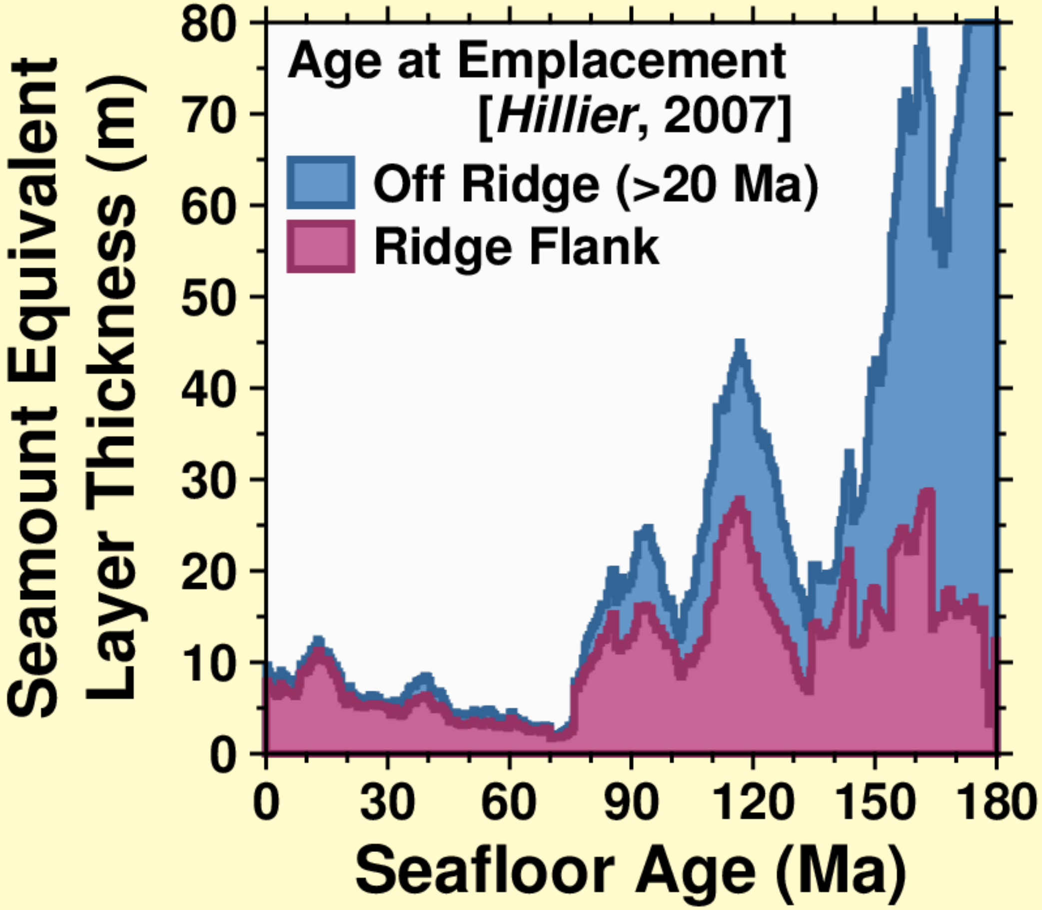


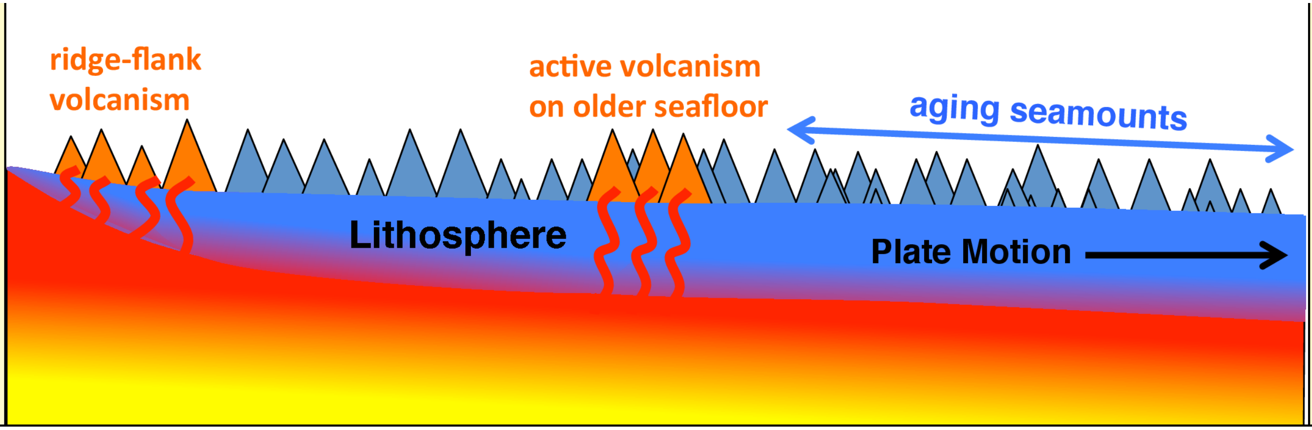
Age of the Seamounts:

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

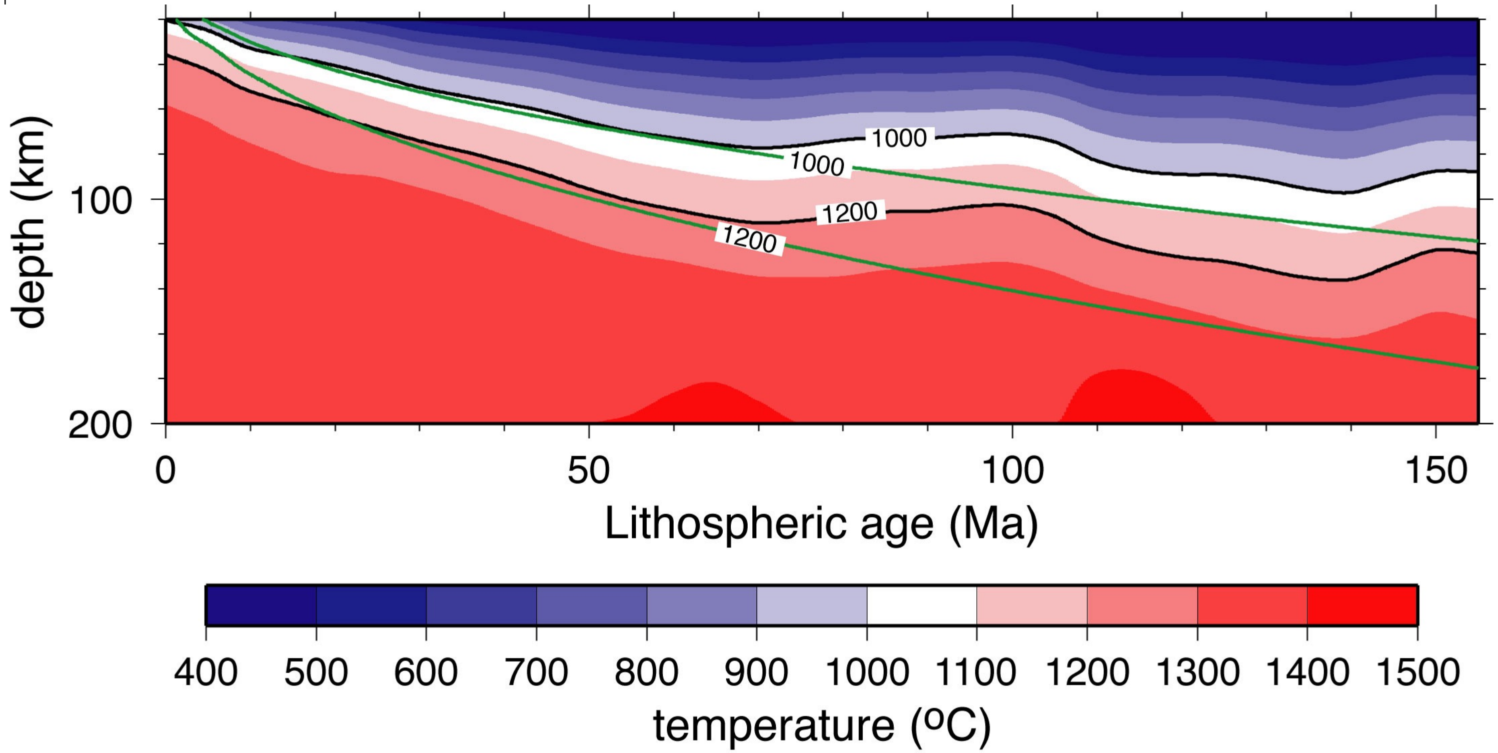








Model of Seamount Emplacement
Conrad et al. [2017]



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

Model for Seamount formation:

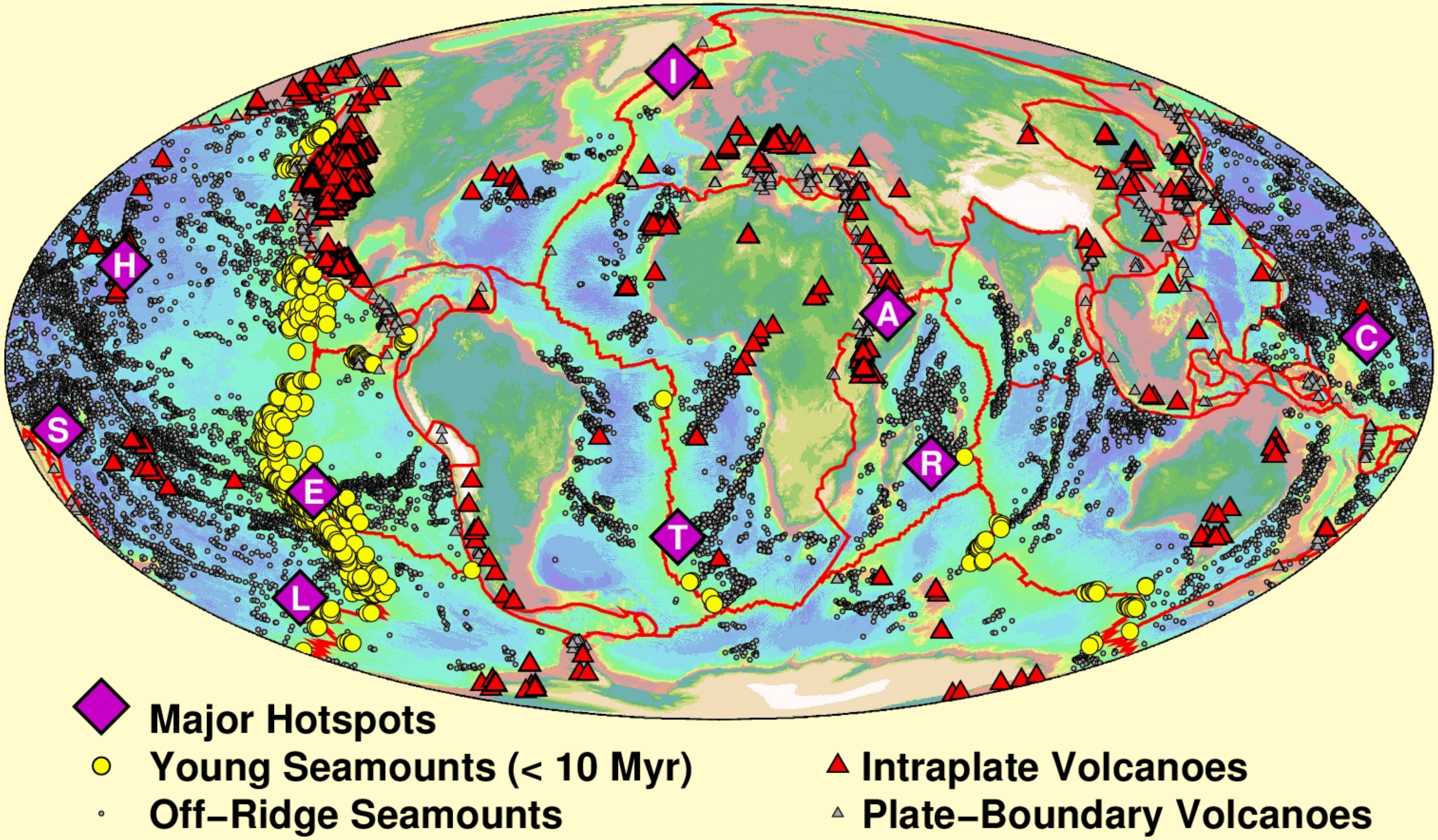
- One population formed on the ridge flanks
- Another population formed on seafloor > 70 Myr old
- Pacific seamount production was faster in the Cretaceous

Intraplate Volcanism

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

→ **How are the lithosphere and asthenosphere important?**

→ **What is the mechanism?**



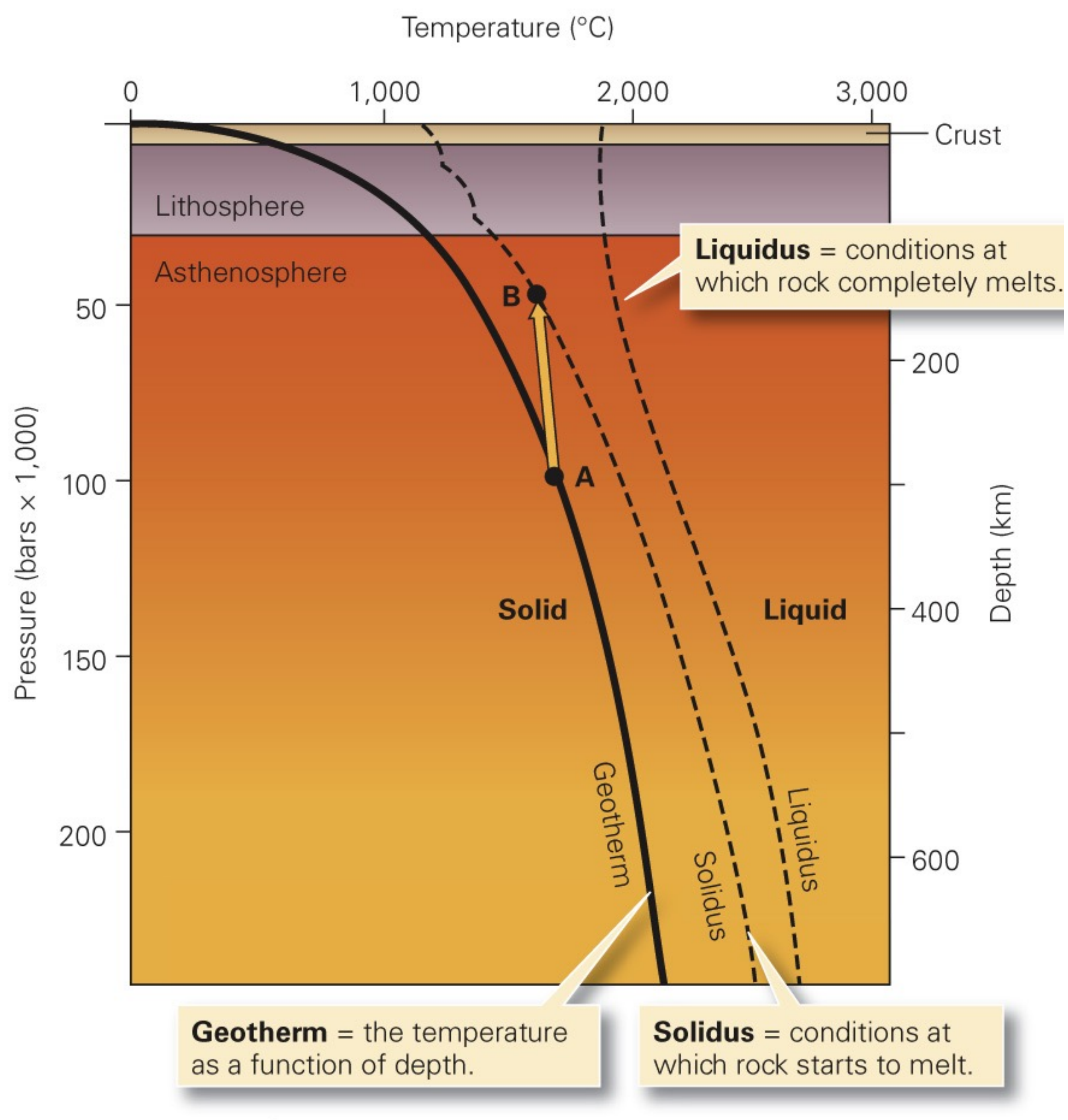
The following can produce melting:

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

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

5 Mechanisms:

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

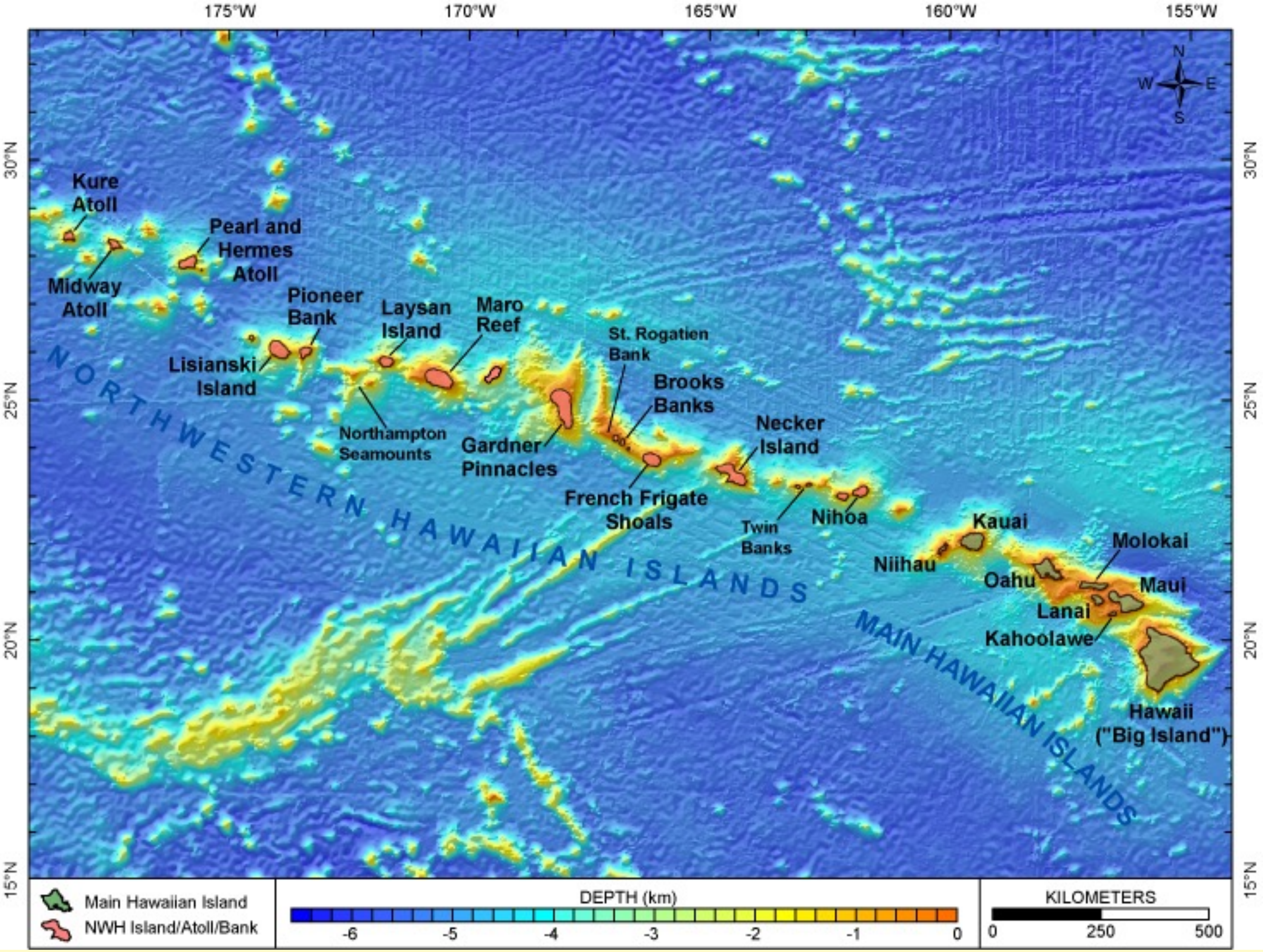


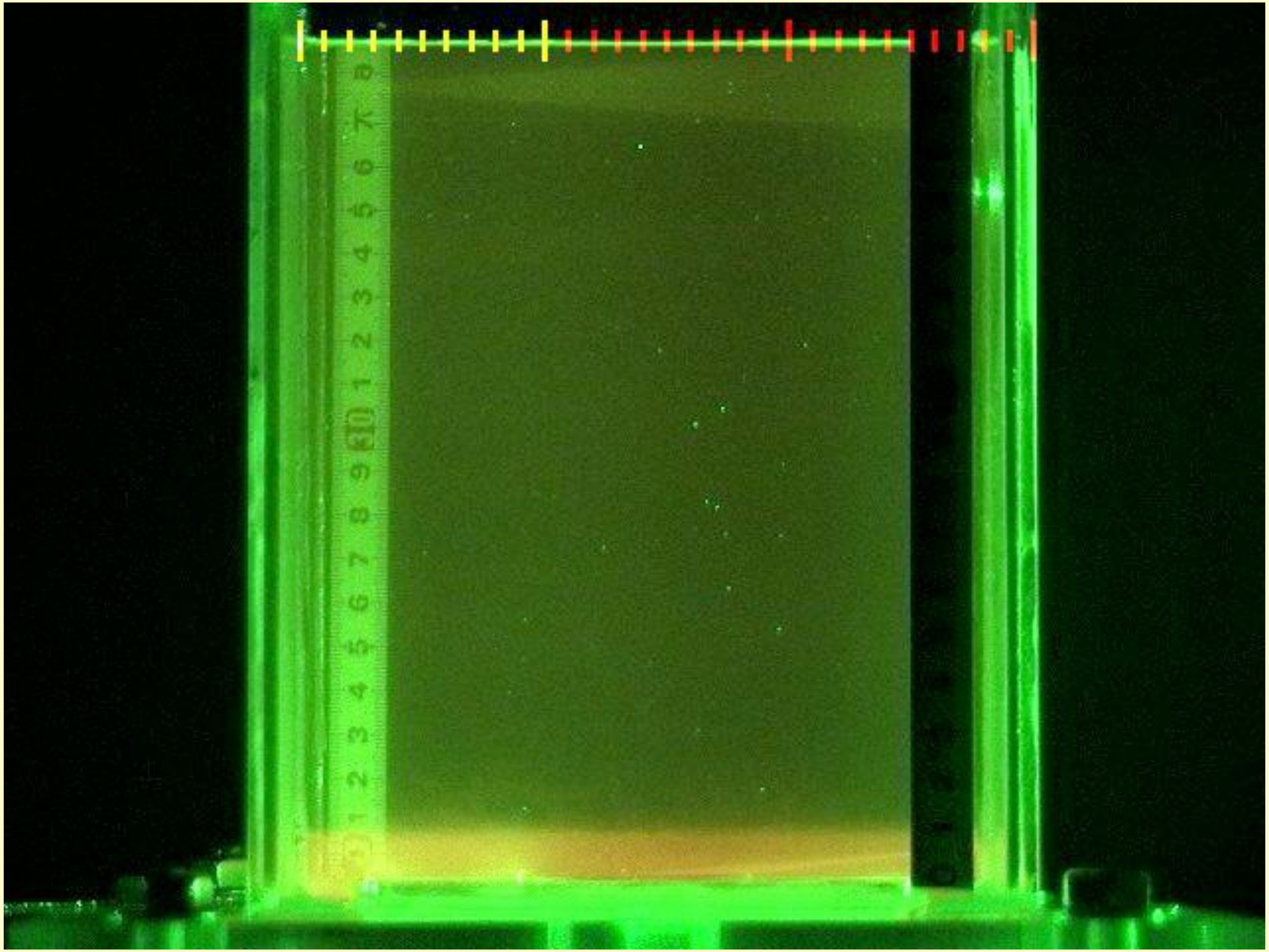
Liquidus = conditions at which rock completely melts.

Geotherm = the temperature as a function of depth.

Solidus = conditions at which rock starts to melt.

