Plate tectonics and some open questions

https://animations.geol.ucsb.edu/2_infopgs/IP1GTect/aWorldPhysMap&Globes.html

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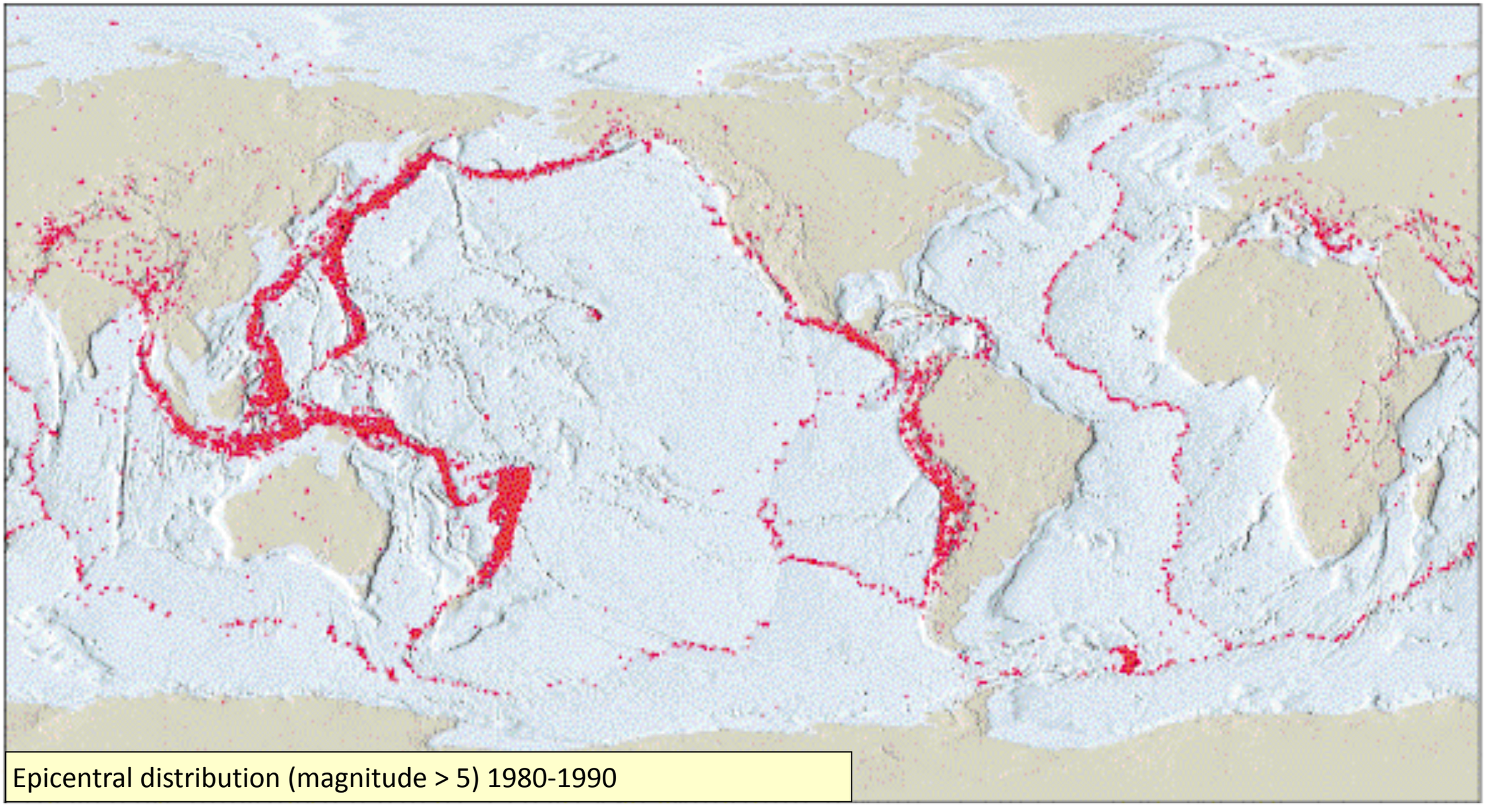
Outline

1. What is plate tectonics?
   History of the North America-Pacific plate boundary

2. What drives plate tectonics?

3. Faulting, magma, and volcanic systems: Current thinking and open problems

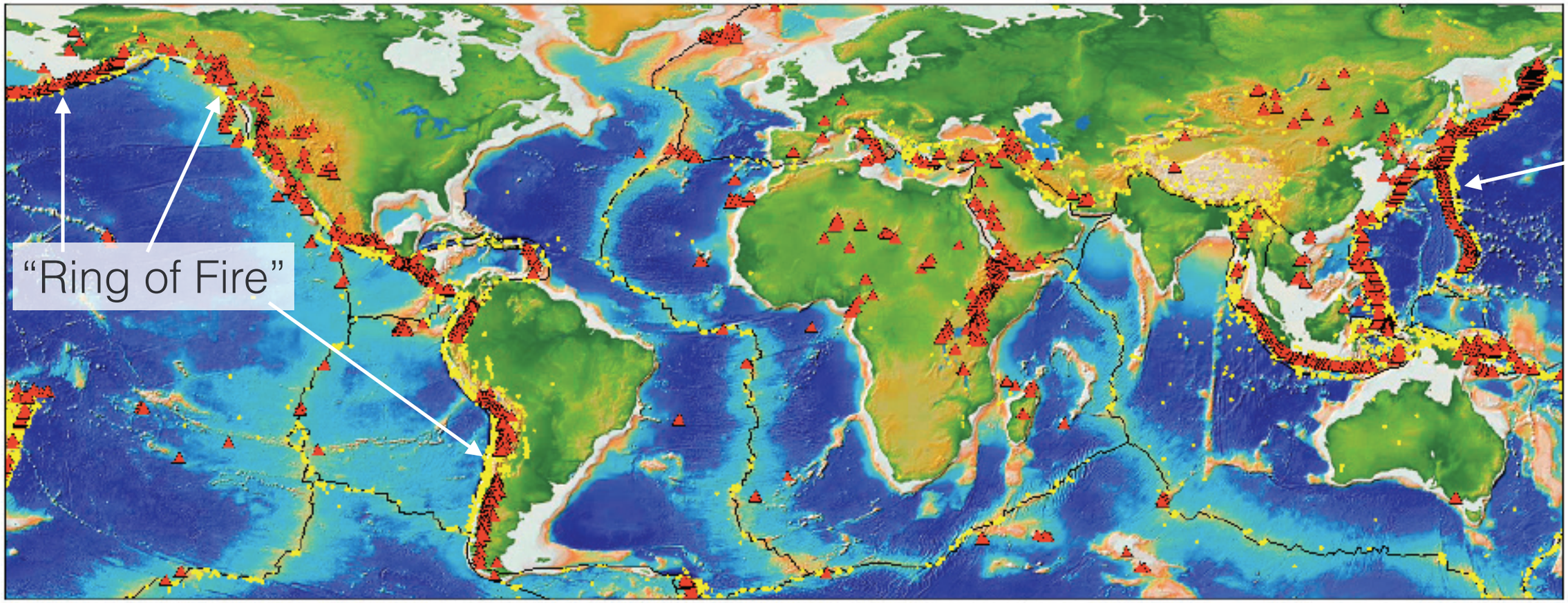
Why do earthquakes occur where they do?



Epicentral distribution (magnitude > 5) 1980-1990

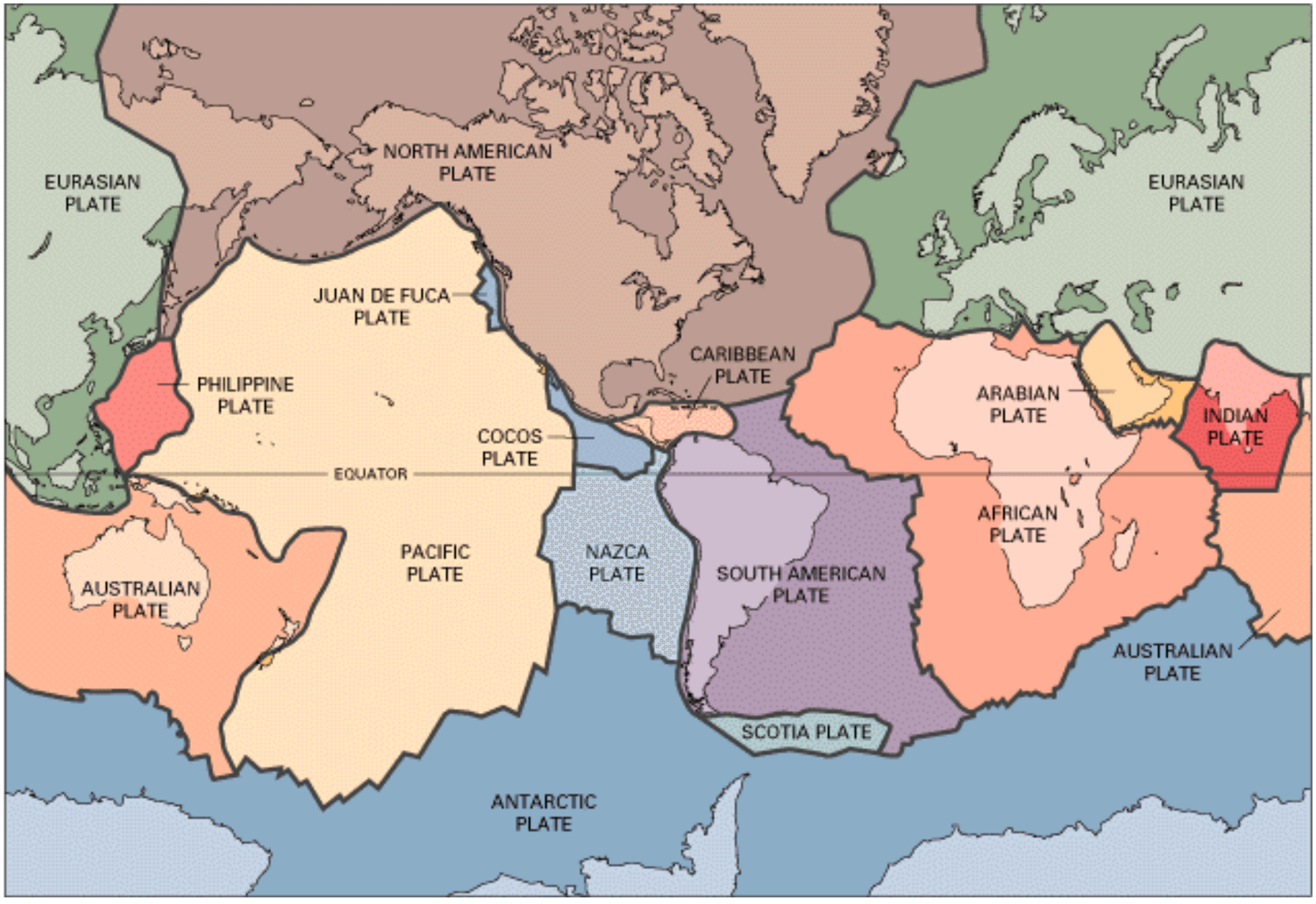
Why do volcanoes occur where they do?

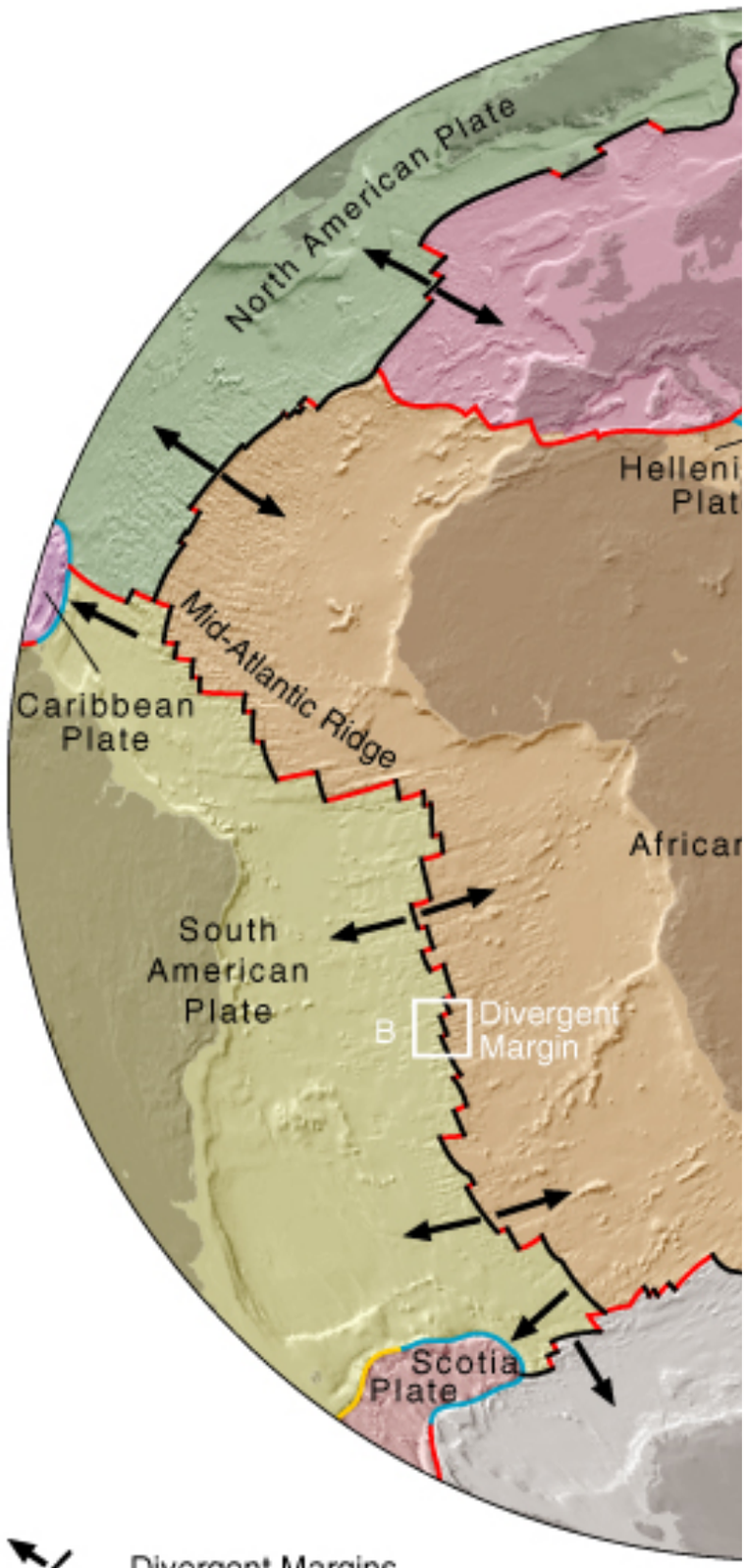
▲ Volcanoes (<10000 yrs); ● Earthquakes (M_w > 5 since 1990)

