# Earth's thermal and tectonic evolution

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By Cris Mel Maverick Romanillos

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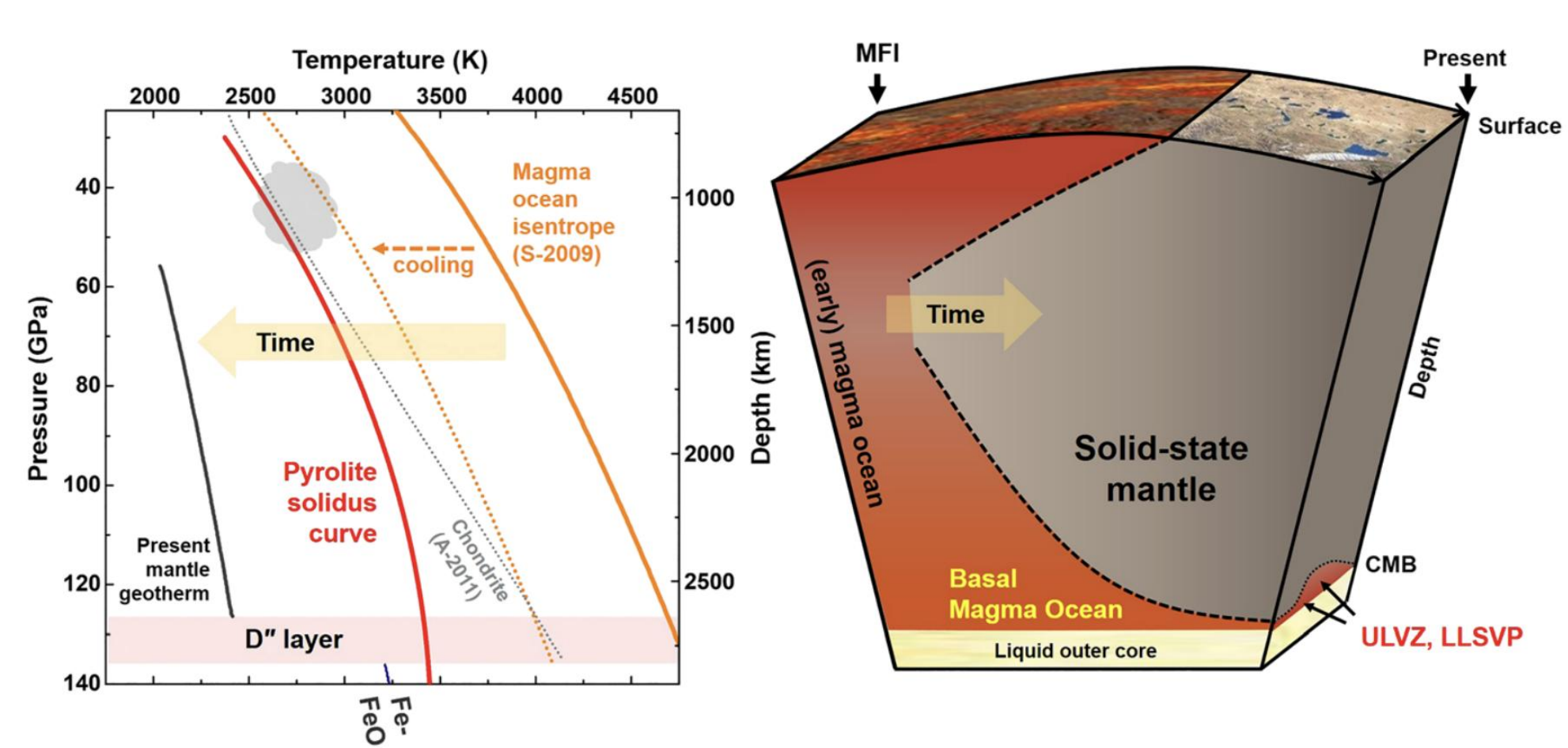

1 Early Earth evolution

2 Understanding subduction

3 Plume dynamics

4 Continental delamination

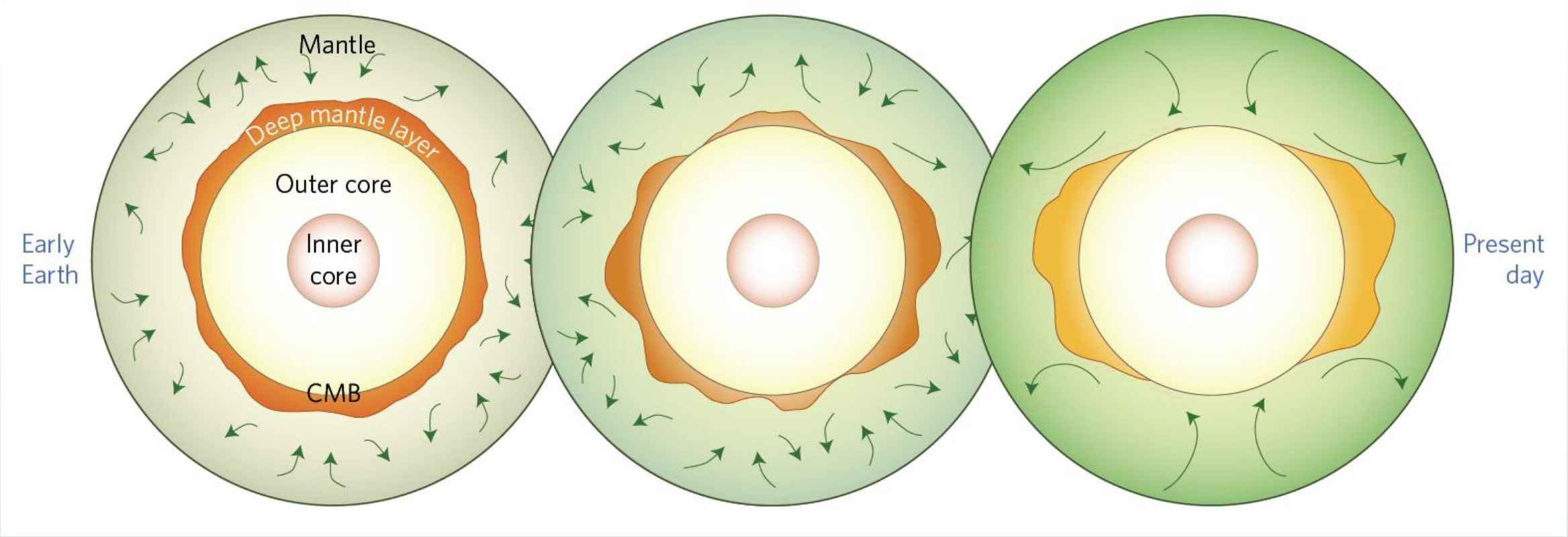
# Solidification of the magma ocean




(Kim et al., 2021)

# Solidification of the magma ocean

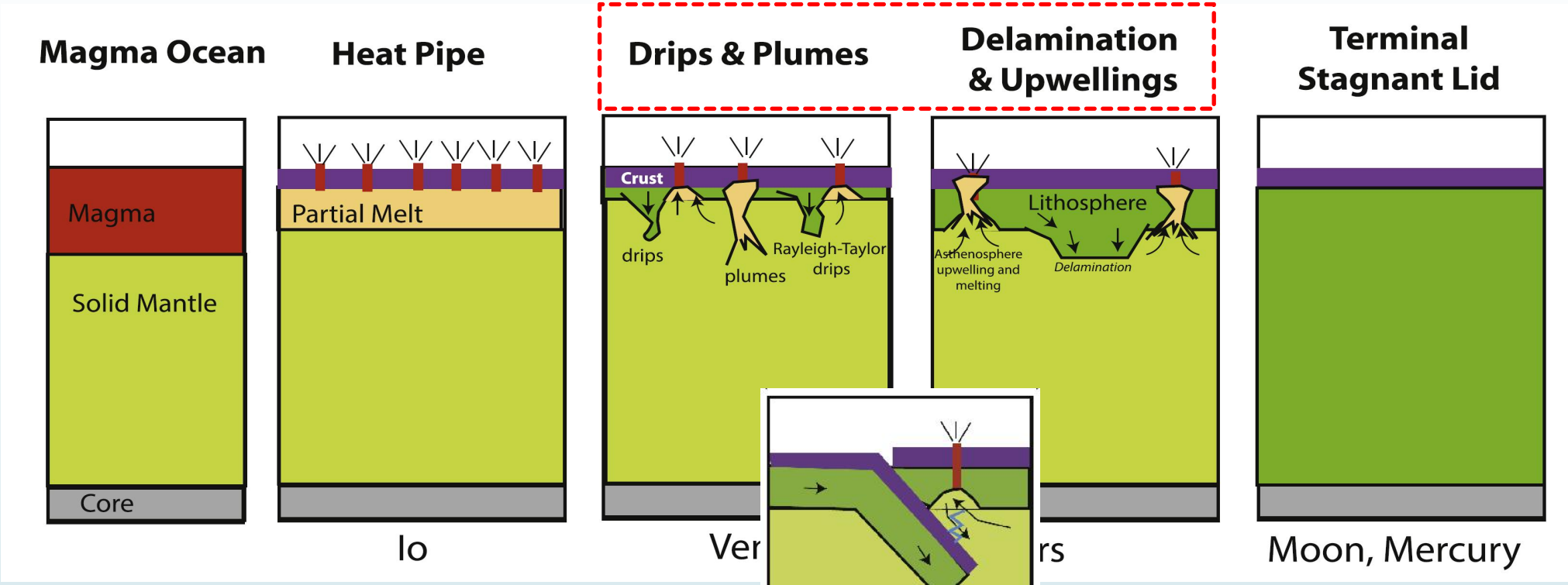
## Basal magma ocean evolved to become the LLSVPs




(Garnero et al., 2016)

# Evolving tectonic modes over time

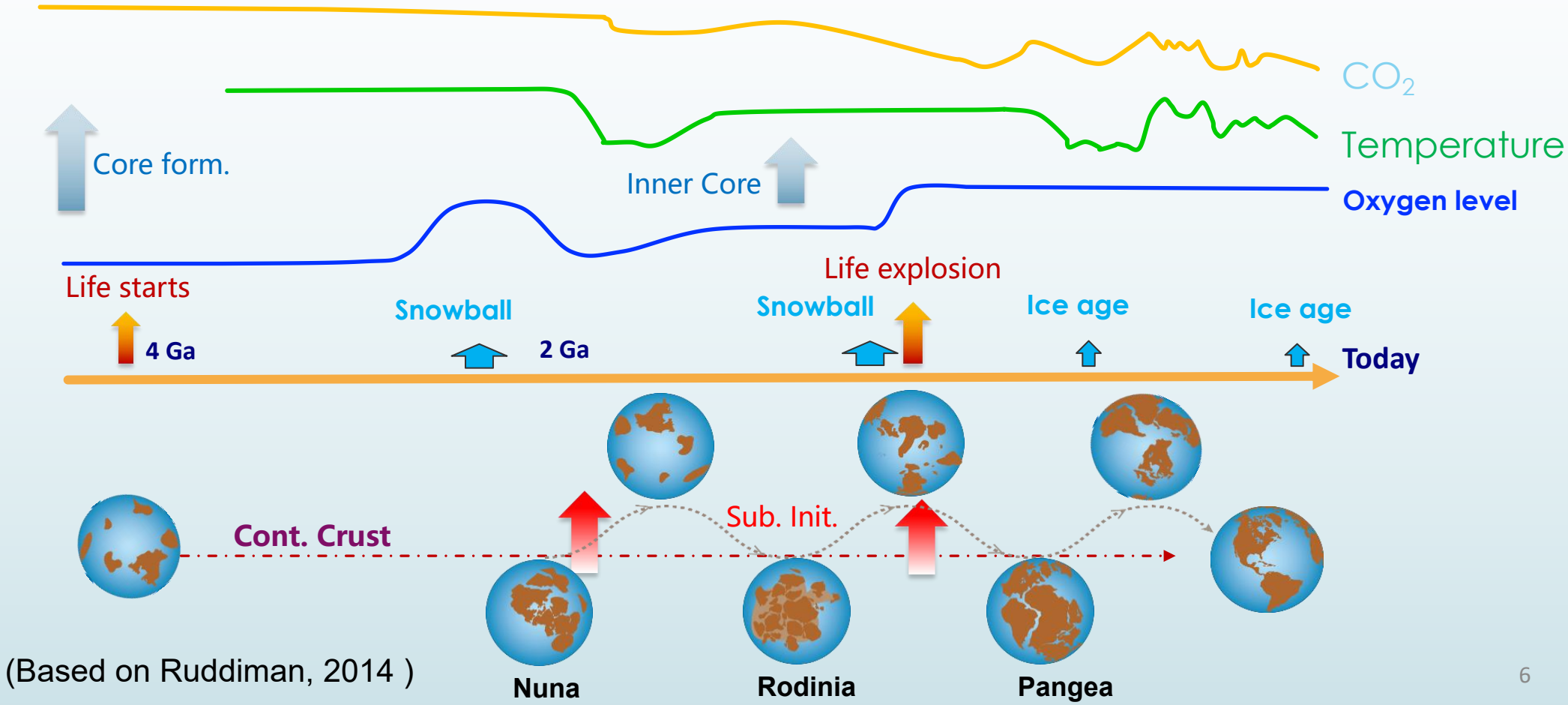
## Upper mantle experienced different tectonic modes




(Stern et al., 2018)

# Coupled surface-interior evolution

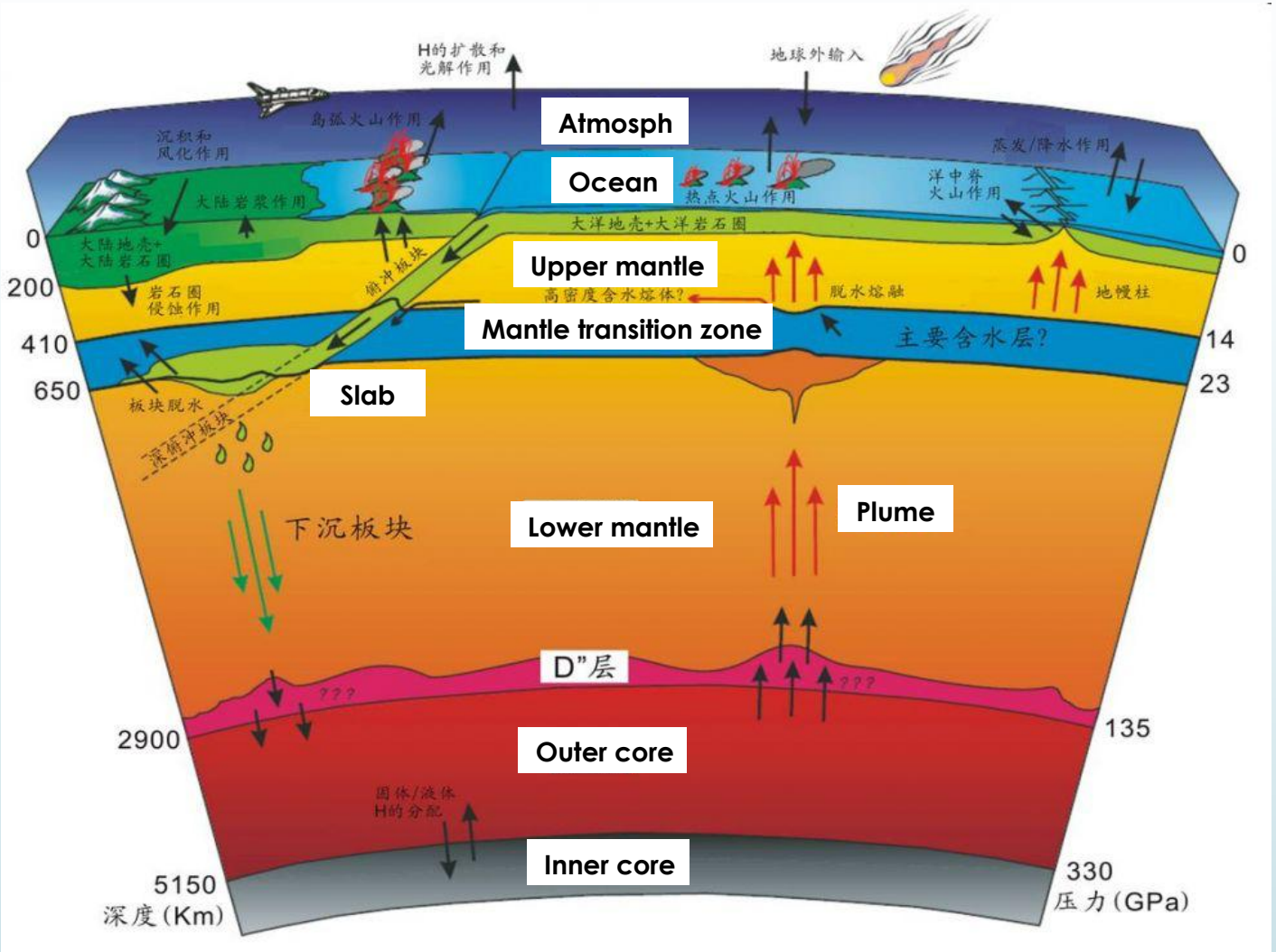
## How did Earth's potential temperature and convection evolve?