1. Mantle Plumes



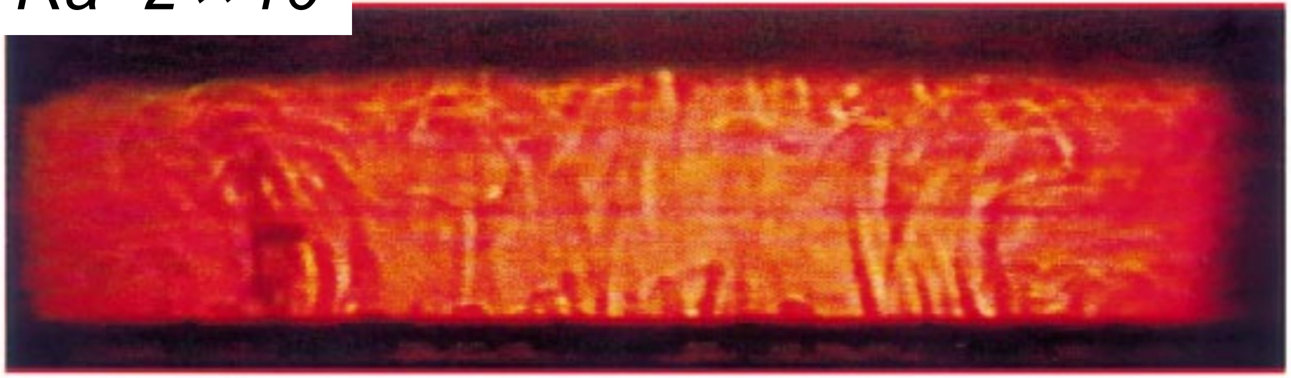


A Plume Experiment in Corn Syrup:
Plumes have heads and tails

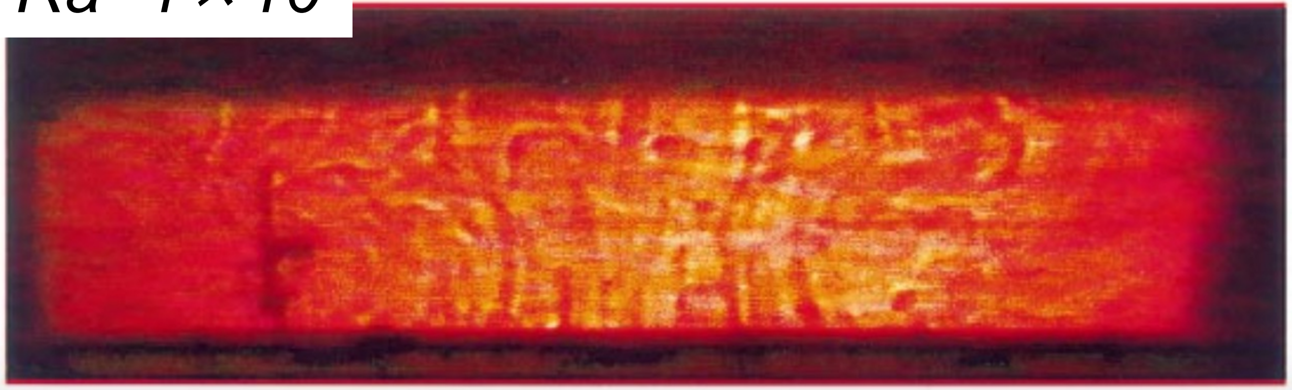
$Ra \sim 4 \times 10^6$

Base is Hot

$Ra \sim 2 \times 10^7$



$Ra \sim 4 \times 10^7$

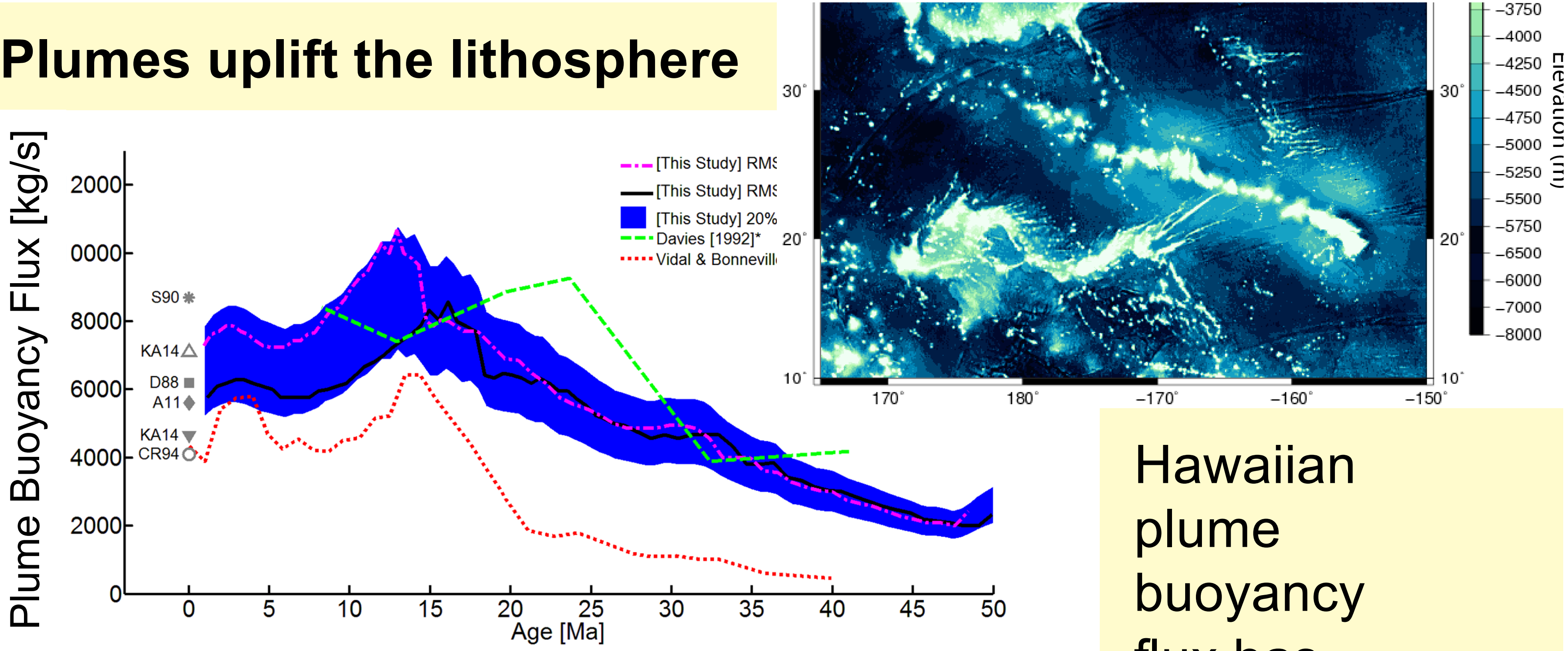


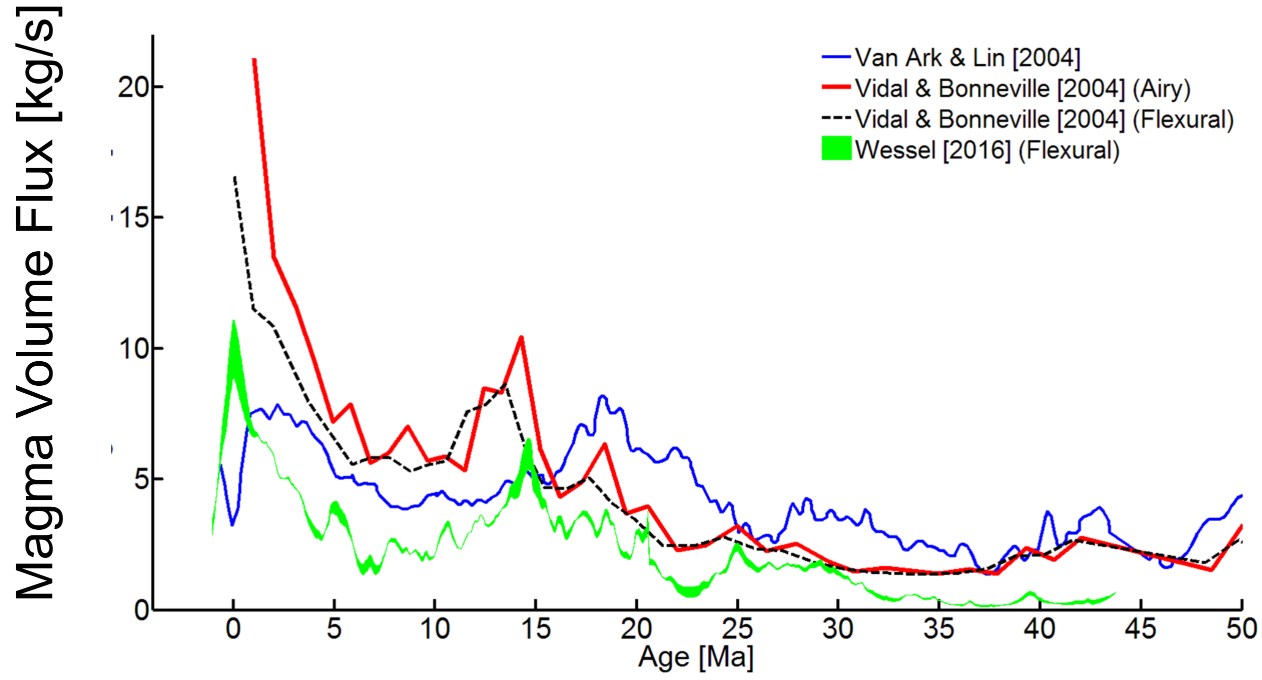
Laboratory experiment of convection in a tank of corn syrup.

Lithgow-Bertelloni et al. [2001]

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

Plumes uplift the lithosphere





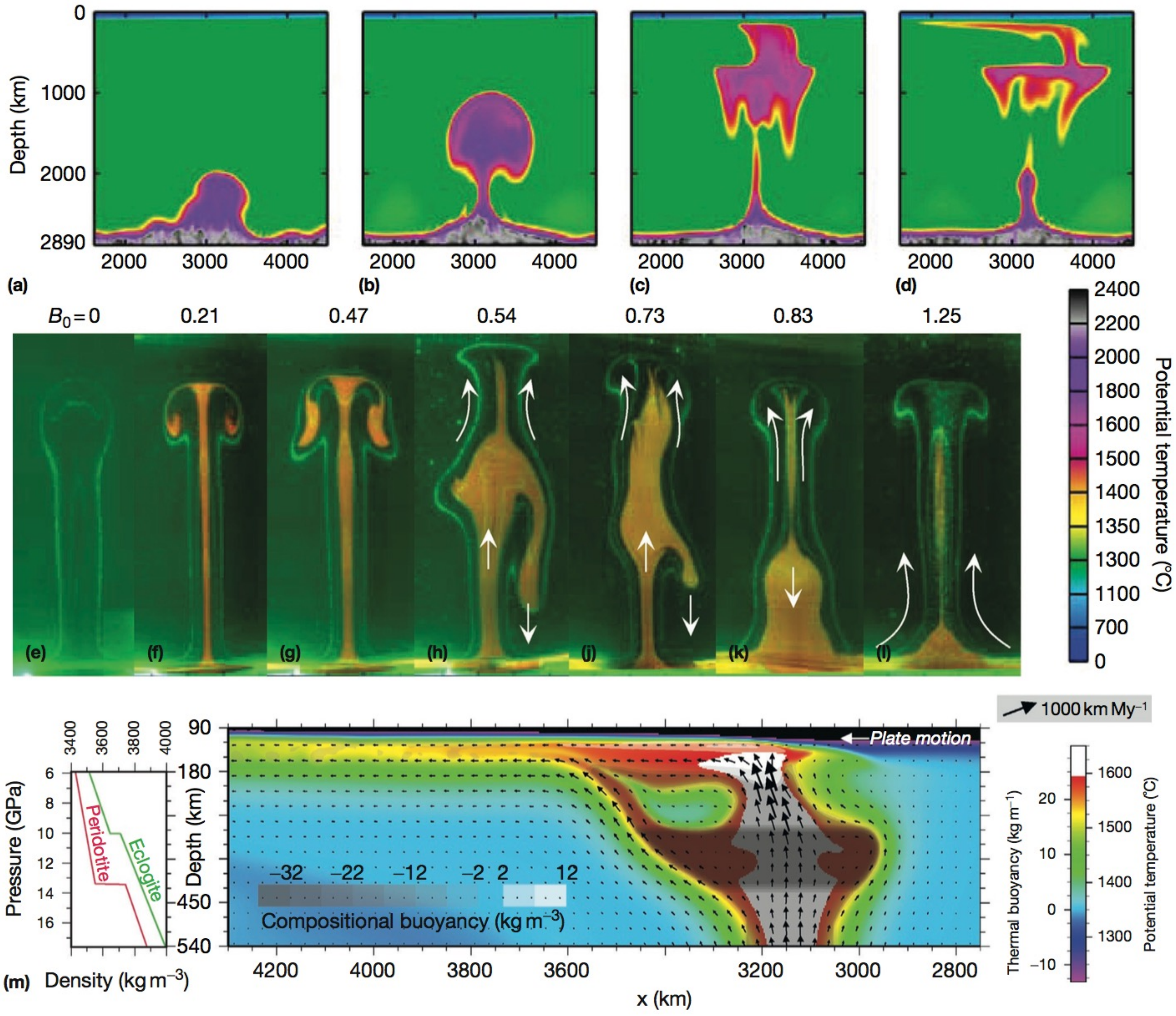
Hawaiian plume buoyancy flux has been growing with time

Togia, MS thesis [2015]

Plumes can exhibit interesting behavior!

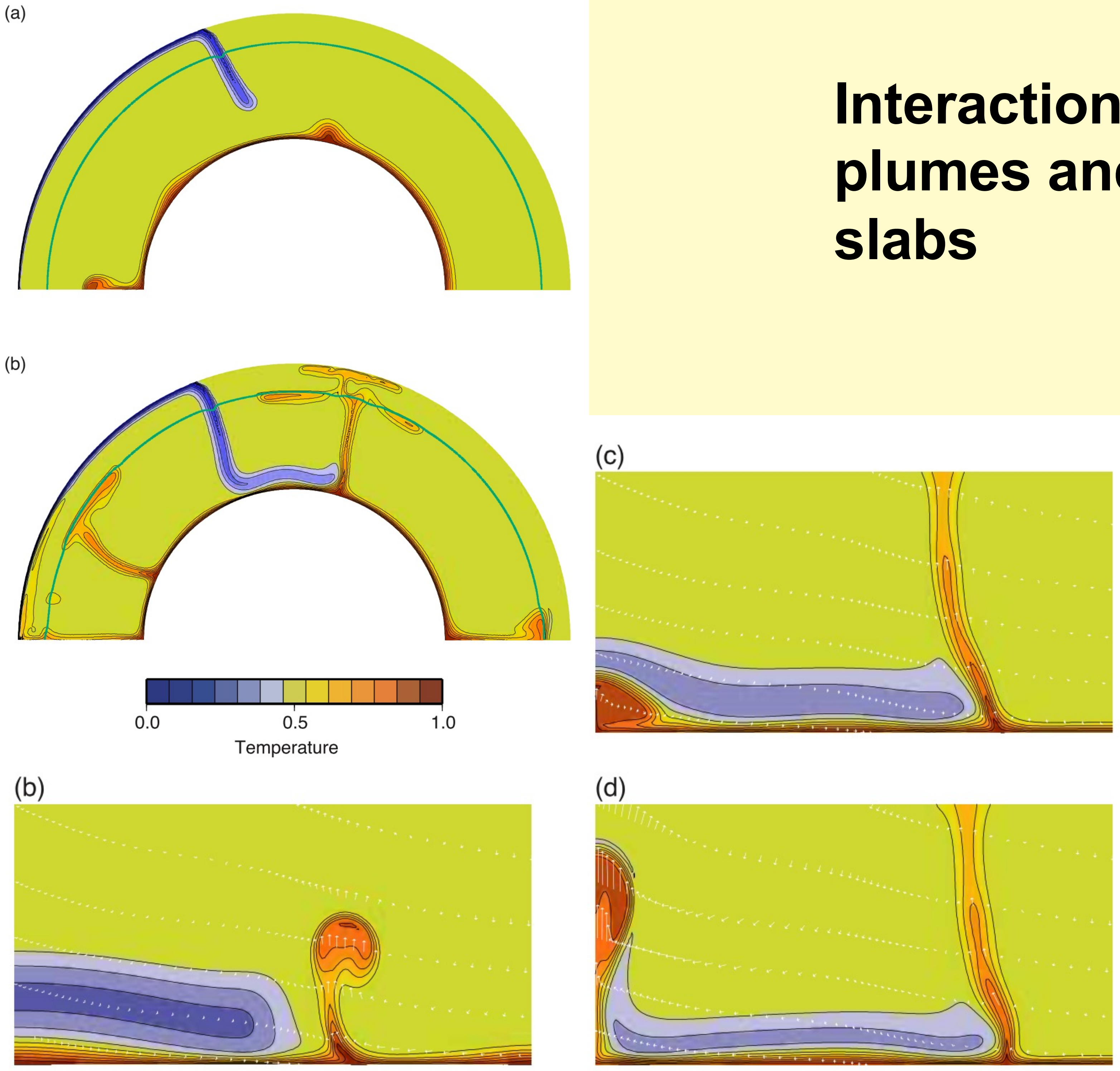
410 km:
Plume
Accelerated

610 km:
Plume
Impeded



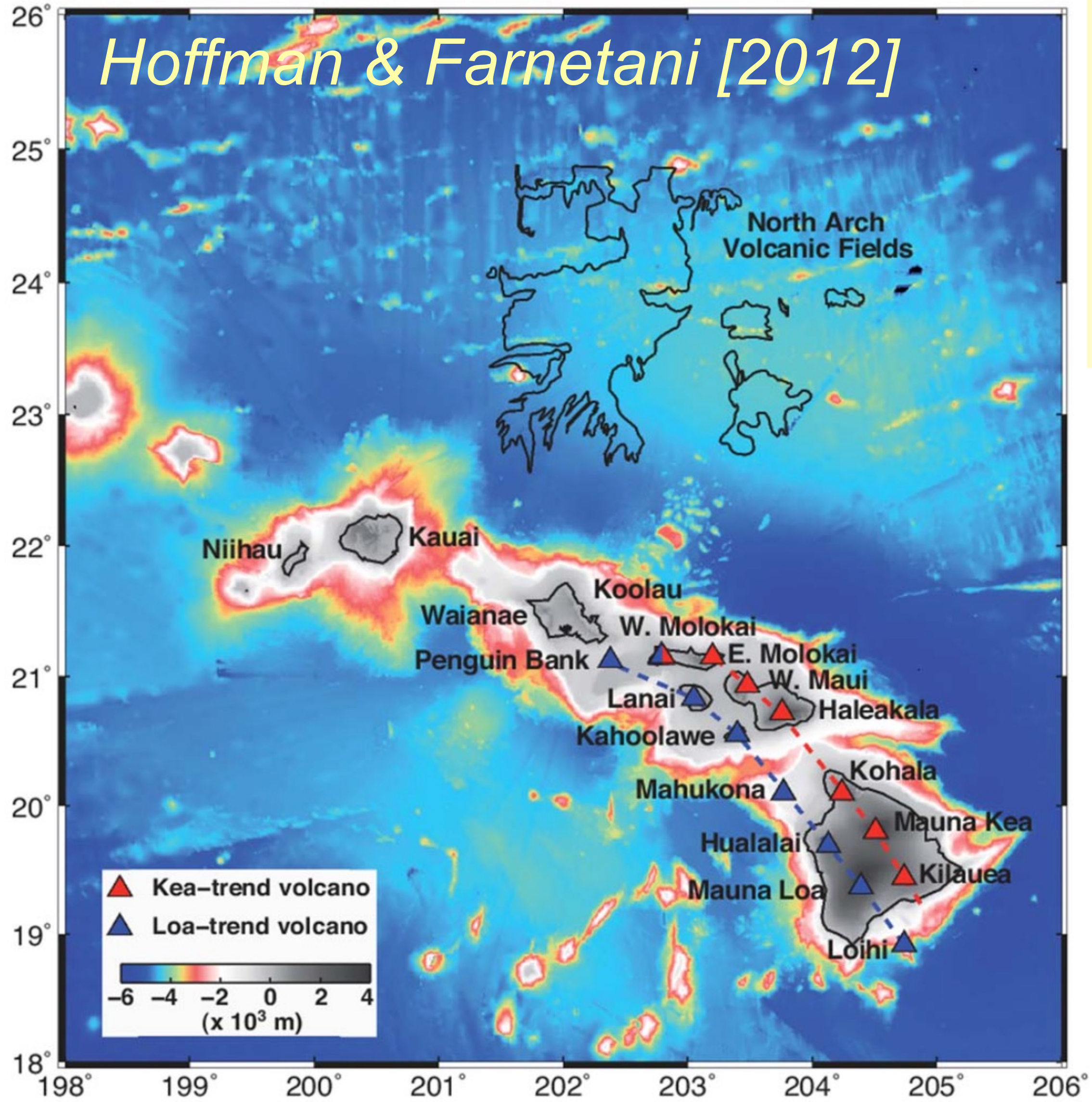
Ballmer et al. [2015]

Interaction of plumes and slabs

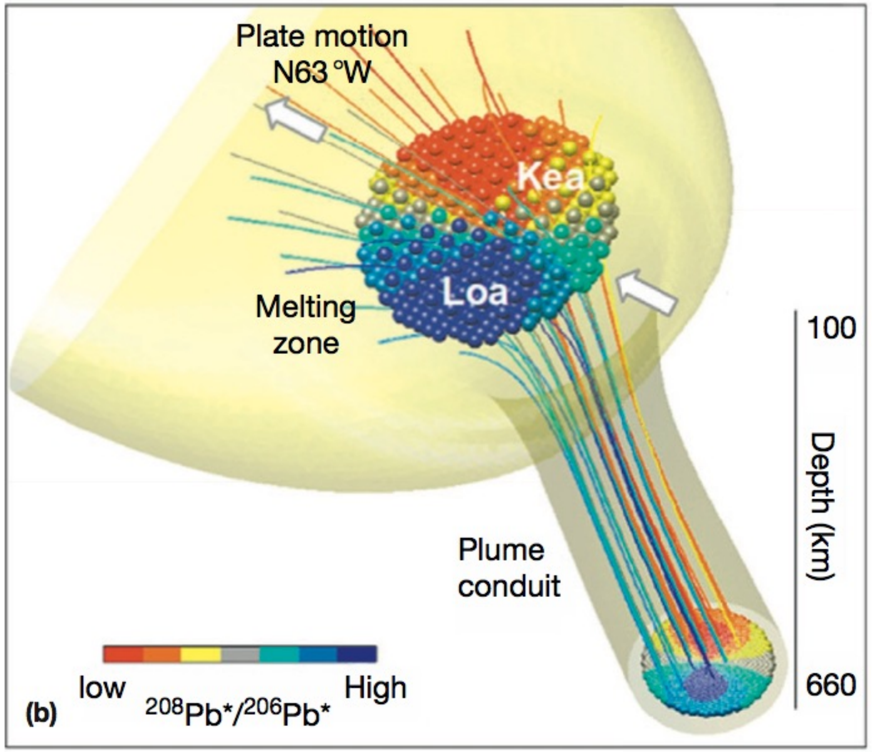


Tan & Gurnis [2002]

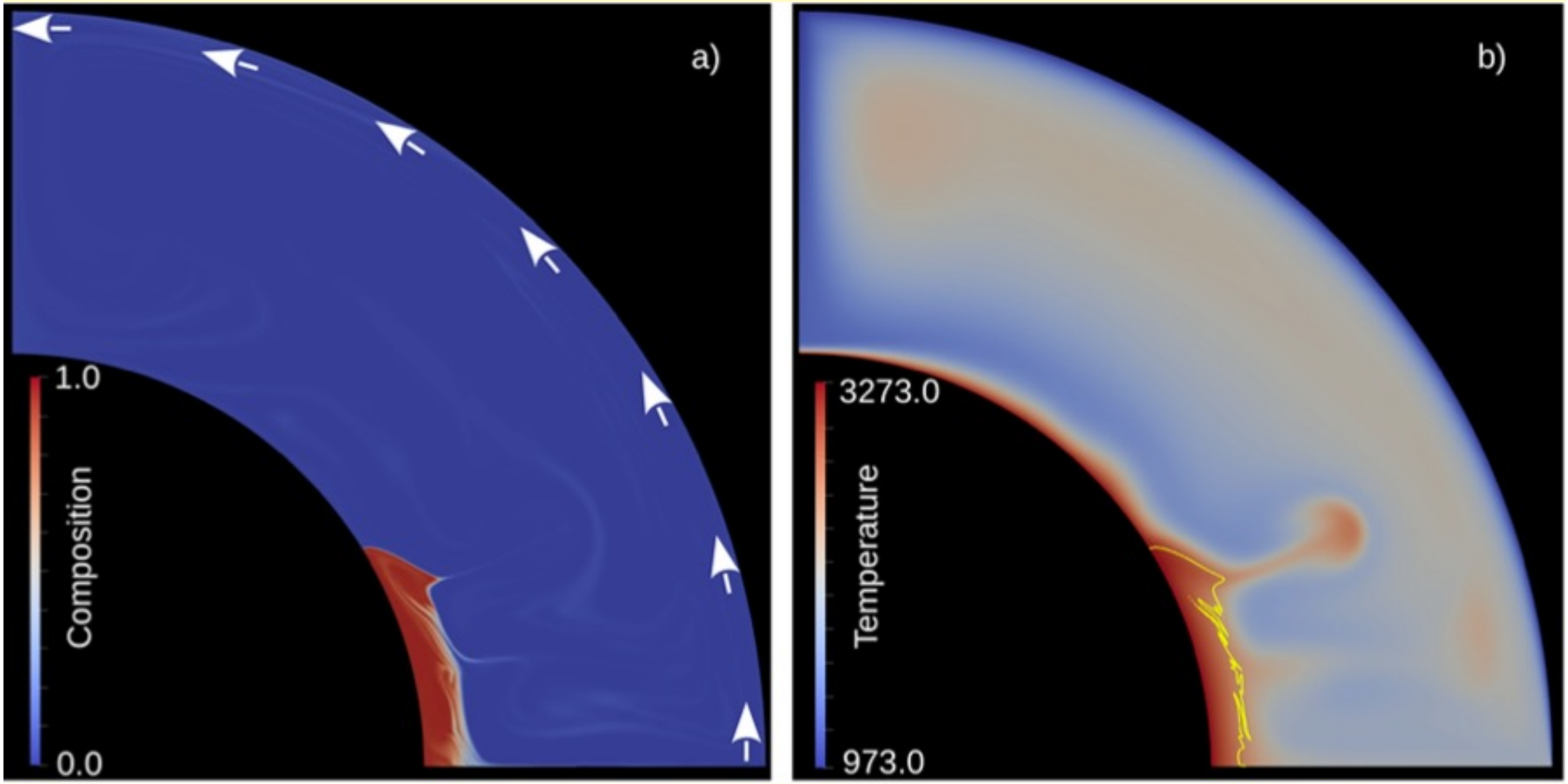
Bisected plumes may sample preserved geochemical gradients from the deep mantle