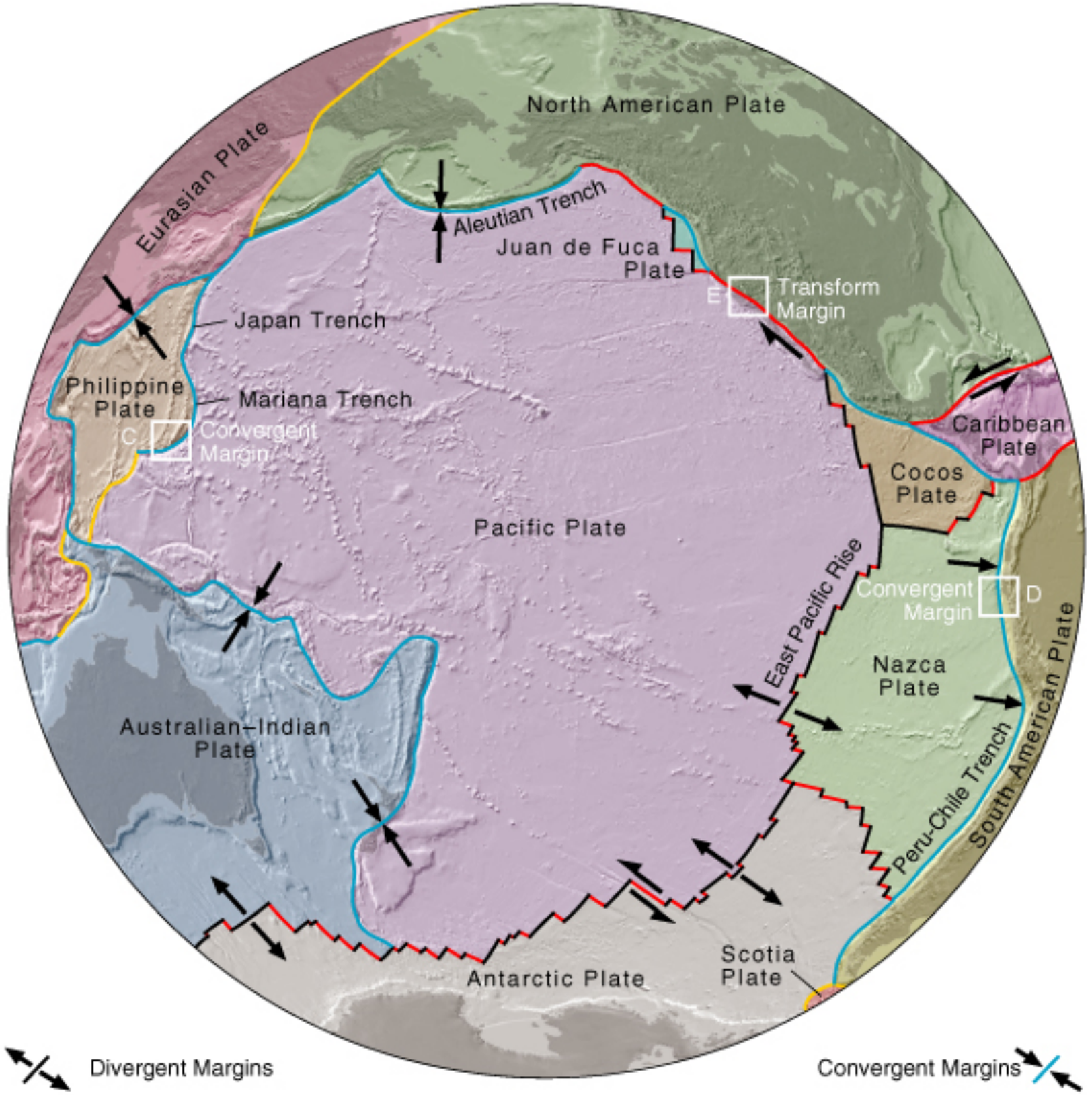


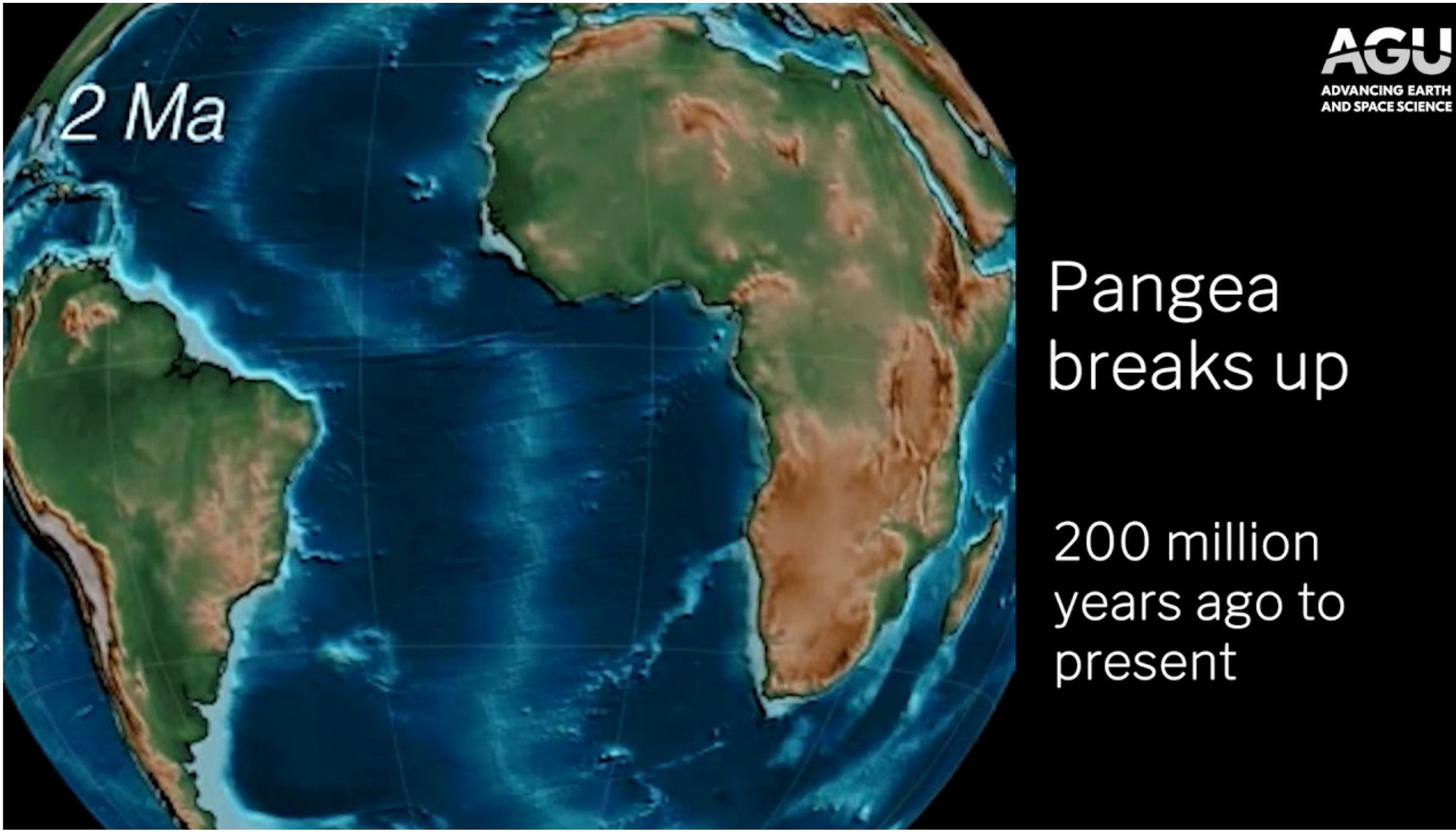
Source: Smithsonian volcano database, NAS ERUPT 2018 report

Tectonic plates on Earth



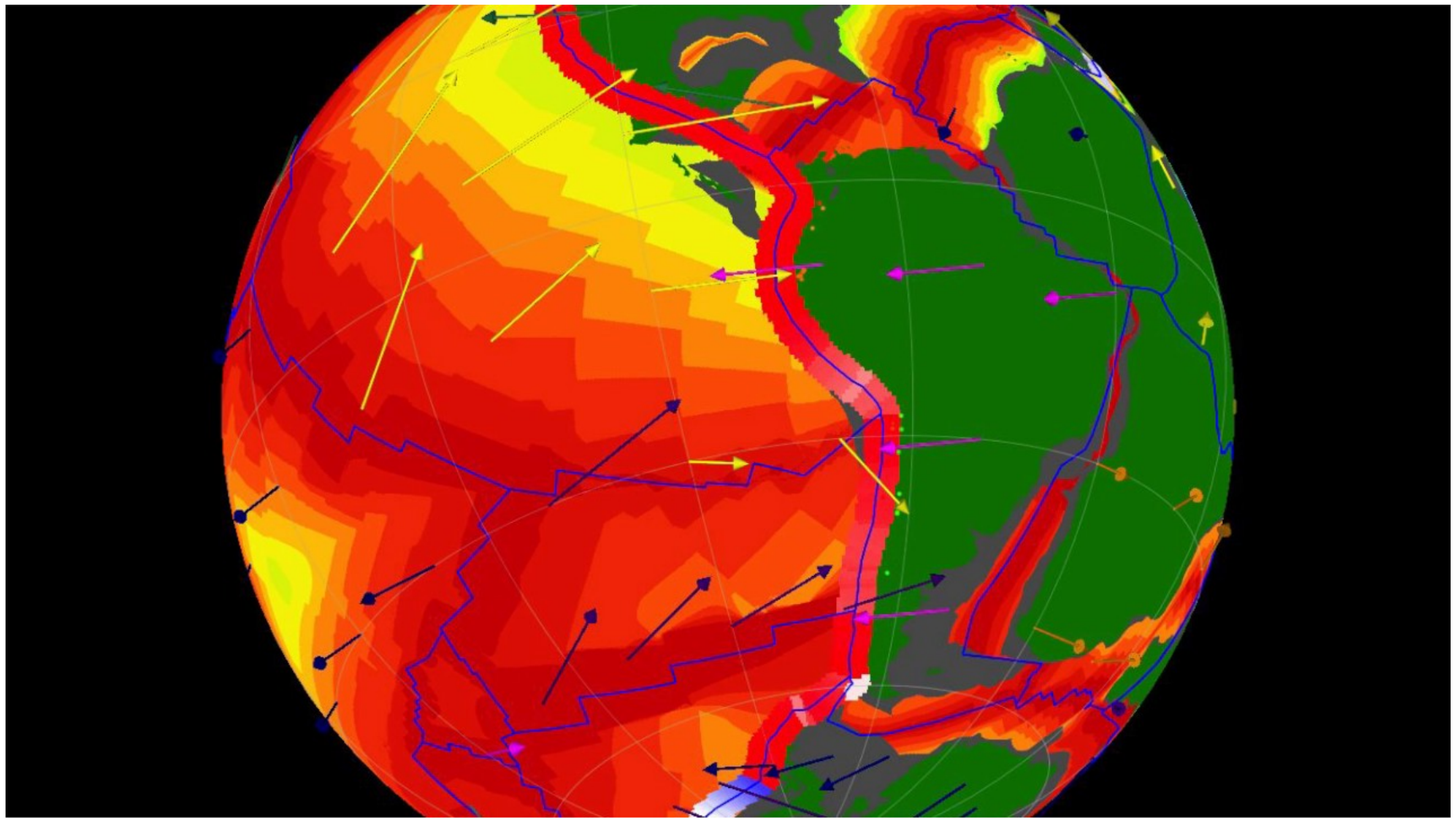





200 Ma
AGU
ADVANCING EARTH AND SPACE SCIENCE
Pangea breaks up
200 million years ago to present

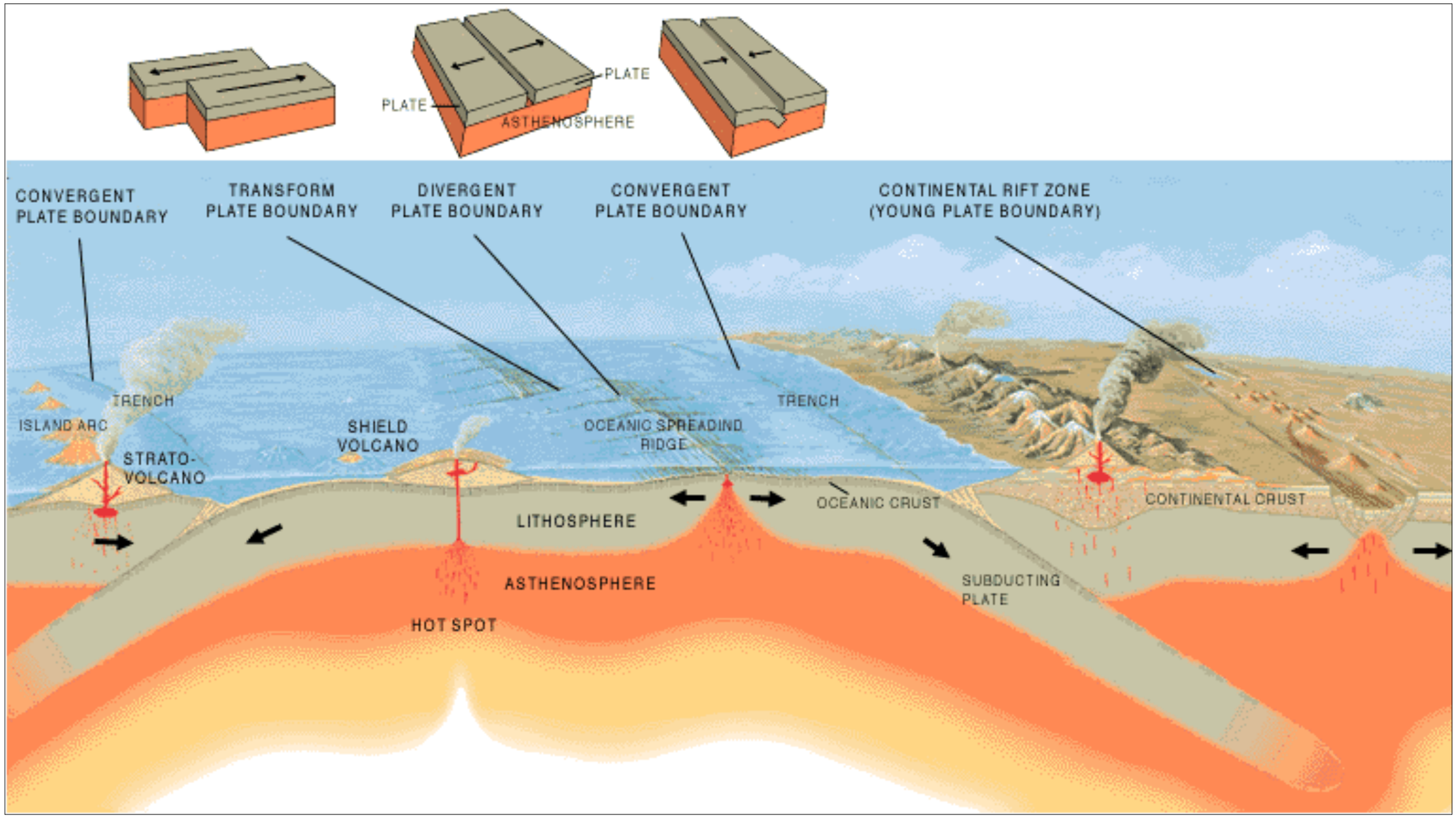
(py)GPlates

https://www.gplates.org



Müller, R. D., Cannon, J., Qin, X., Watson, R. J., Gurnis, M., Williams, S., et al. 2018. GPlates: Building a virtual Earth through deep time. Geochemistry, Geophysics, Geosystems, 19. doi:10.1029/2018GC007584.