(Based on Ruddiman, 2014 )

# Present Earth internal dynamic processes

## How exactly do these processes work?



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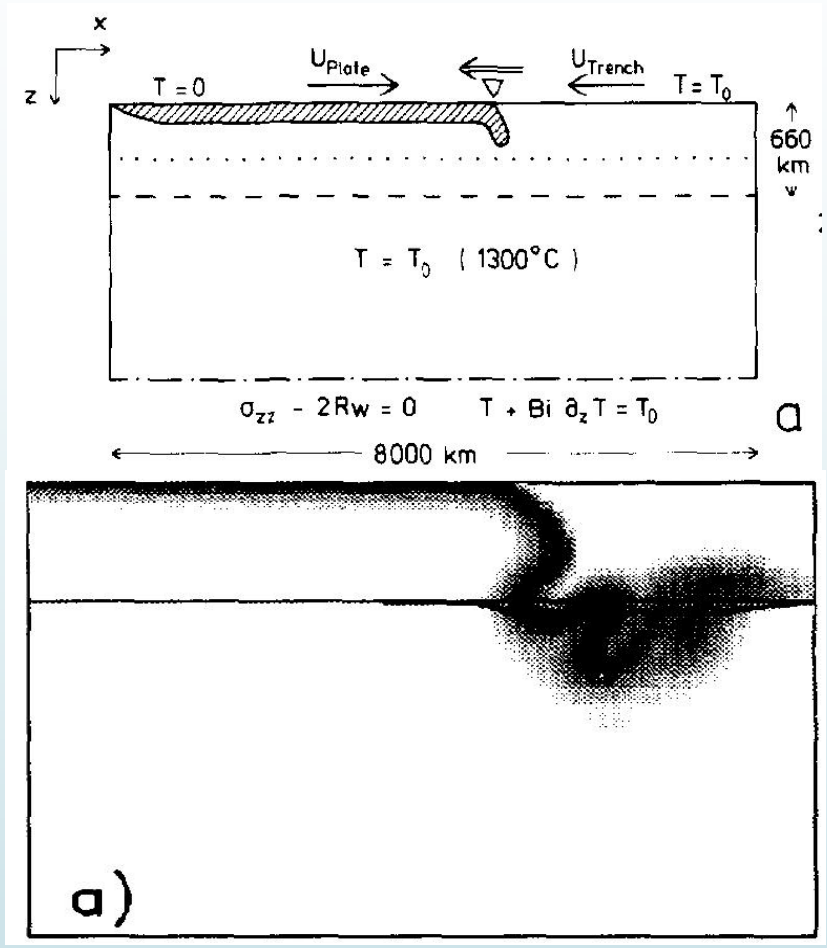
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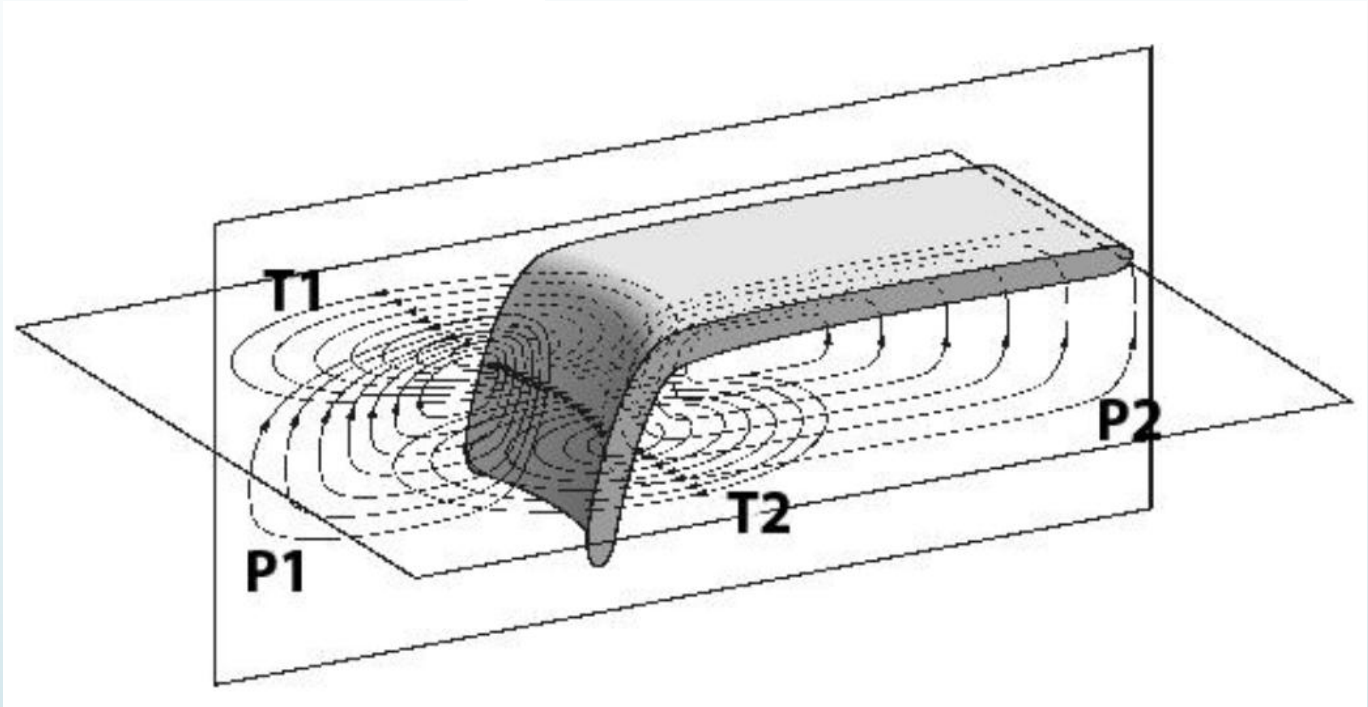
4 Continental delamination

# Generic model：targeted as explaining concept

- **Usually with simplified initial & boundary conditions**



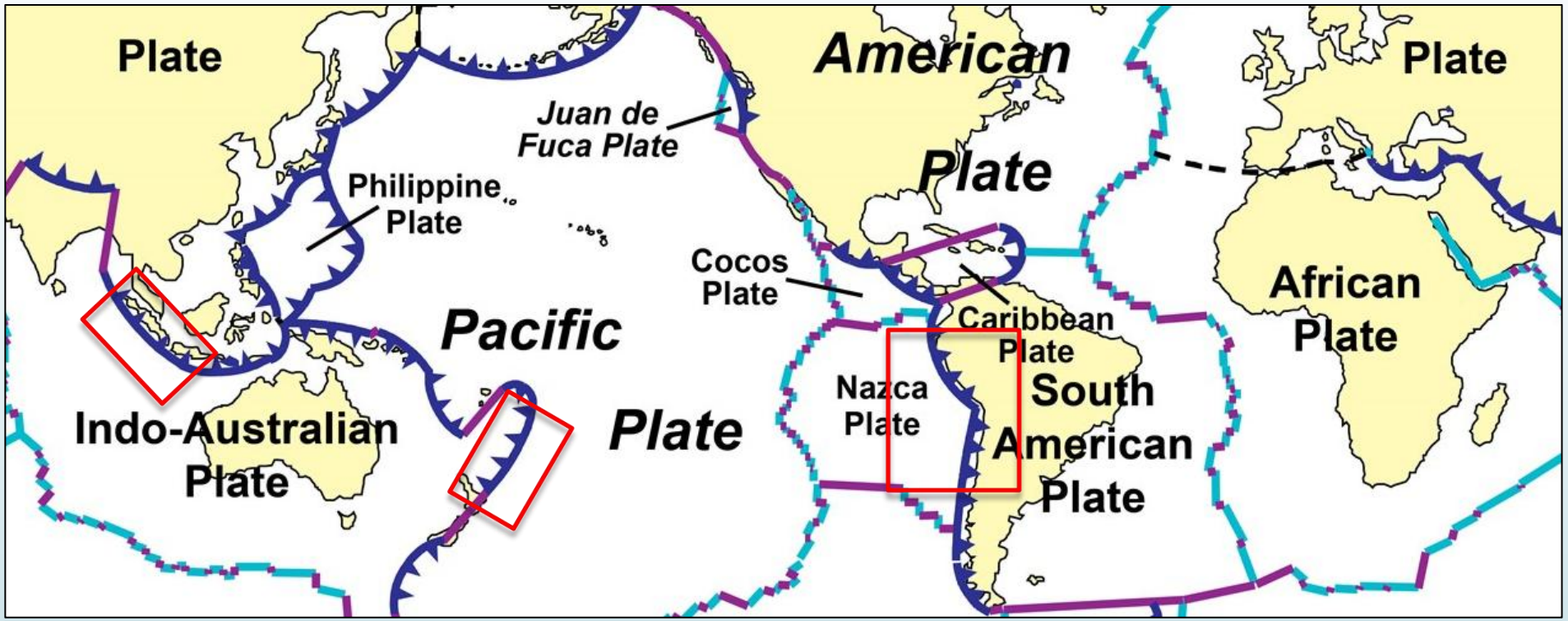

(Christensen, 1996)




(Stegman et al., 2006)

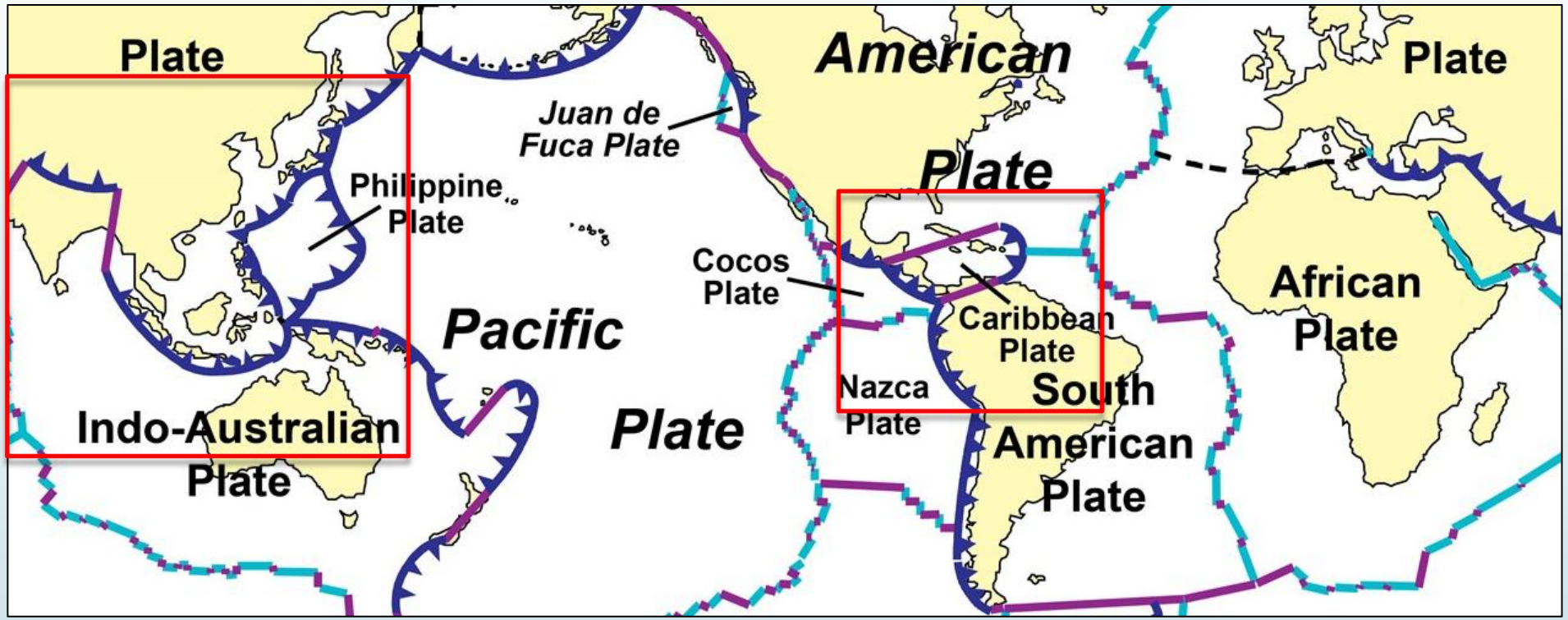
# Generic model：targeted as explaining concept

- Usually with simplified initial & boundary conditions
- Assuming a single-slab system