Hoffman & Farnetani [2012]

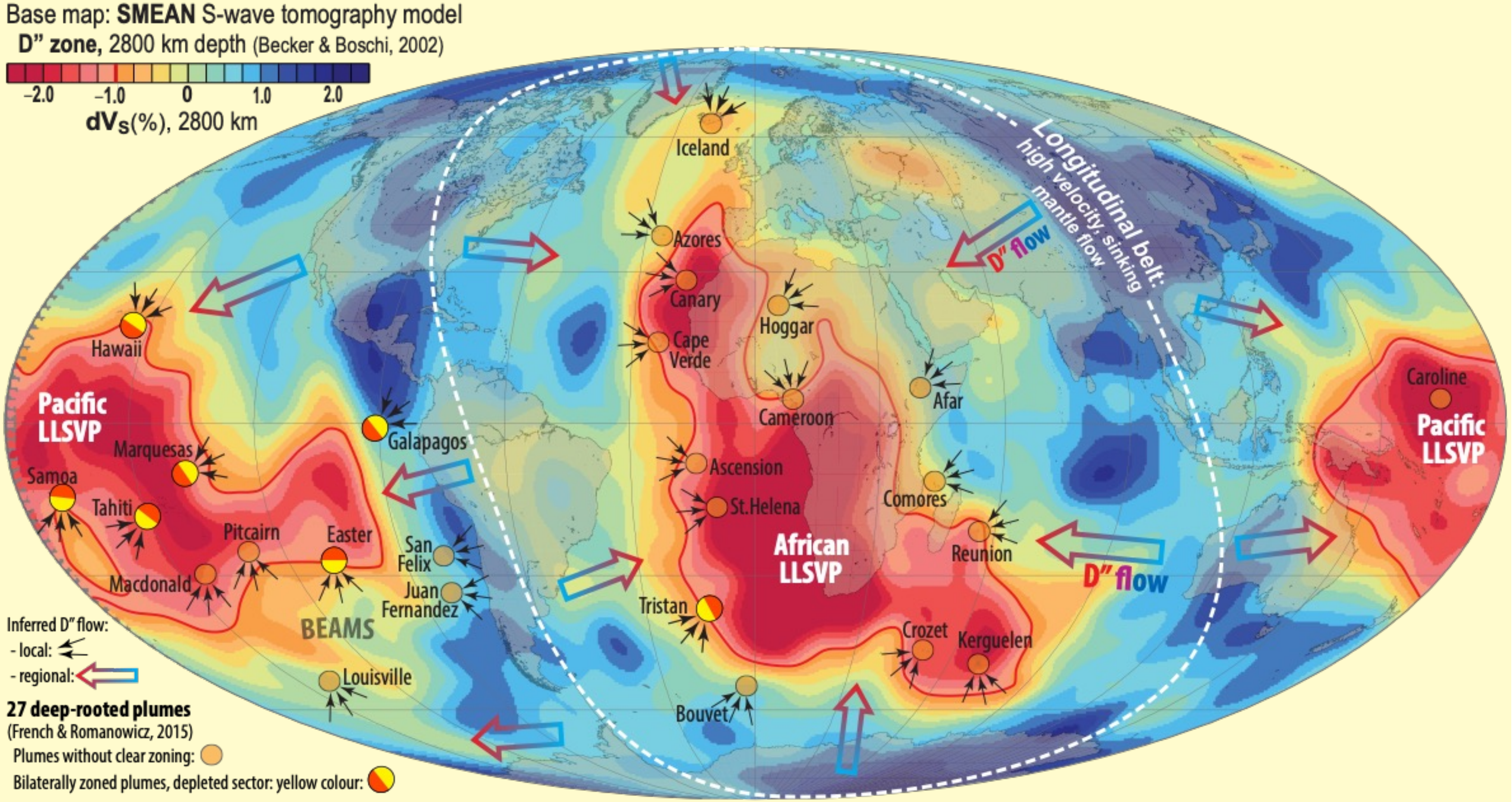


Bisected plumes may sample preserved geochemical gradients from the deep mantle

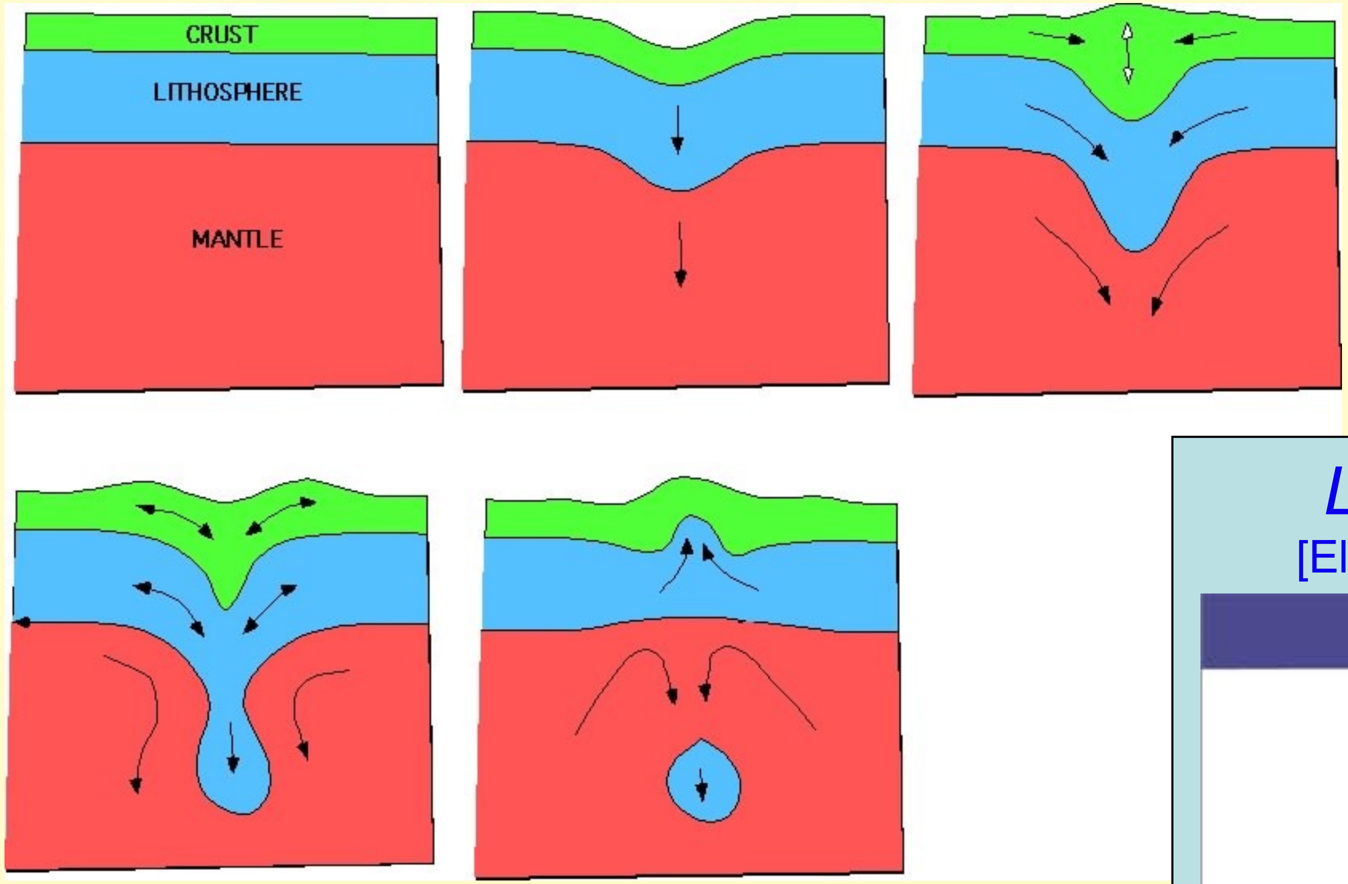


Plumes rise from the edges of the LLSVPs in the lower mantle [*Heyn et al., 2020*]

Bisected plumes may sample preserved geochemical gradients from the deep mantle



2. Small-Scale Convection

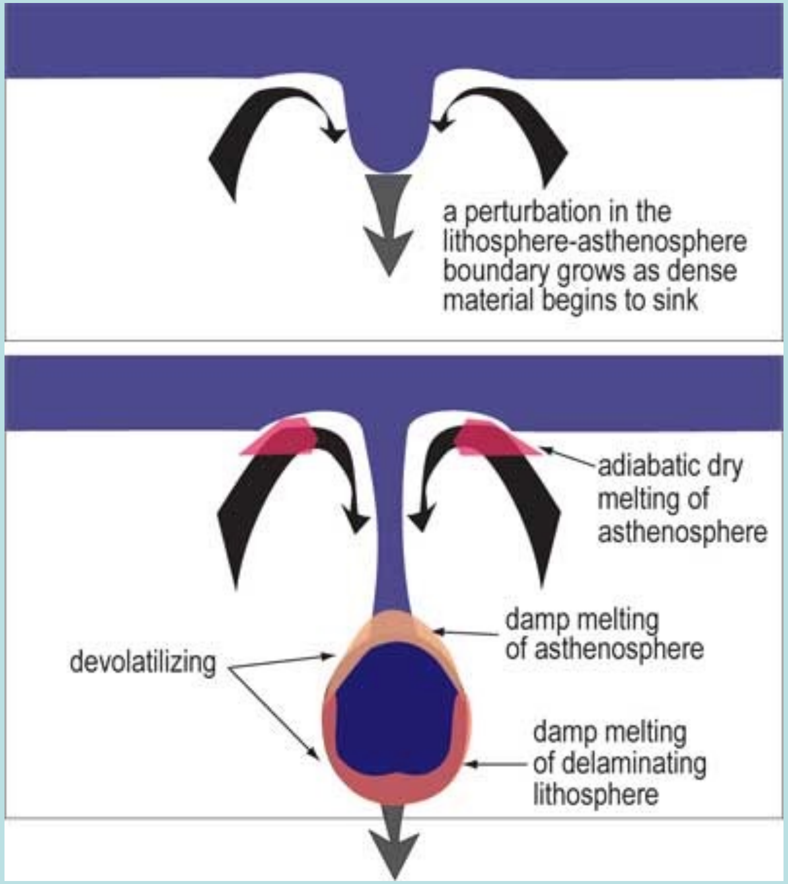


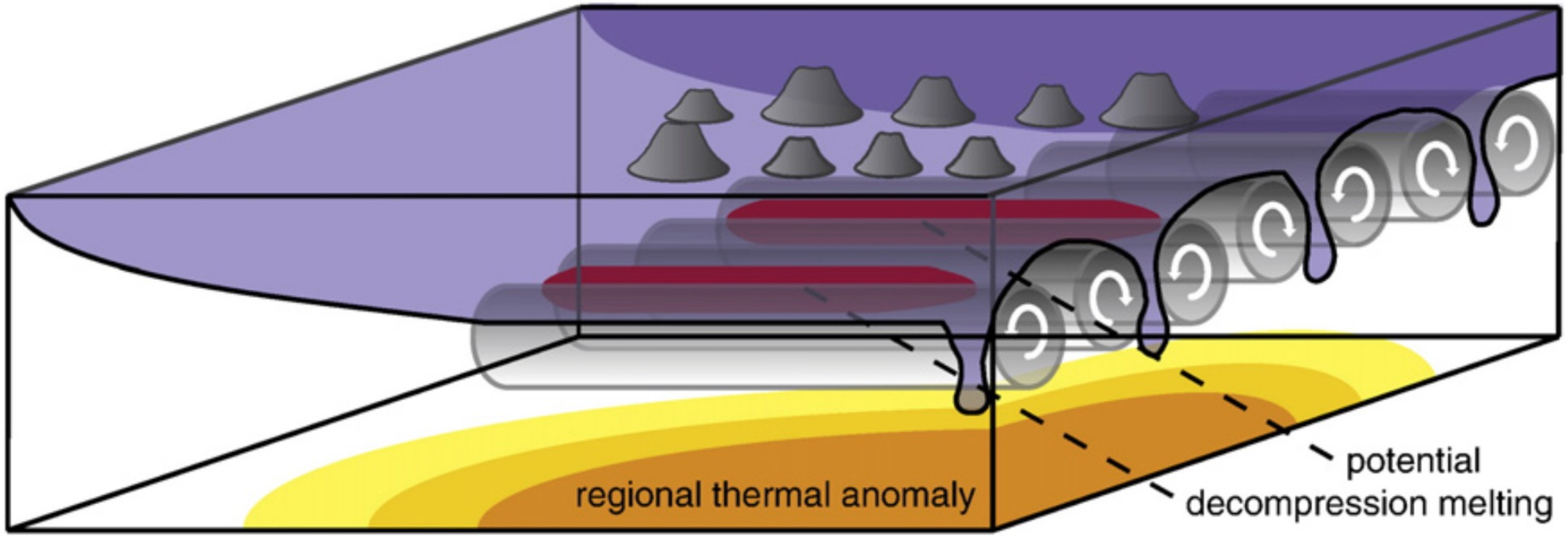
- Like an upside-down plume:
- Cold “drips” sink into the mantle.
- Return flow involves upwelling
  → produces melting.

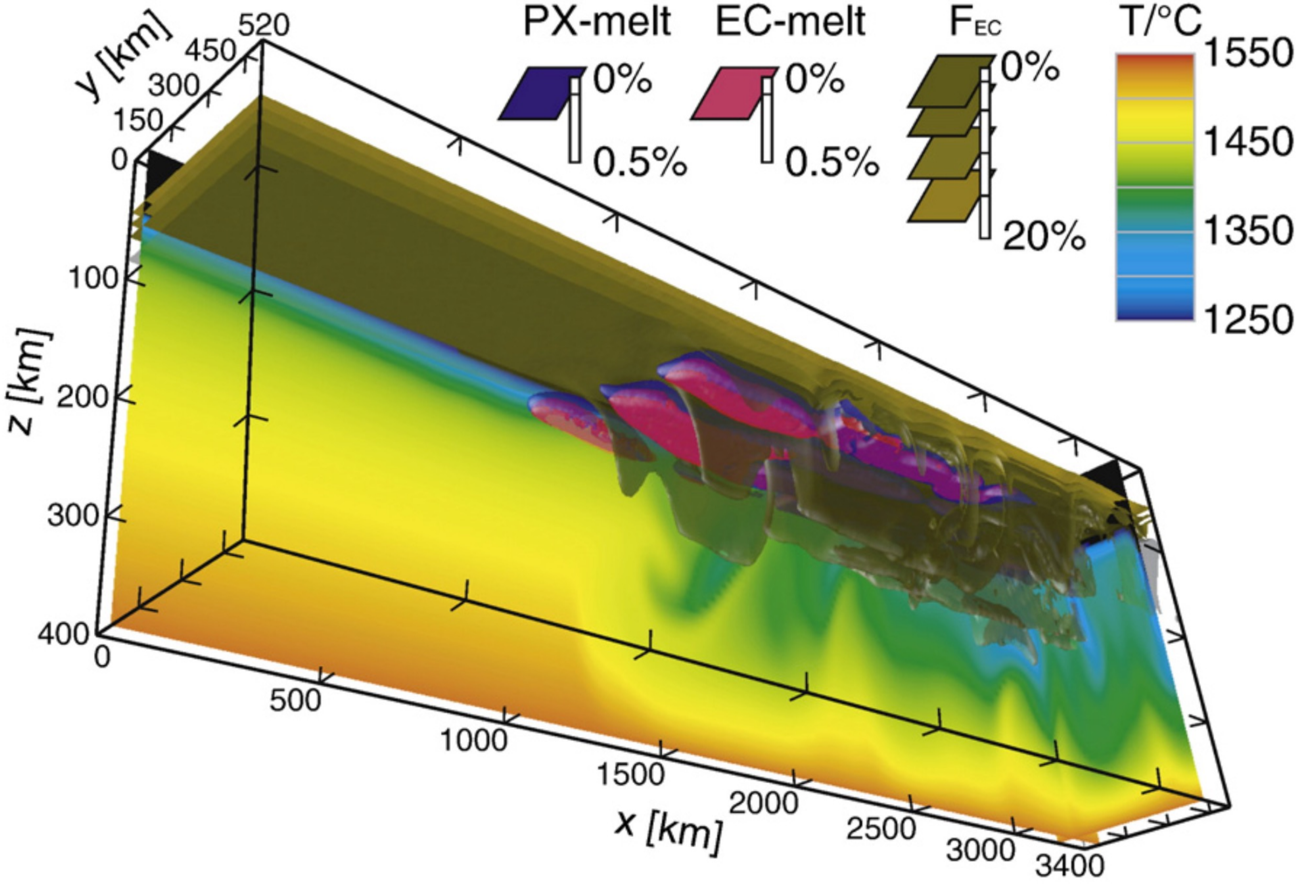
→ Explains some intraplate volcanism (continents & oceans)

Lithospheric Drips

[Elkins-Tanton & Hager, 2000]

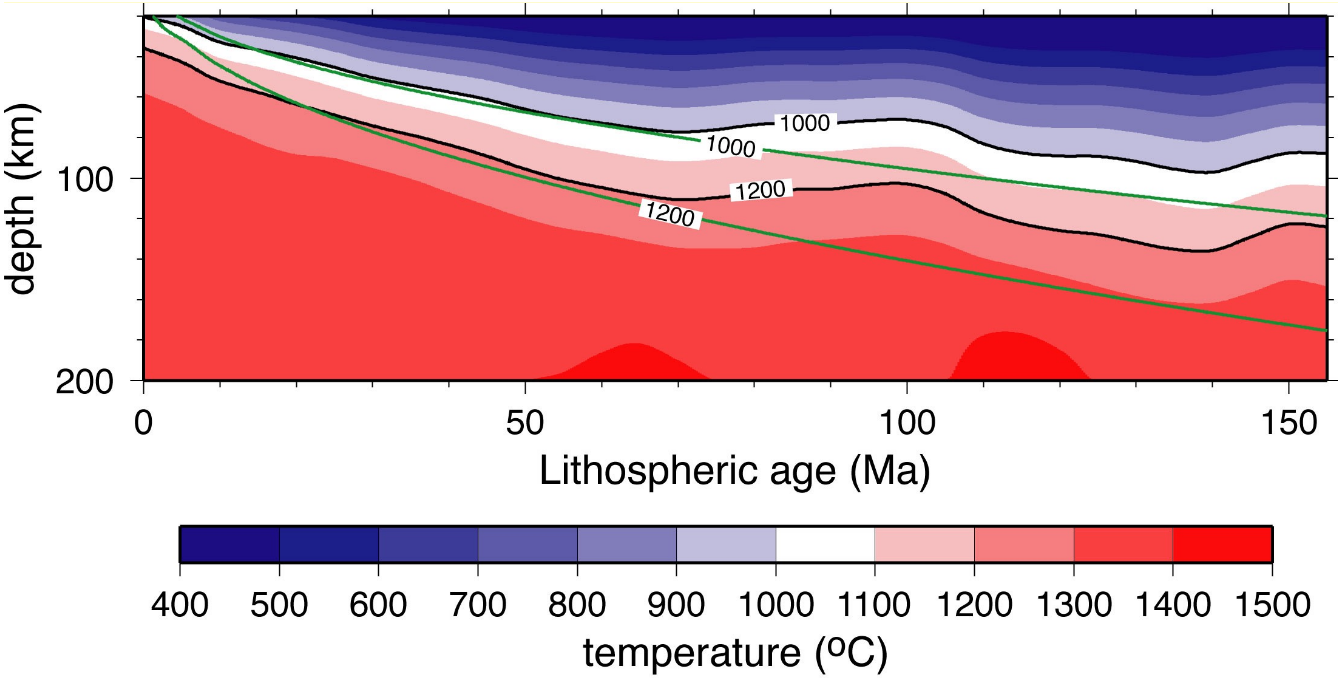






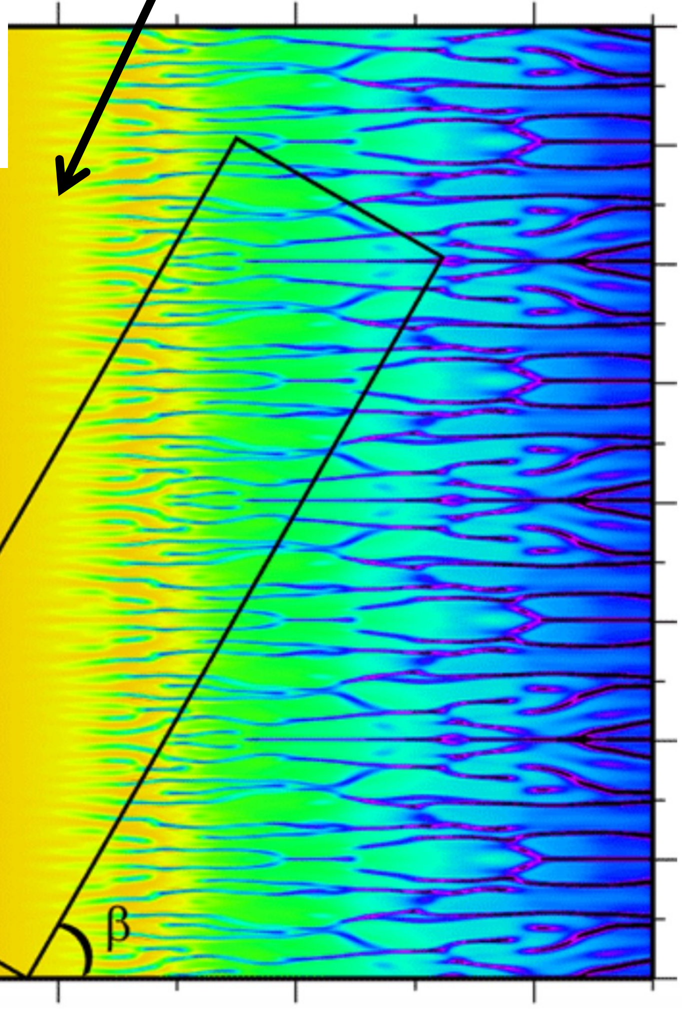
Small-Scale Convection (SSC) beneath the oceanic plates.
[*Ballmer et al.*, 2010]

“Richter Rolls” organize the volcanism into linear trends



Onset of small-scale convection

→ Occurs at a critical plate age

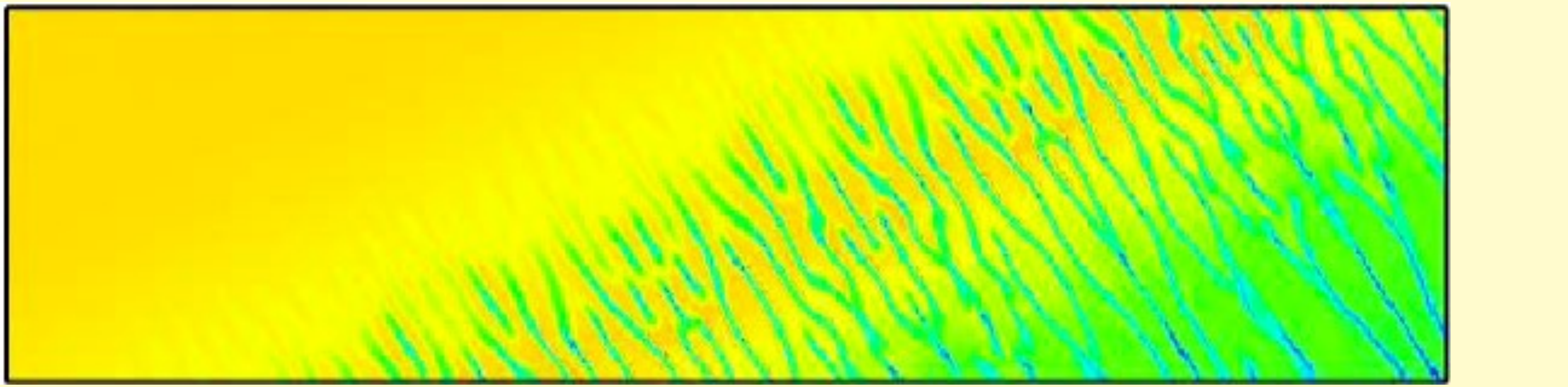


Thermal Profile of the Pacific Lithosphere

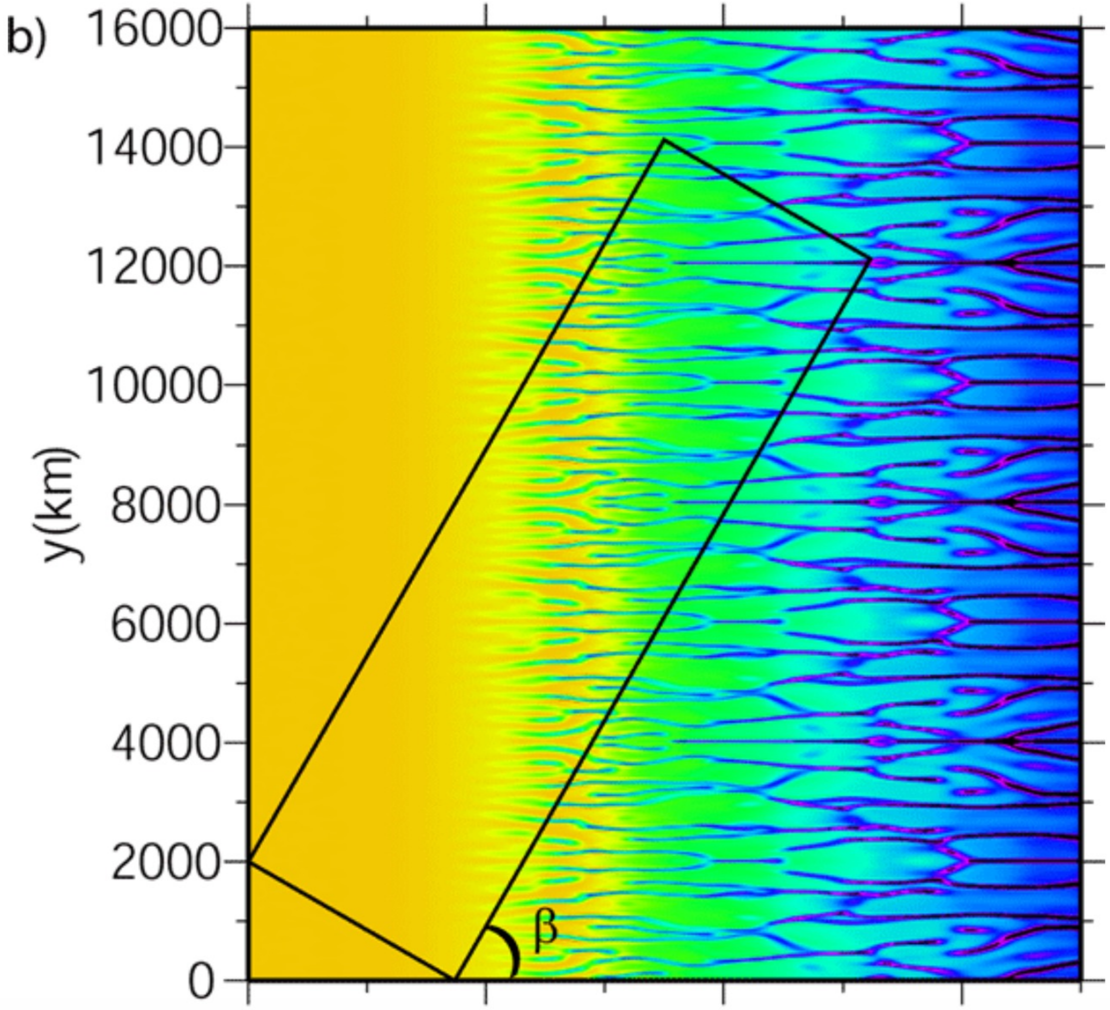
→ Onset at ~70 Myr (?)