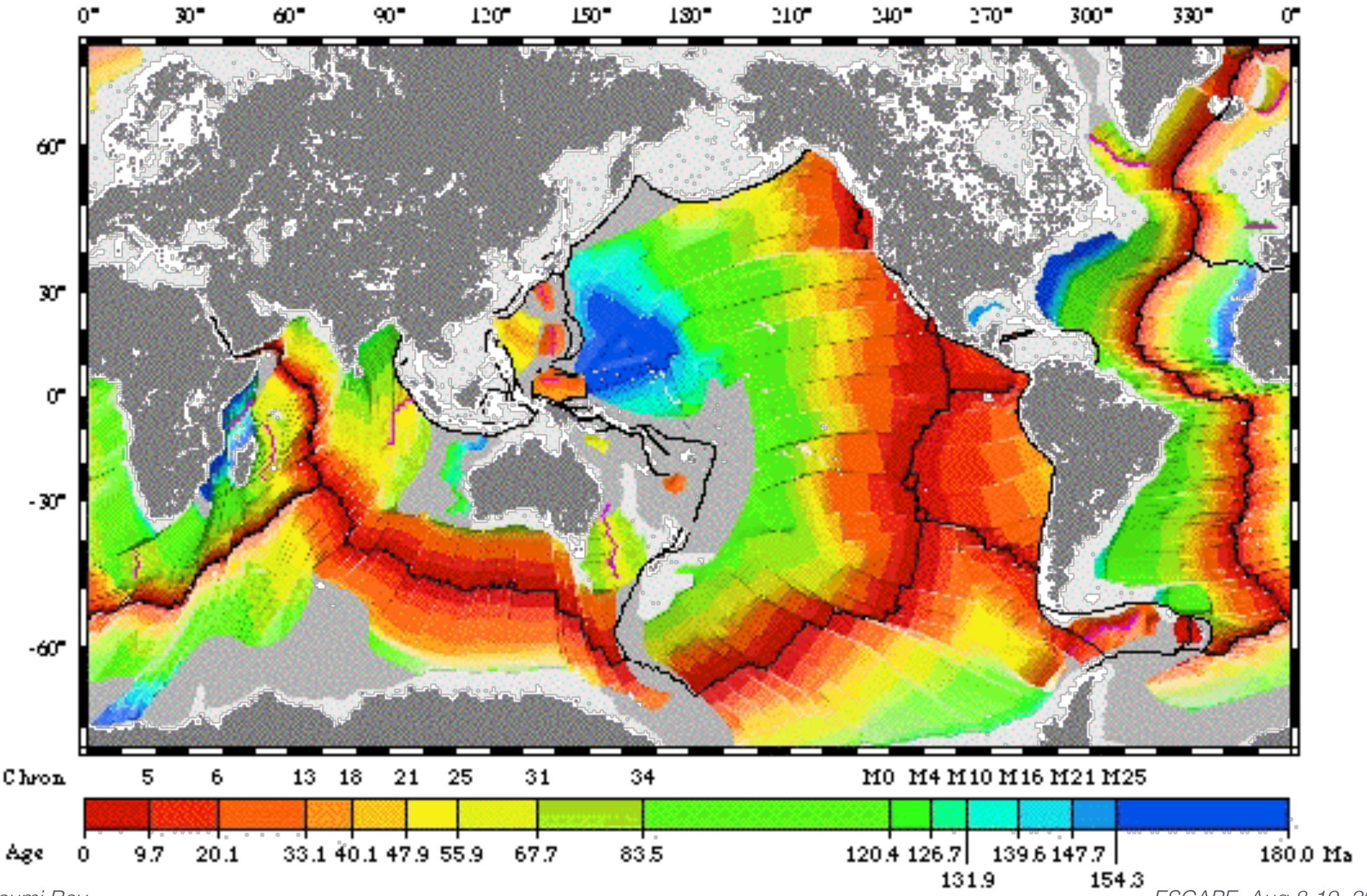
Plate boundaries – 3 types



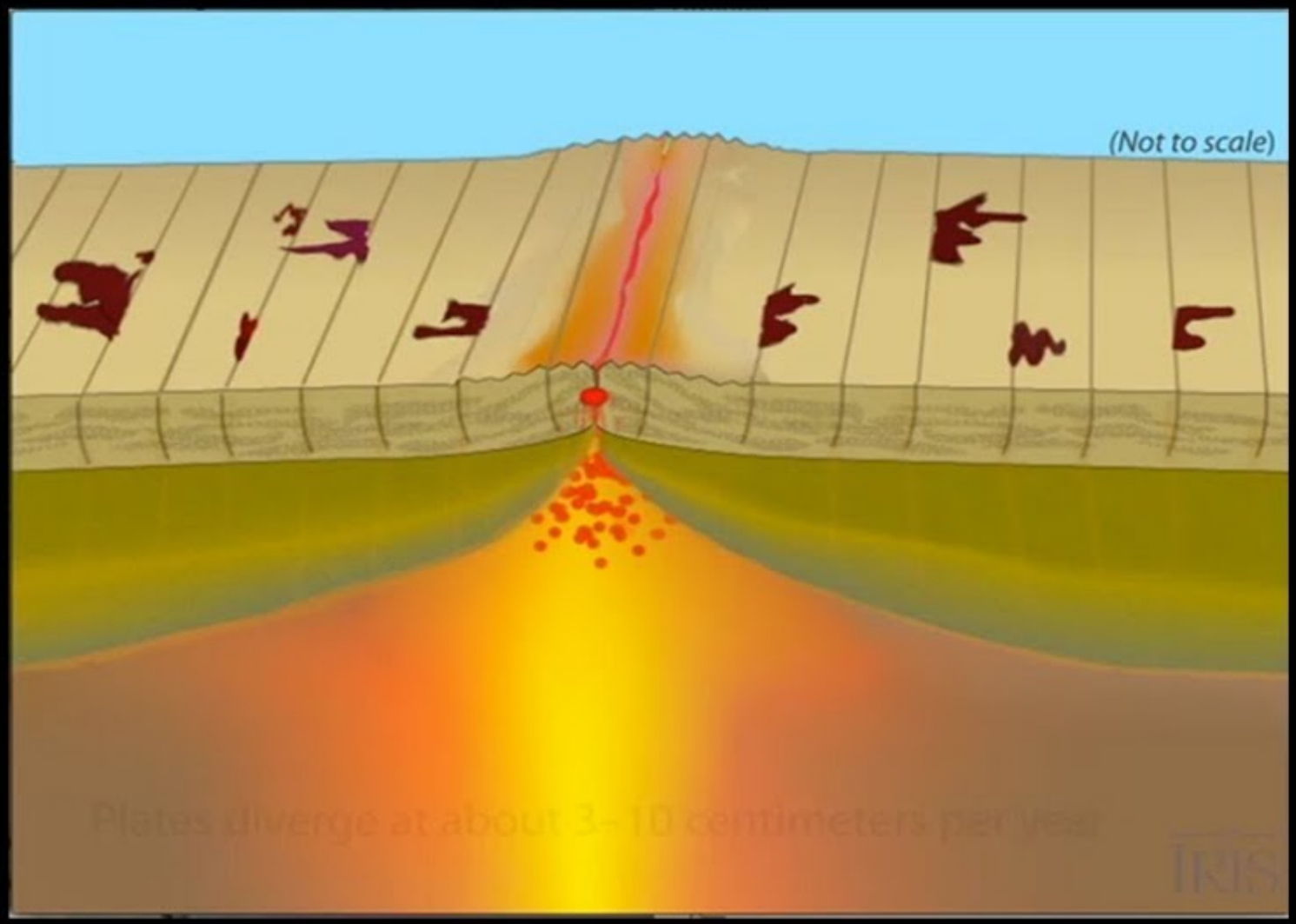
DIVERGENT PLATE BOUNDARIES

AGE OF THE OCEAN FLOOR

Age determined from magnetic anomalies



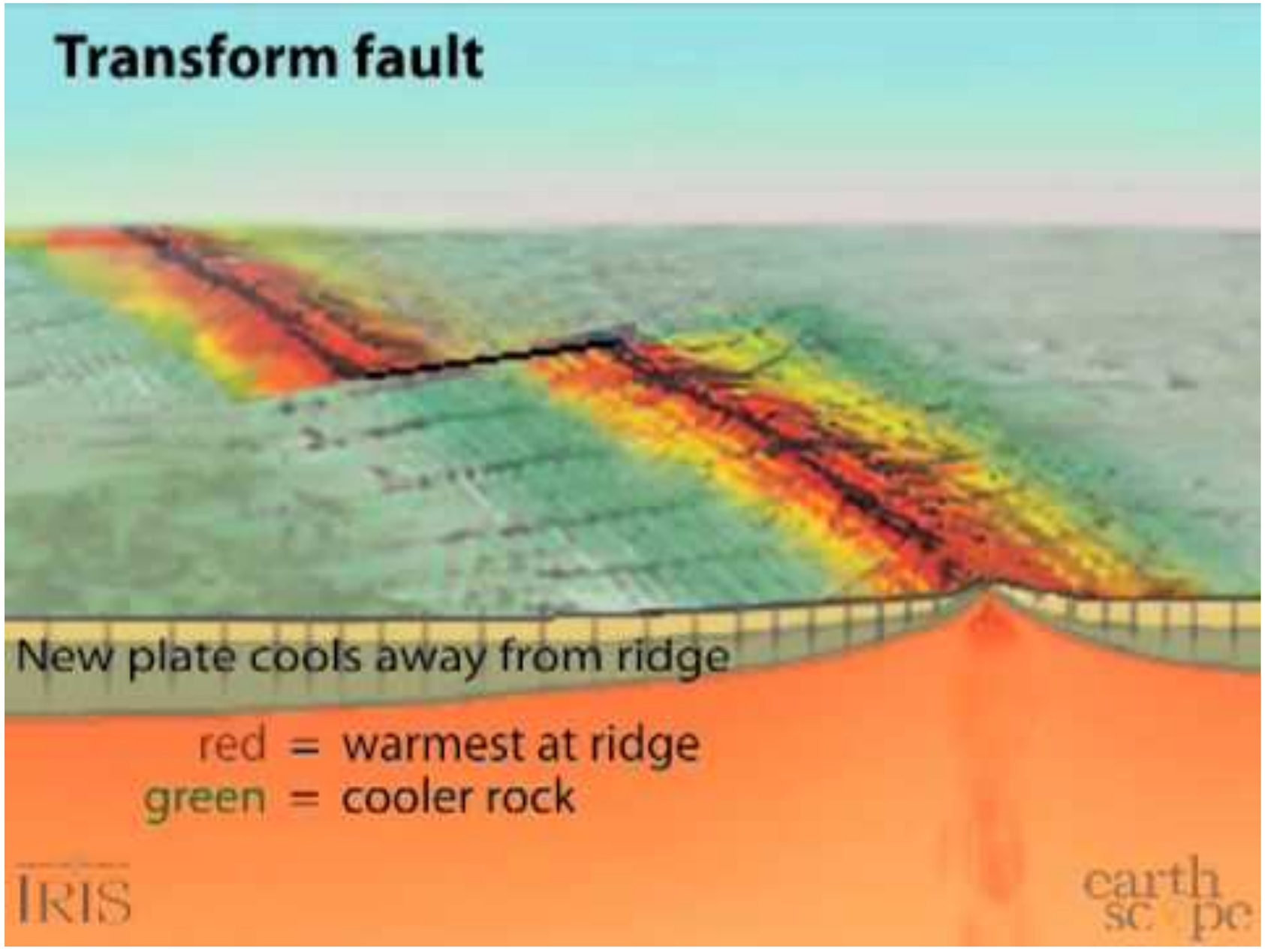
Divergent Boundaries–Overview



Mid-ocean ridge processes

IRIS

NSF


Transform fault
New plate cools away from ridge
red = warmest at ridge
green = cooler rock
IRIS
earthscope

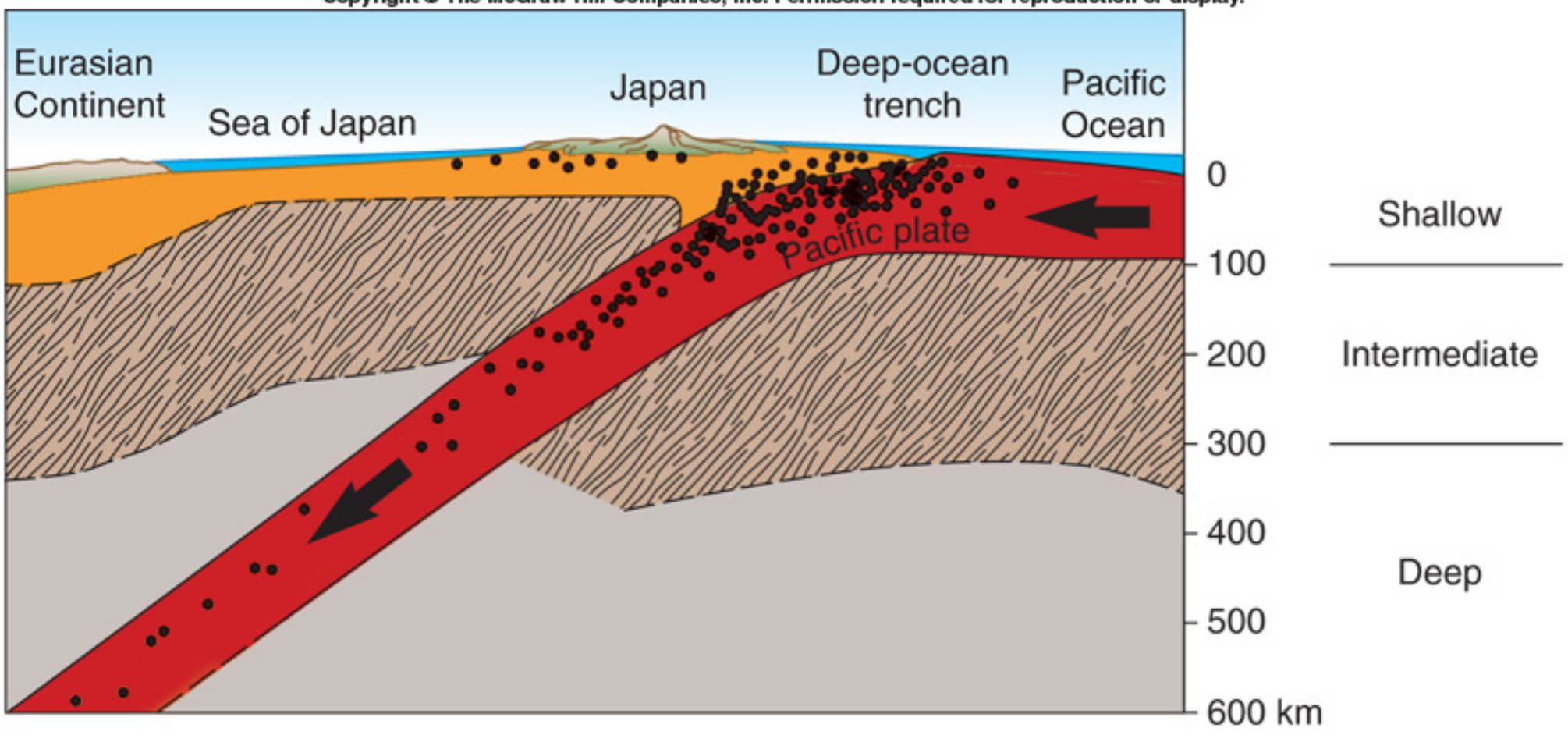
Continental rifts that are in the process of forming oceans