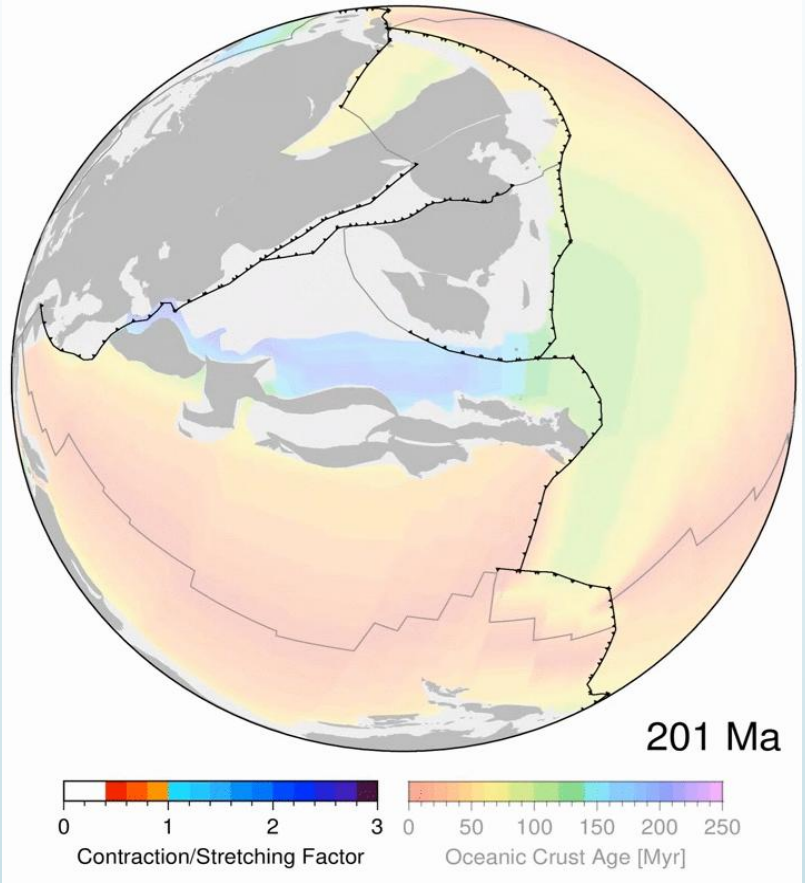
# Generic model：targeted as explaining concept

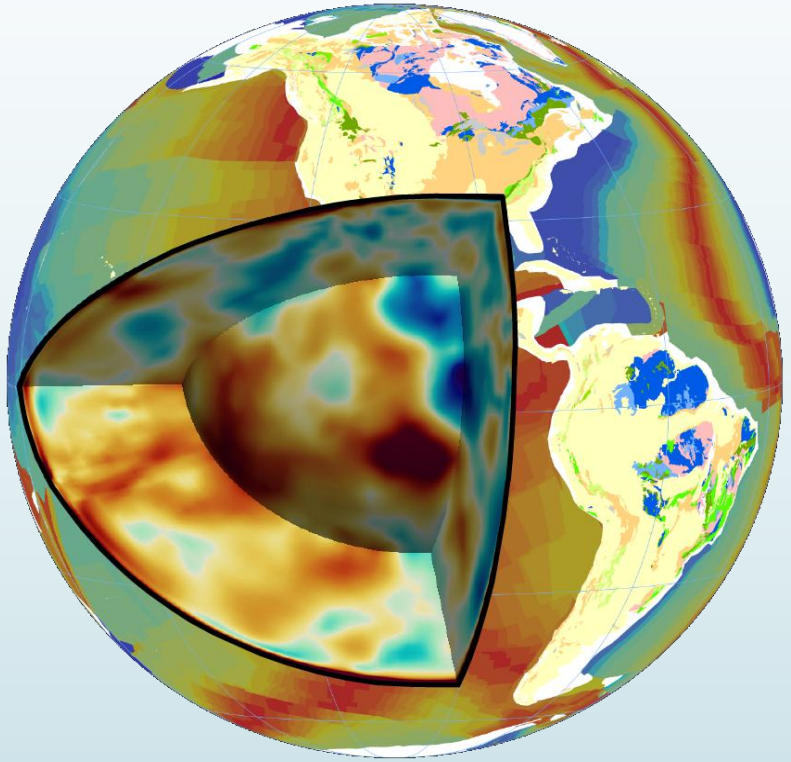
- Usually with simplified initial & boundary conditions
- Slabs interact with each other in complex ways…



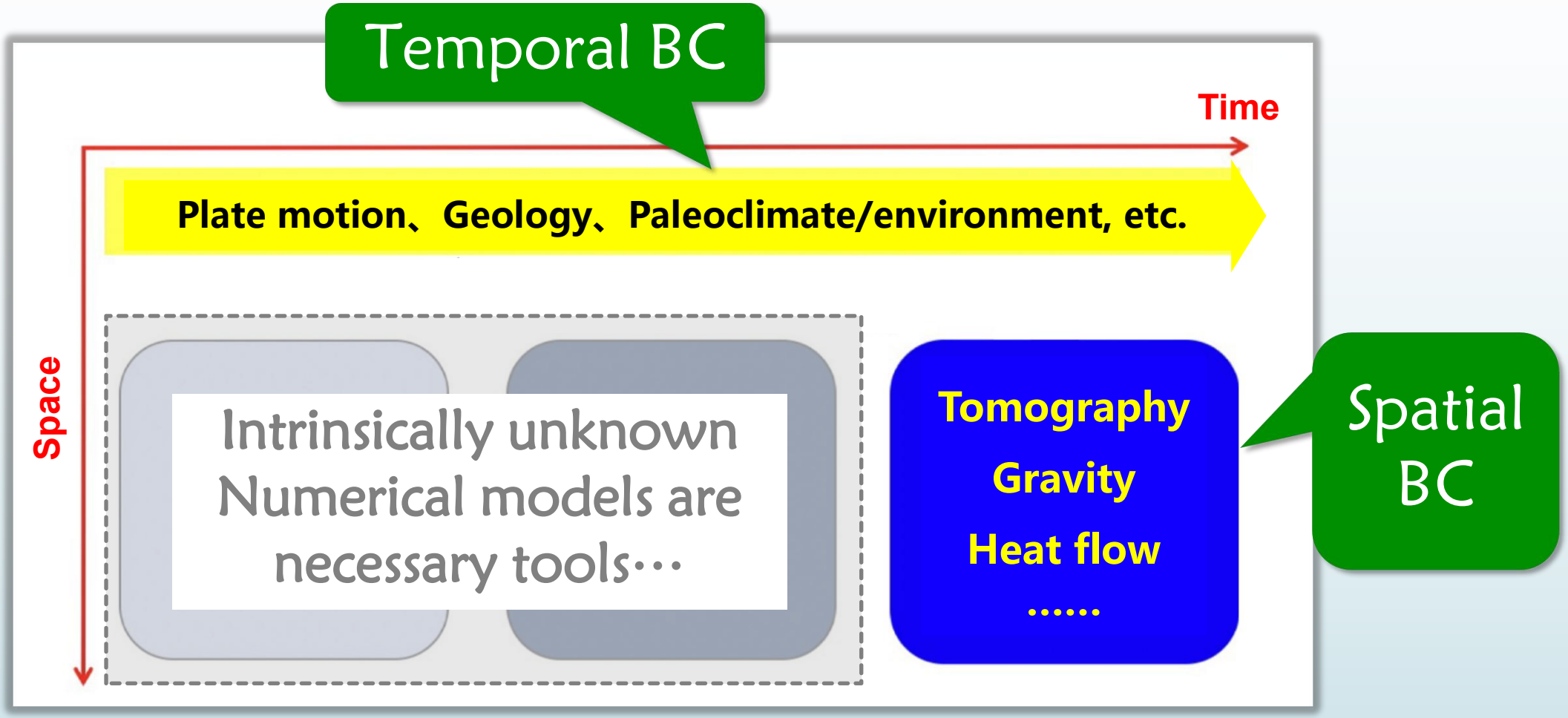
# Generic model：targeted as explaining concept

- Usually with simplified initial & boundary conditions
- Slabs interact with each other in complex ways…



# Knowns & unknowns of 4D Earth evolution



# Effects of boundary conditions



Initial state

# Effects of boundary conditions



Initial state



4 turns clockwise

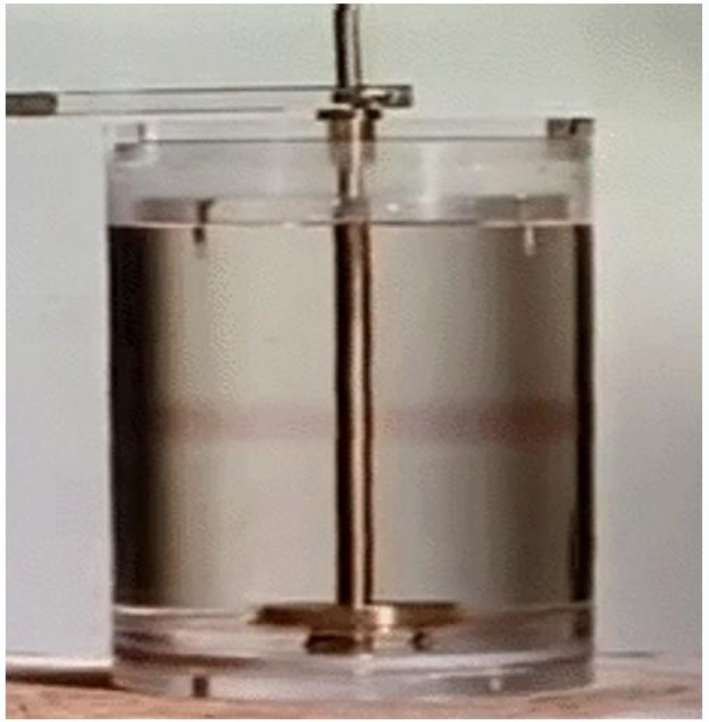
(plate motion history)

# Effects of boundary conditions

## With known spatial-temporal BCs, low Re# flow is reversible!



Initial state



4 turns clockwise

(plate motion history)



4 turns c.c.w.

(reverse plate motion)

# The idea of data assimilation

**True initial condition**





**Present observation**



# The idea of data assimilation

## Sequential DA
## (Karmen filter)

South American subduction



(Hu et al., 2016, *EPSL*)



Initial state (guessed)

time

Final state

Plate motion drives convection



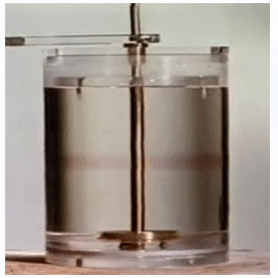
True I.C.

Compare

Observed state

# The idea of data assimilation

**Sequential DA**
**(Karmen filter)**



Initial state (guessed)

time

Final state

Plate motion drives convection



True I.C.

Compare



time

Initial state (solved)

Observed state

Reverse plate motion

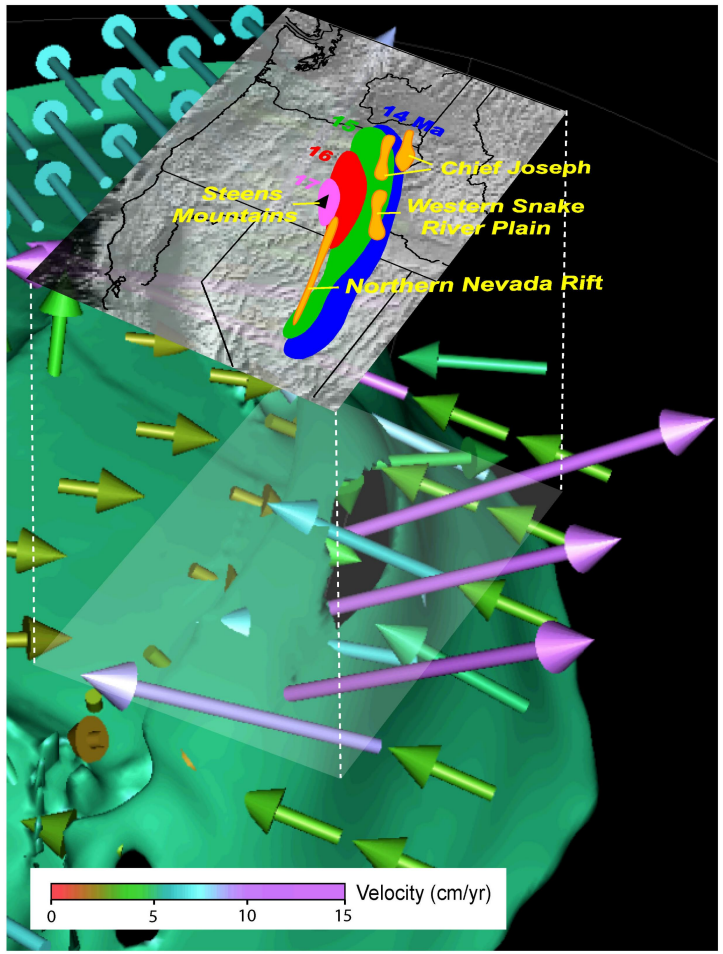
Iteratively counteract diffusion

**Backward DA**
**(adjoint method)**

Conjugate of energy Eqn

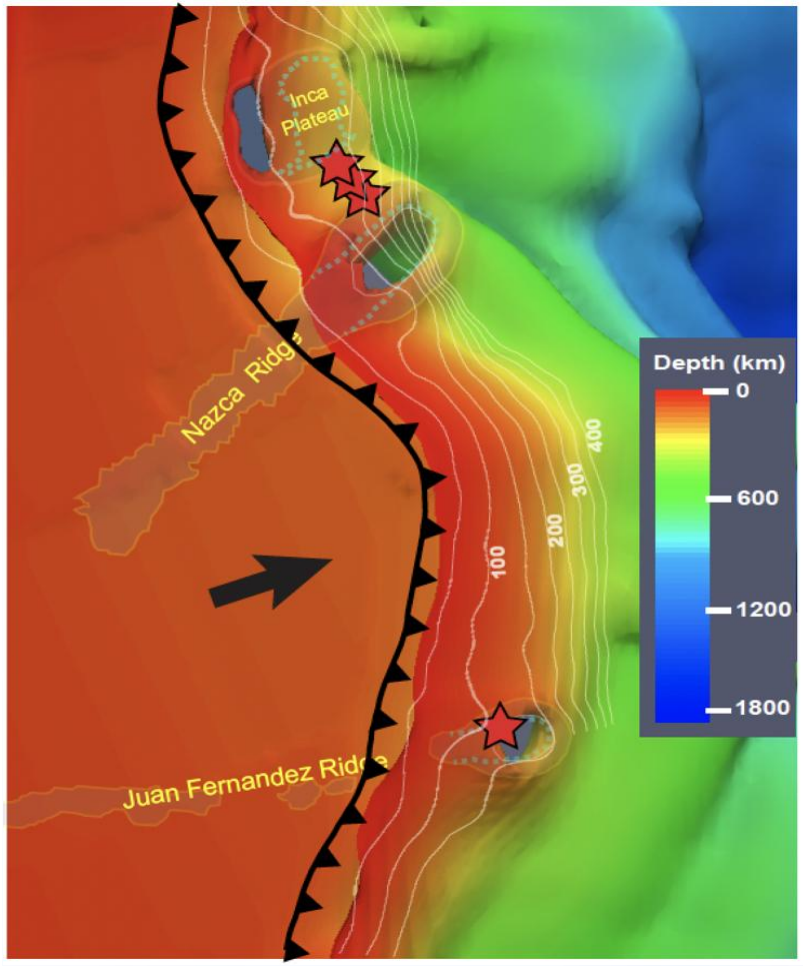
# Realization of Earth-like subduction in forward DA

**Young slab tears along hinge**




(Liu & Stegman, *Nature*, 2012)

**Flat slab tears along buoyancy**




(Hu & Liu, *EPSL*, 2016)