[*Ritzwoller et al.*, 2004]

van Hunen & Zhong [2006]

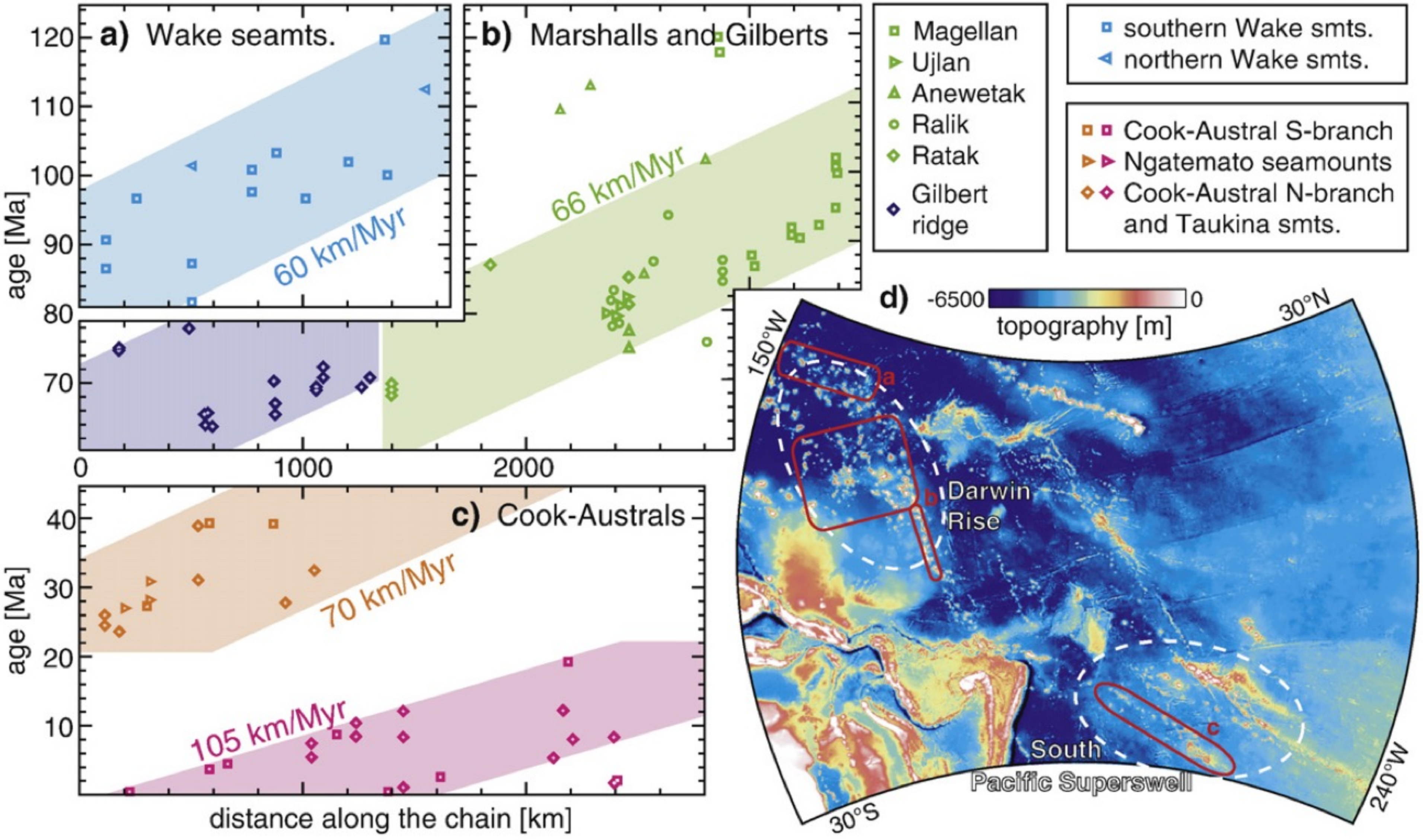


Richter Rolls organize into the direction of plate motion

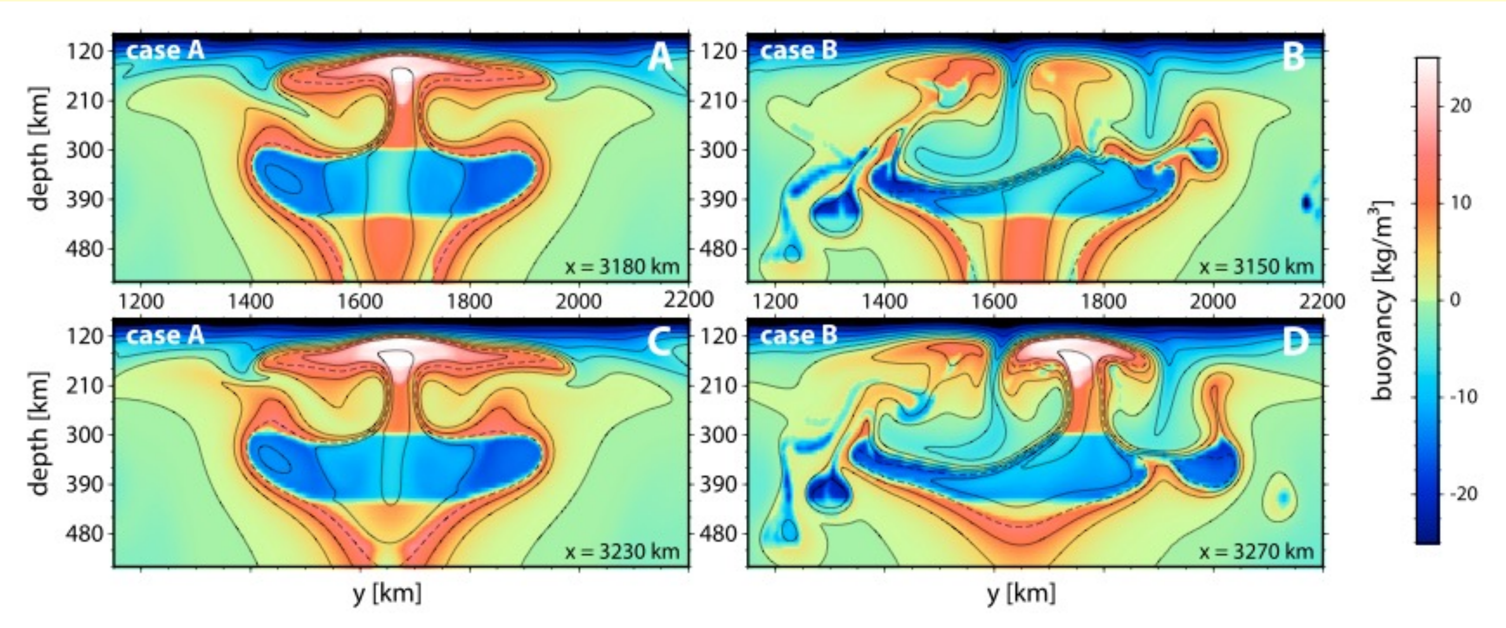


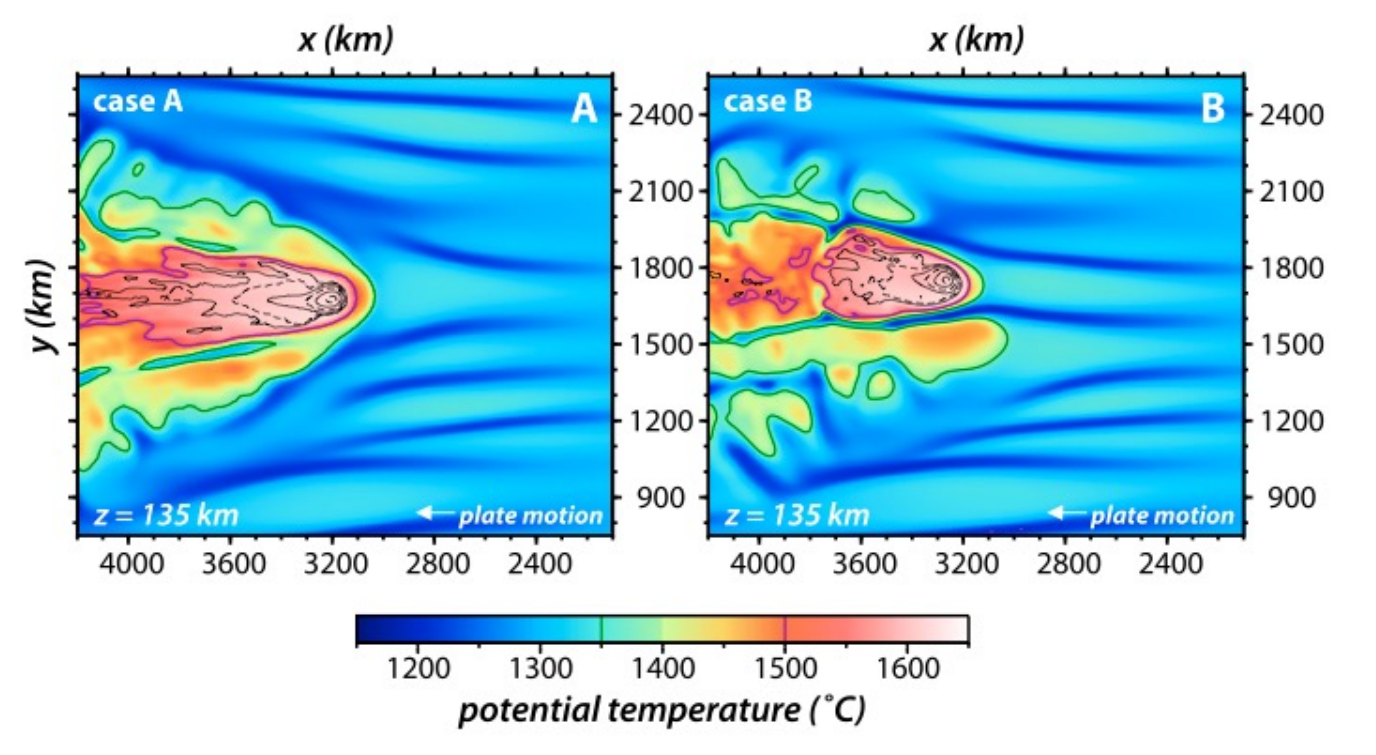
van Hunen & Zhong [2006]

SSC may explain some mountains and minor volcanism.



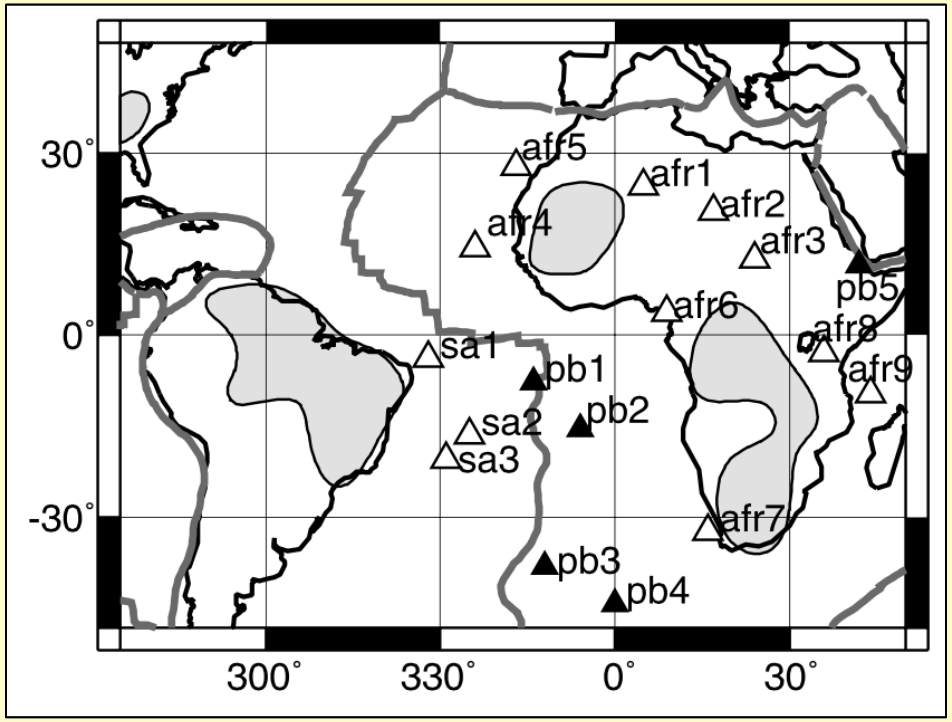
Ballmer et al., 2010



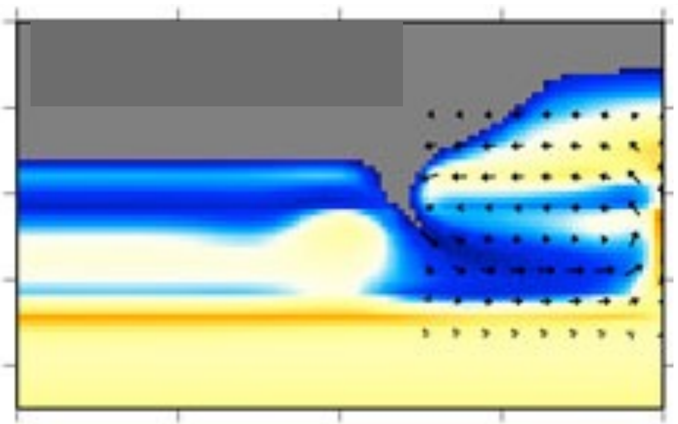


Interaction of a plume with small-scale convection

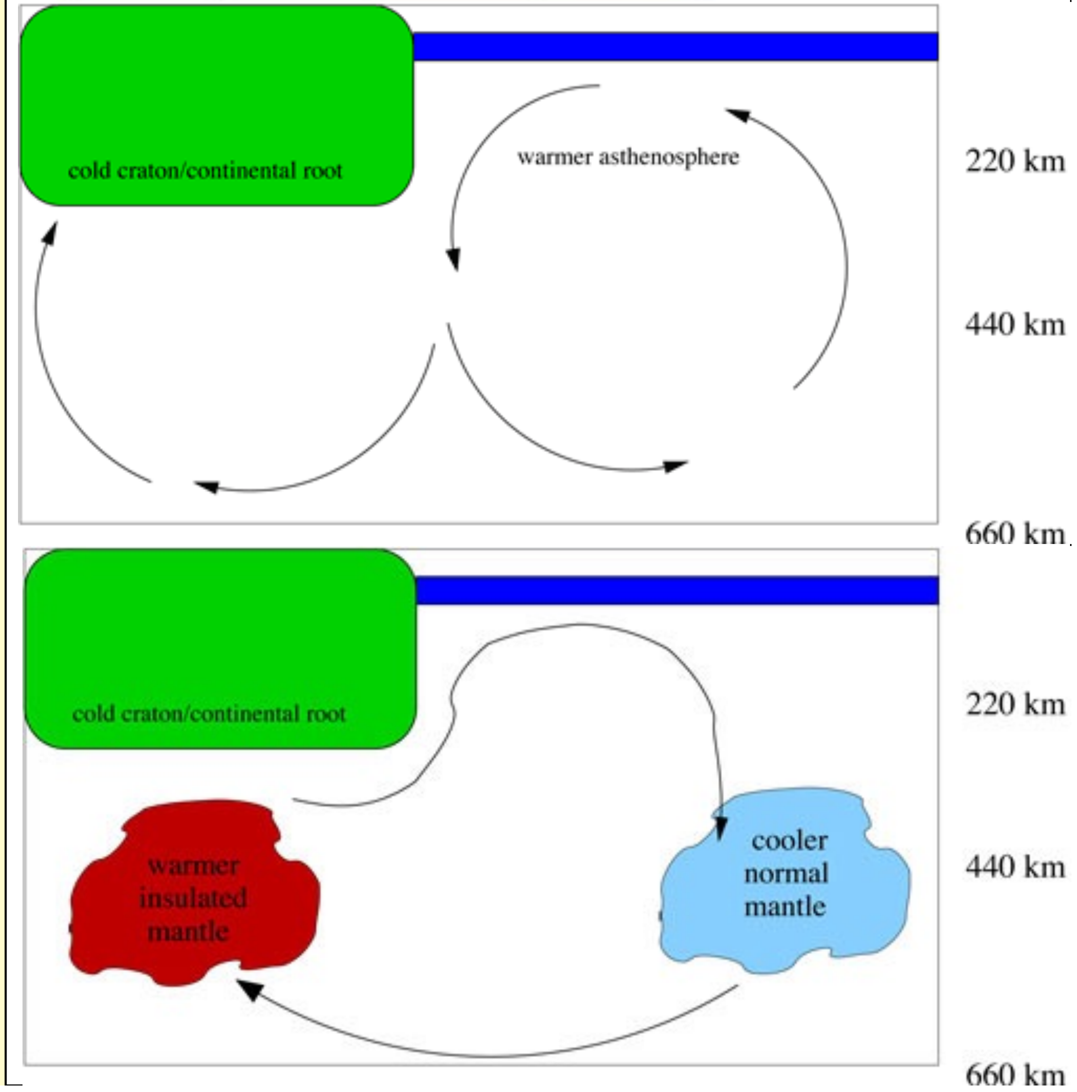
Ballmer et al., 2013



King & Ritsema [2000]



King & Anderson [1998]



Edge-Driven Convection

The edge of a craton focuses upwelling flow that leads to volcanism.

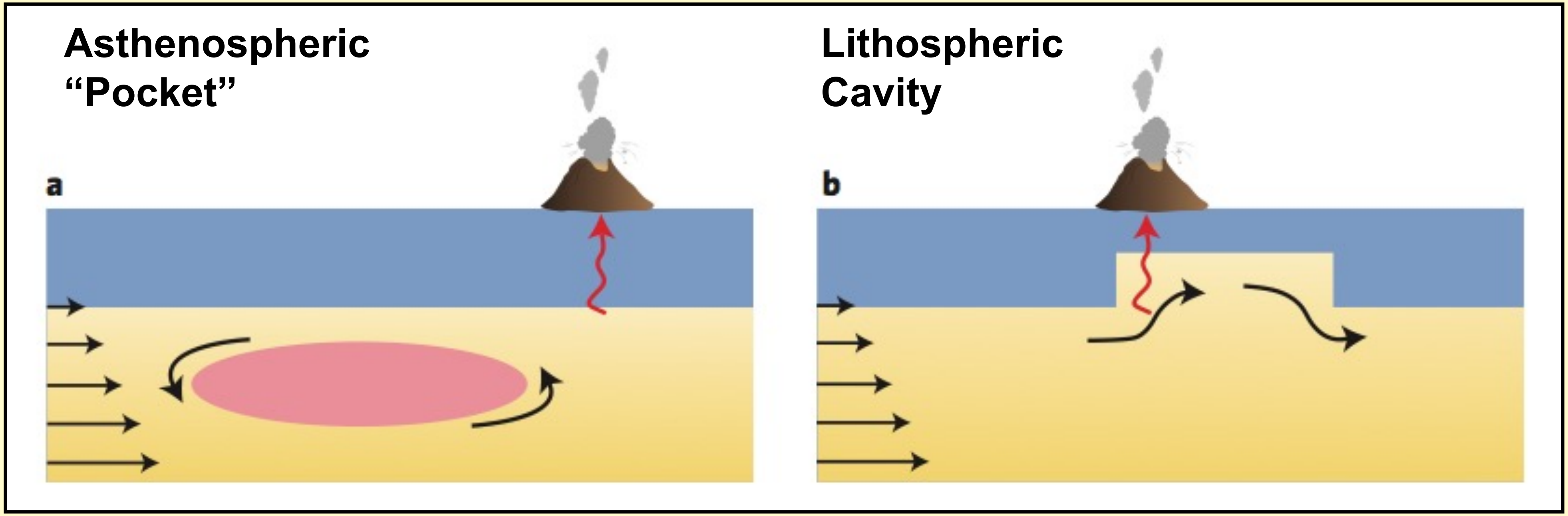
3. Shear-Driven Upwelling (SDU)

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

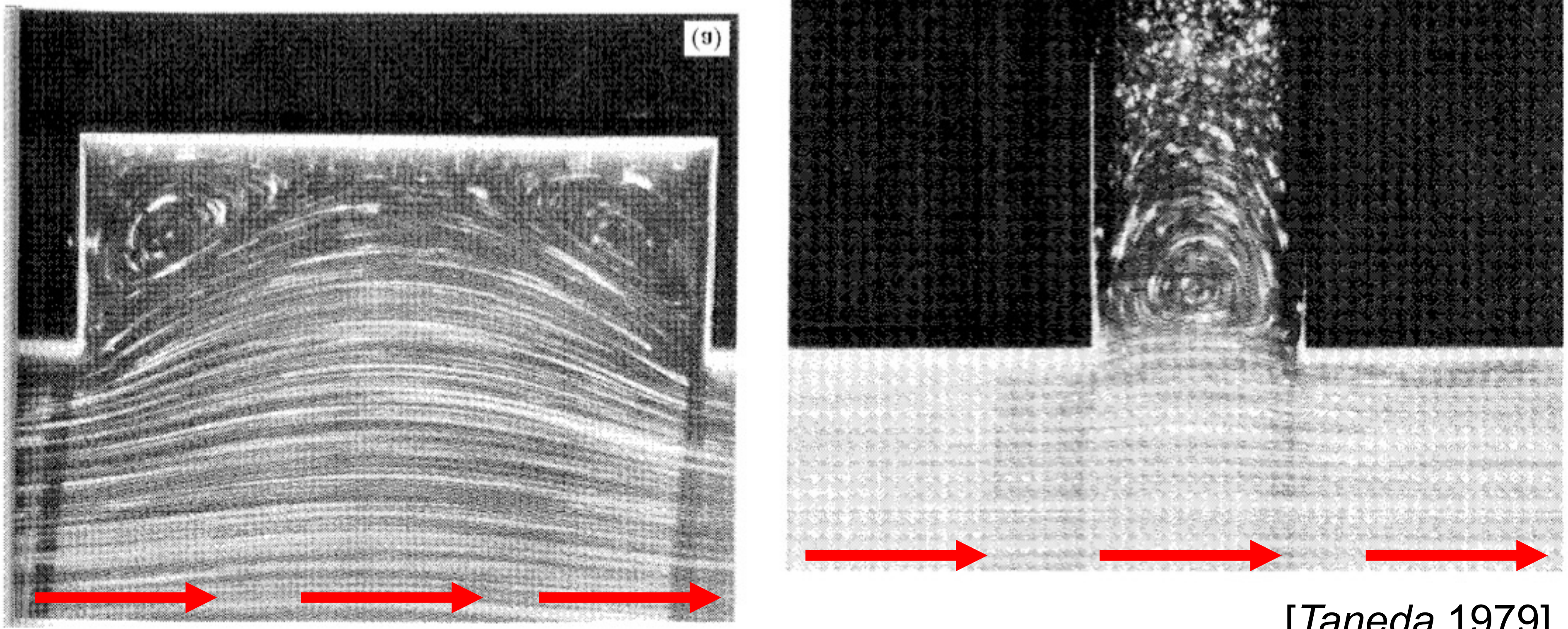


King [*News & Views, Nature Geoscience*,2011]