Gulf of California, Mexico

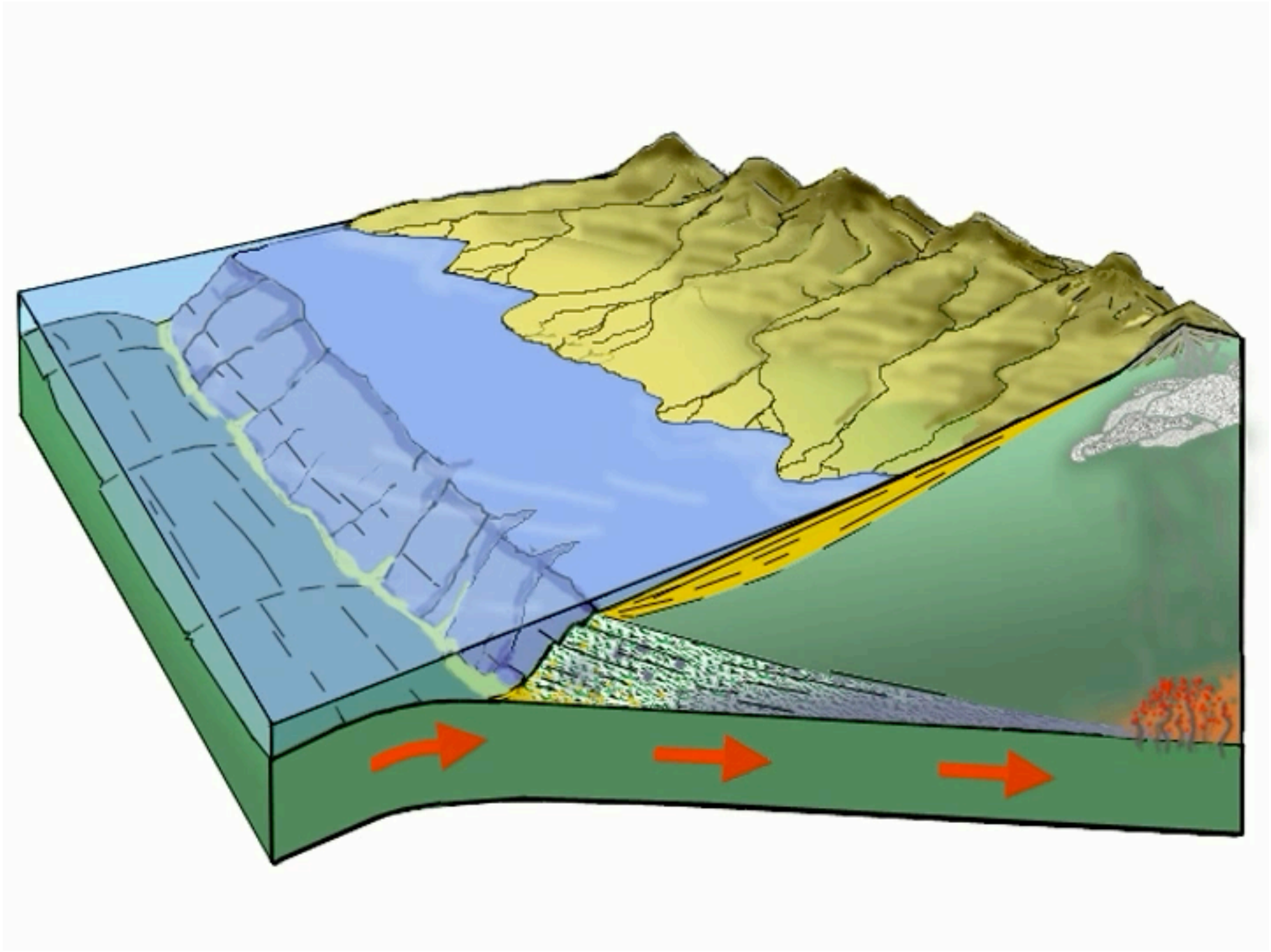
Red Sea

CONVERGENT PLATE BOUNDARY

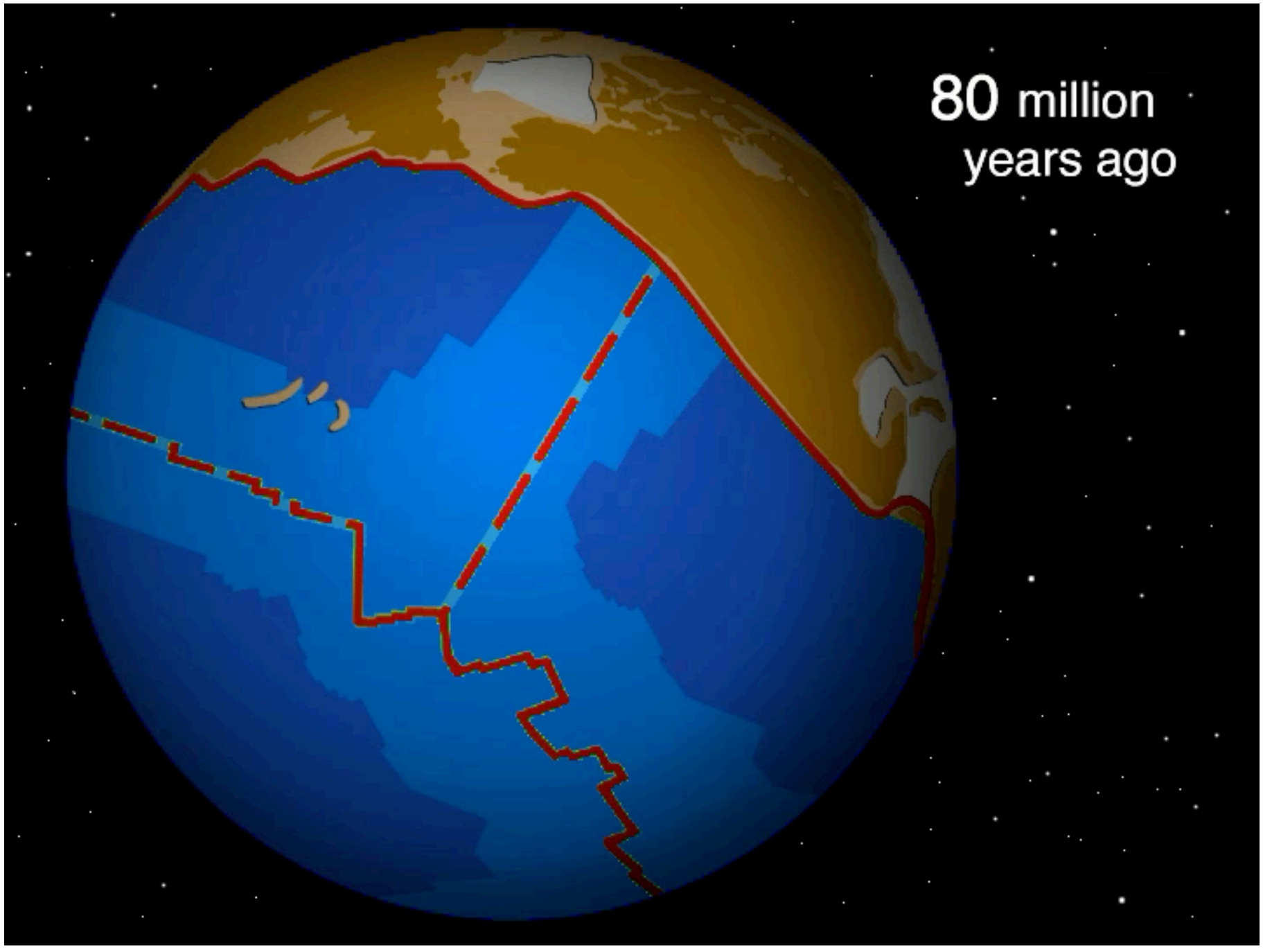
Subduction zone



Cross section showing earthquake locations at depth. Notice the inclined plane defined by the earthquake sites. Notice the deep-ocean trench, the volcanoes on the island of Japan and the ocean floor to the west.



https://animations.geol.ucsb.edu/1_DownloadPage/Download_Page.html#GlobalTectonics



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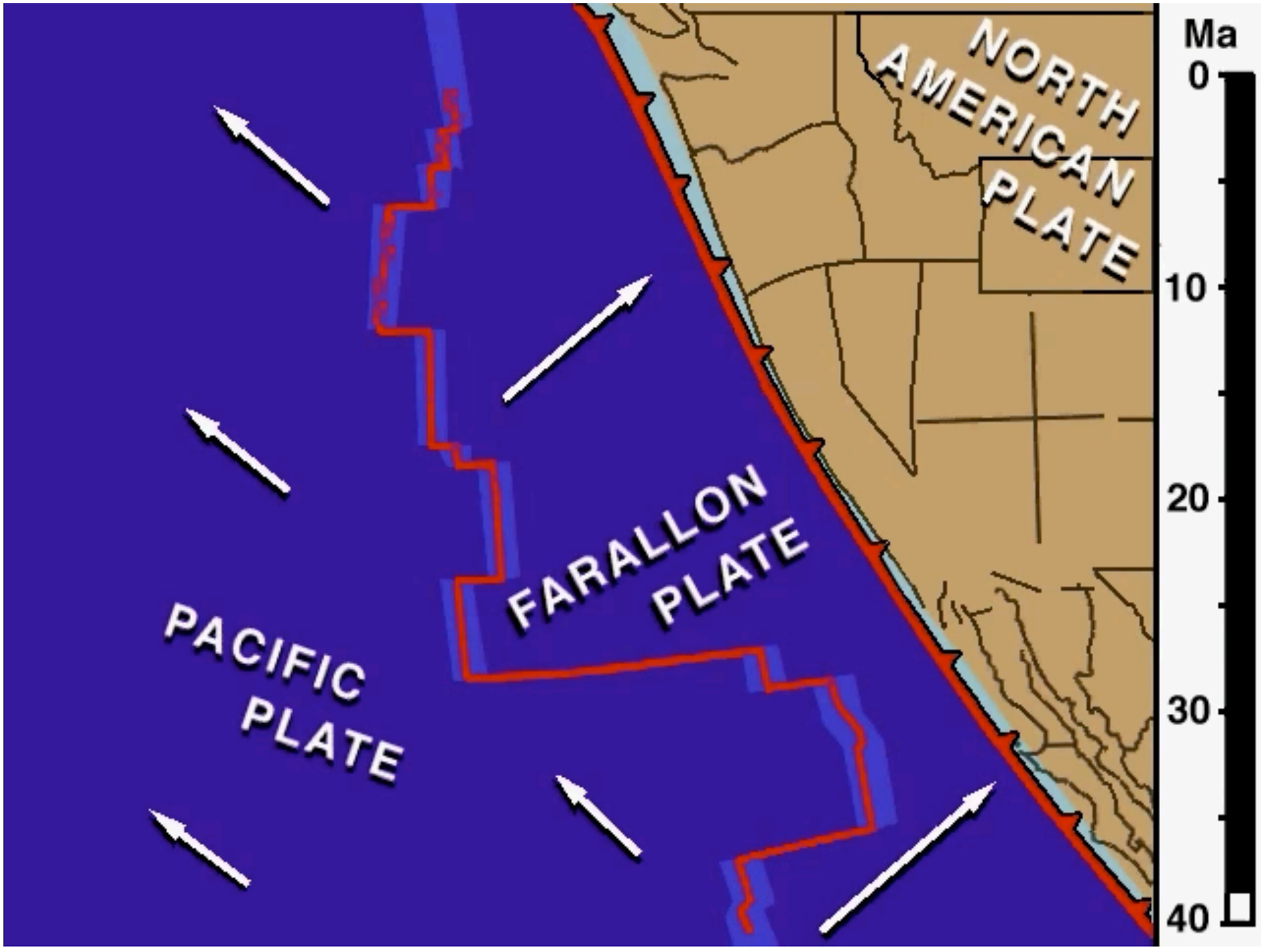

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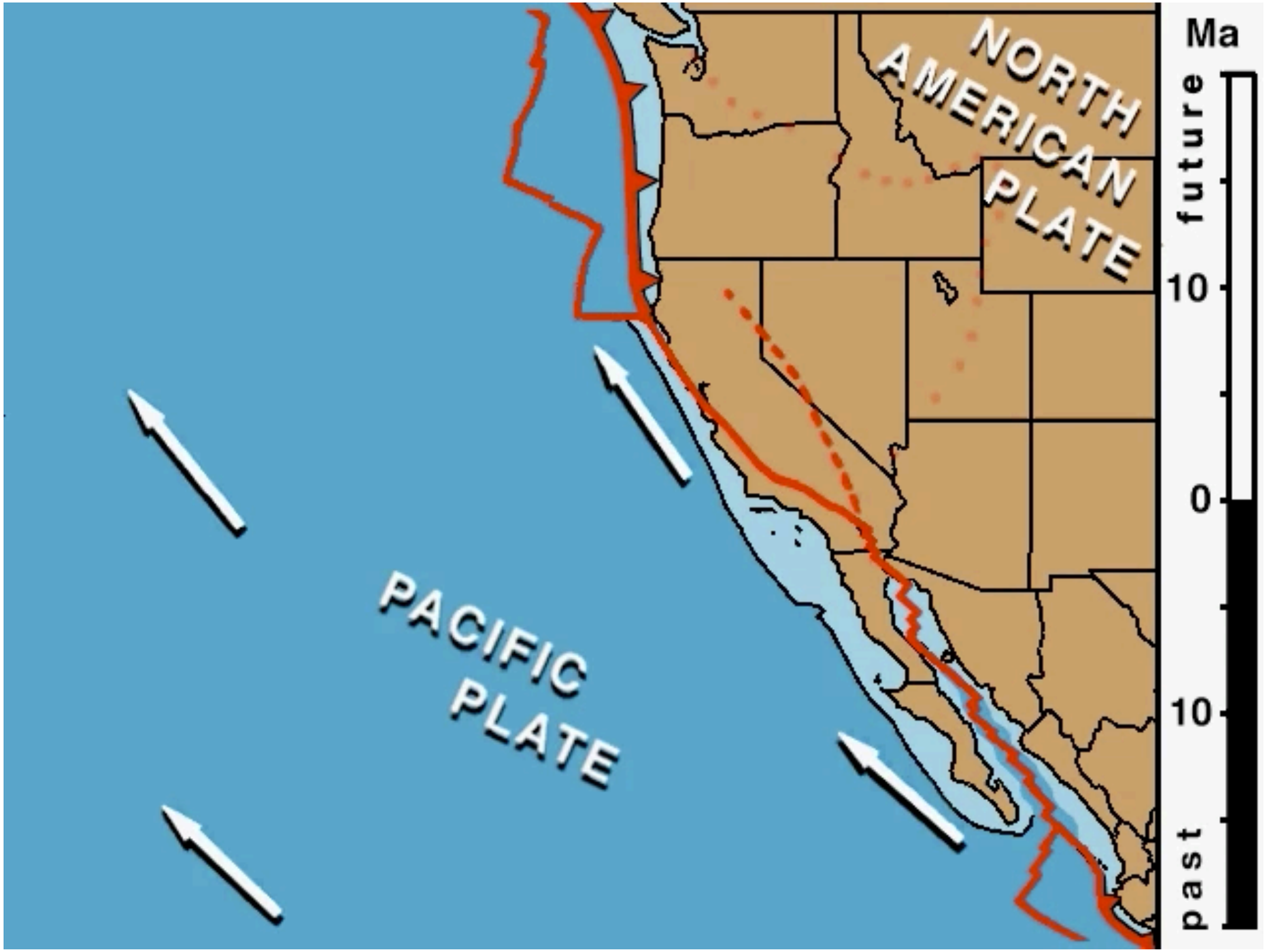