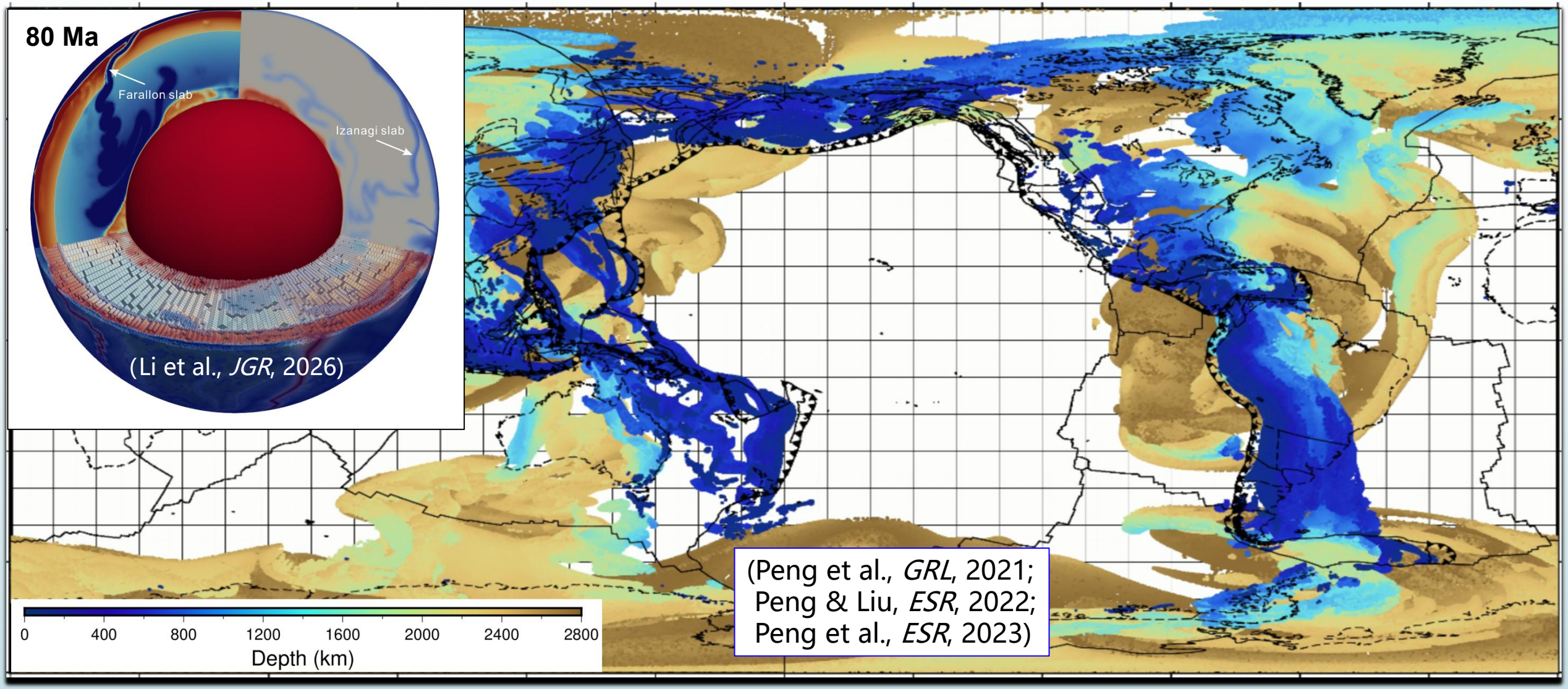
**Global subduction**



(Hu et al., *EPP*, 2018)

# Reproduced slab geometry using forward DA

**Allowing investigation:** slab tearing, sinking rate, dip angle variation, mantle flow, plume evolution...



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# Evolving views on mantle plume

**Purely thermal plume**

⬇

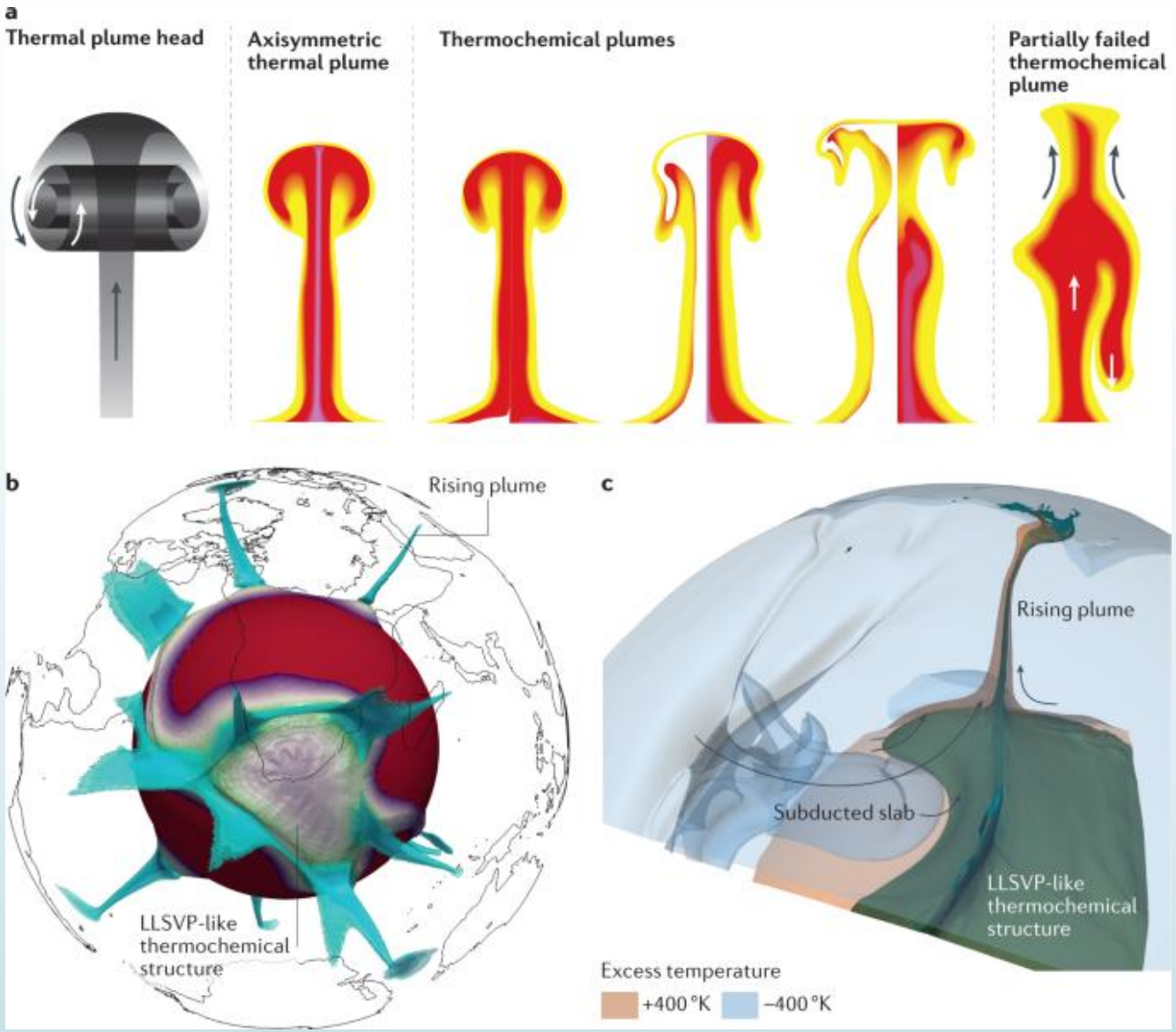
**Thermal-chemical plume**

⬇

**Plume clustering**

⬇

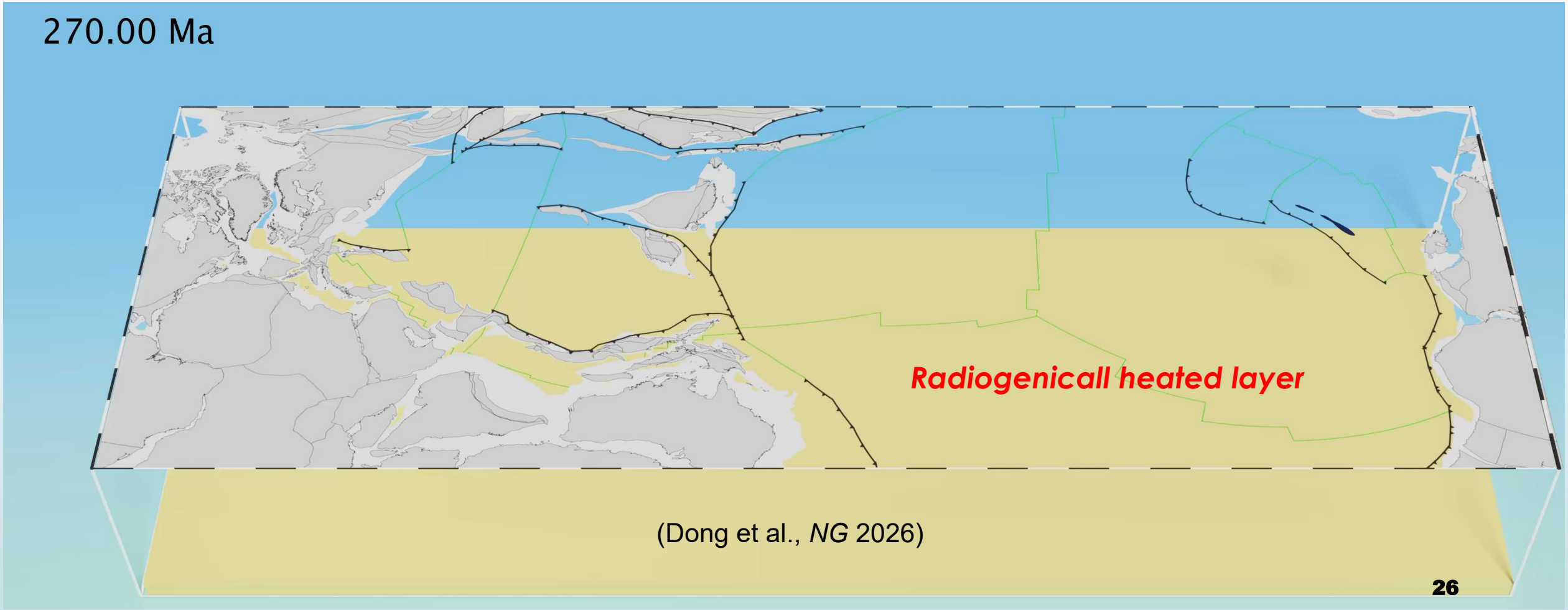
**Slab-plume interaction**




(Koppers et al., 2021)

# Quantifying slab-plume evolution in one model

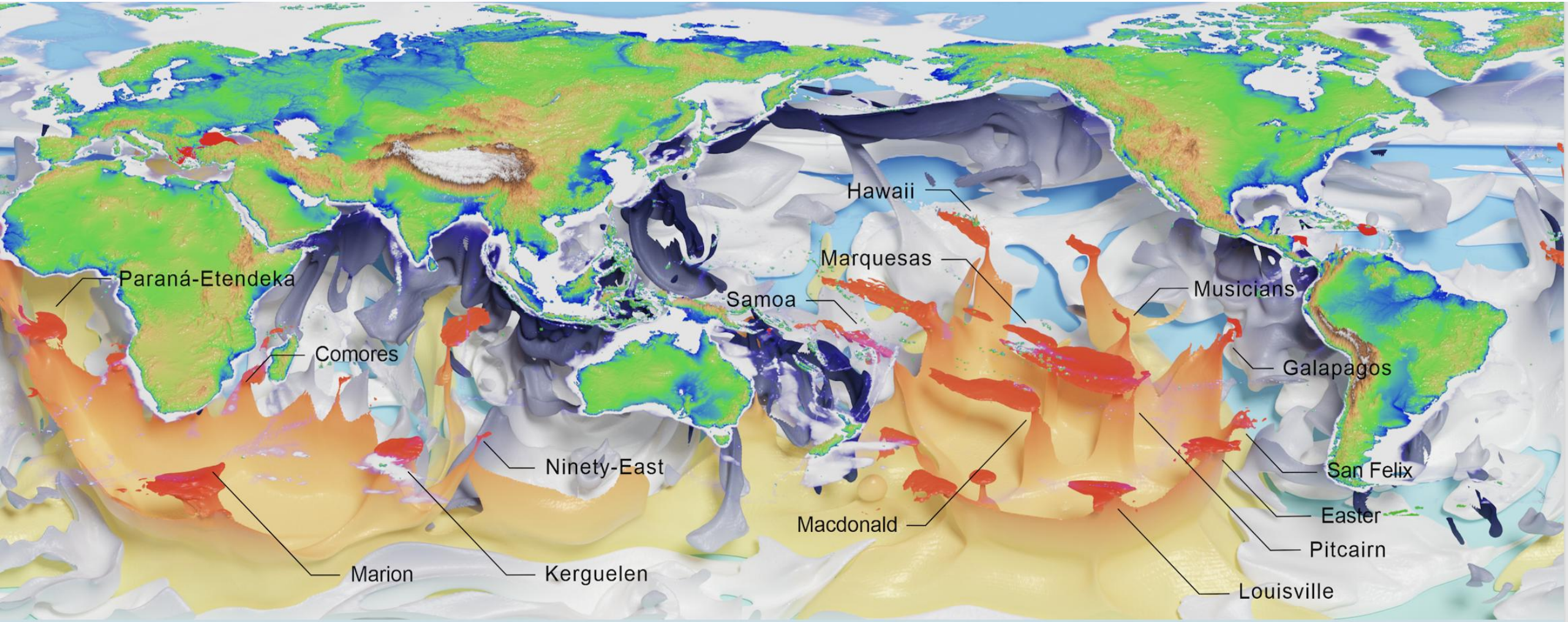
## Simulated past 270 Ma global subduction & plume evolution