Shear-Driven Cavity Flow
A classic engineering problem

Industrial Applications:

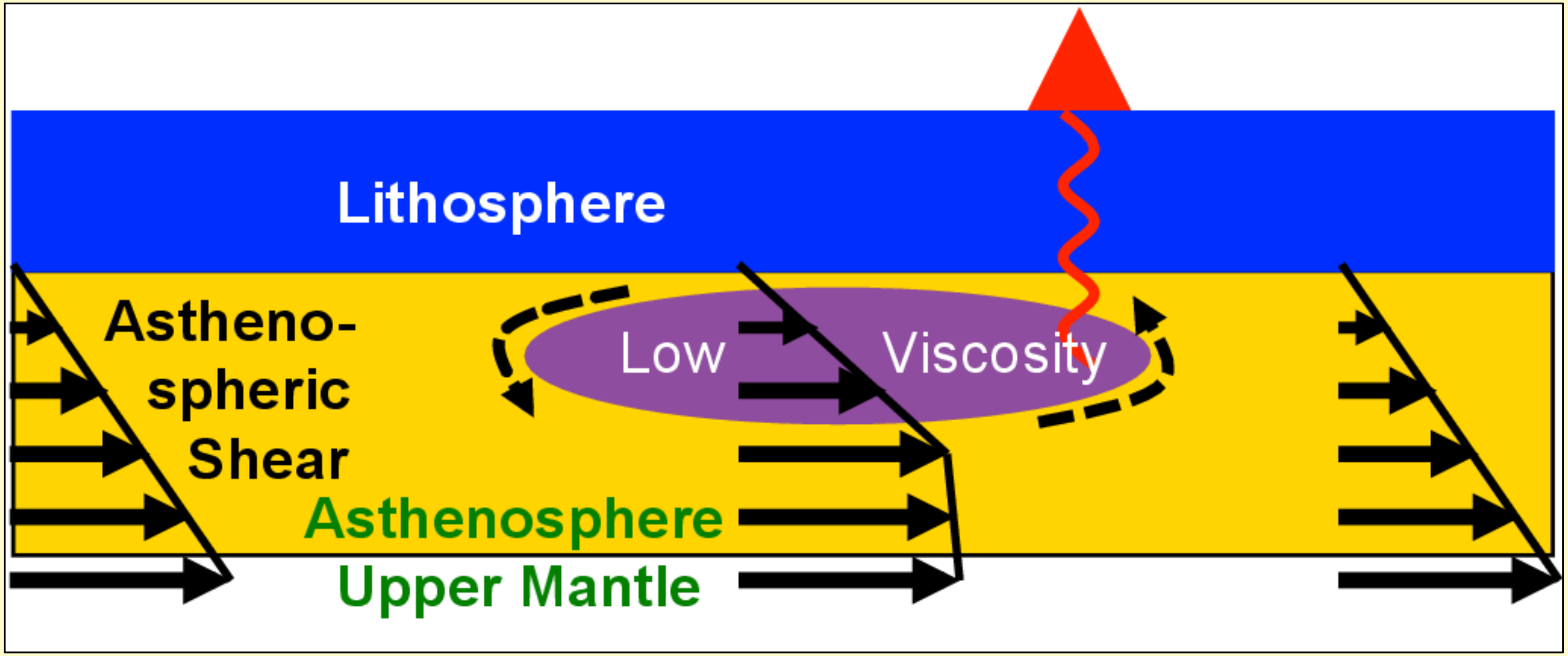
- Spin Coating
- Mixing Processes
- Liquid cooling by melt spinning
- Benchmark for computational schemes


Shear-Driven Cavity Flow

[*Taneda*,1979]

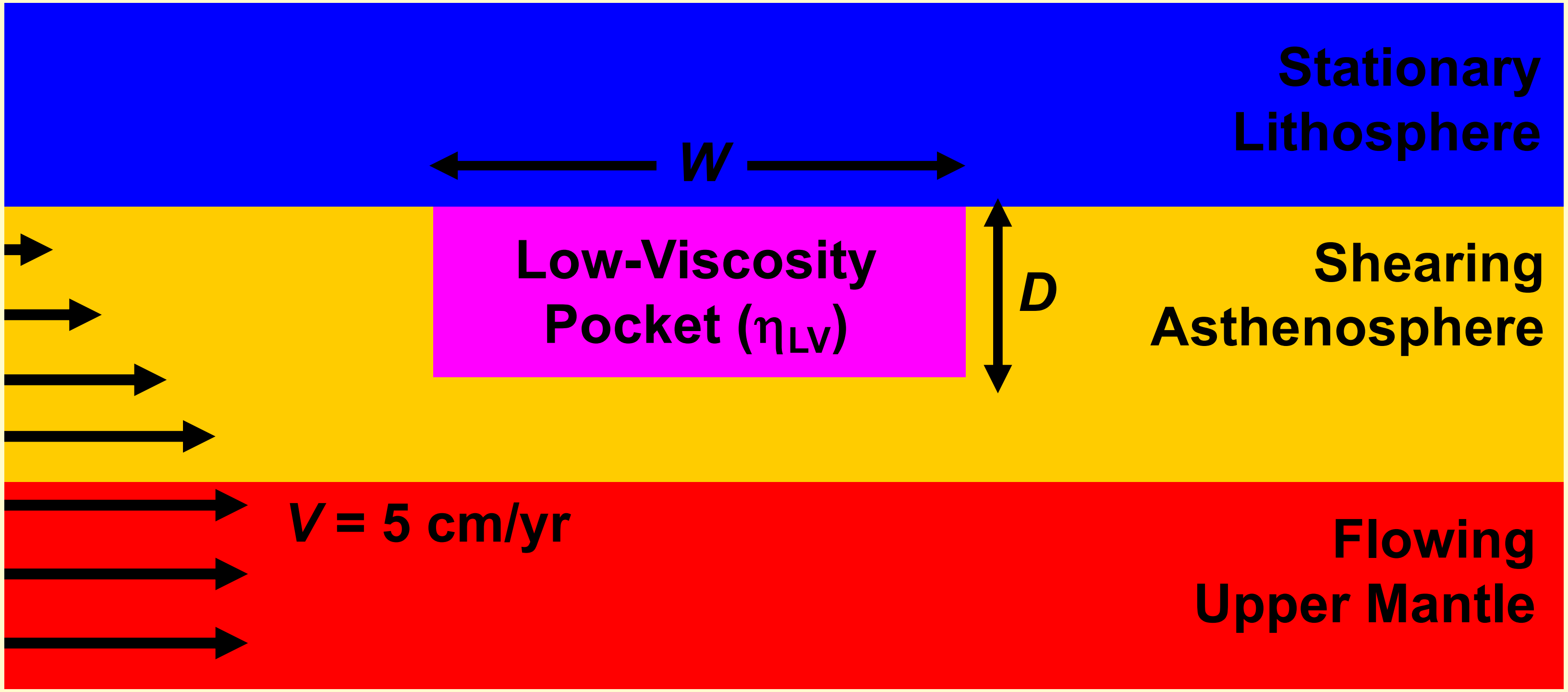
Shear-Driven Upwelling within an Low-Viscosity Pocket

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



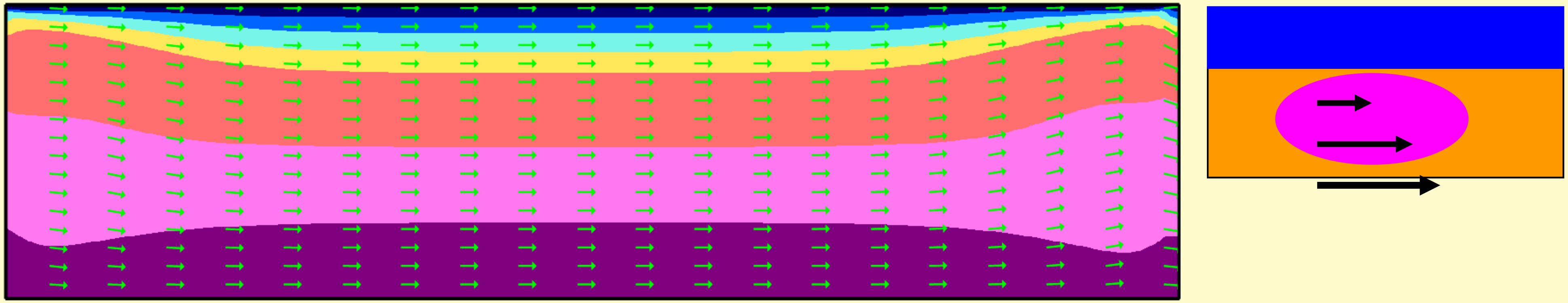
Measuring SDU within an Low-Viscosity Pocket

- Flow simulation of viscous shear in 2D
- Vary the dimensions and viscosity of the pocket
- Measure maximum upwelling

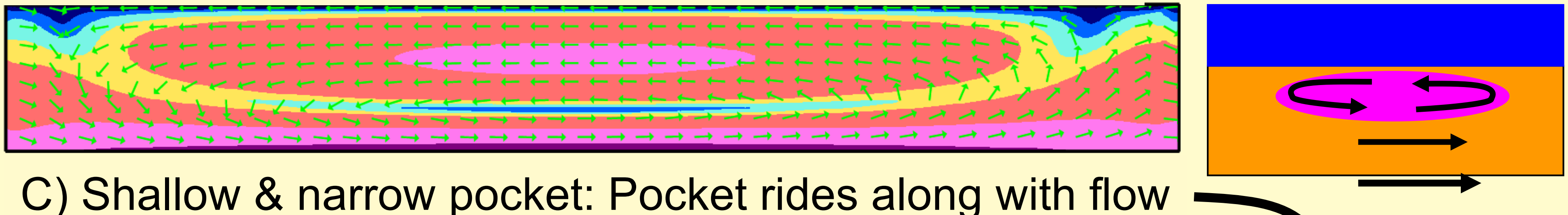


Flow patterns within a low-viscosity "pocket"

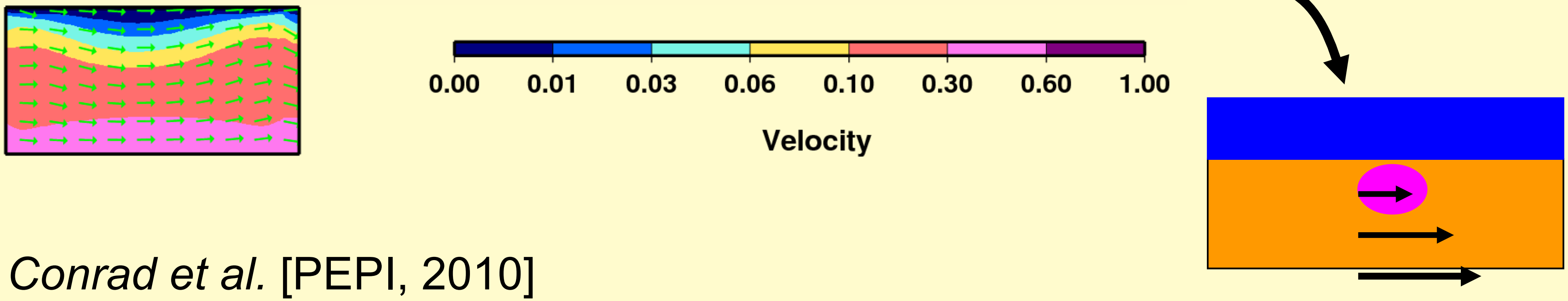
A) Thick pocket: Shear develops within the pocket



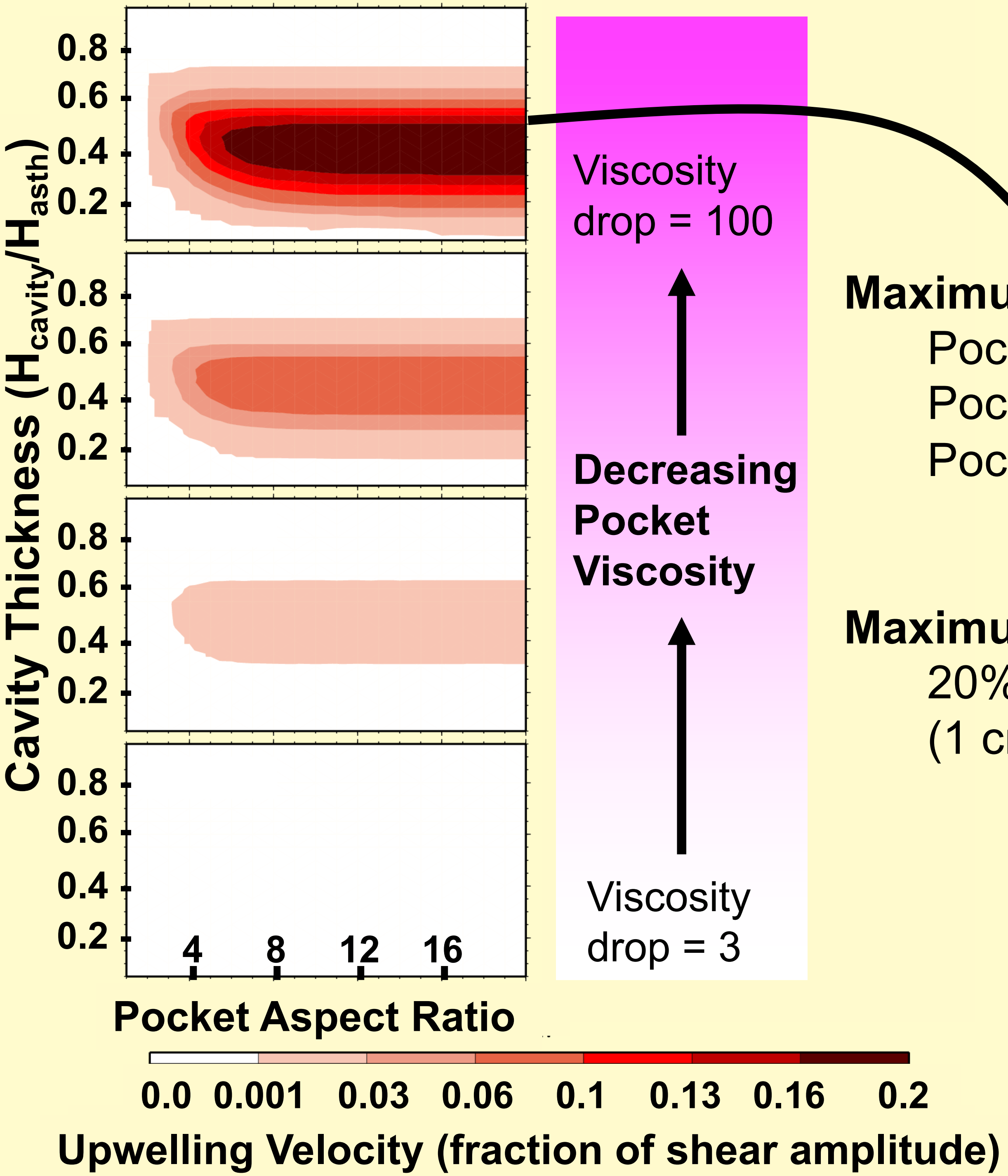
B) Shallow & wide pocket: Circulation within the pocket



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



Conrad et al. [PEPI, 2010]



Maximum upwelling occurs for:

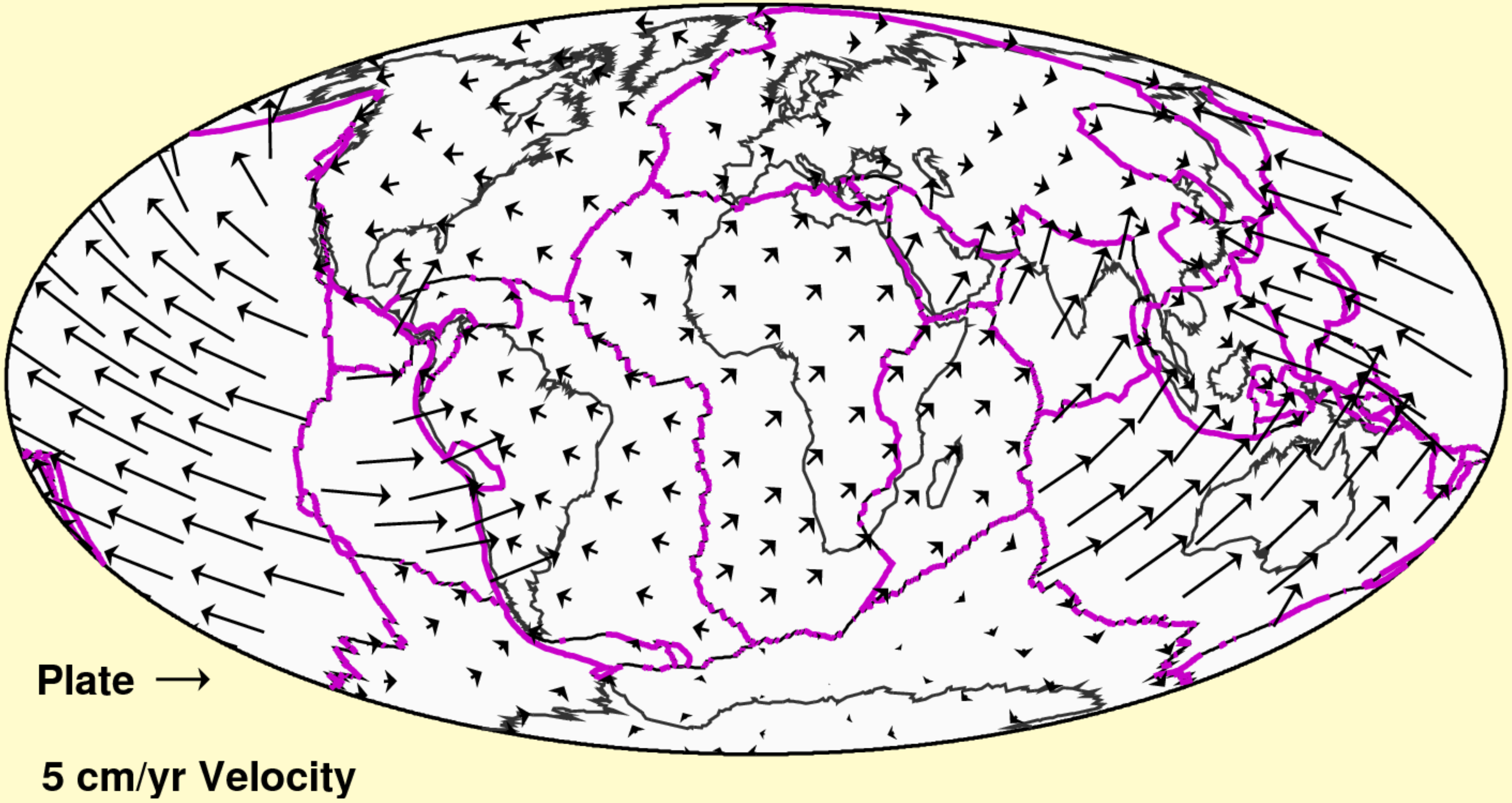
Pocket viscosity drop of 100
Pocket aspect ratio > 5
Pocket occupies the upper
20-60% of asthenosphere

Maximum rate of upwelling:

20% of *V*
(1 cm/yr)

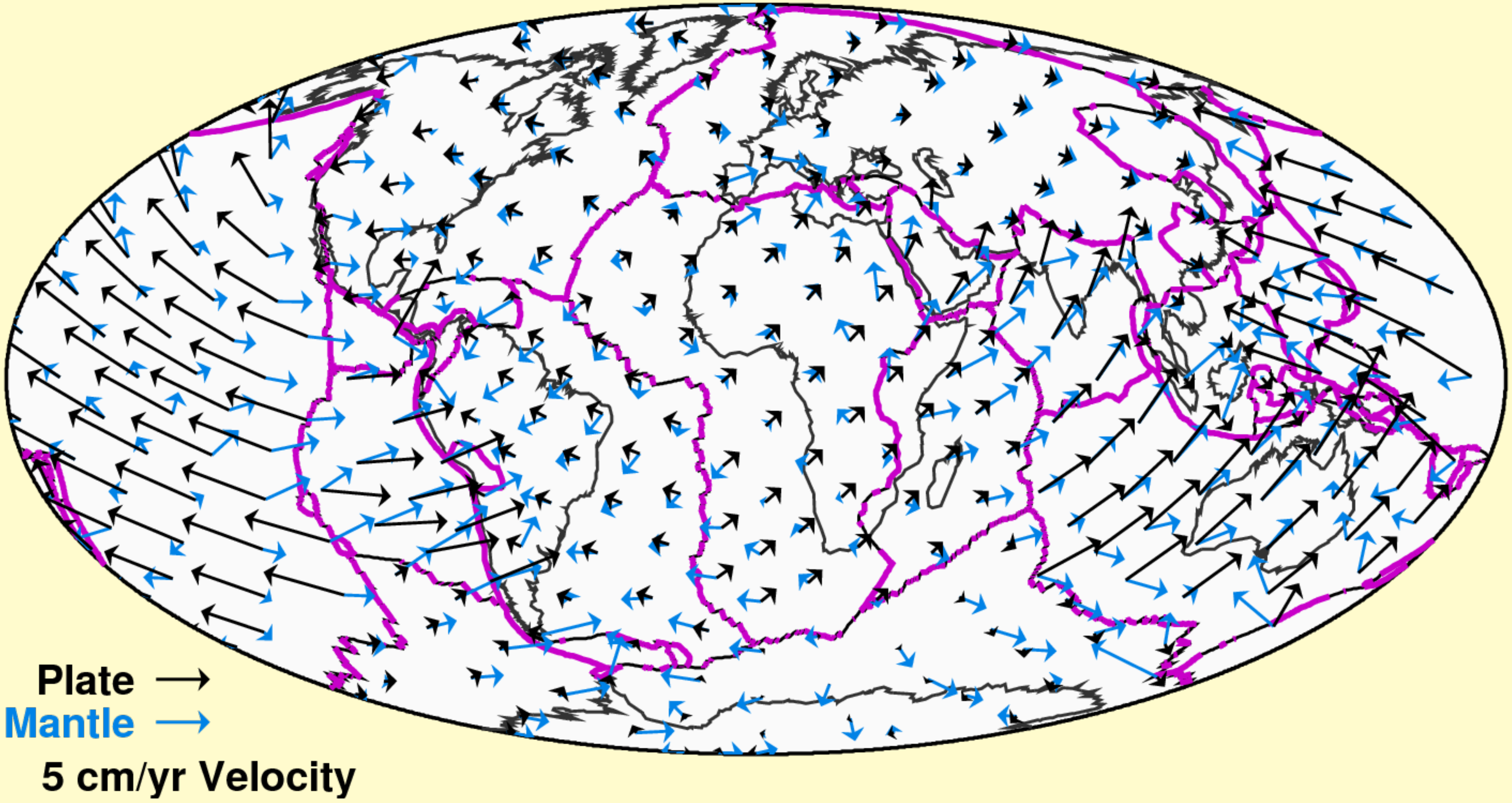
Conrad et al. [PEPI, 2010]

Where is asthenospheric shear largest?