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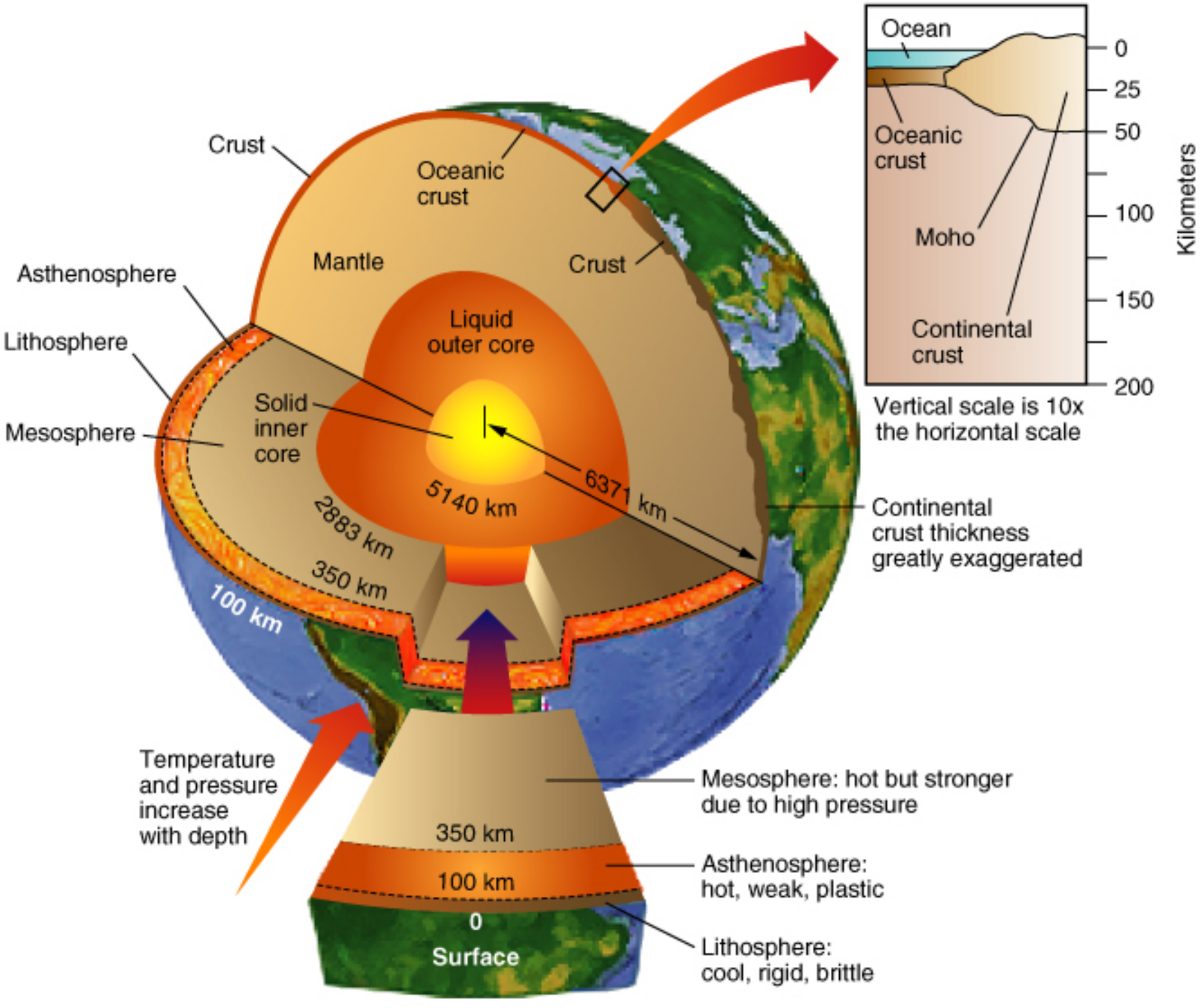
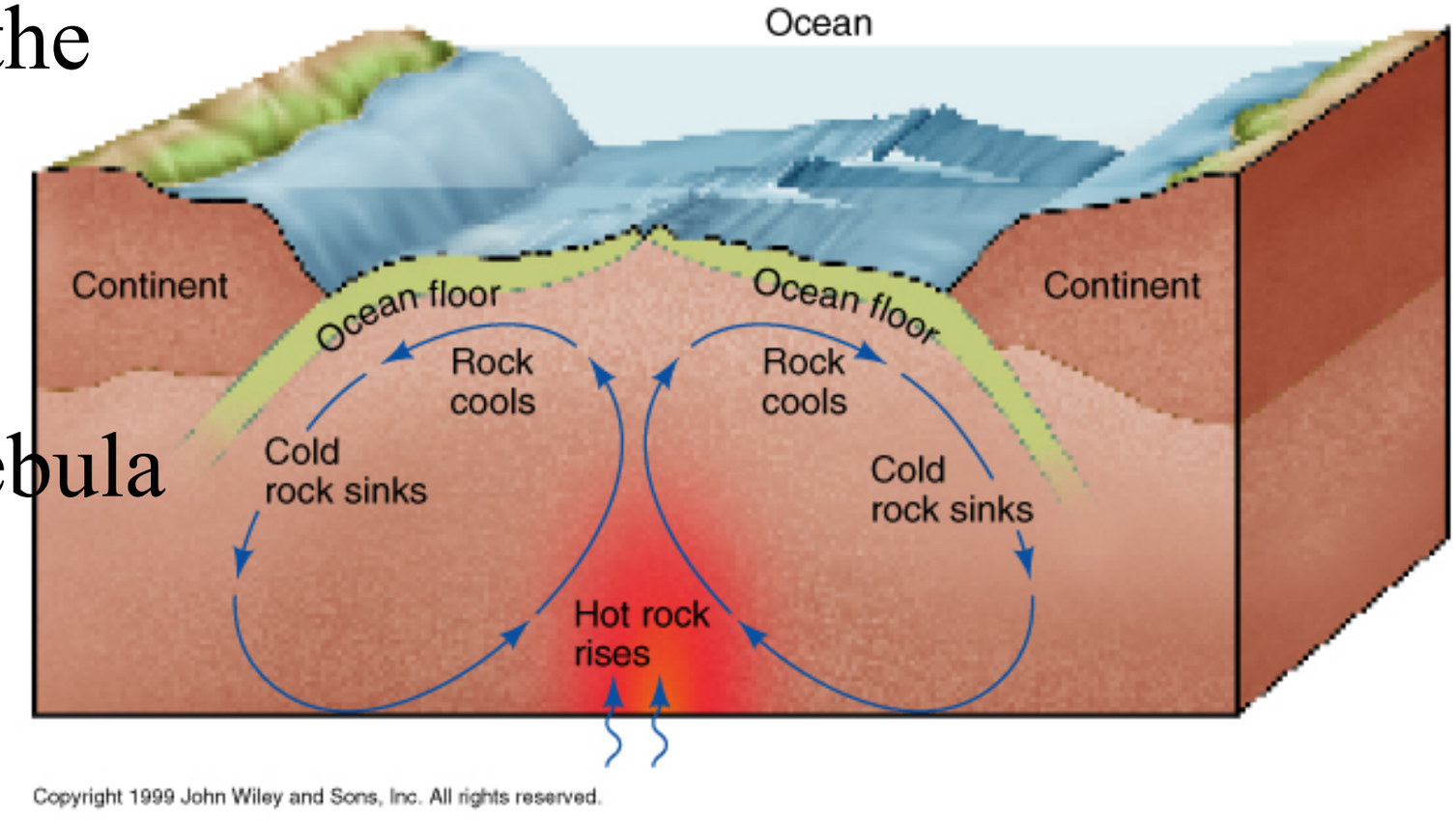


What causes plate motion?

- Circulation within the mantle – mantle rocks flow very slowly, over millions of years!

• This flow allows the Earth to lose heat – primary heat loss mechanism – the cooling from the nebula continues today!



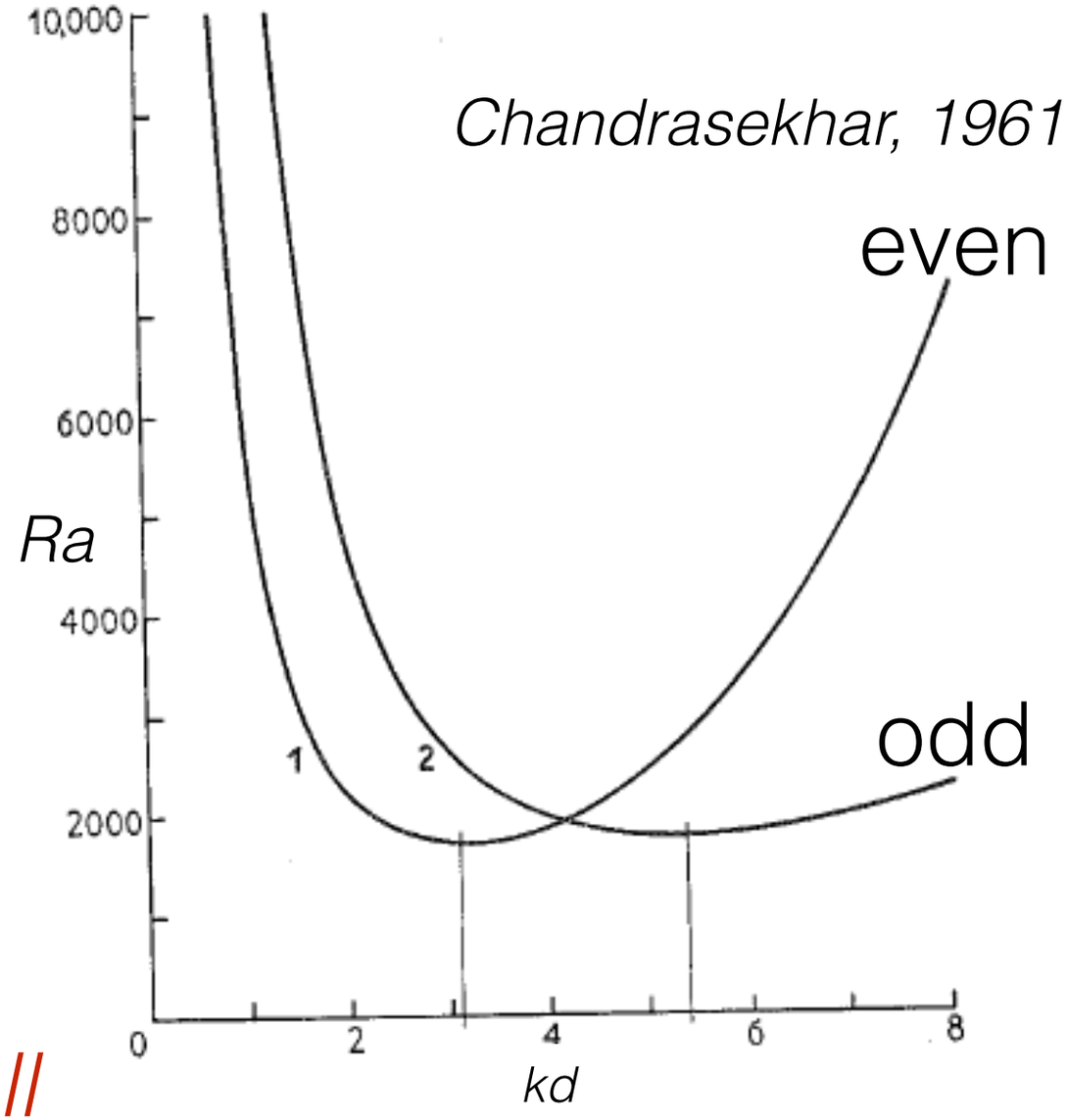
Incompressible, isoviscous two rigid walls