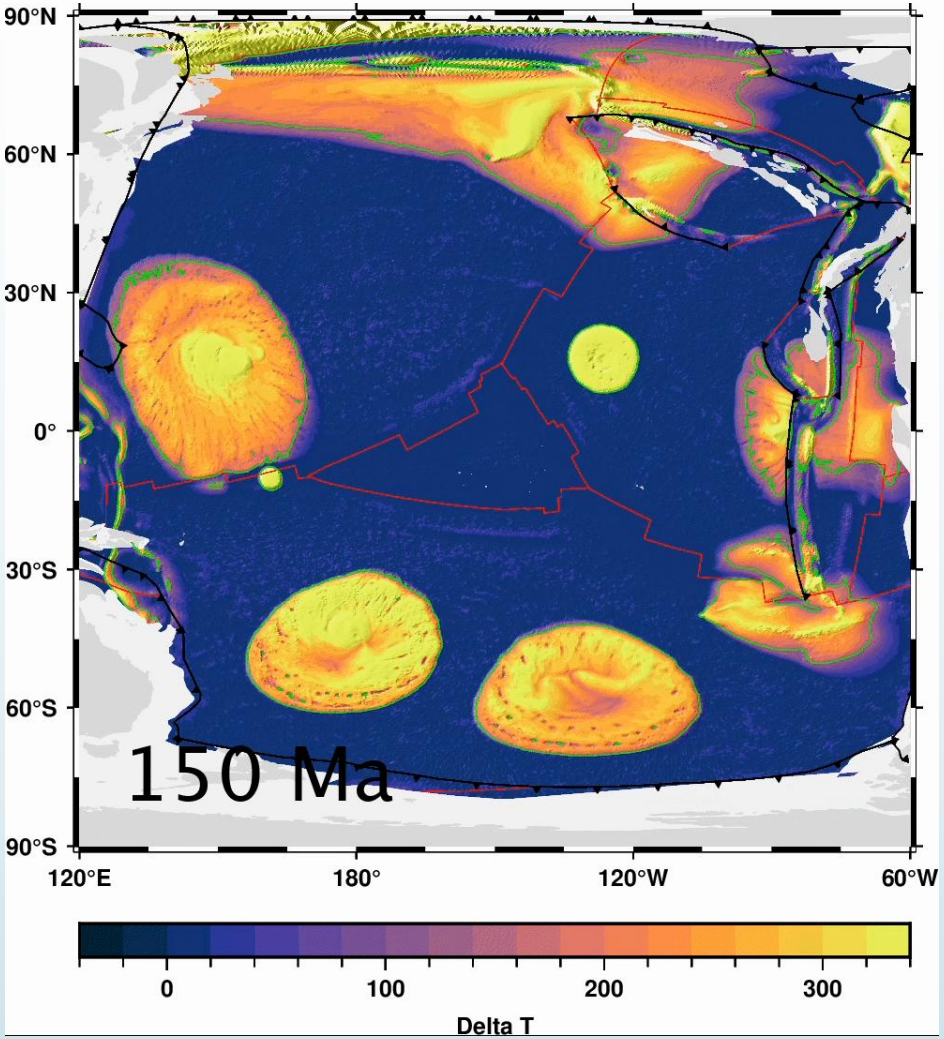

(Dong et al., *NG* 2026)

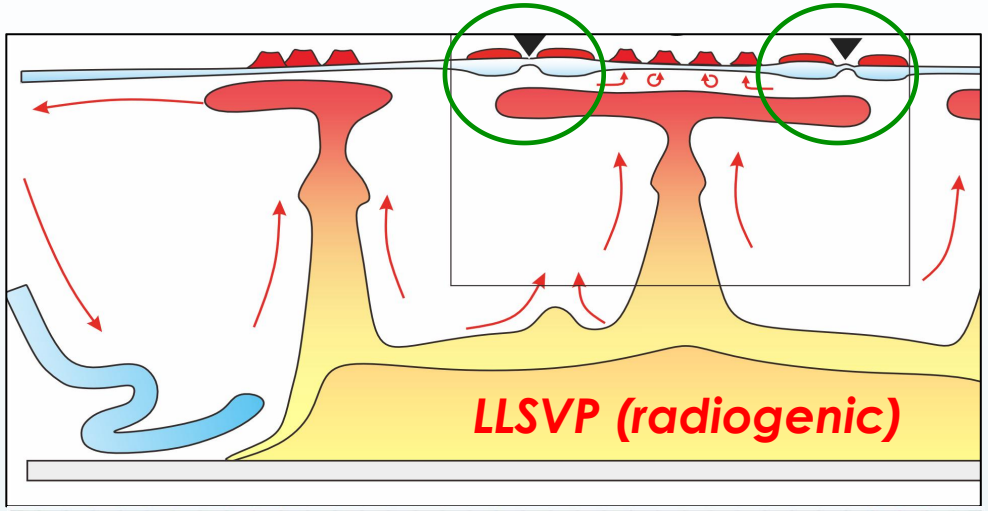
# Quantifying slab-plume evolution in one model

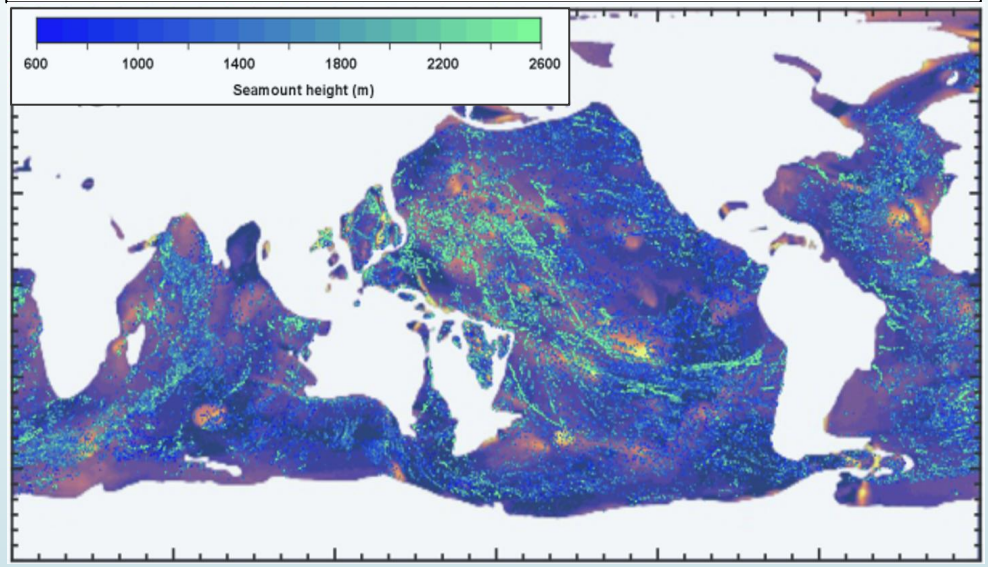
## Predicted present-day mantle structure vs hotspot records



- Oceanic plateaus formed where plumes spread to reach MOR
- Plume-generated residual asthenospheric heat trigger widespread seamounts




(Dong et al., *NG,* 2026)

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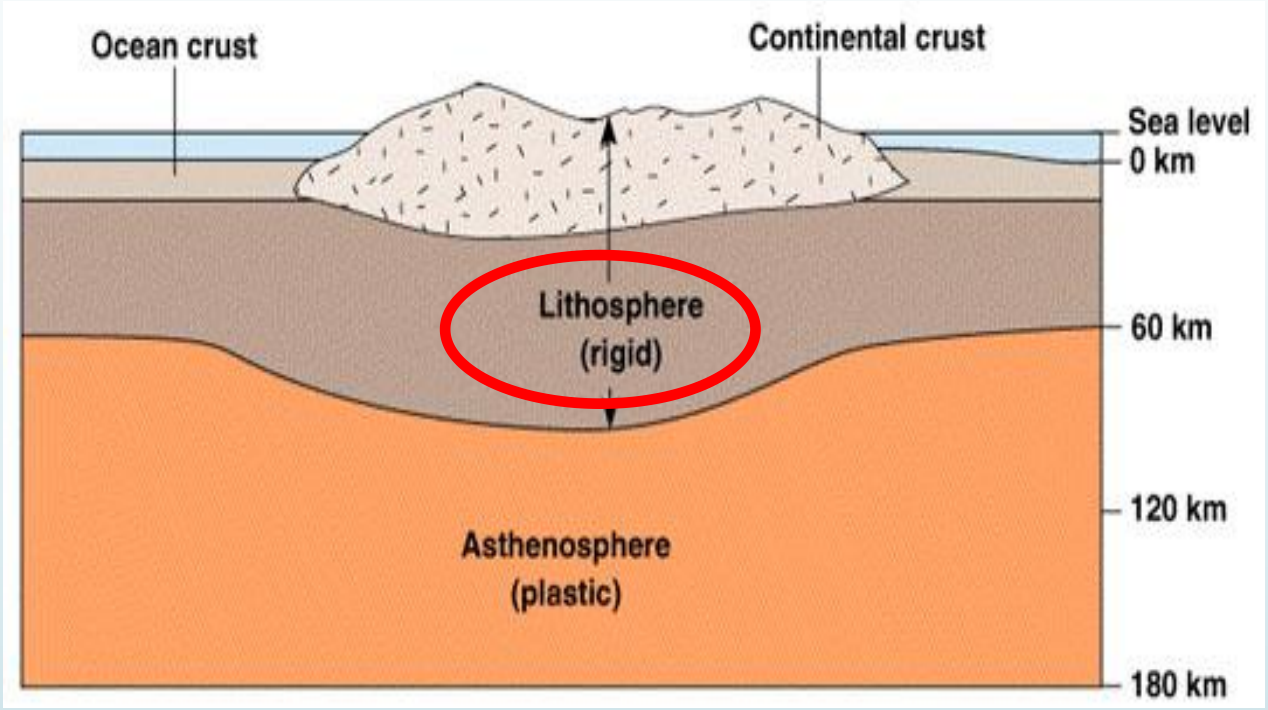
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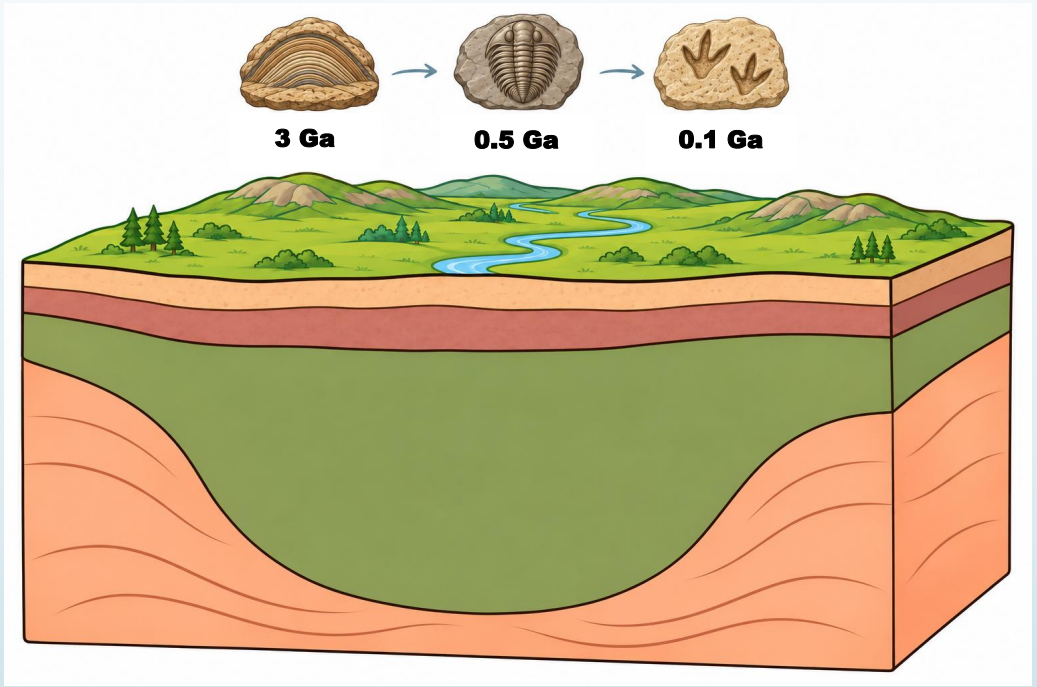
# Cratonic mantle is traditionally considered buoyant & stable

- The keel is compositionally buoyant and mechanically strong
- Continent topography follows **crustal (Airy) isostasy**




*[http://geosymphony.weebly.com/mantle.html]*

Long-term stability




(AI generated)

# Continents follow lithospheric (not crustal) isostasy

$$\rho_w \cdot 2.5km + \rho_{basalt} \cdot 7km + \rho_m \cdot 90.5km = \rho_{andesite} \cdot H_C + \rho_m \cdot (100\ km - H_C + h_{iso})$$

Solve for $h_{iso}$ with:

- $\rho_{andesite}$ = 2.85 g/cm$^3$
- $\rho_{basalt}$ = 3.0 g/cm$^3$
- $\rho_{mantle}$ = 3.3 g/cm$^3$
- $H_c$ = 41 km

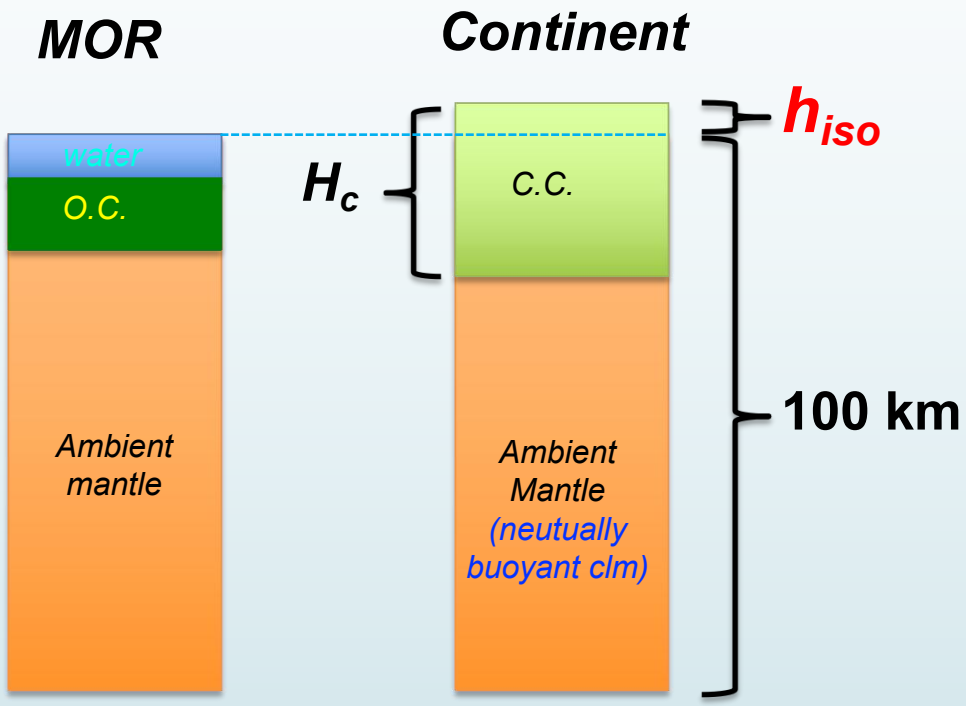
**$h_{iso}$ = 3.2 km**

**$h_{obs}$ = 0.5 km**

This requires a $H_c$=30 km, a valued adopted in previous studies.