Surface Plate Motions

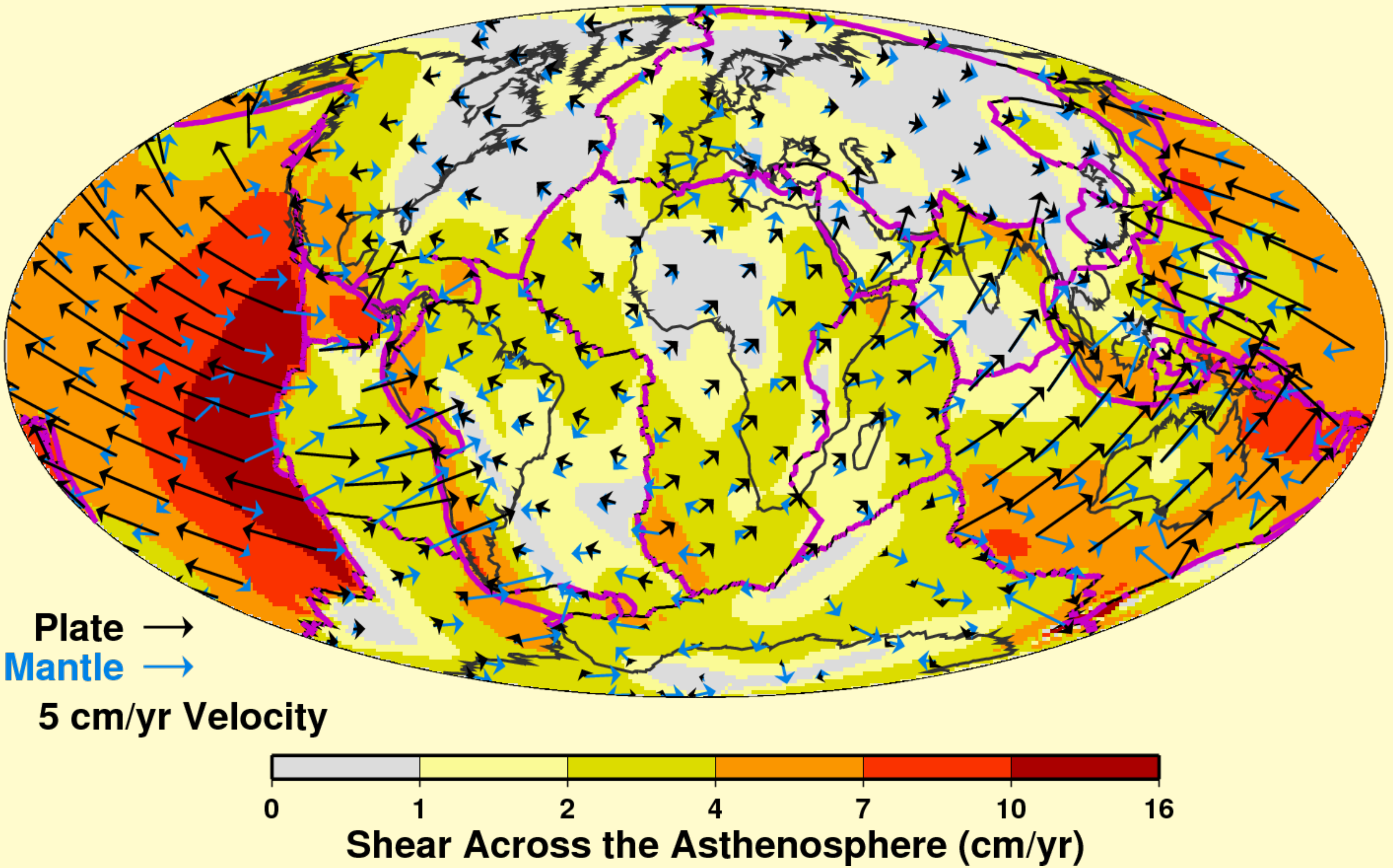
Where is asthenospheric shear largest?



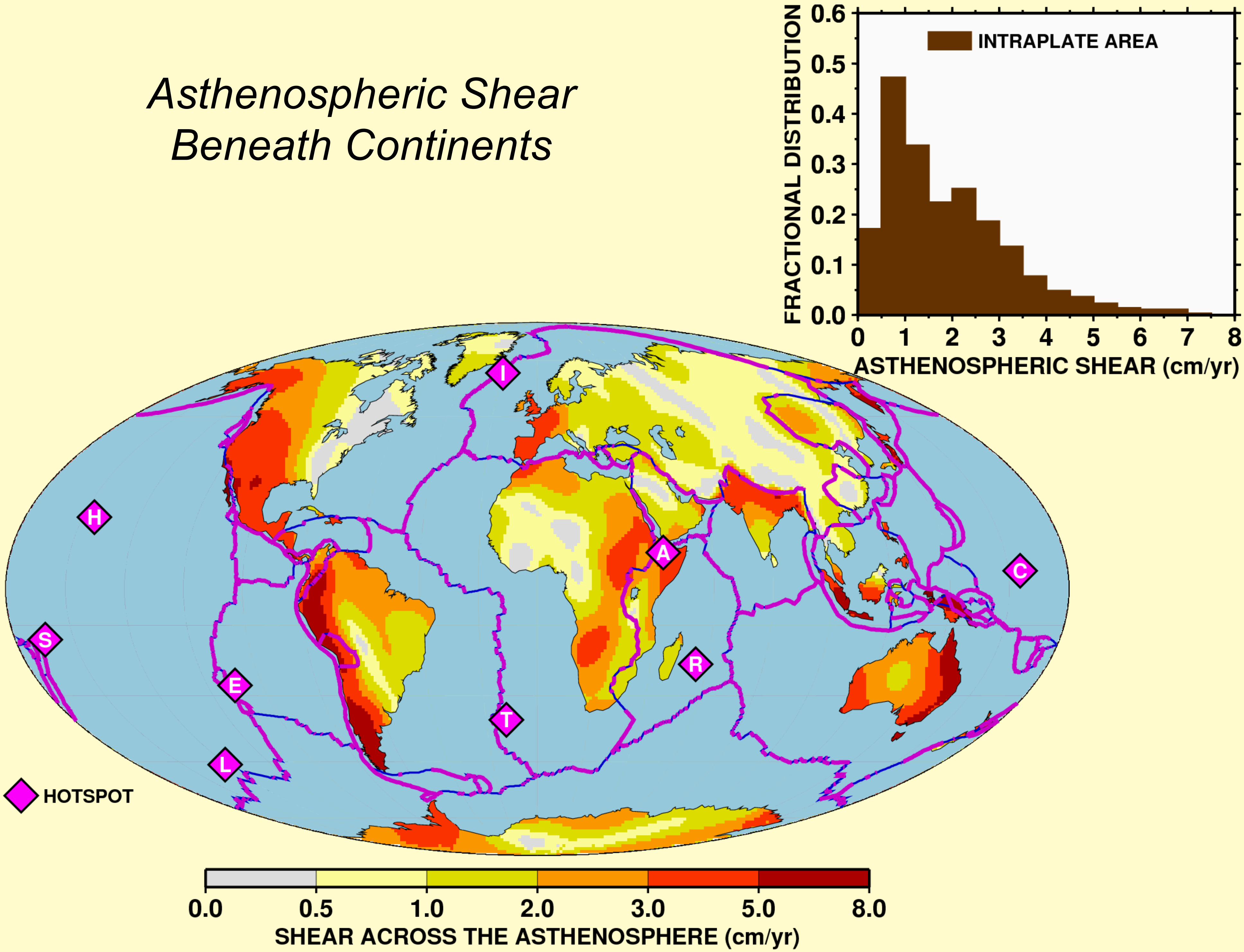
Surface Plate Motions and Mantle Flow at 300 km

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

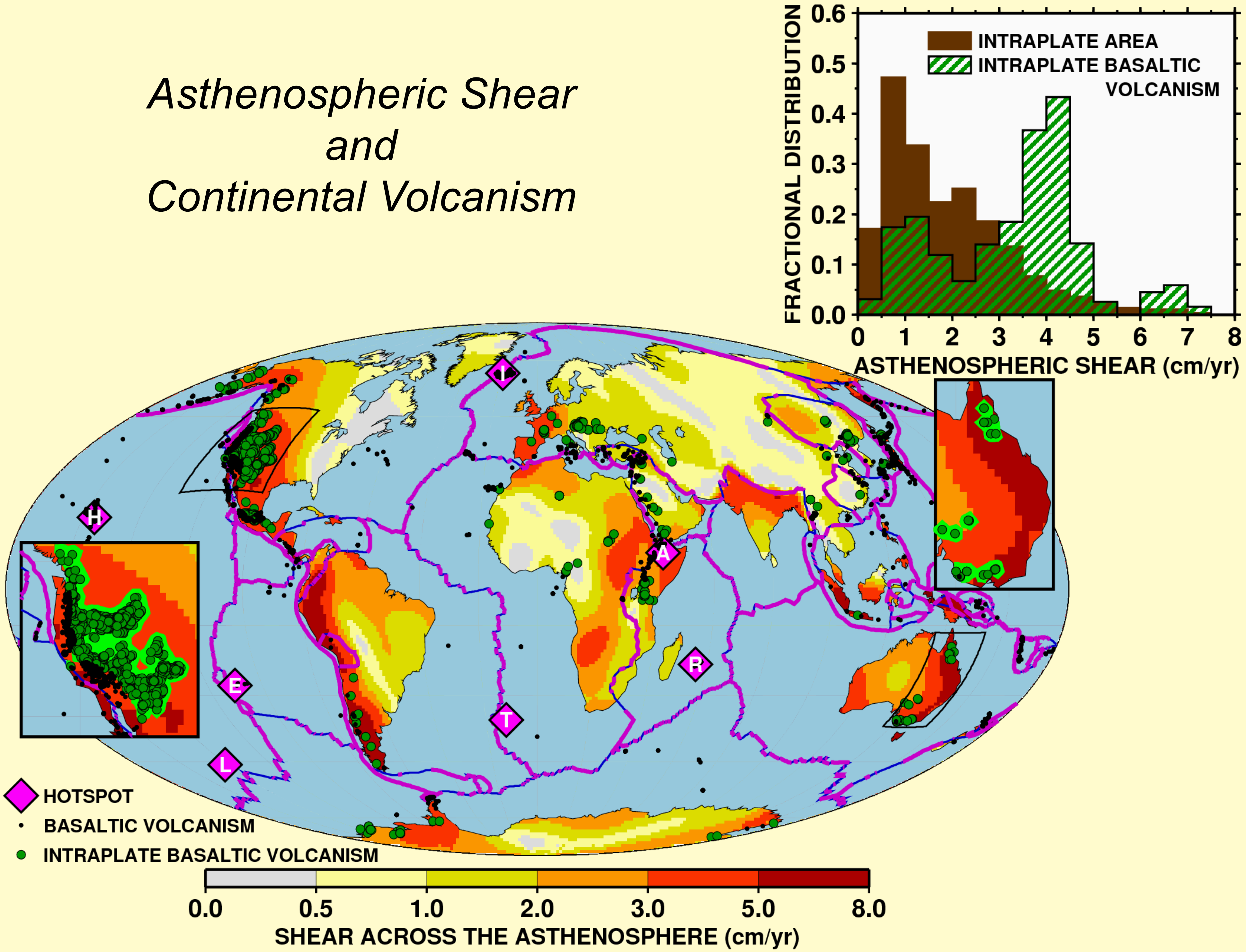
Where is asthenospheric shear largest?



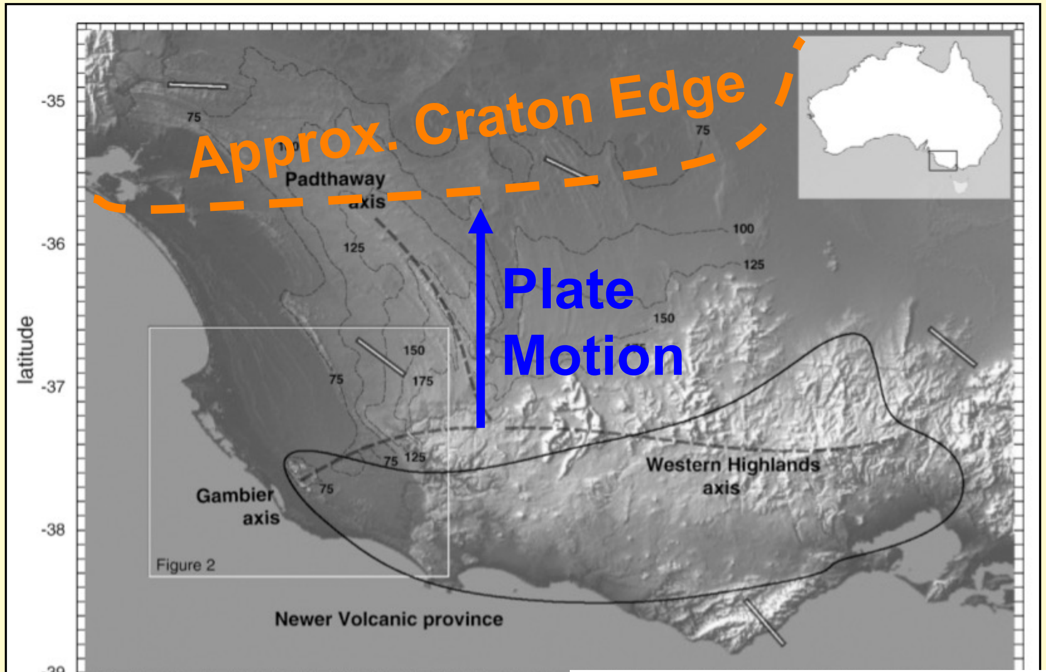
Asthenospheric Shear Beneath Continents



Asthenospheric Shear and Continental Volcanism

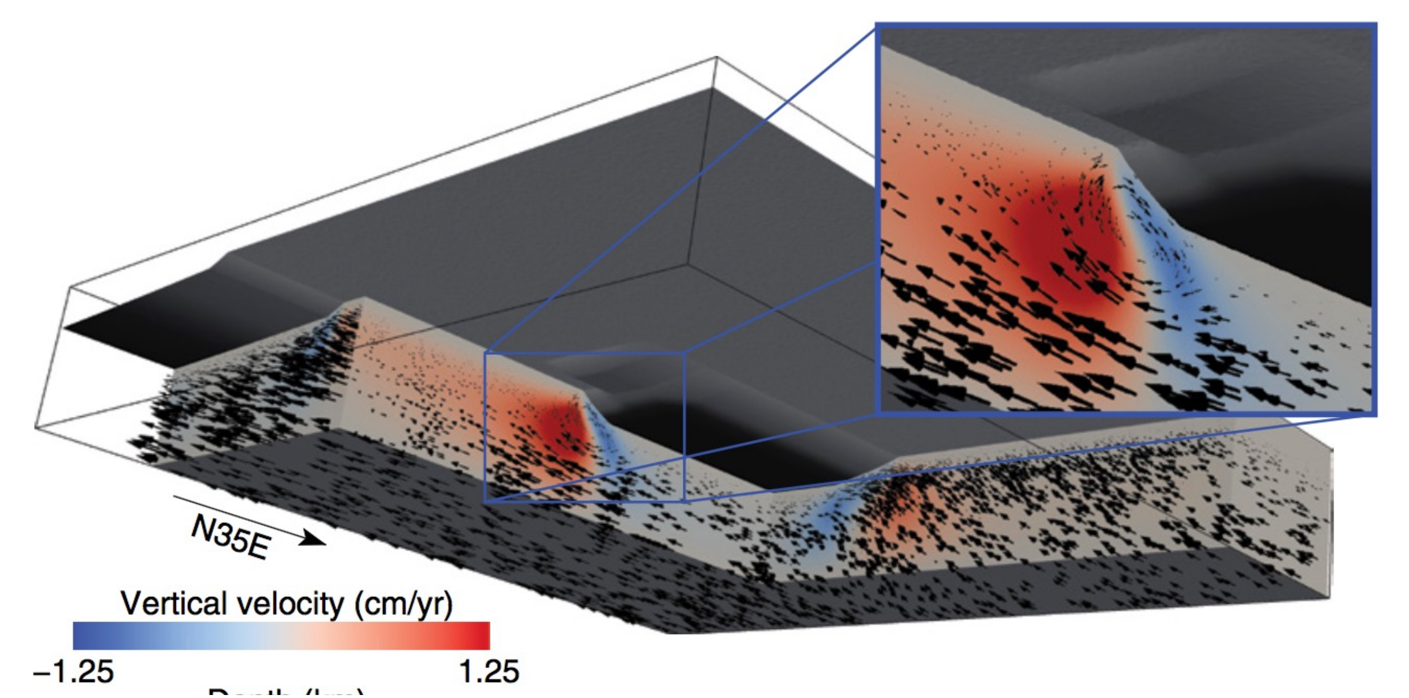


The Newer Volcanic Province (South Australia)



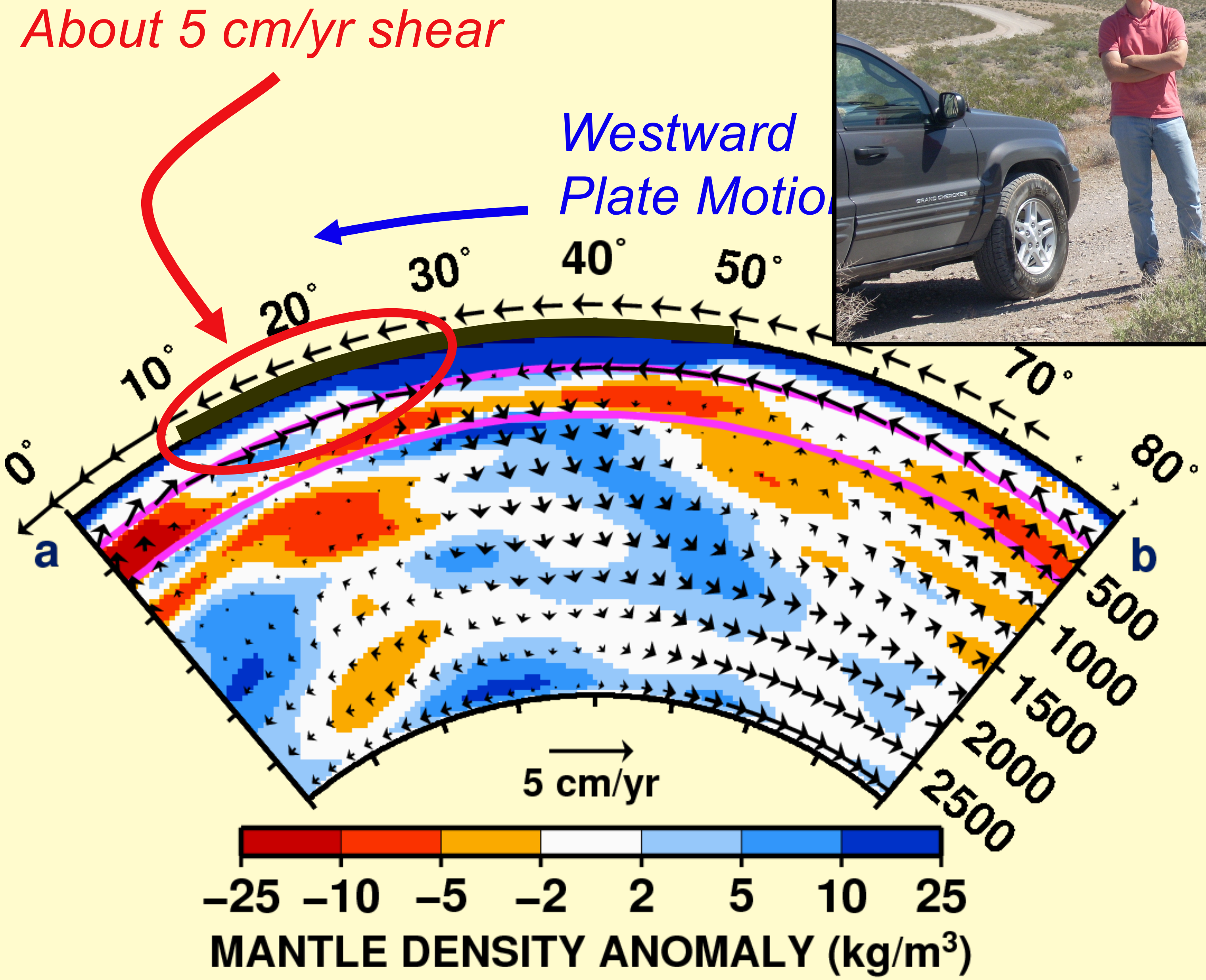
Mt. Gambier, Erupted 4500 yrs ago

SDU-like model →



Davies & Rawlinson [2014]