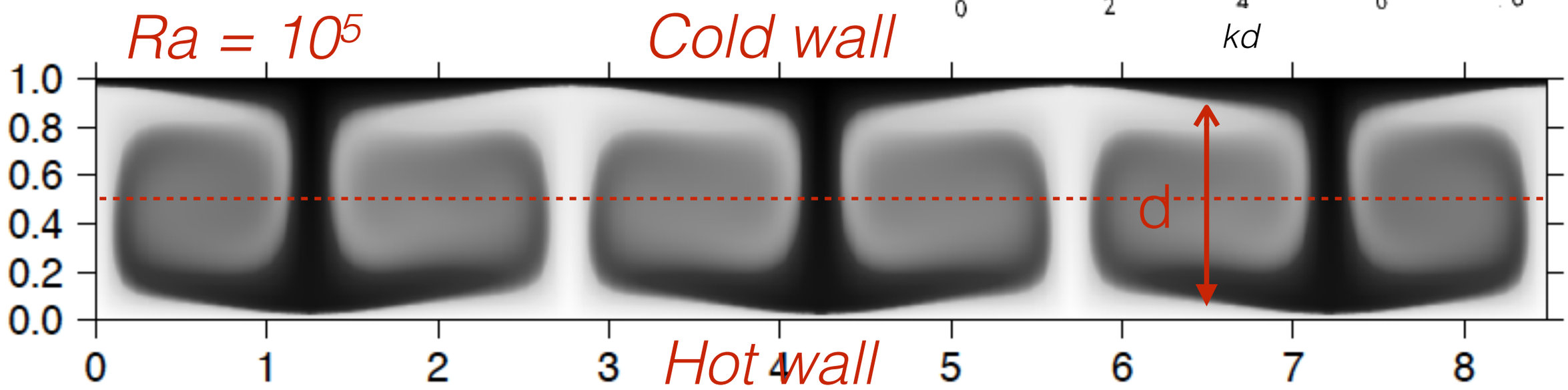
Rayleigh number

$$Ra = \frac{\rho g \alpha \Delta T d^3}{\mu \kappa}$$

$\Delta T = T_{hot} - T_{cold}$

$Ra_{mantle} \sim 10^7$



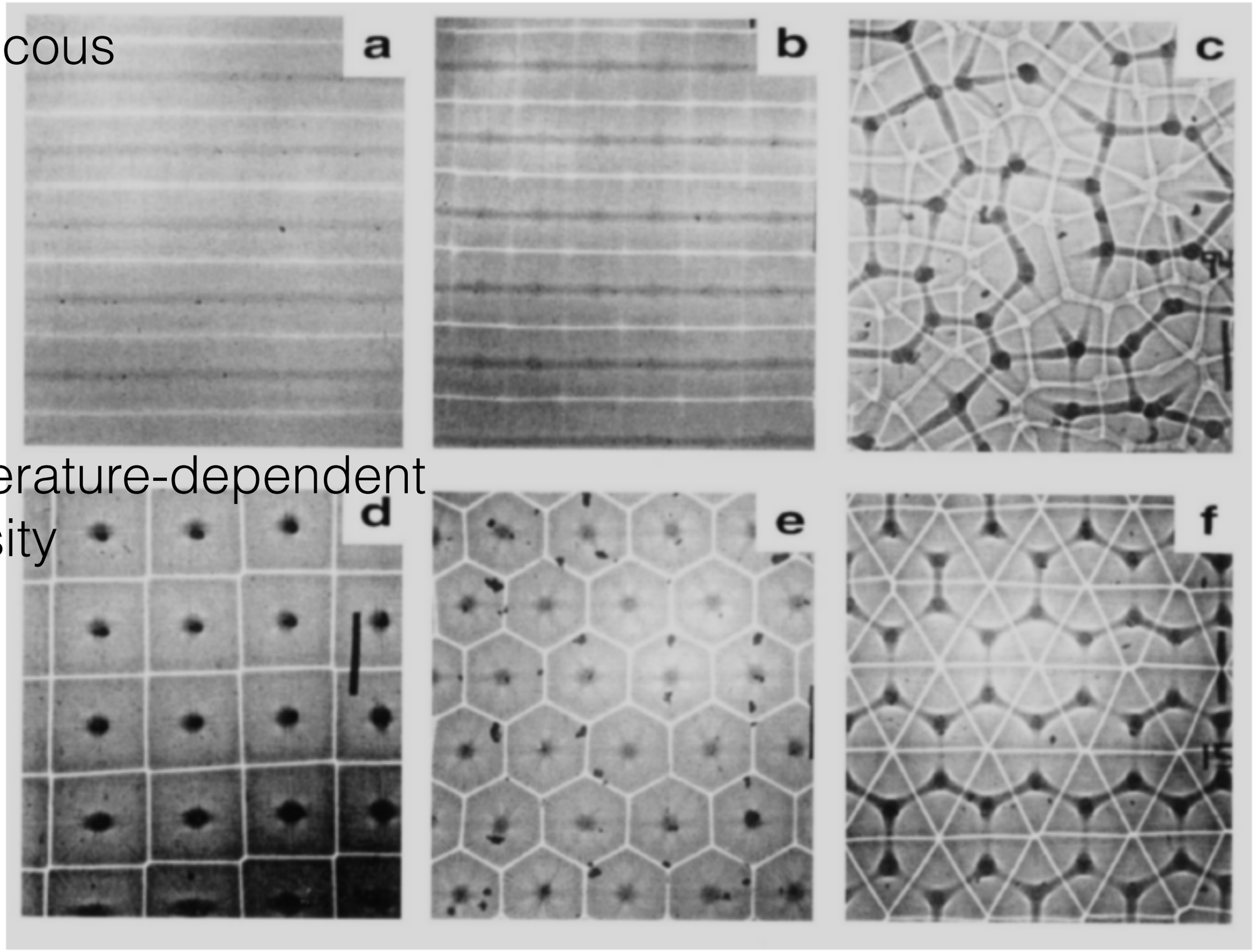


Bercovici et al., 2013

Increasing Ra ——————->

Isoviscous

Temperature-dependent viscosity



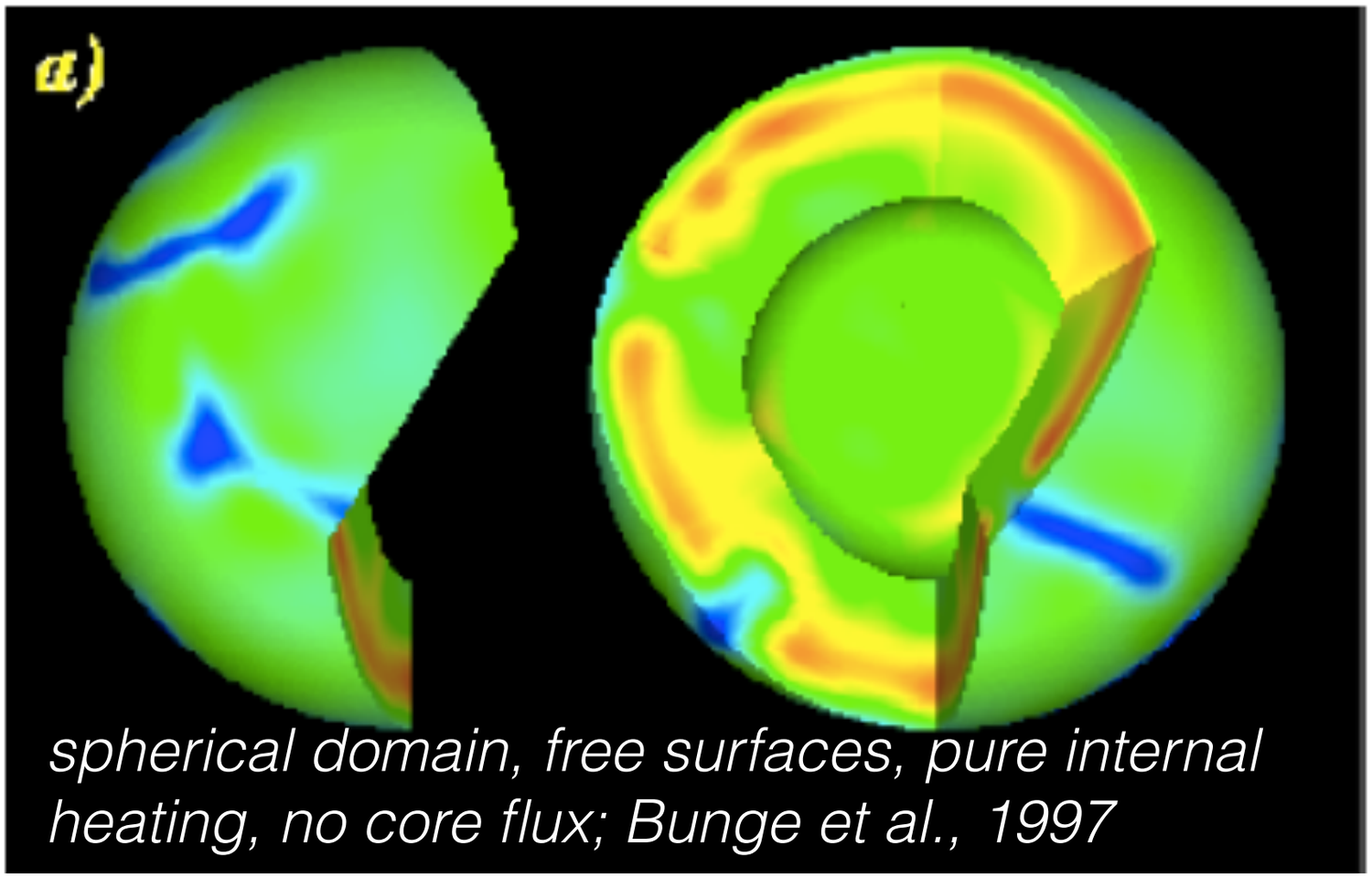
White, 1988

black = hot, white = cold

Problem: “Earth-like” convection?

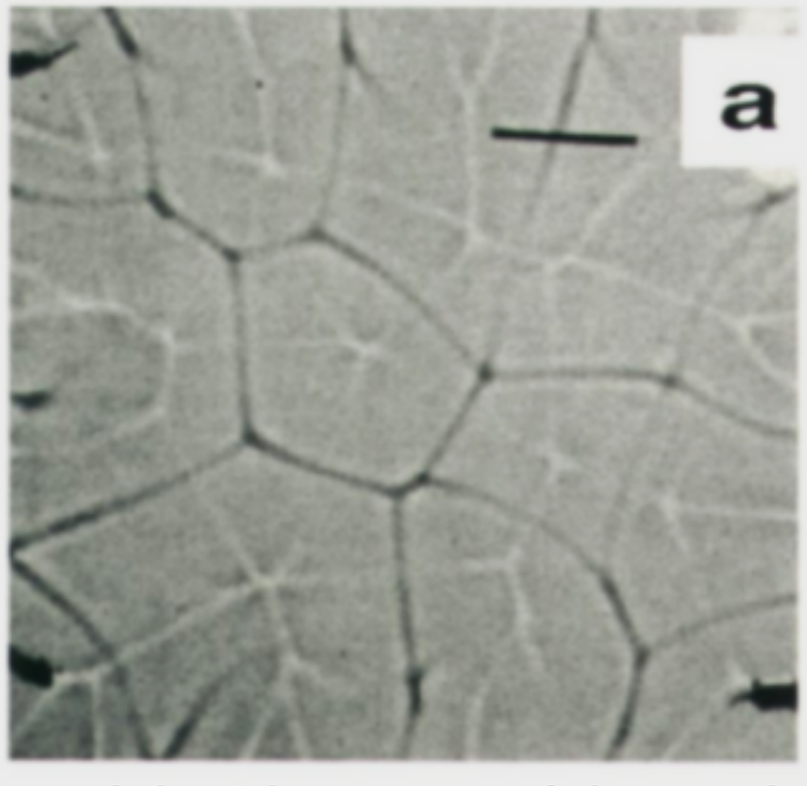
Intense, localized downwellings

diffuse, not localized, upwelling return flow

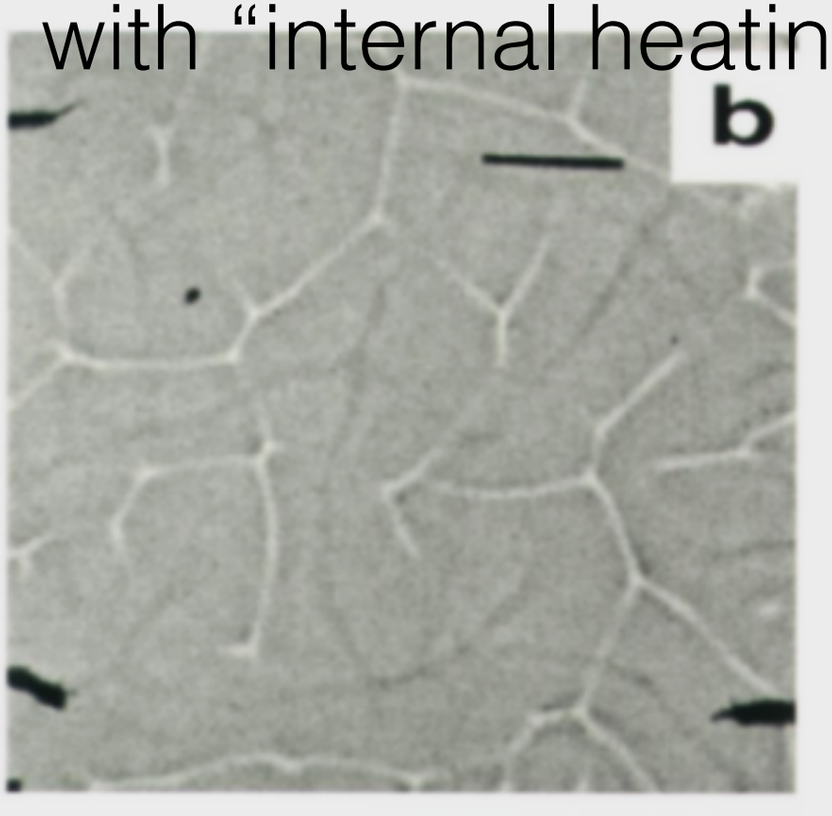


spherical domain, free surfaces, pure internal heating, no core flux; Bunge et al., 1997

no internal heating

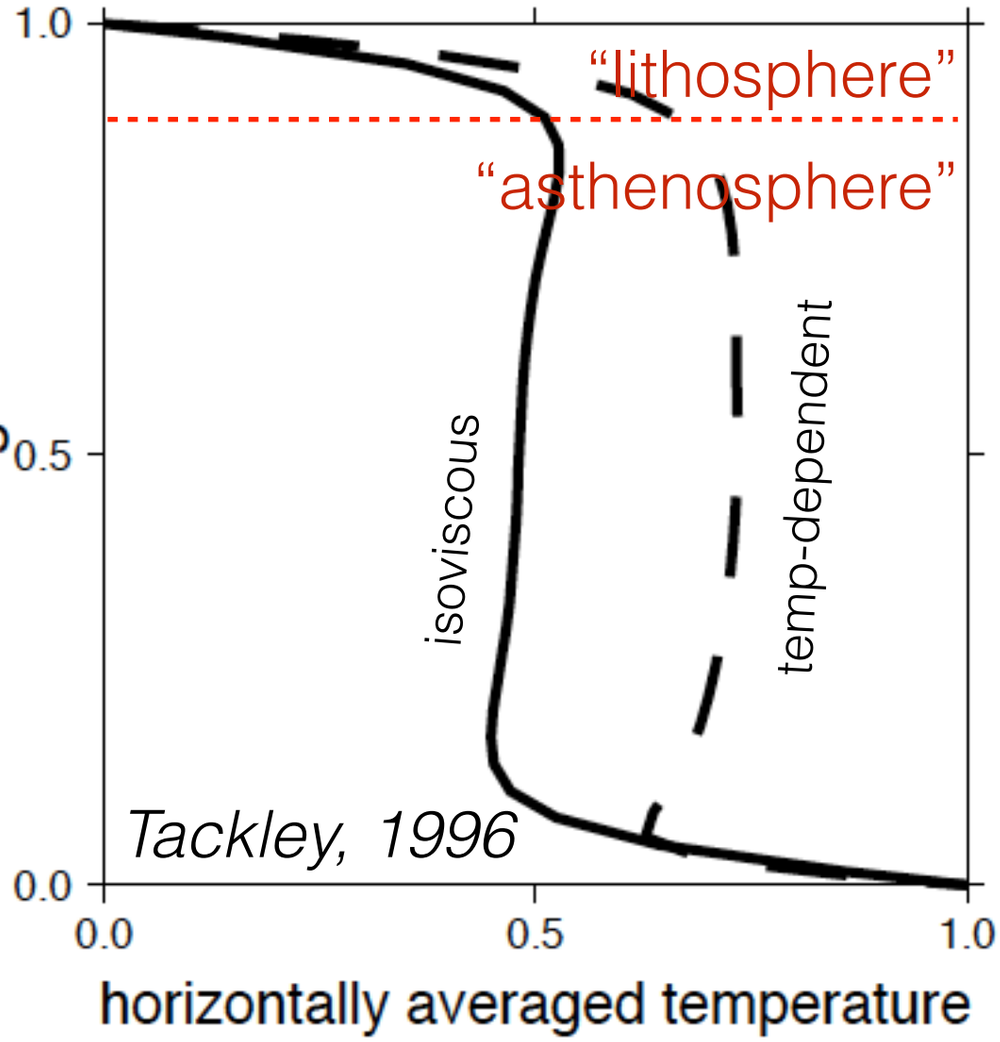


with “internal heating”