**$h_{obs} - h_{iso}$ = -2.7 km** → Need downward pull.

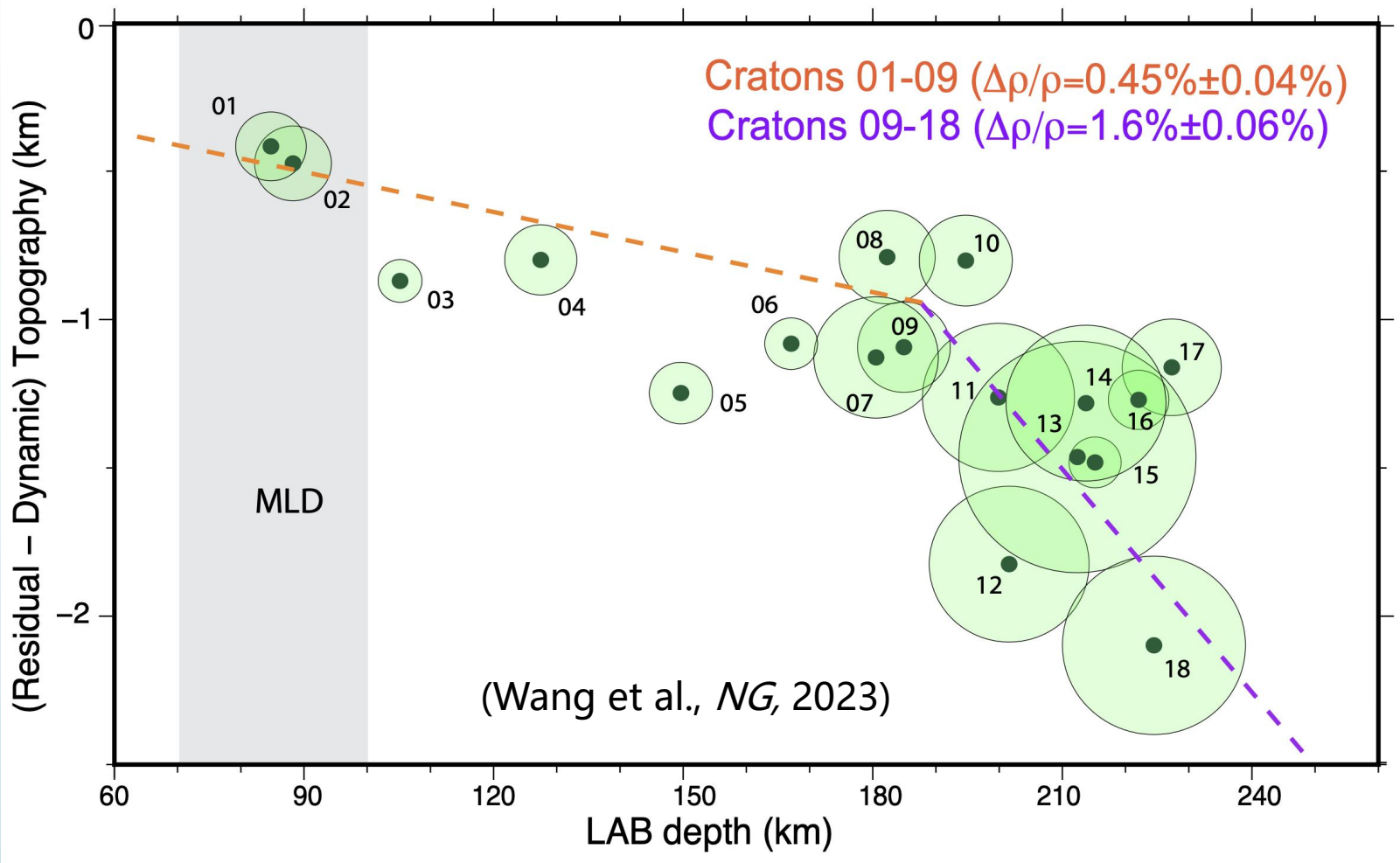
**Requires dense mantle lithosphere !**



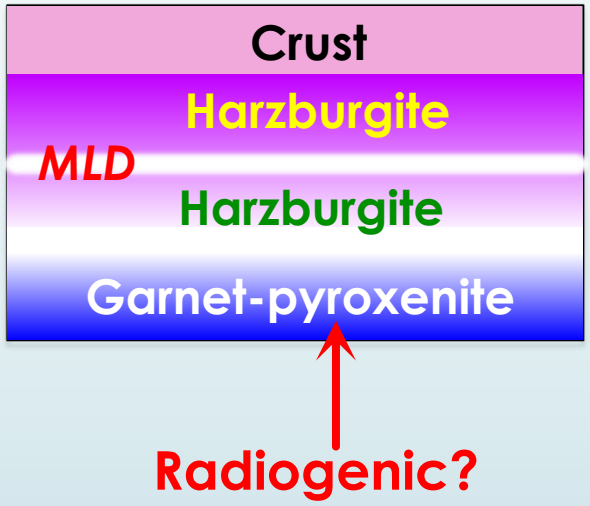

(Liu et al., *NSR*, 2025)

# Continents follow lithospheric (not crustal) isostasy

## (1) Dense CLM (2) Layered CLM structure

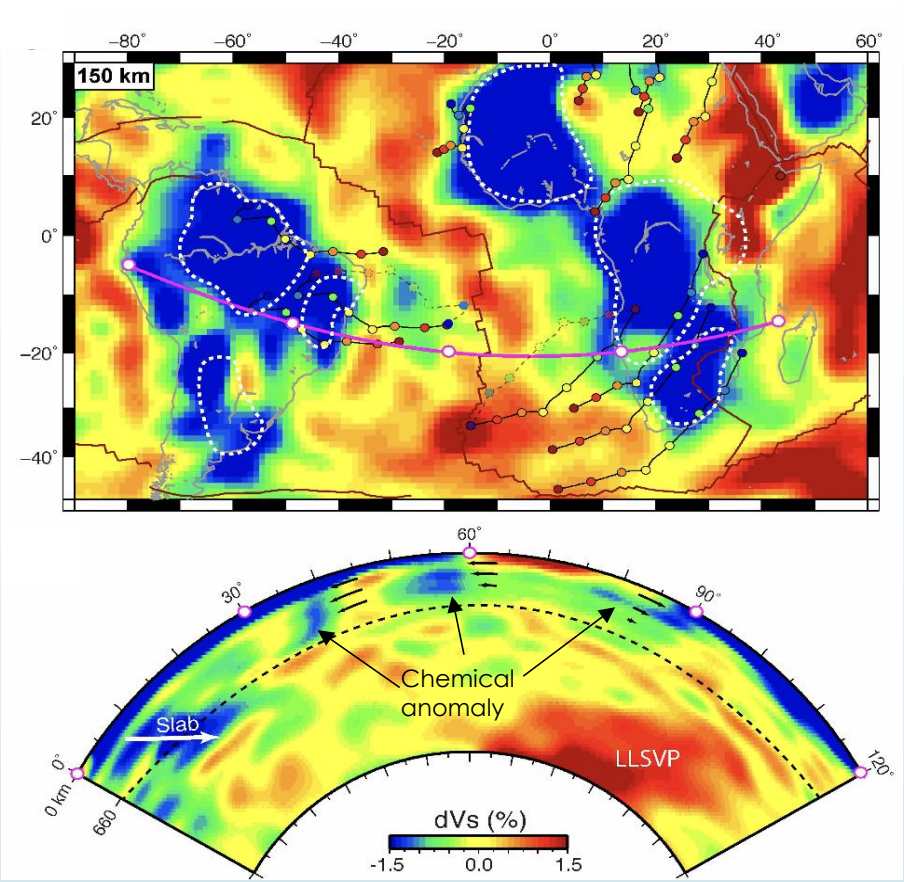



Cratonic lithosphere structure

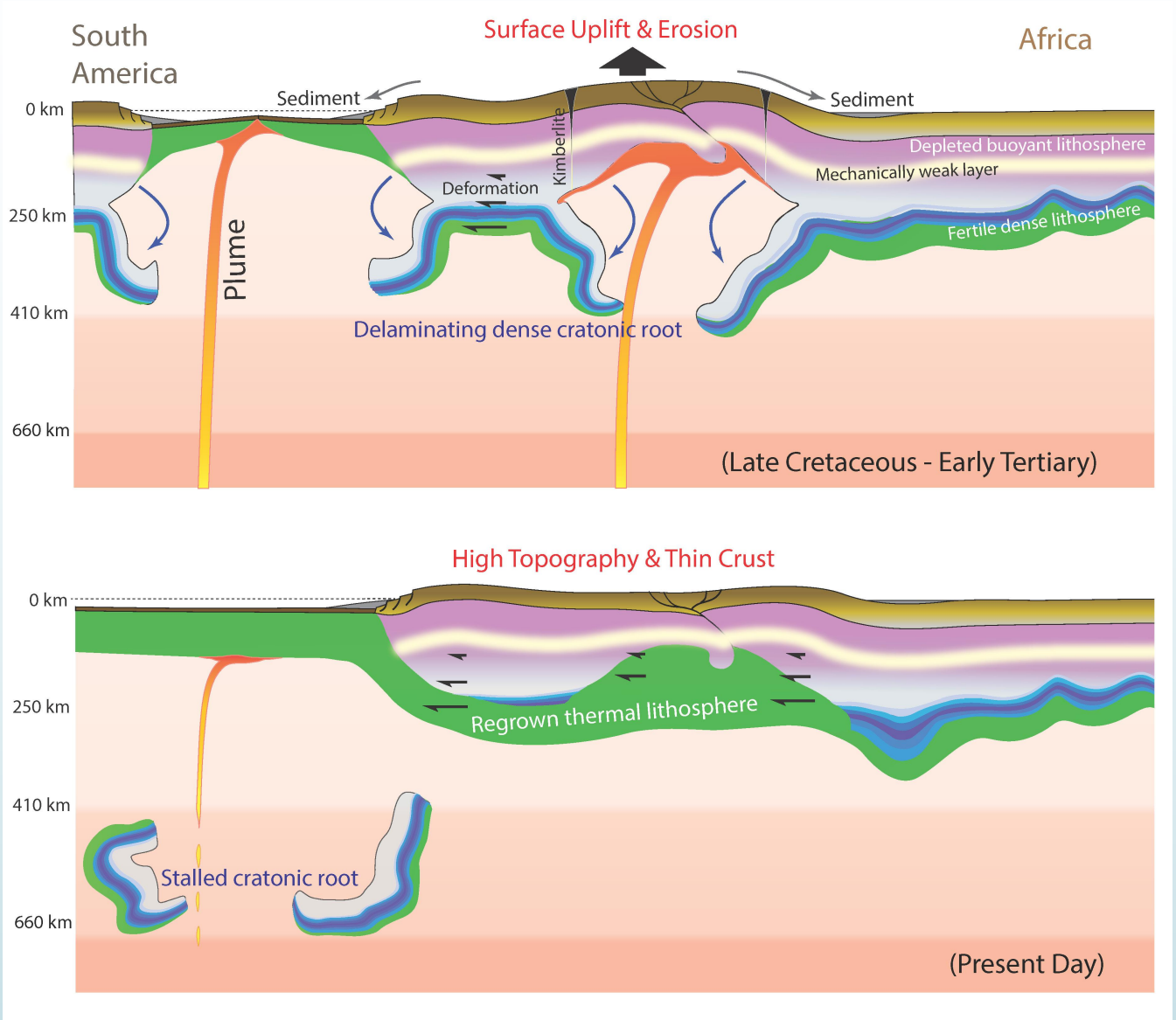


# Cratonic lithosphere may become unstable and delaminate

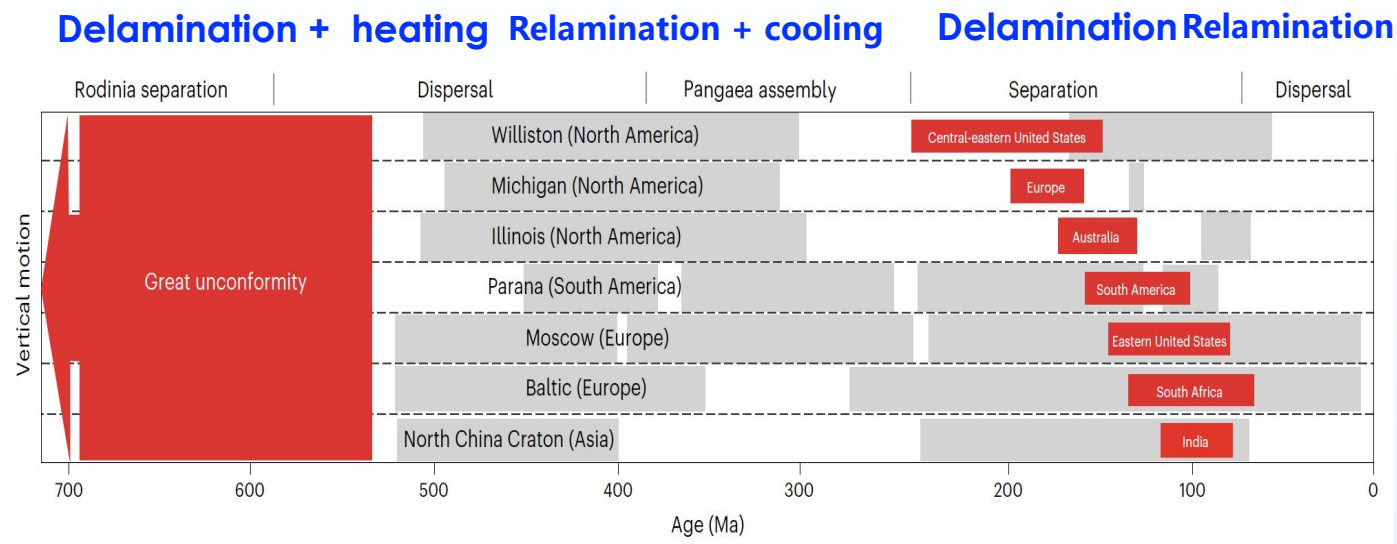
## Seismic evidence

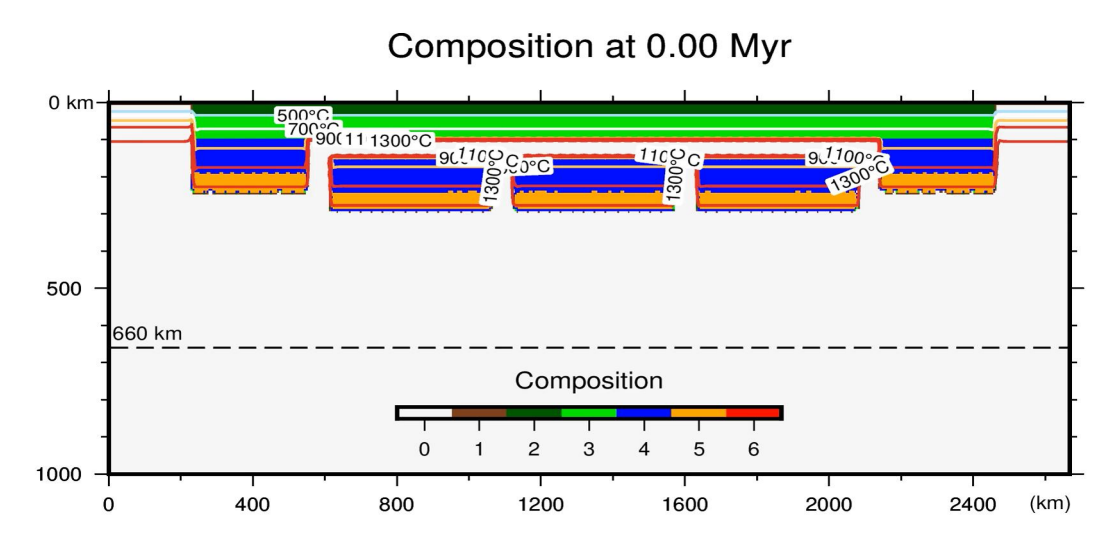



(Hu et al., *NG*, 2018)