Asthenospheric Shear beneath the Western US

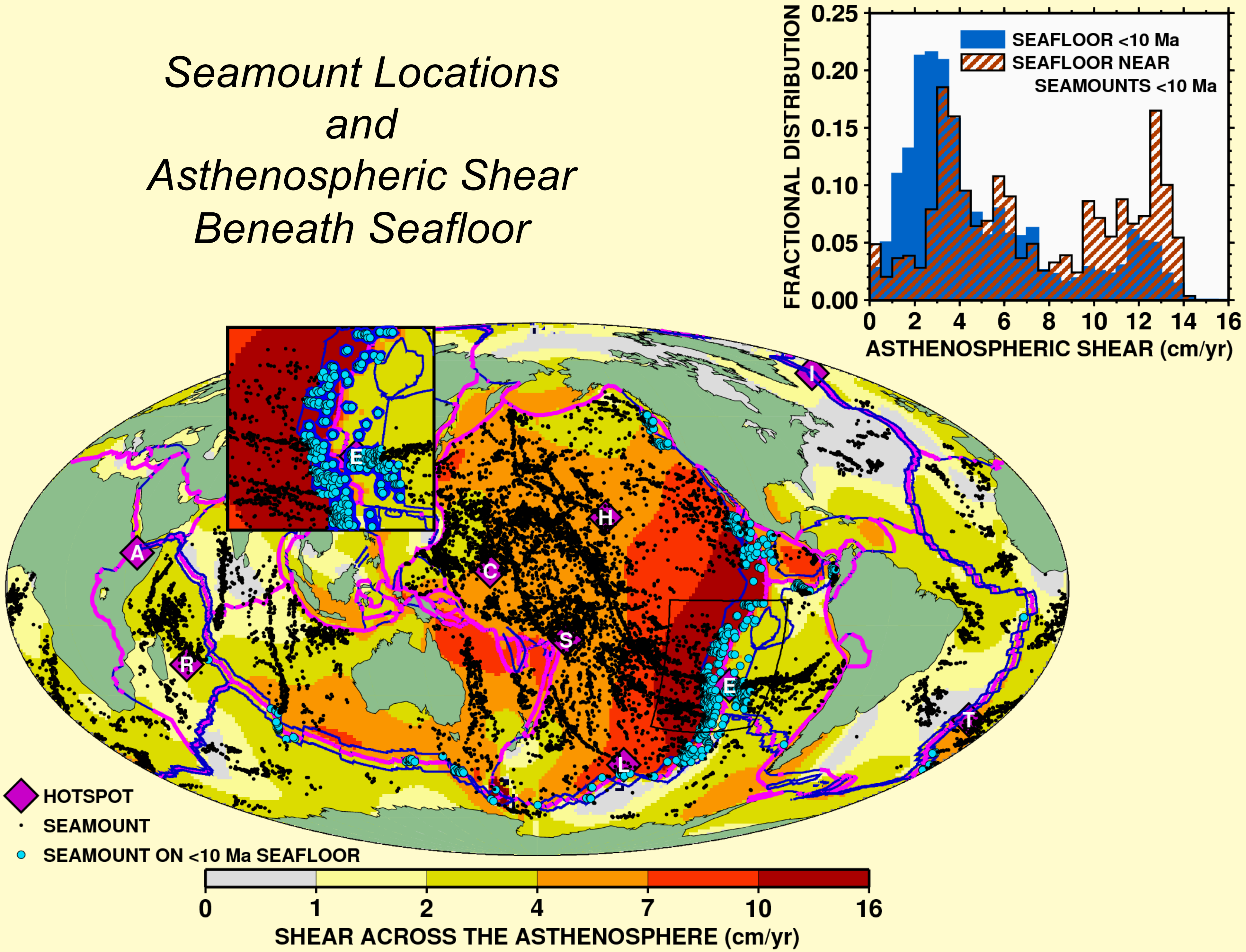


About 5 cm/yr shear

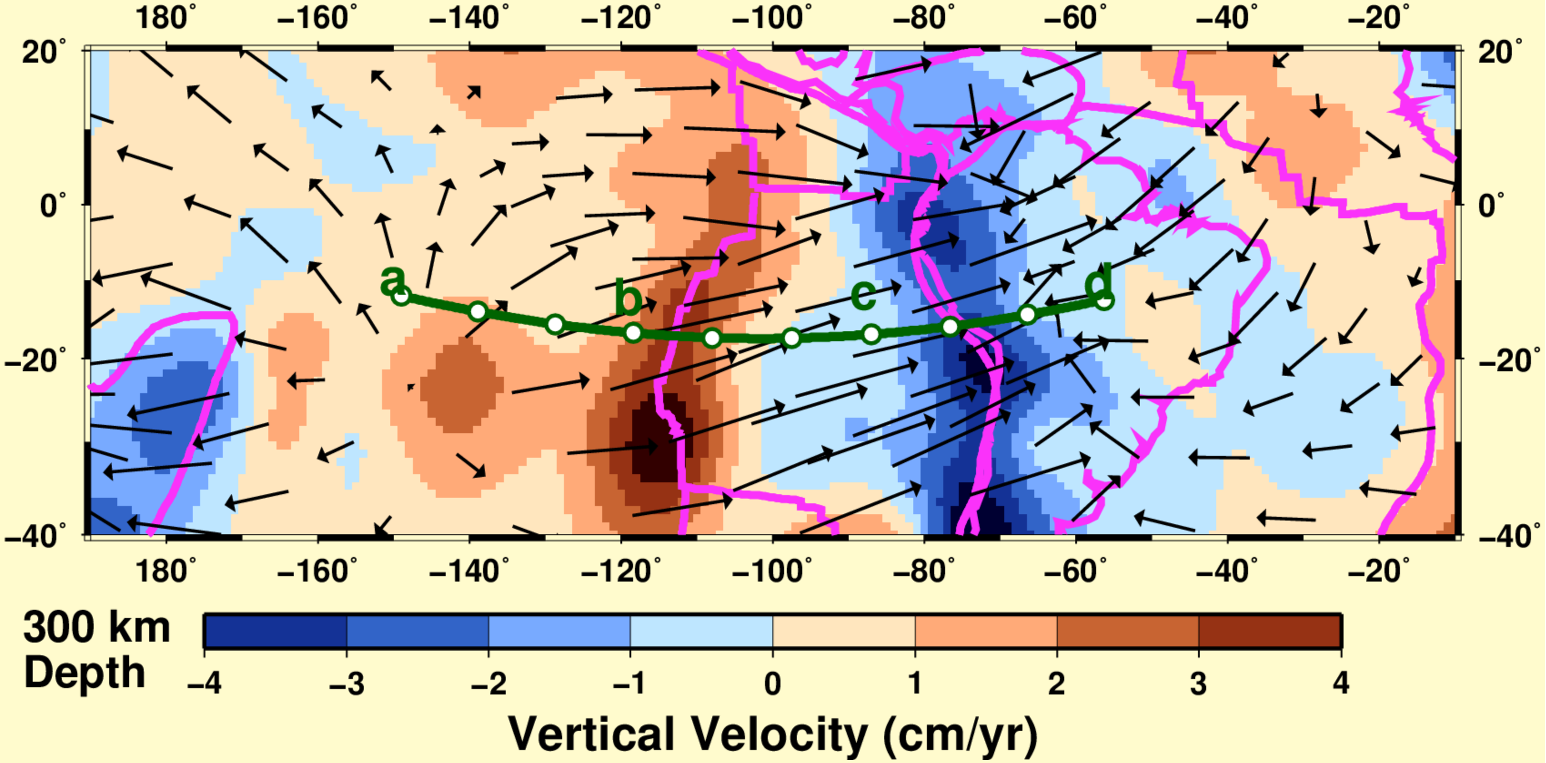
Westward Plate Motio

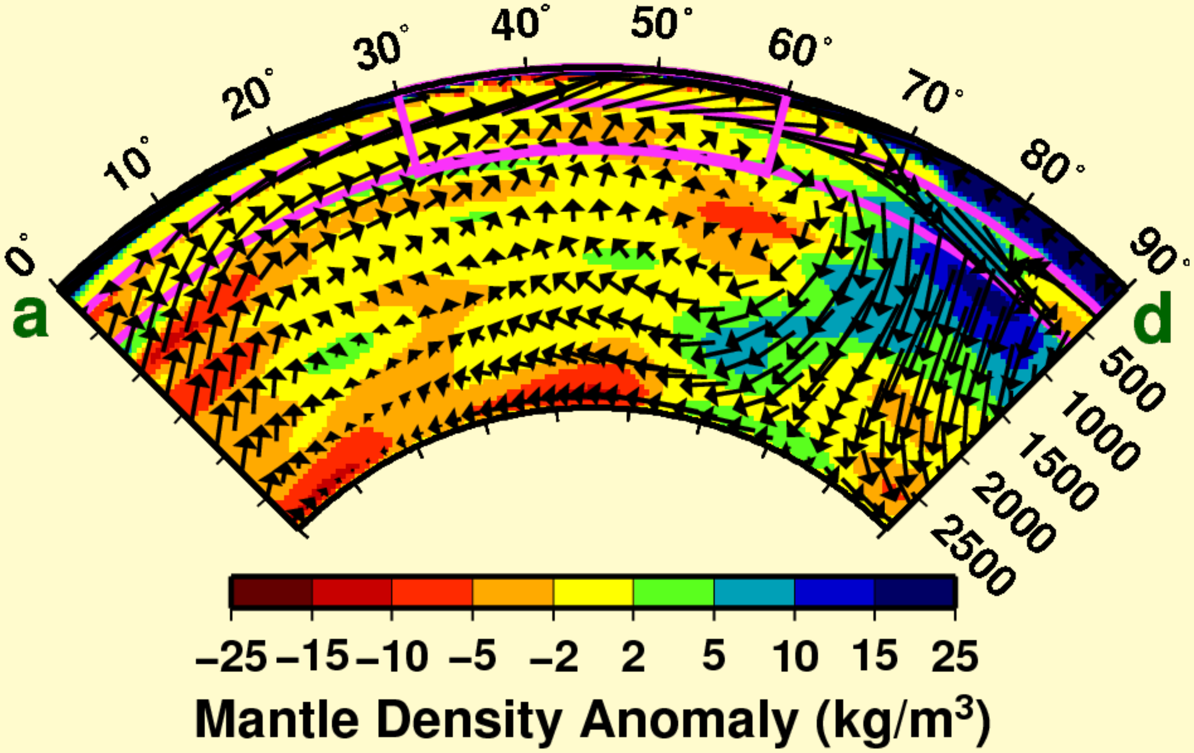
Crater Flat, Southern Nevada

Seamount Locations and Asthenospheric Shear Beneath Seafloor

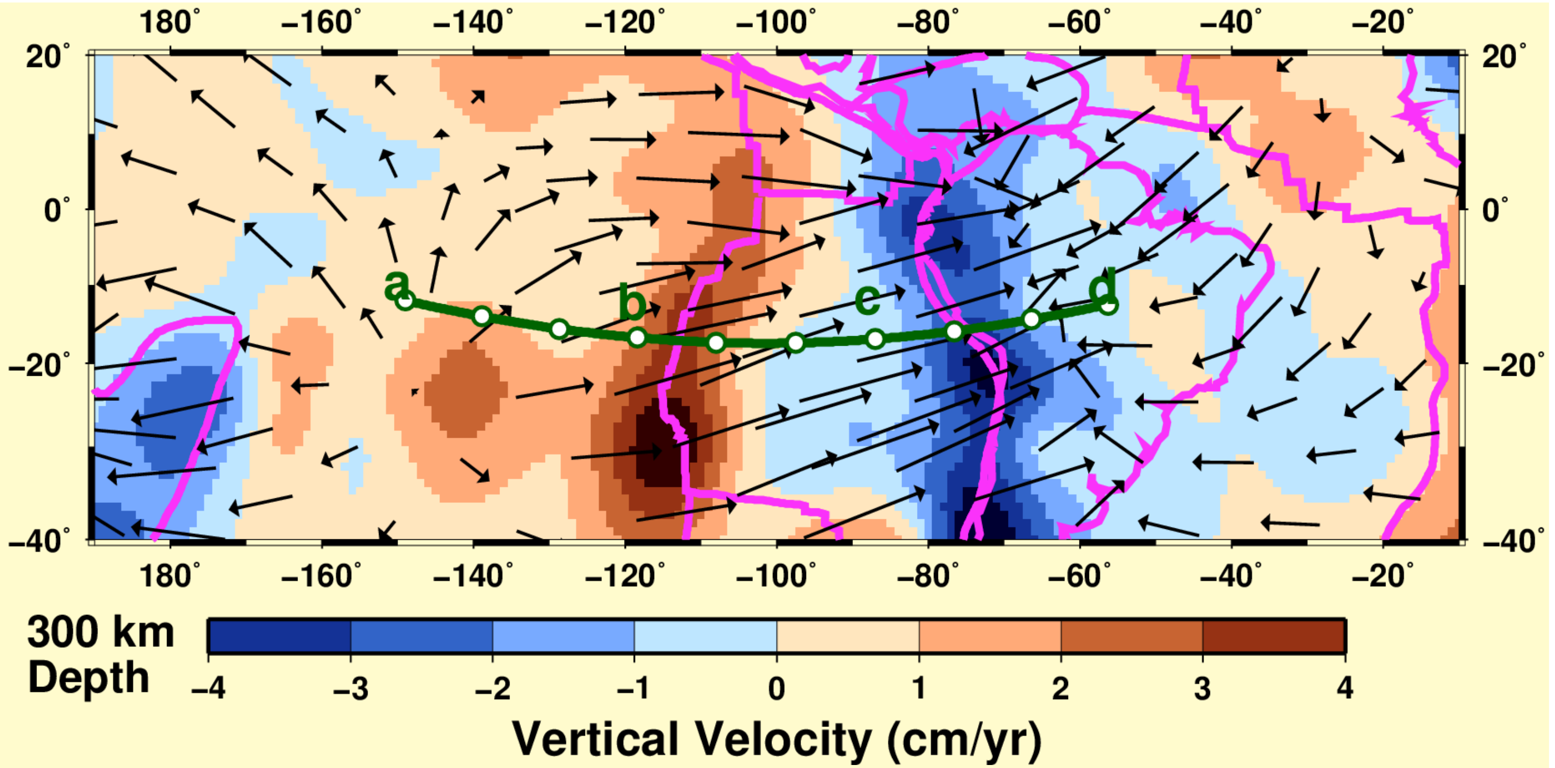


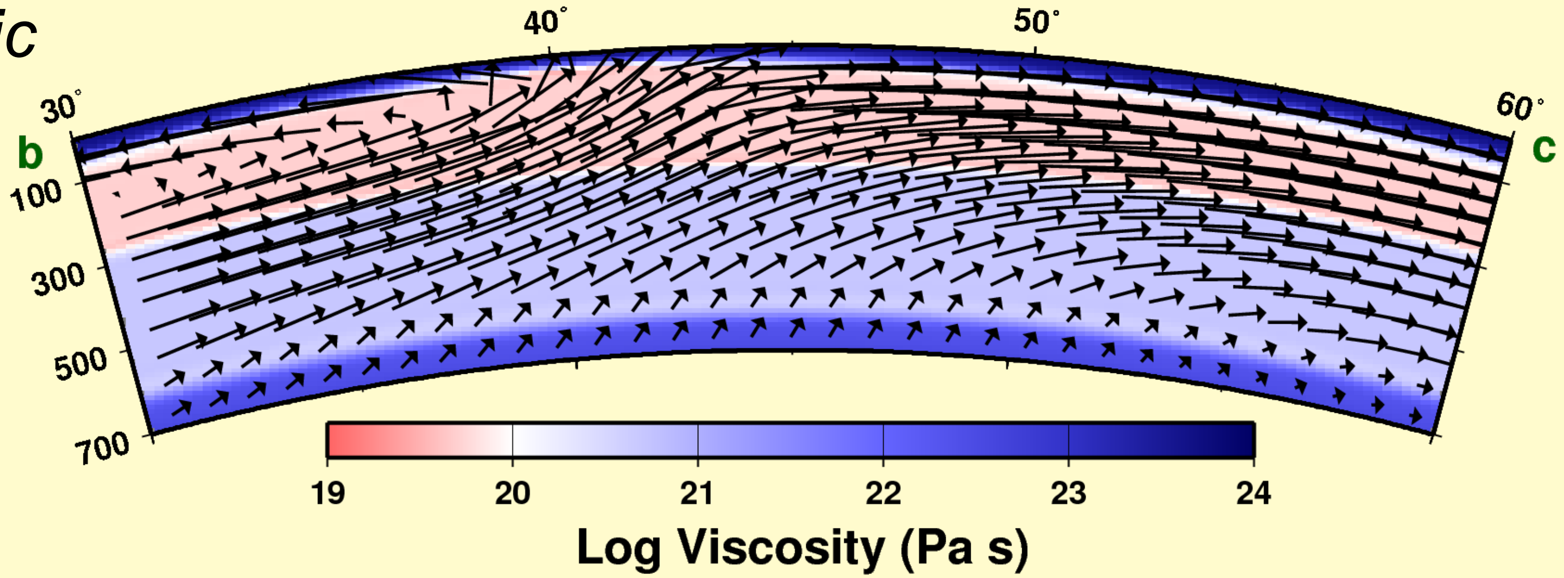
Mantle Flow beneath the South Pacific





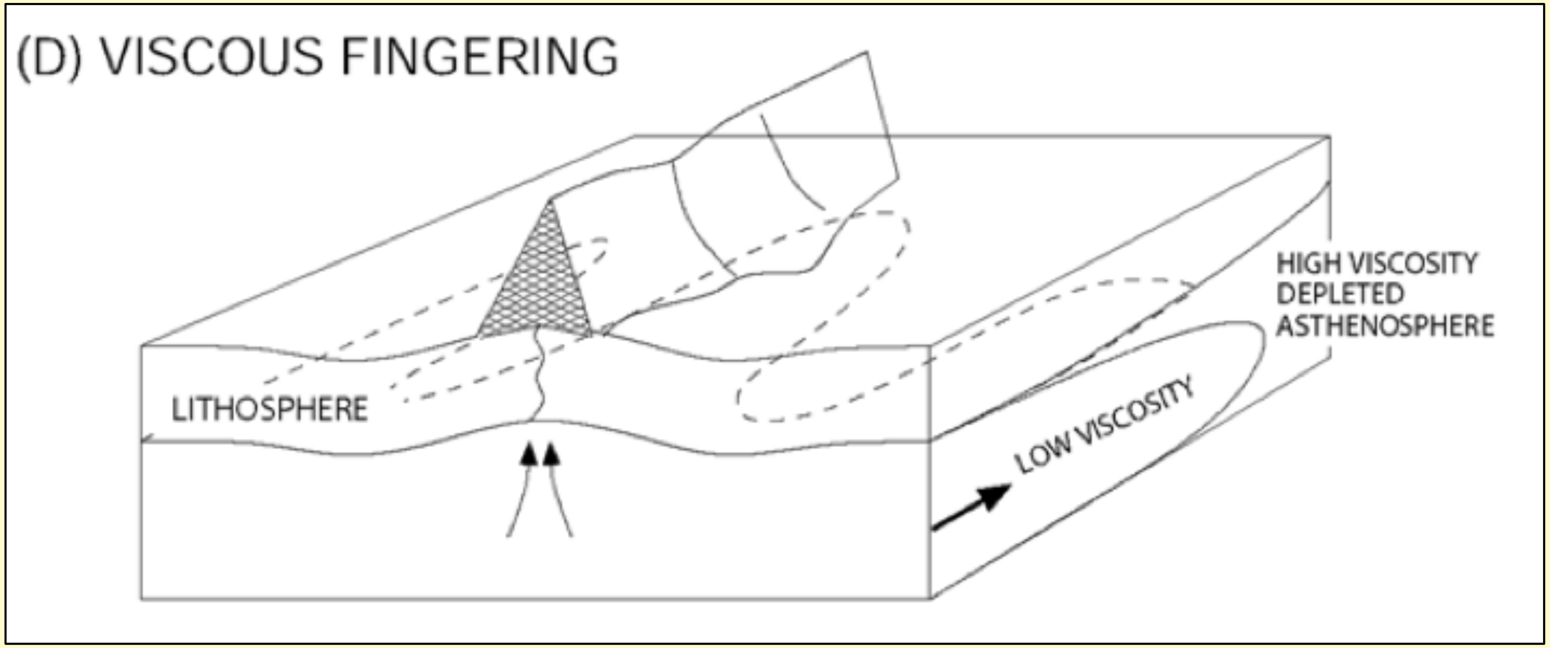
Mantle Flow beneath the South Pacific





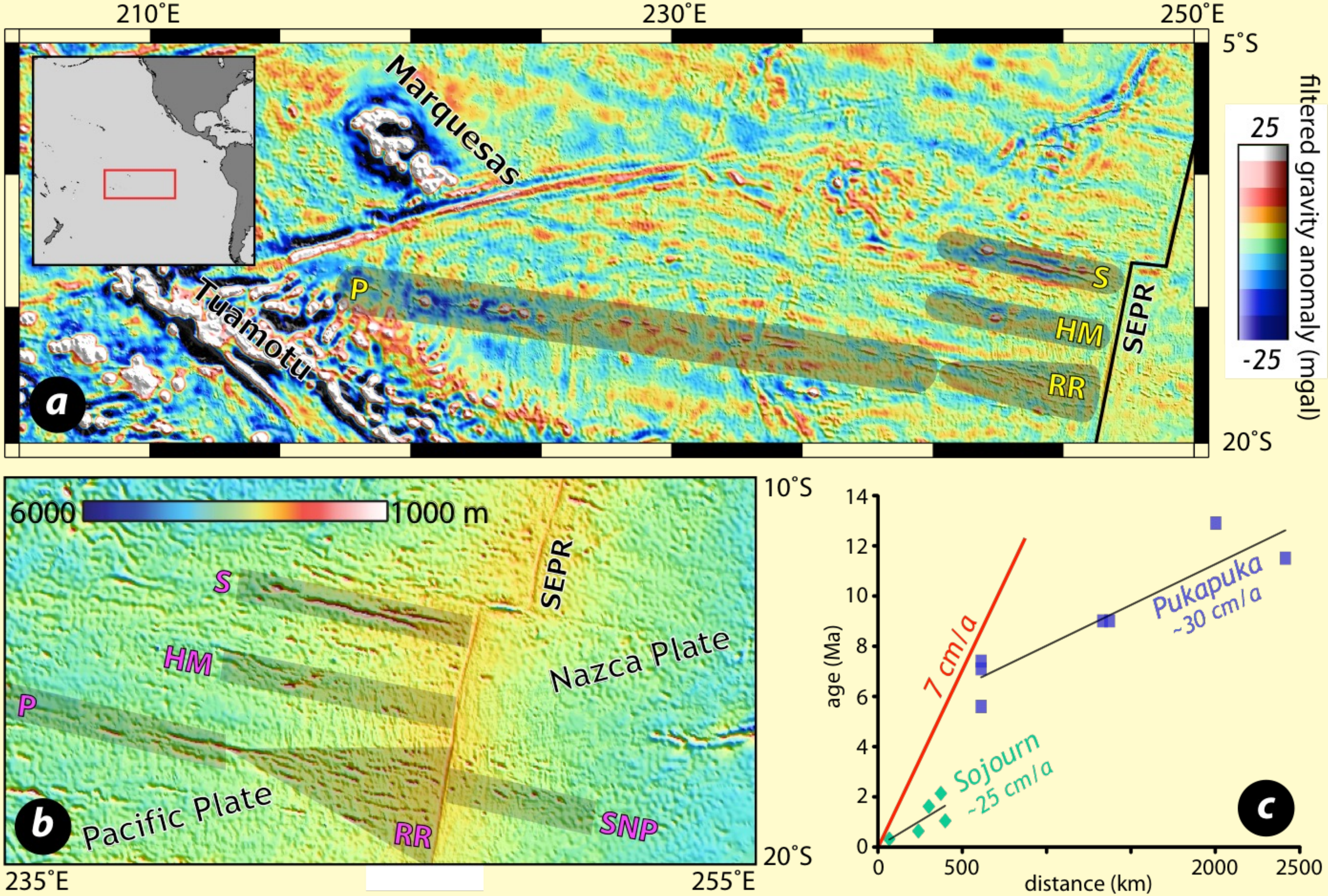
Viscous Fingering:
Injection of a less-viscous fluid into a more viscous one

Is viscous fingering important in the South Pacific?



Weerarante et al. [JGR, 2007]

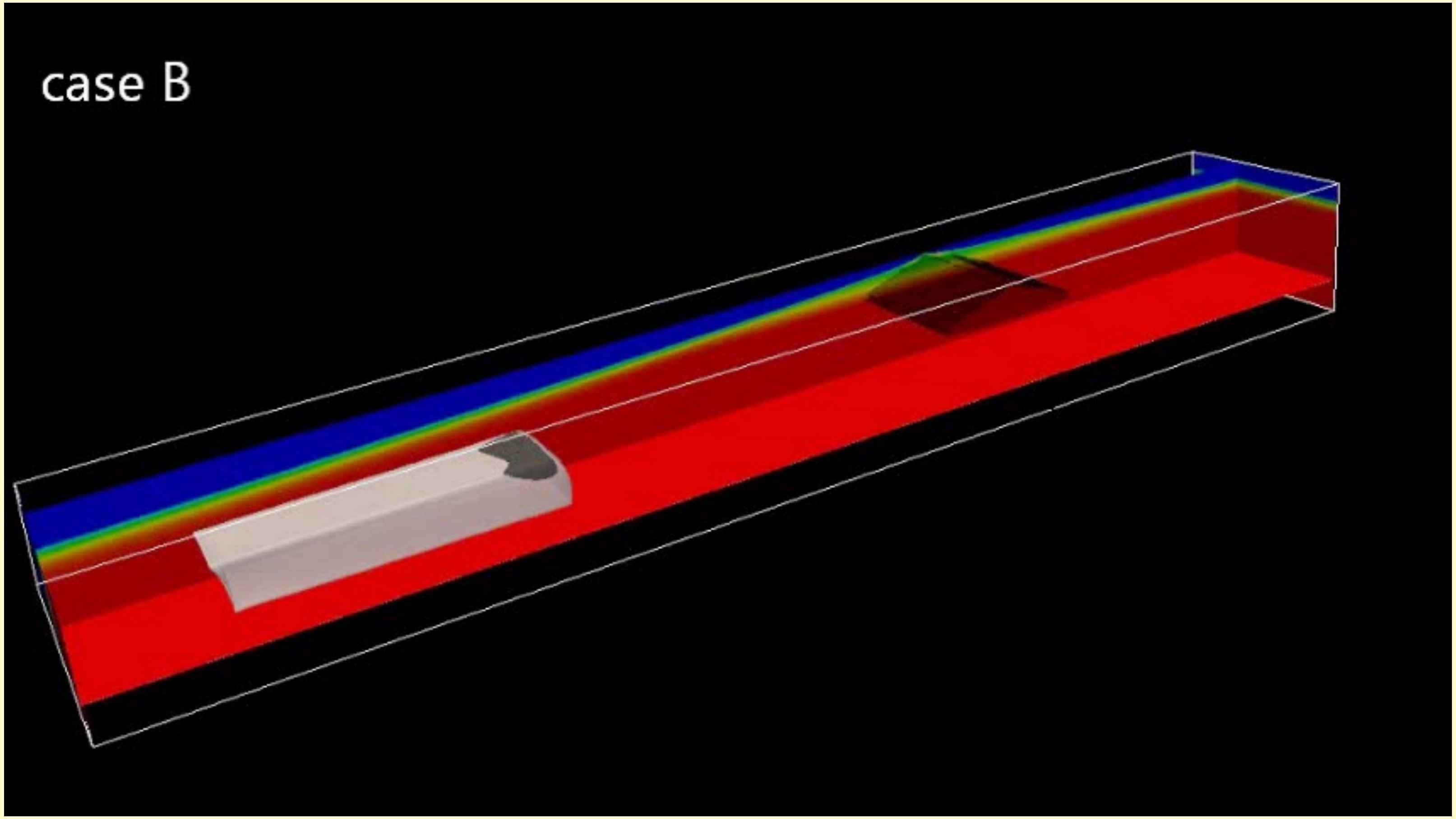
Volcano chains in the South Pacific



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

Ballmer et al. [*Geology*, 2013]

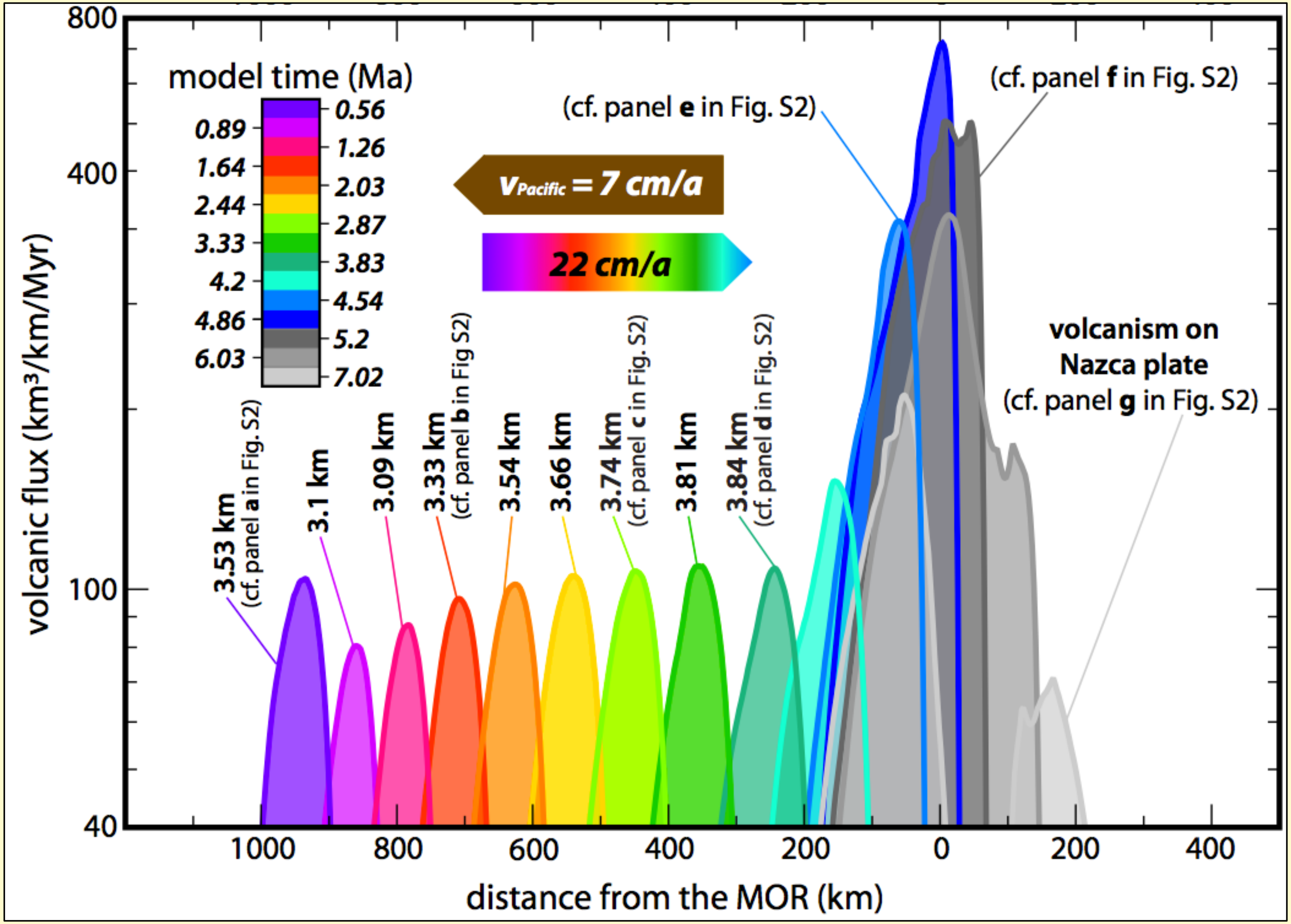
Hot and Wet Anomaly being pushed toward the East Pacific Rise