Weinstein and Olson, 1990

Plates as thermal boundary layers



BUT:
Secular cooling?
Internal heat production?

$$C\frac{dT_i(t)}{dt} = H(t) - Q(t)$$

T_i = average internal temperature
C = heat capacity of the whole Earth
~7 x 10^{27} JK^{-1}

Urey ratio $\gamma = H(t)/Q(t)$

γ_{Earth} ~0.2±0.1 *Korenaga, 2008*

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8^{4}\mathrm{He} + 6\mathrm{e}^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}, \quad (1)$$

$$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb} + 7^{4}\mathrm{He} + 4\mathrm{e}^{-} + 4\bar{\nu}_e + 46.0\ \mathrm{MeV}, \quad (2)$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6^{4}\mathrm{He} + 4\mathrm{e}^{-} + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}, \quad (3)$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}, \quad (4)$$

$$^{40}\mathrm{K} + \mathrm{e}^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\ \mathrm{MeV}, \quad (5)$$

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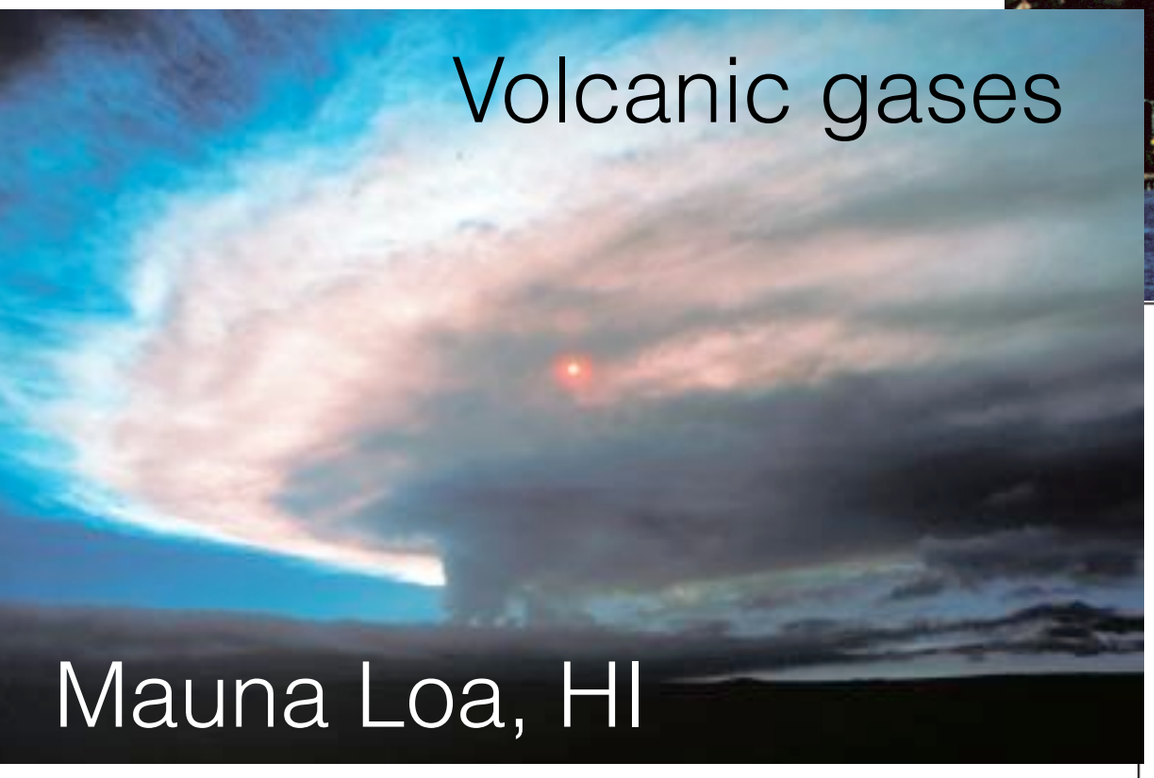
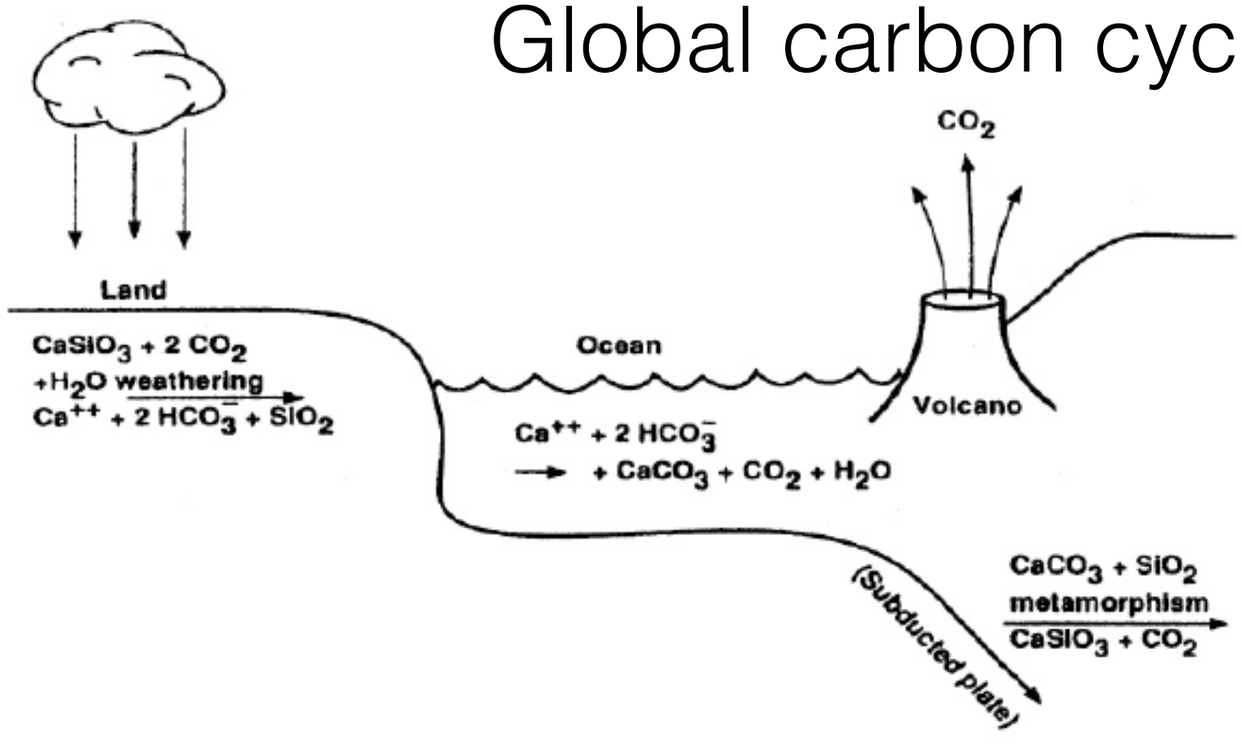
Why should we care about volcanic systems?

Hazards
Fundamental science


Seattle, WA


Mauna Loa, HI

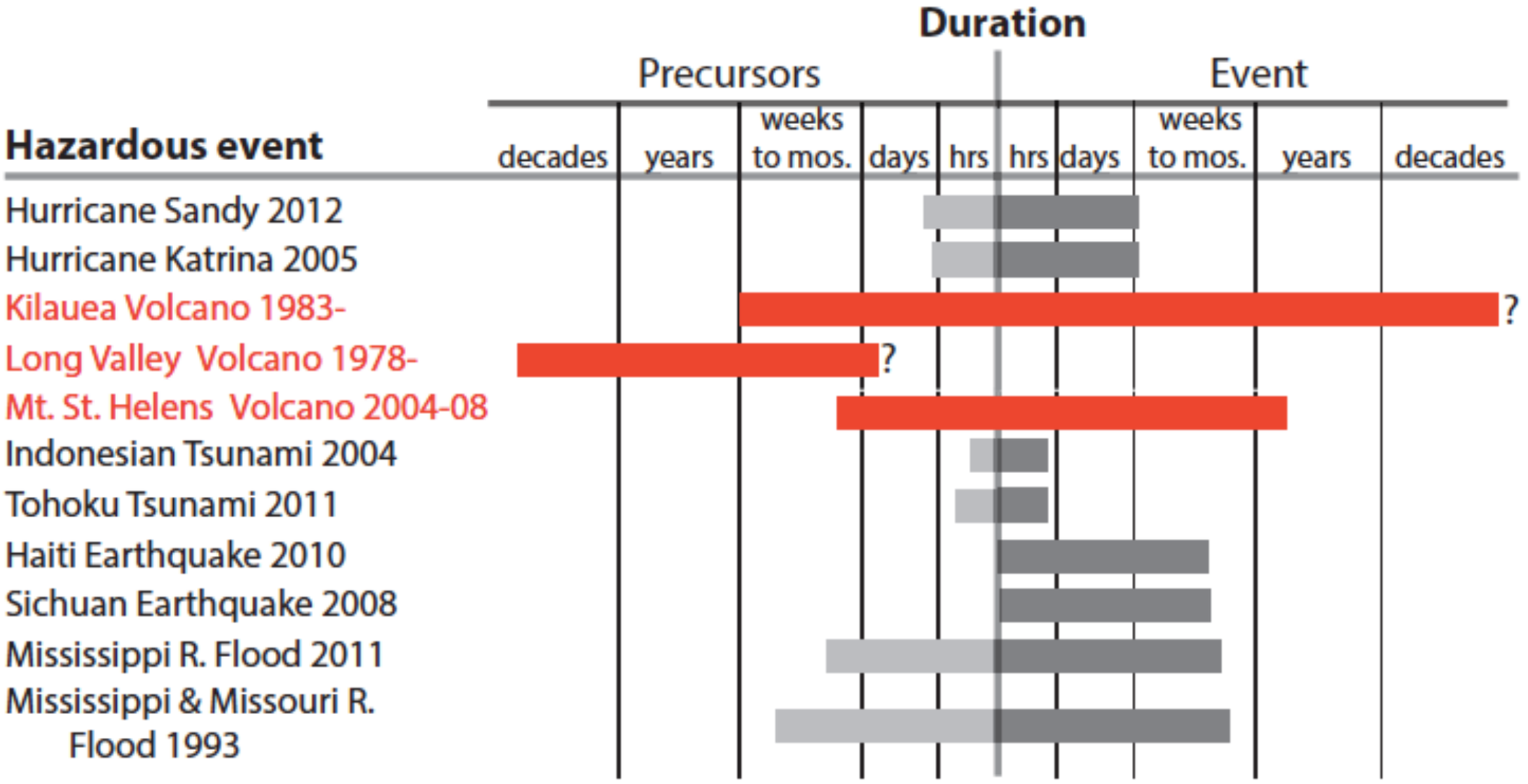
Global carbon cycle



How can we predict volcanic eruptions?

Precursors - any (predictive) hint of an eruption

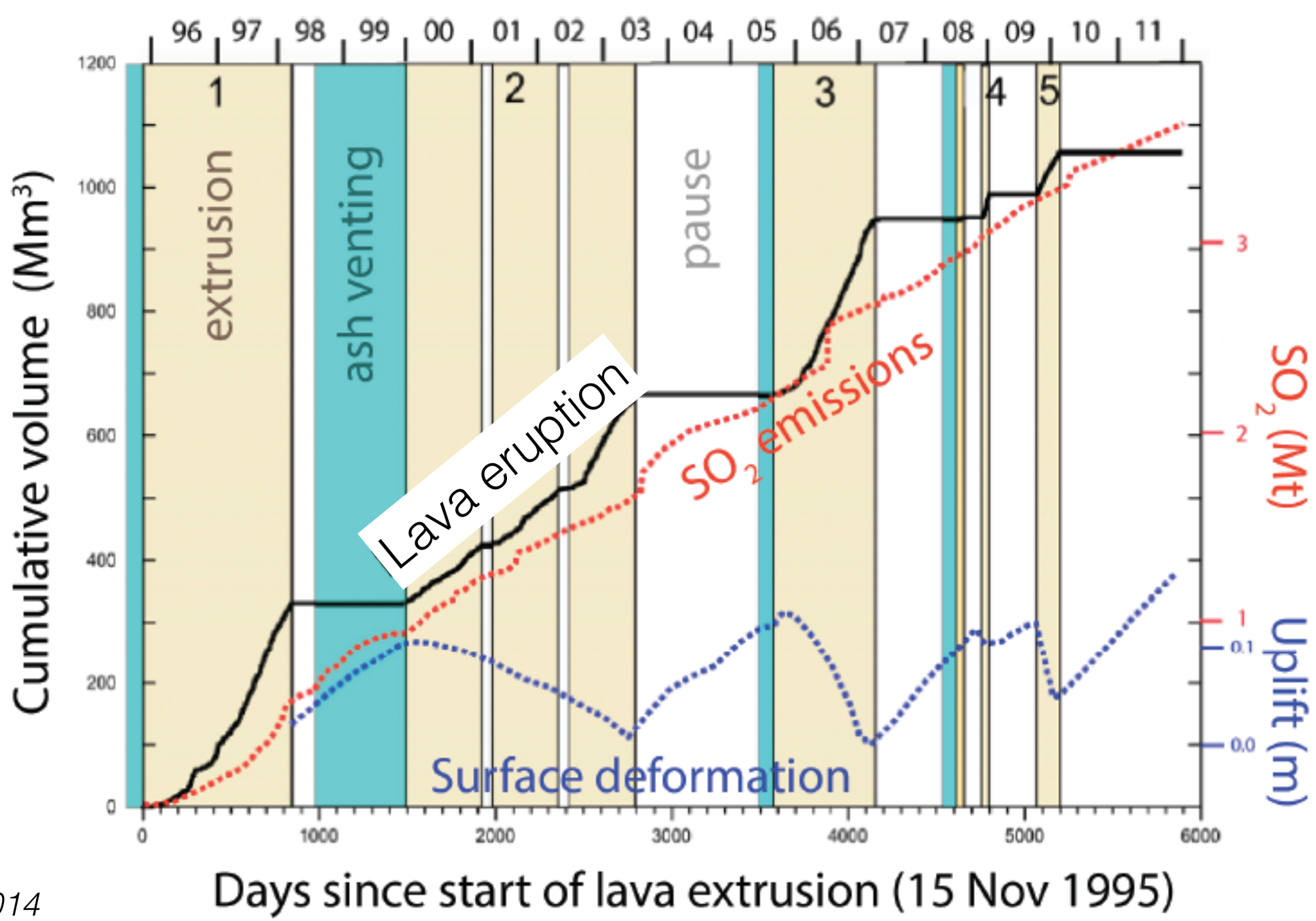
"unrest": ground deformation, gas emissions, earthquakes



How can we predict volcanic eruptions?