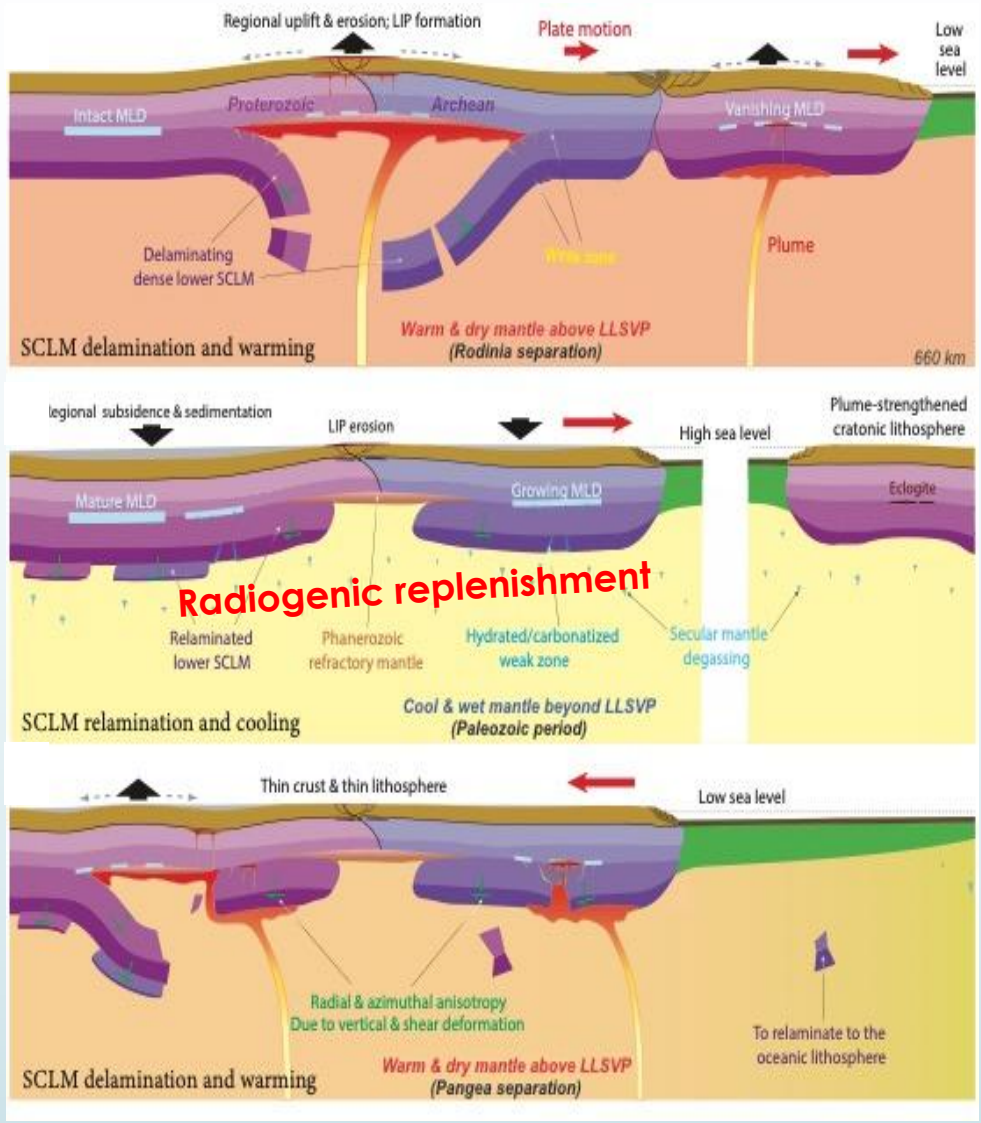


# Cratonic delamination may have occurred multiple times



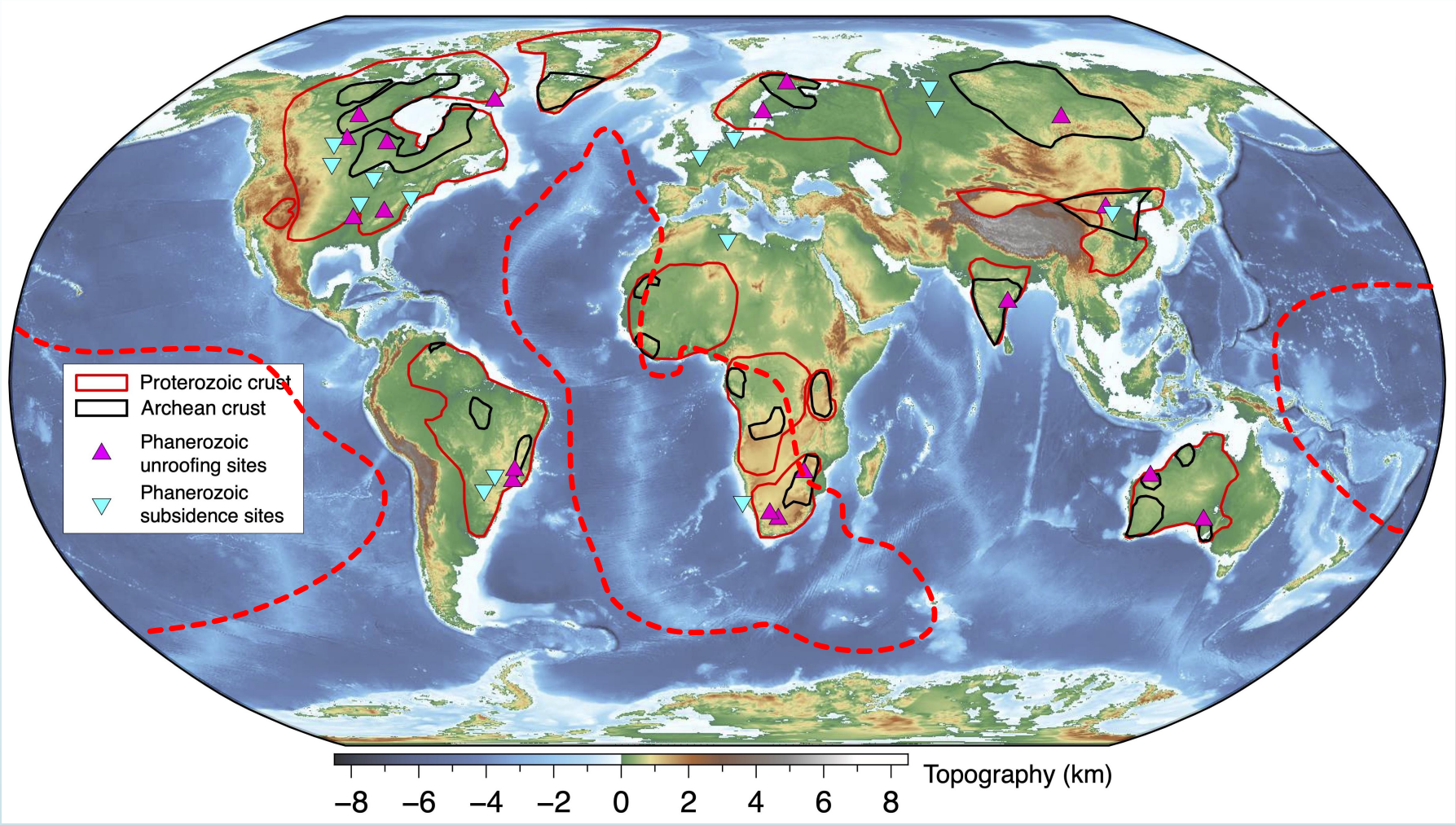

(Peng et al., *EPSL*, 2022)




(Wang et al., *NG*, 2023; Liu et al., *NSR*, 2025)

# Ideal locations for geoneutrino detection

## Within the black contours…



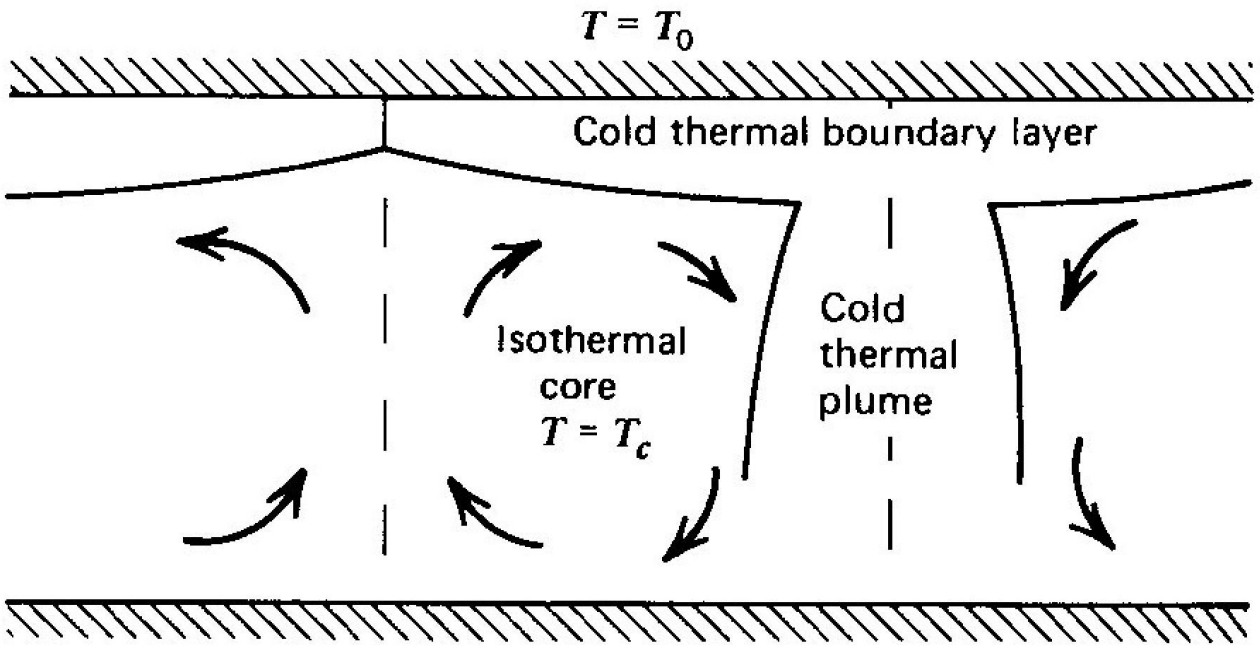

(Liu et al., *NSR*, 2025)

# Conclusion

- Understanding modern Earth's dynamics is key for deciphering its past evolution.
- Oceanic subduction represents the dominant driver for modern mantle dynamic processes, including plume formation and evolution.
- Continental lithosphere is more unstable than previously thought and may modulate evolution of the solid Earth, especially over the supercontinent time scale.

# Subduction is a consequence of plate tectonics

## Symmetric downwelling: not Earth-like subduction




(Turcotte & Schubert, 2002)

## Constitutive laws

$$\nabla \cdot \mathbf{v} = 0$$

$$\nabla \cdot (\eta(\nabla \mathbf{v} + (\nabla \mathbf{v})^T)) - \nabla p = \mathrm{Ra}\left(\frac{\alpha(z)}{\alpha_0} T + B_i \, C_i\right)\mathbf{e}_\mathrm{r}$$

$$\partial_t T + \mathbf{v} \cdot \nabla T = \nabla^2 T + H$$

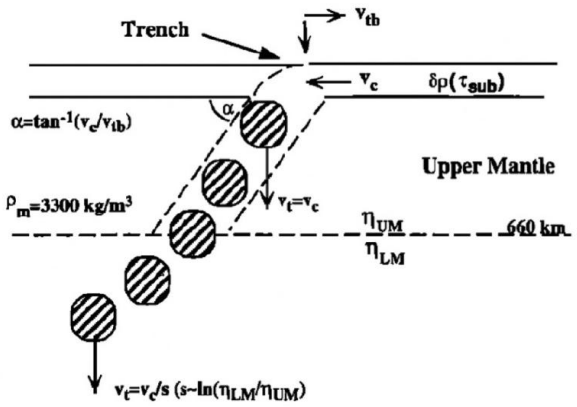
$$\partial_t C_i + \mathbf{v} \cdot \nabla C_i = 0$$

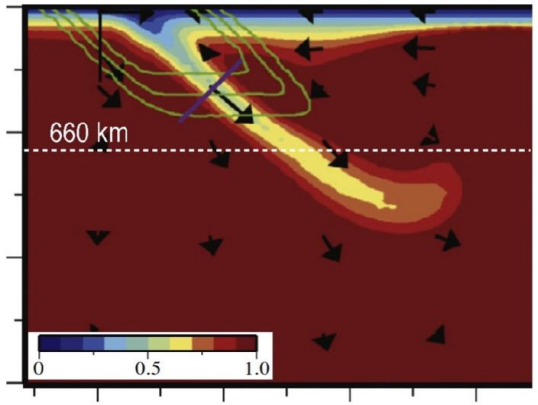
# Realistic Earth models

Asymmetrical subduction

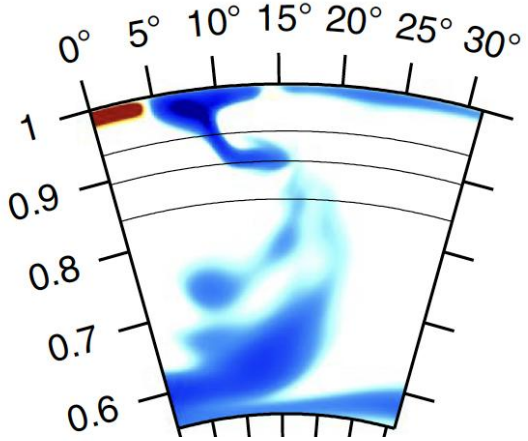
Complex plate boundaries

**Pure thermal models**

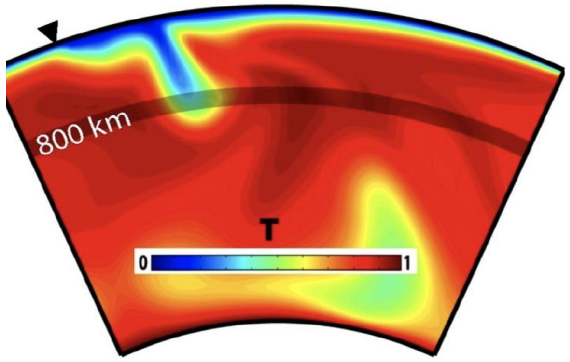



(Bower et al., 2015)