Like a “sideways” plume

Ballmer et al. [2013]

Case B: Hot and Wet Anomaly (Pukapuka)

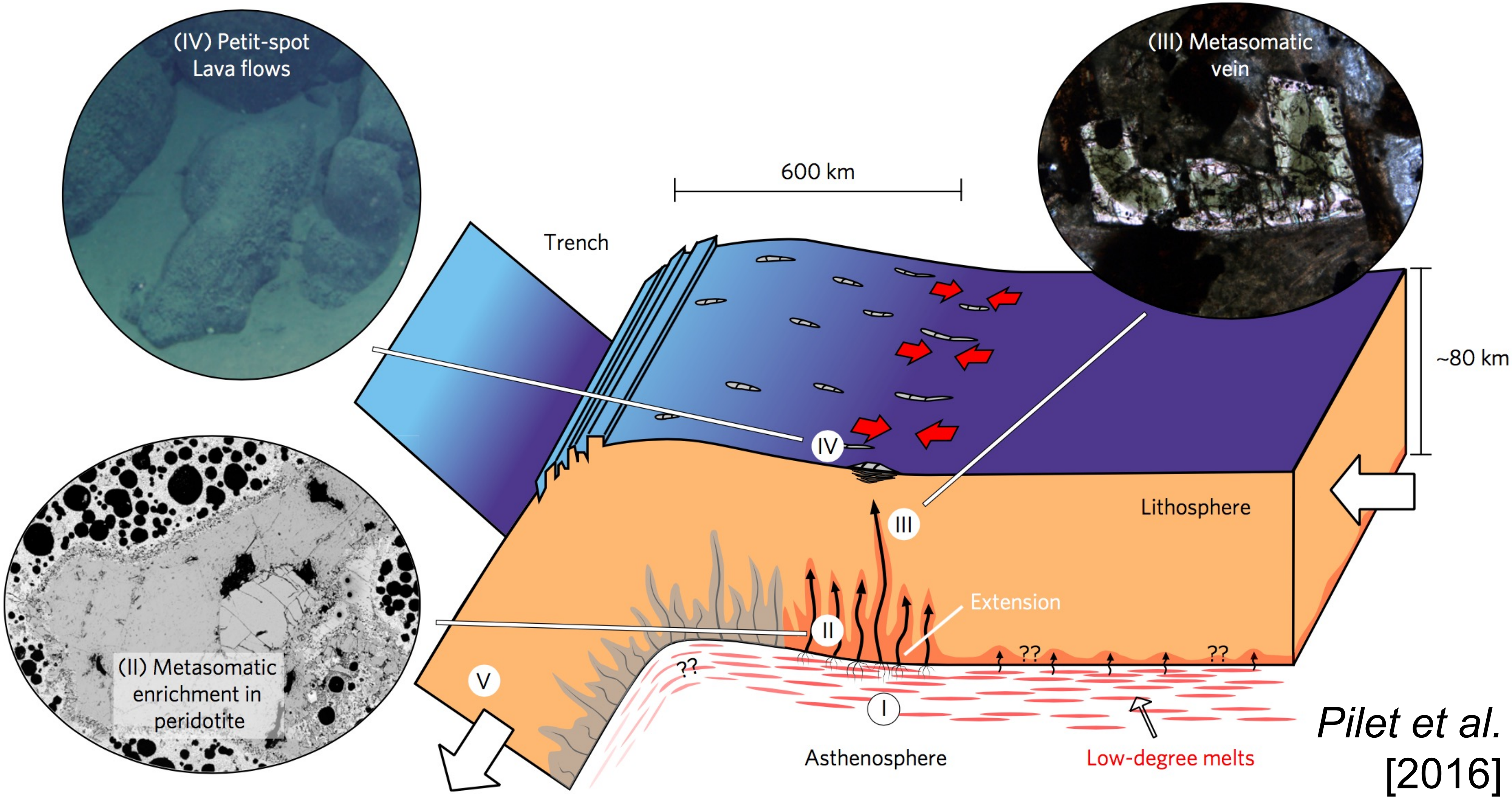


Ballmer et al. [Geology, 2013]

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

- Very minor volcanism
- Happens near trenches
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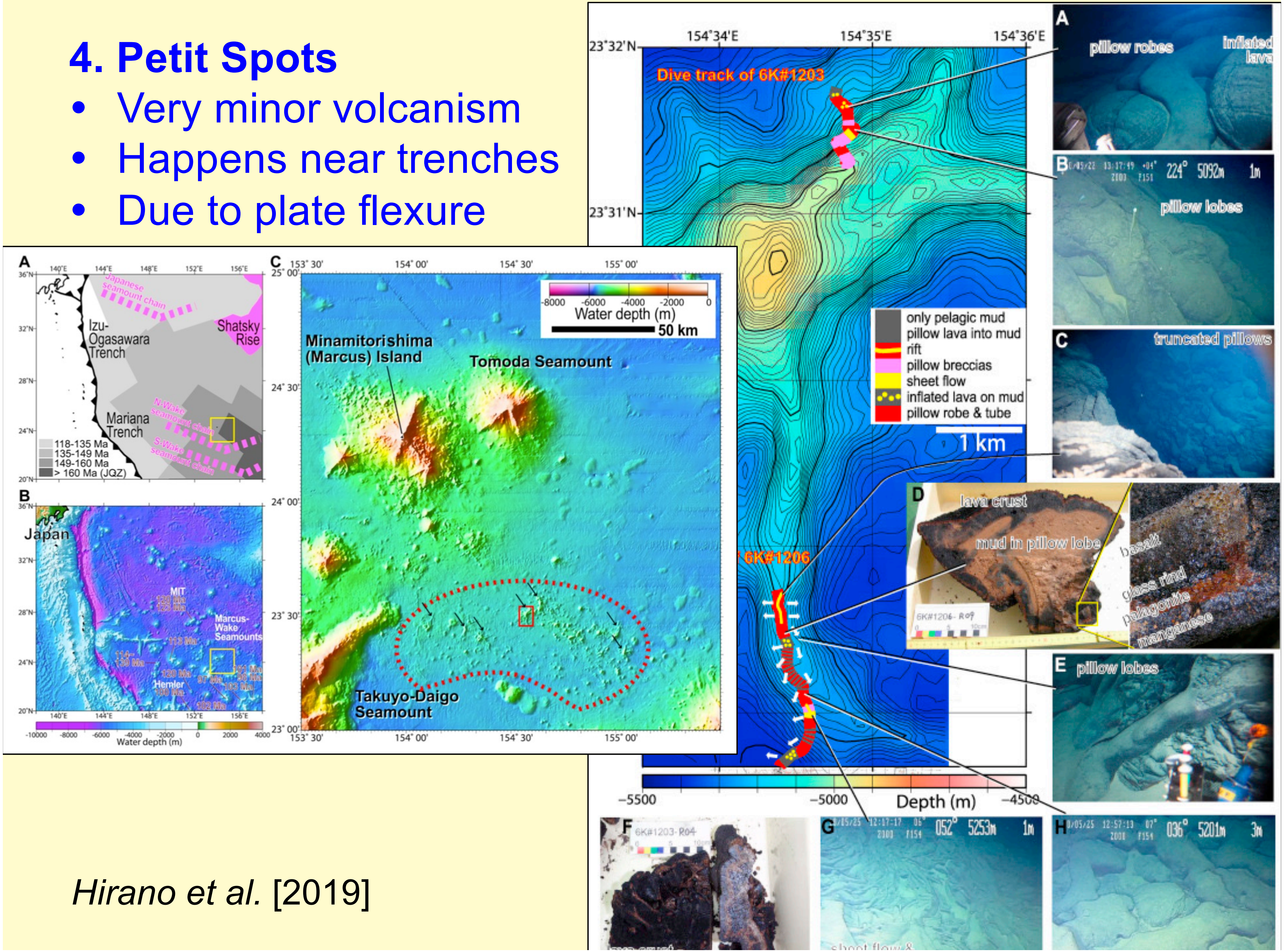
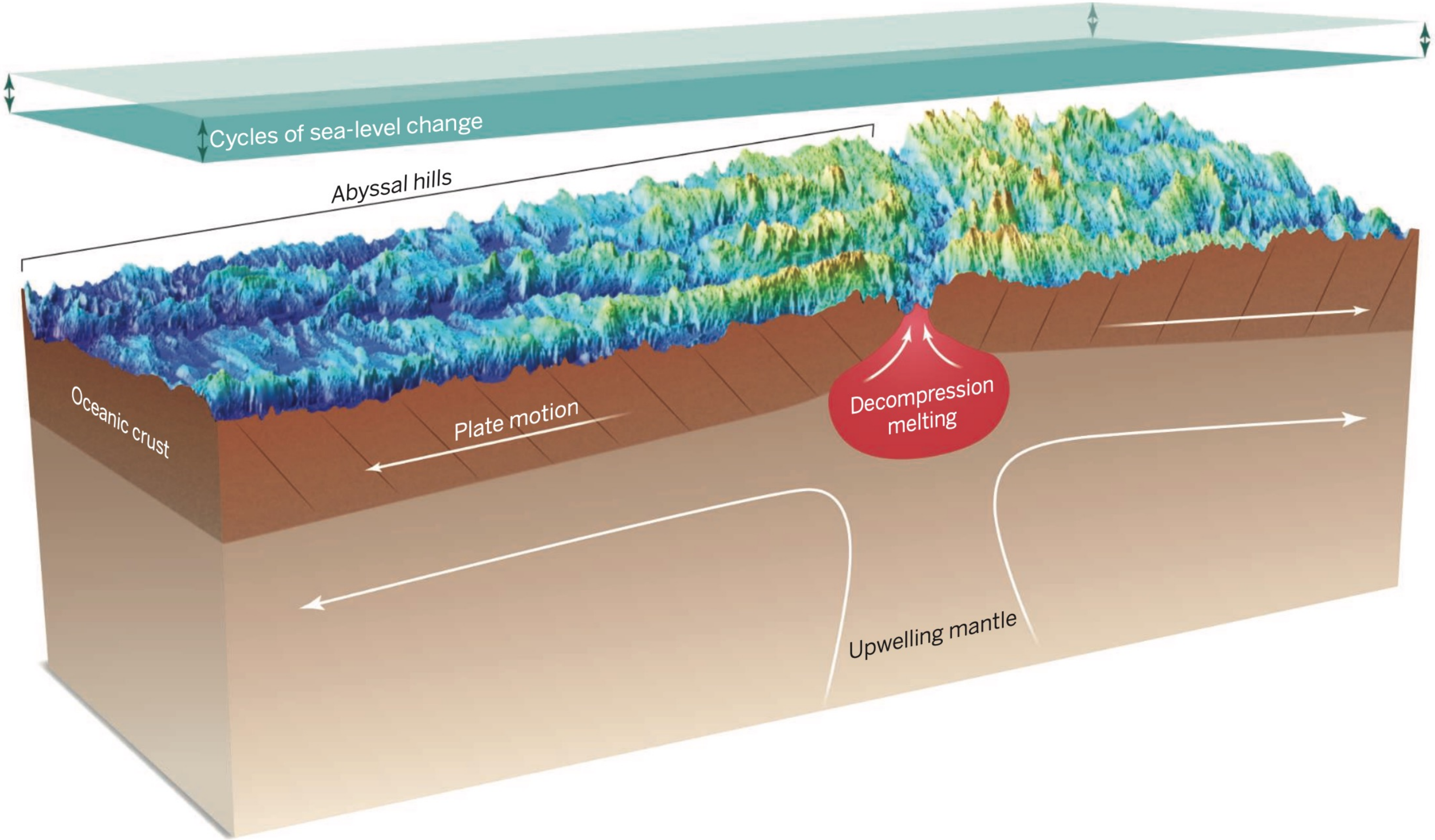


Hirano et al. [2019]

5. Surface Loading Affects on Volcanism



Conrad [2015]

Are the abyssal hills caused by sea level changes?

Rising Sea Level:

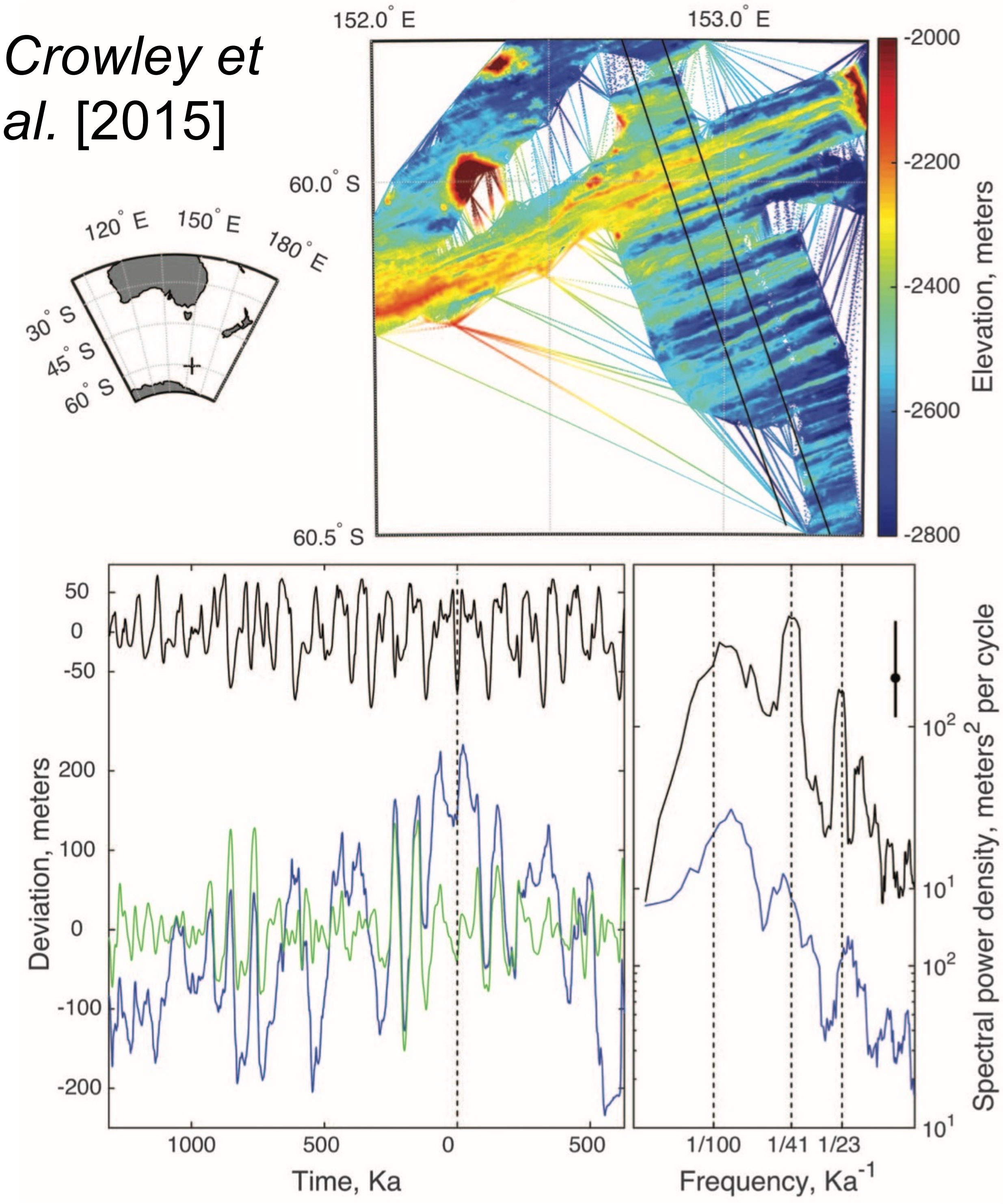
- **→ Increasing pressure**
- **→ Melting is suppressed**
- **→ Less volcanic output**
- **→ A “valley” in the abyssal hills**

Falling Sea Level:

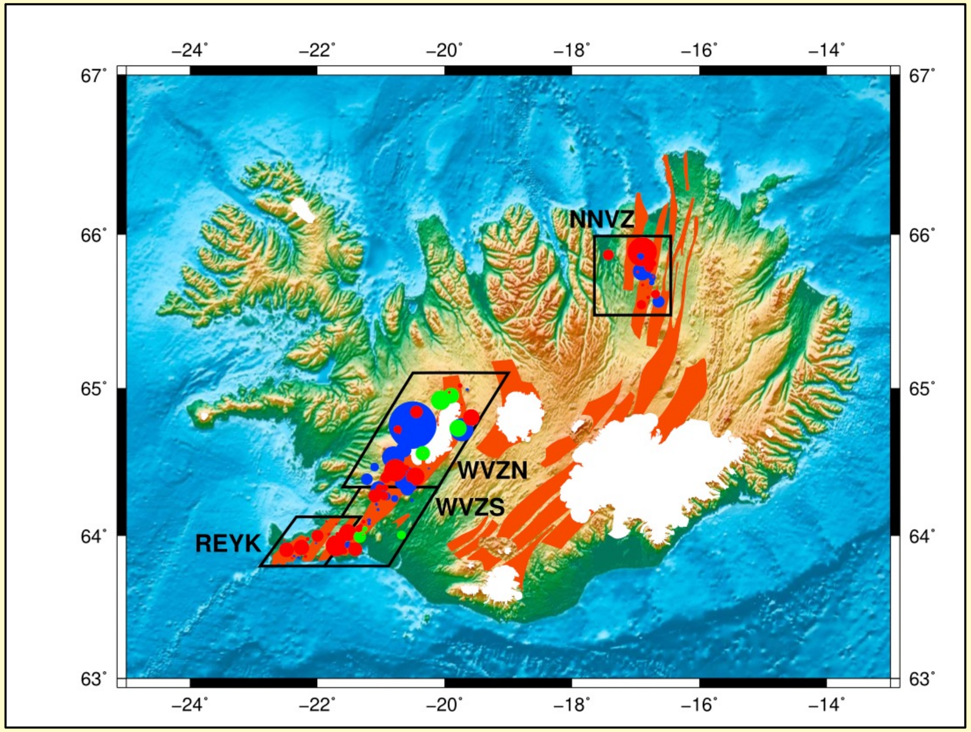
- **→ Decreasing pressure**
- **→ Melting is enhanced**
- **→ More volcanic output**
- **→ A “peak” in the abyssal hills**

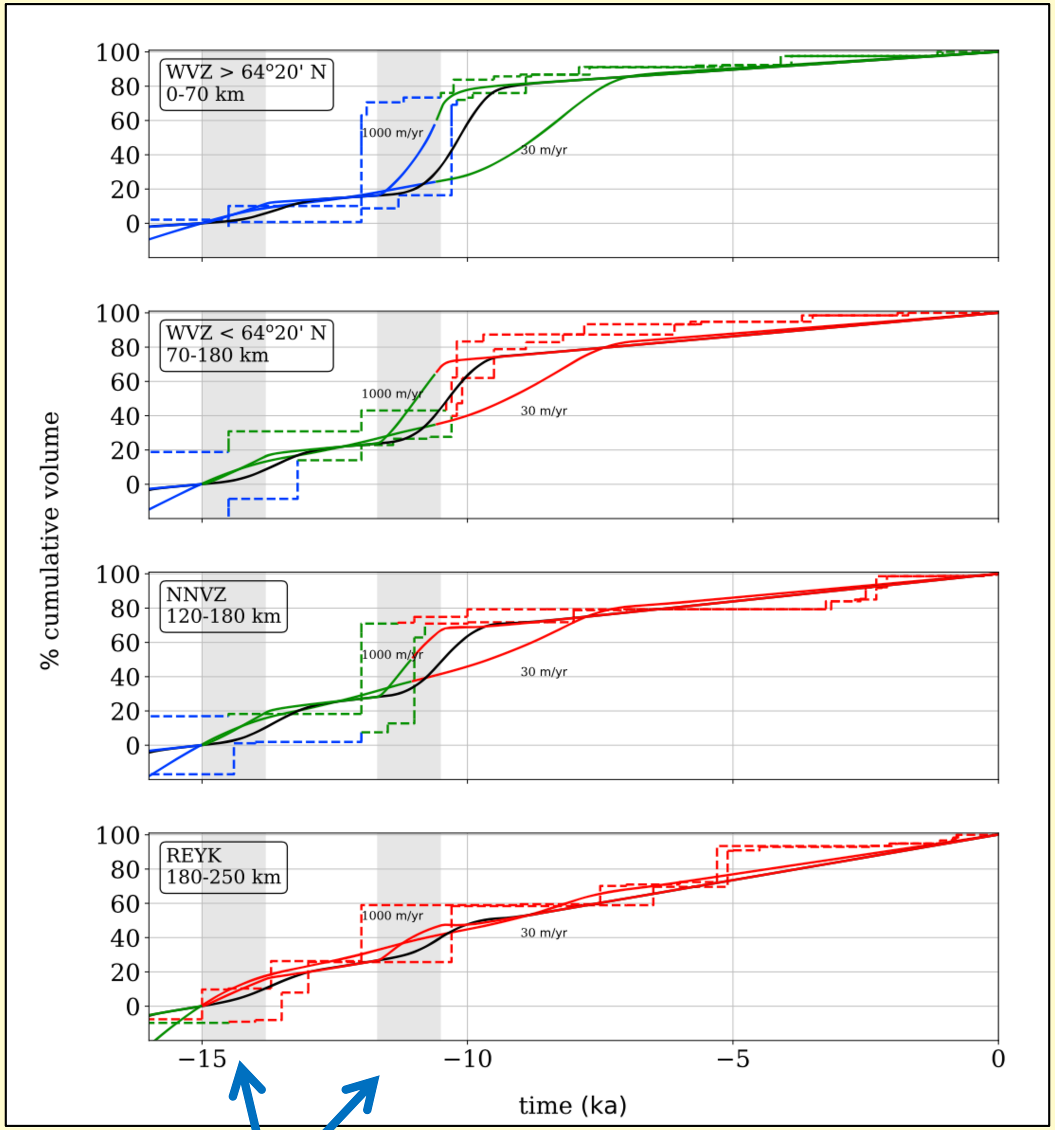
Observation of Milankovitch timescales in the abyssal hill fabric →

Crowley et al. [2015]



Amplification of Icelandic volcanism during deglaciation





Deglaciation periods

Eksinchol et al. [2019]

Intraplate Volcanism - in the oceans and on land

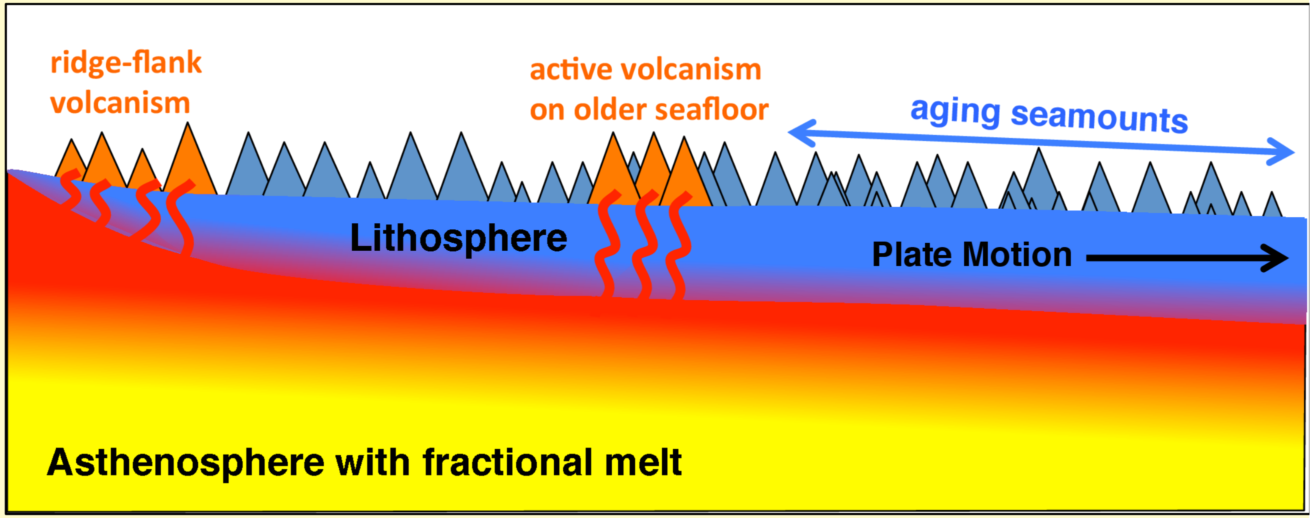
- More than 24,000 seamounts on the seafloor
- Many still undiscovered and we don't know their ages
- Many fields of minor volcanism on continental areas

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
- Removal of surface loads

Implications:

→ Mantle beneath the plates is close to melting or is already partially melted



→ Climate change can cause volcanism