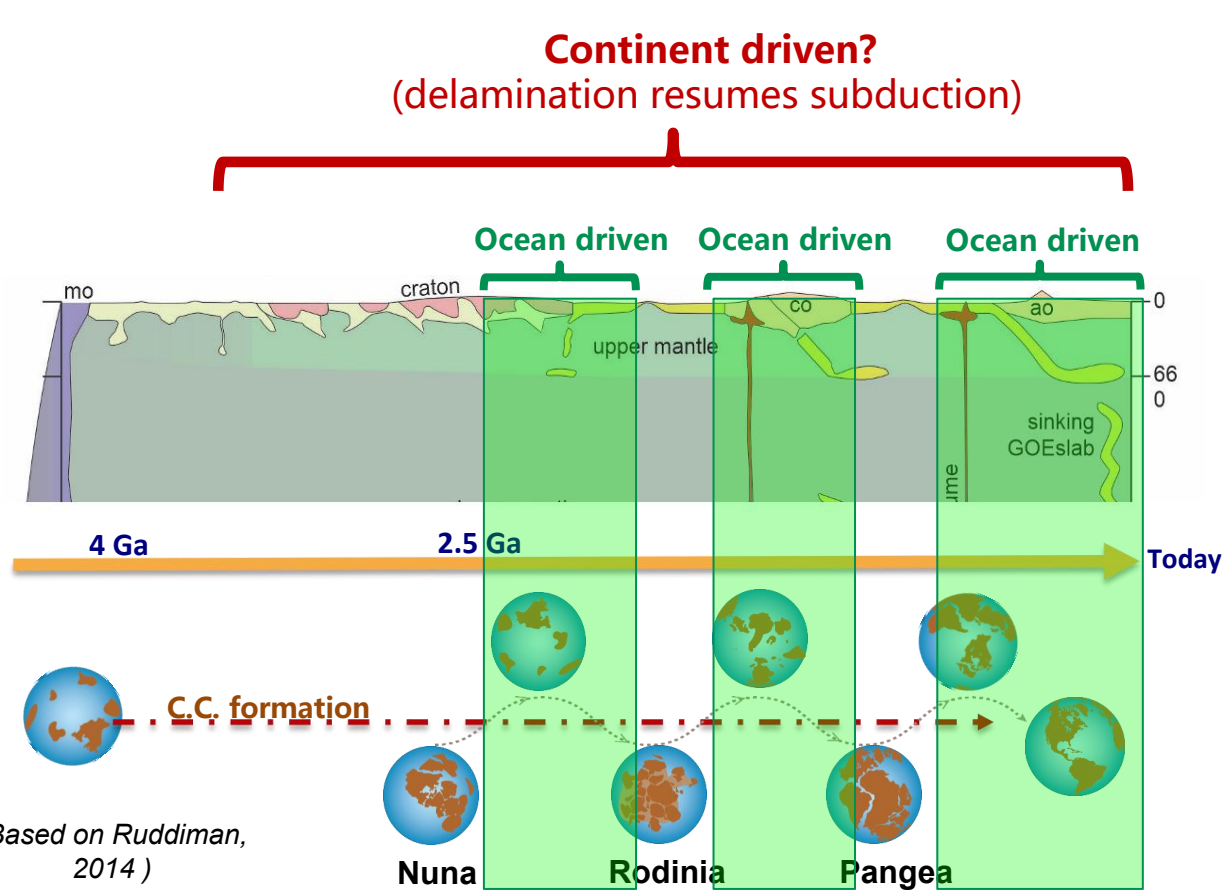



(Mao & Zhong, 2018)



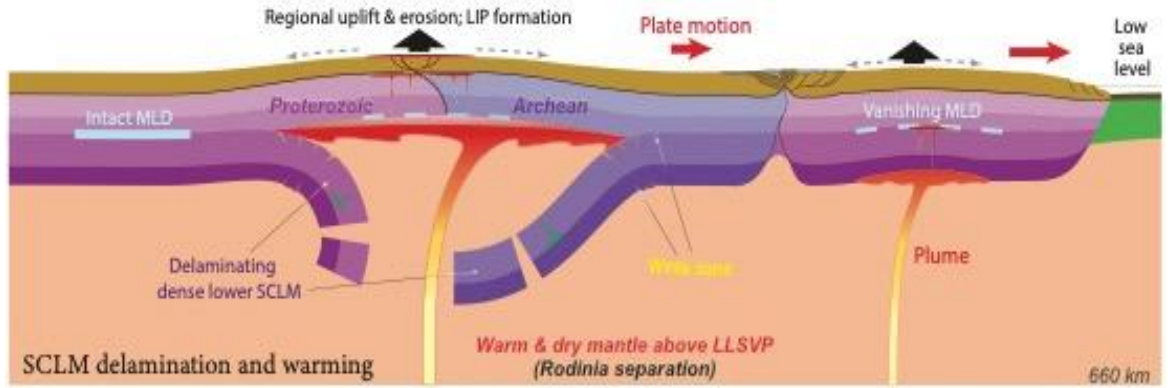

(Bello et al., 2015)

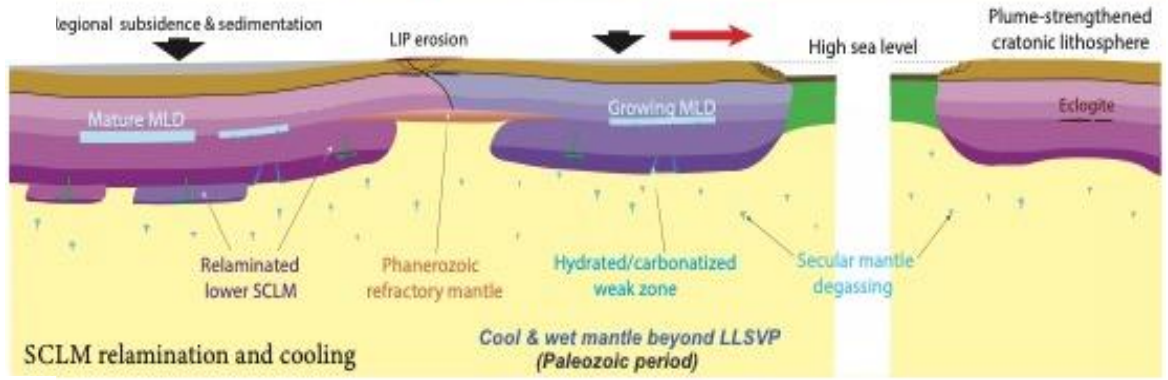
# Cratonic delamination accompanying supercontinent cycles




(Based on Ruddiman, 2014 )

(Wang et al., *NG*, 2023;
Liu et al., *NSR*, 2025
Cao et al., *EPSL*, 2026)



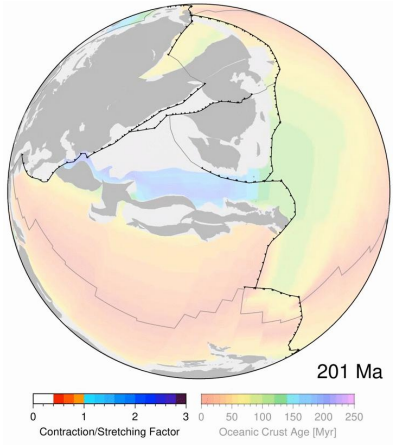





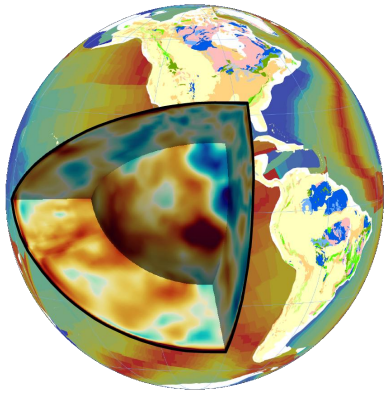

# Data assimilation to account for complex boundary conditions

## Data Assimilation (DA)

Plate kinematic history

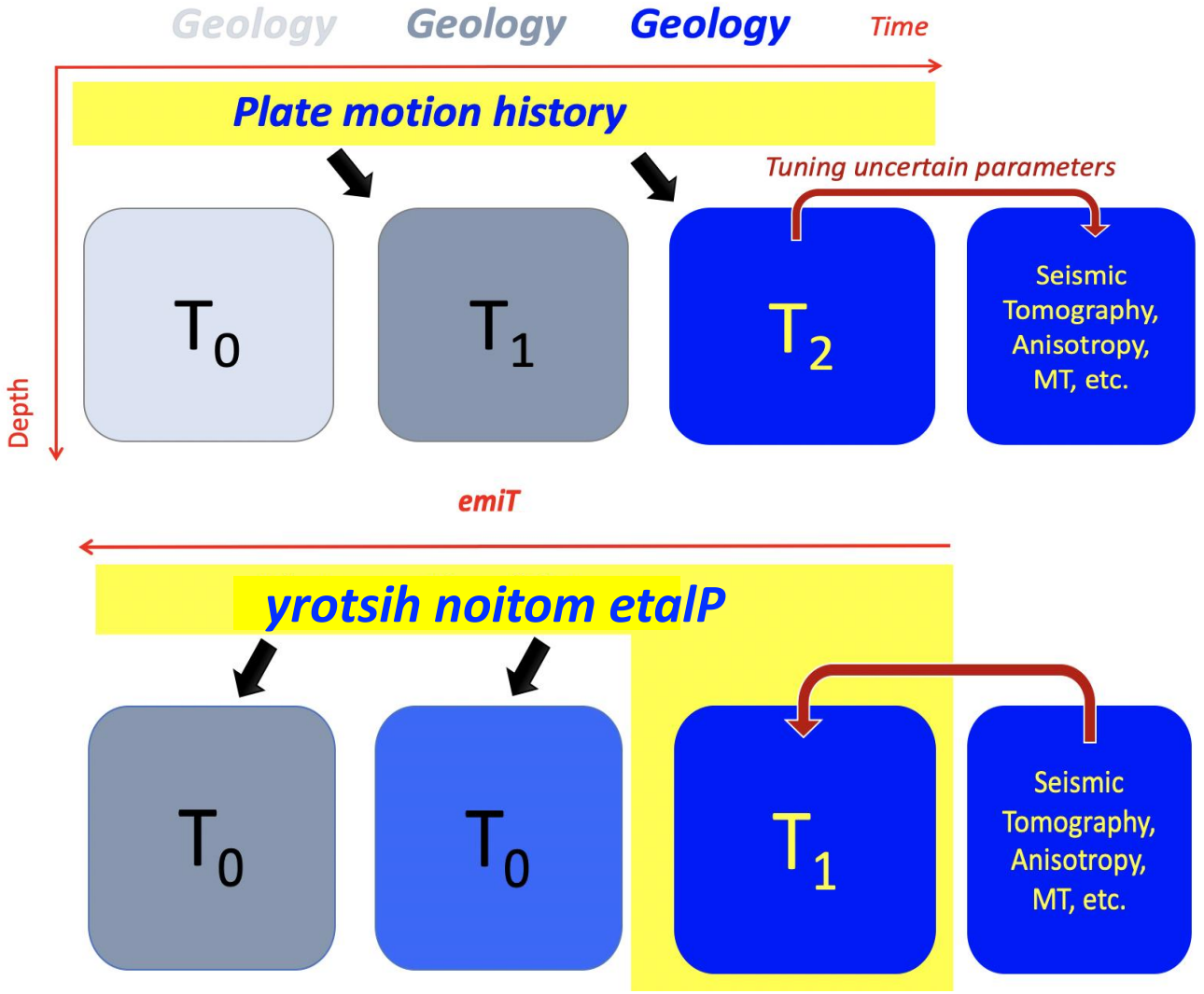



Present mantle structure



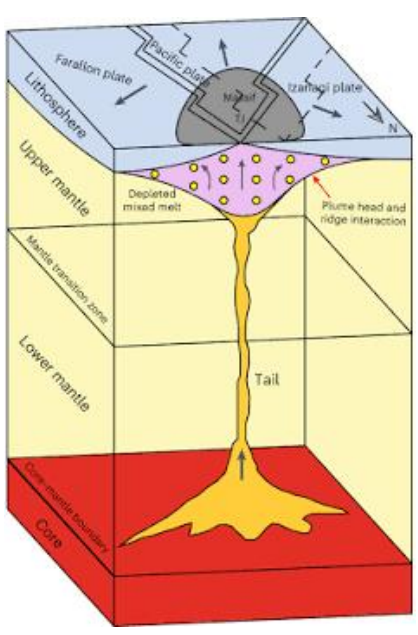
Forward DA

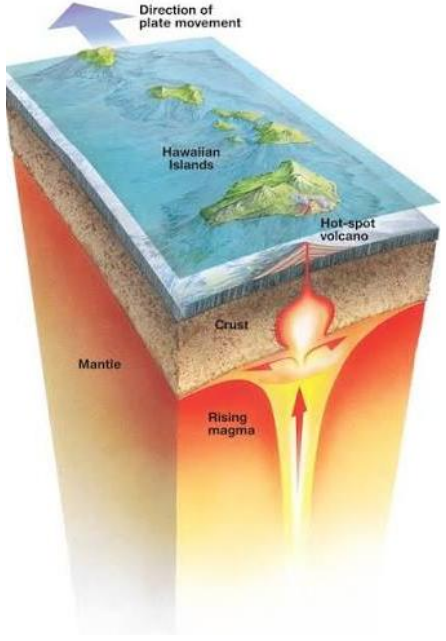
Backward DA



# Related scientific questions/debates

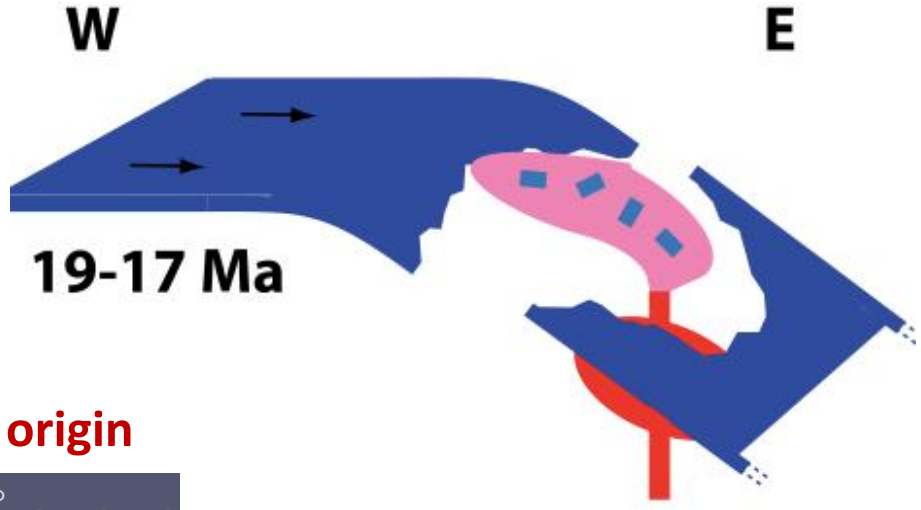
## Oceanic plateau / hotspot tracks



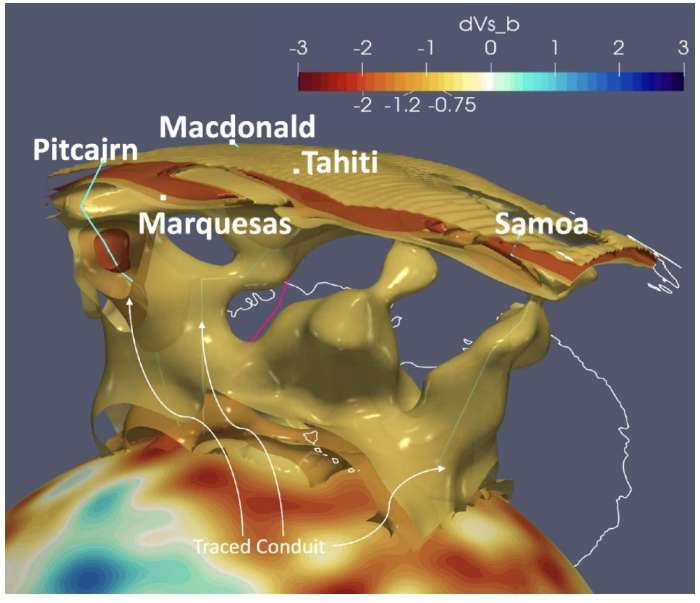

(Zhang et al., 2023)

## Slab-plume interaction




(Obrebski et al., 2010)

## Plume morphology & origin




(SEMUCB-WM1)