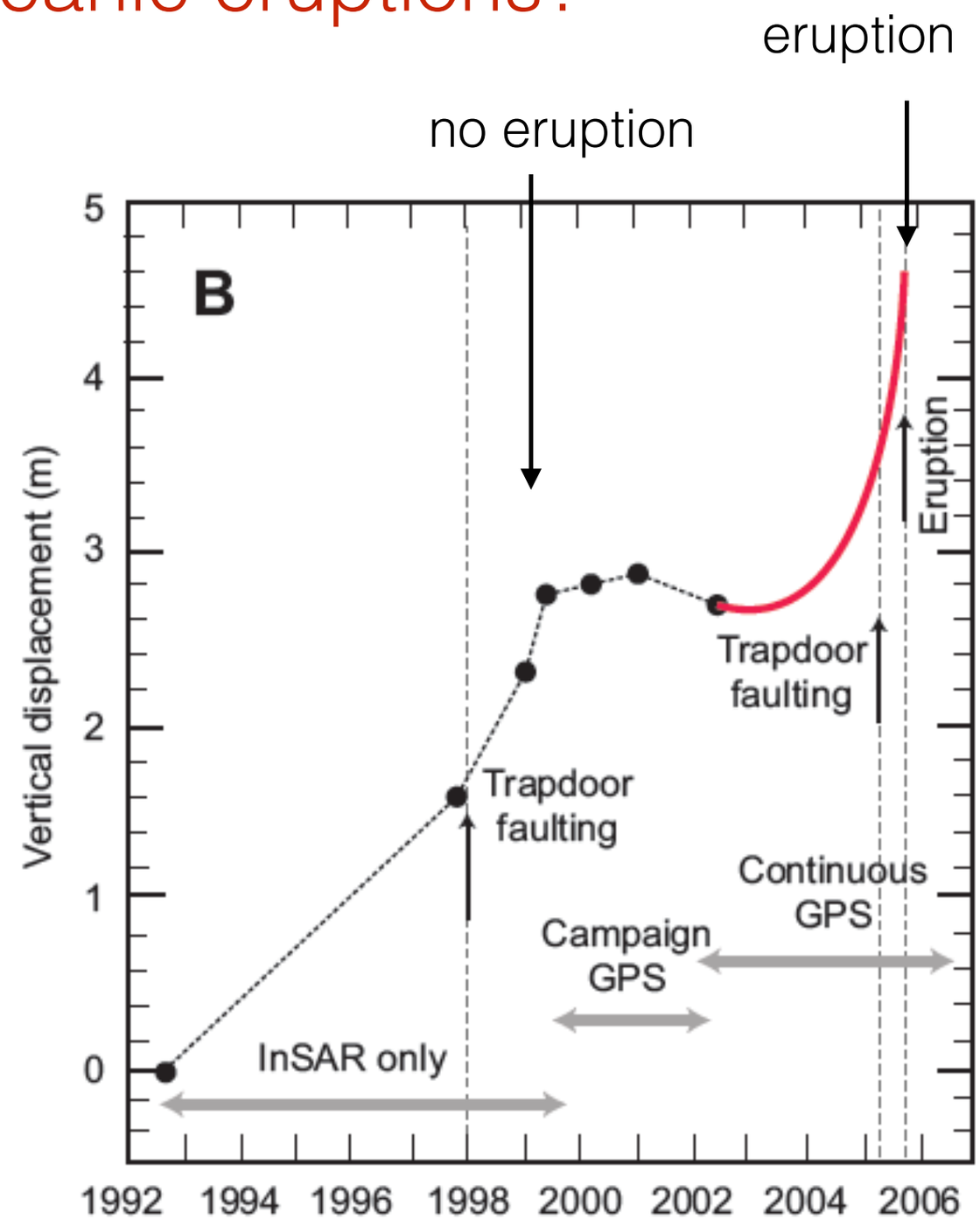
>15 year record
Clear inflation/deflation cycles

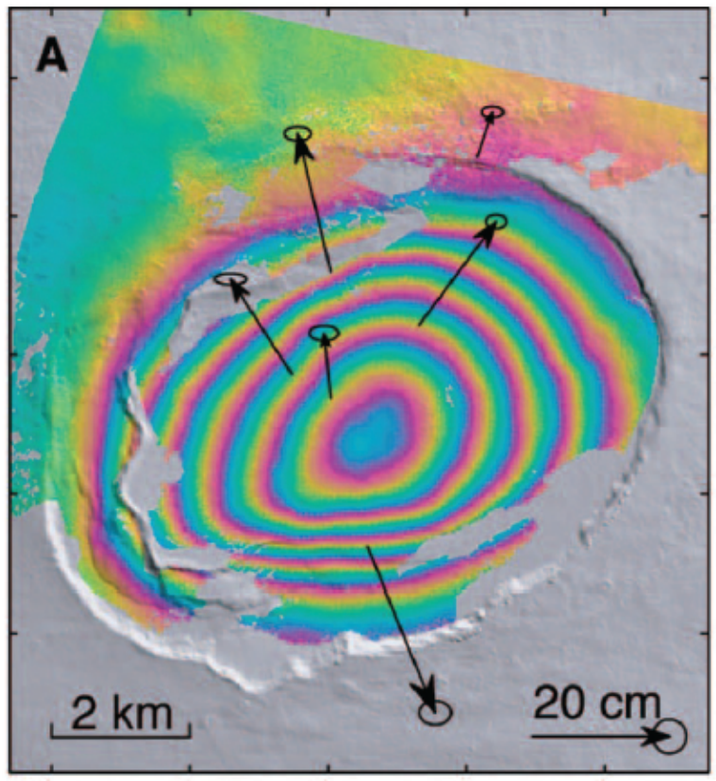
Montserrat
Soufriere
Hills
Volcano



Wadge et al., 2014

How can we predict volcanic eruptions?





Sierra Negro, Galapagos

Chadwick et al., 2006

How do melts move?

- Shallow (0-10 km) plumbing system — volcanoes

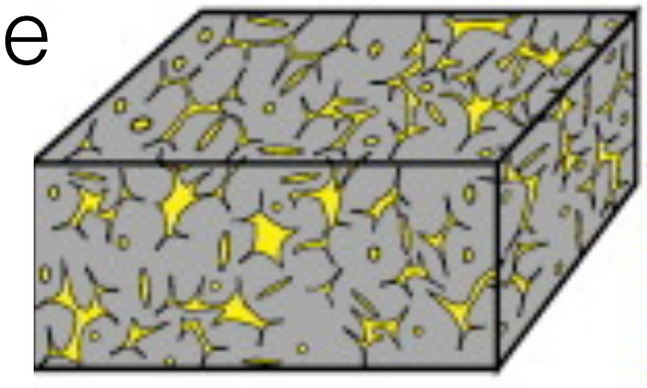
↑ ??

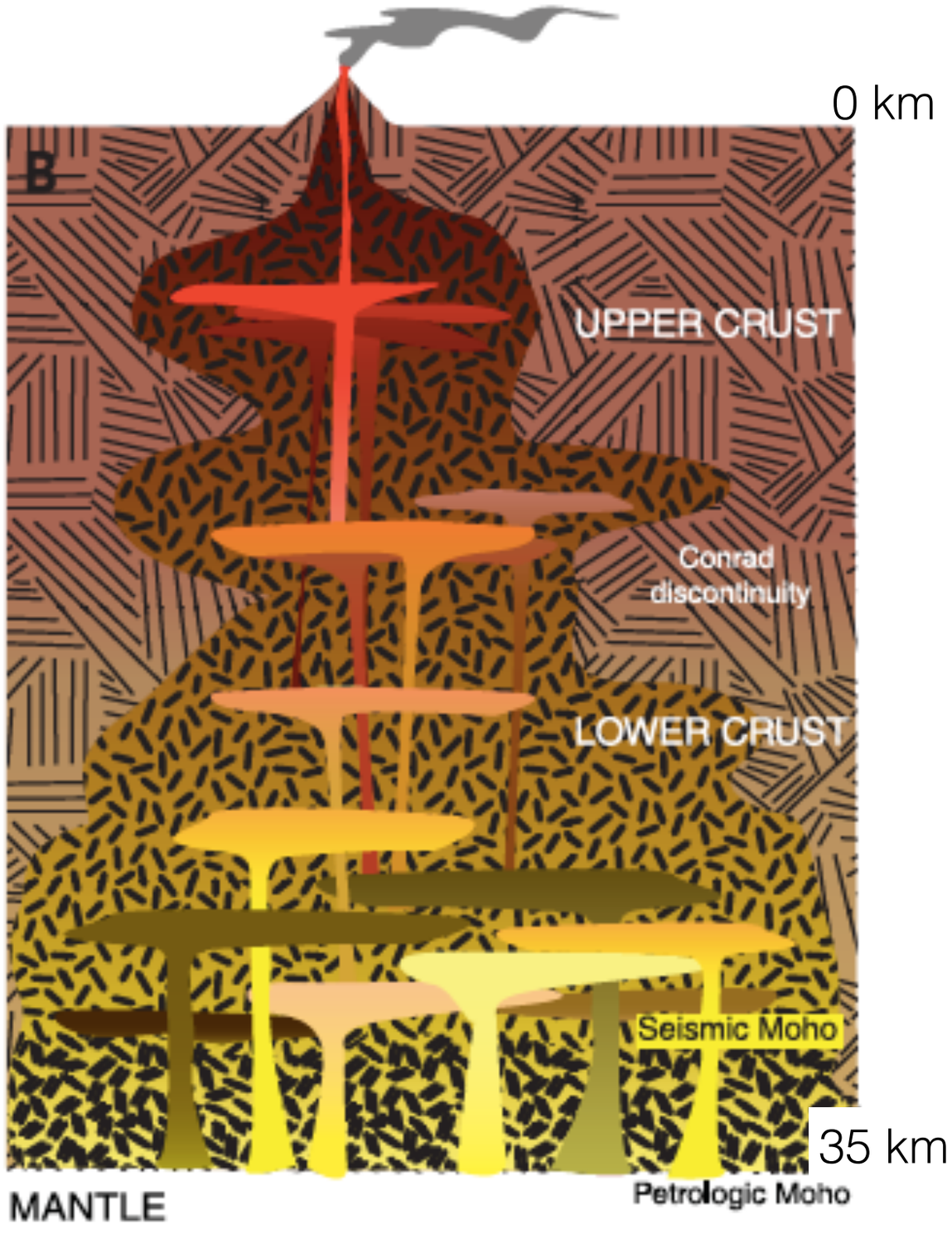
Crustal reservoirs (10-35 km)

↑ ??

↑ percolation in deformable rock

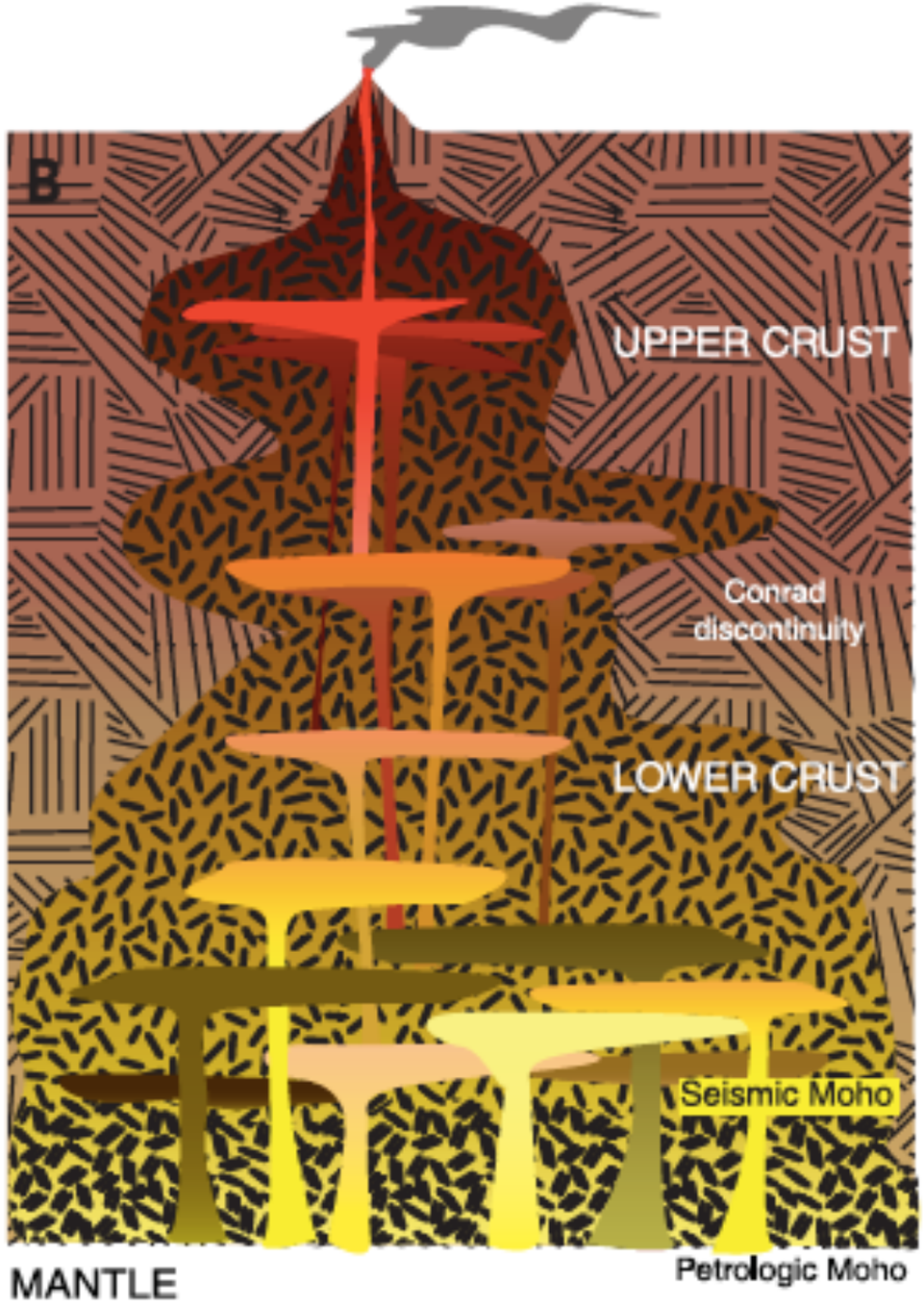
McKenzie, 1984

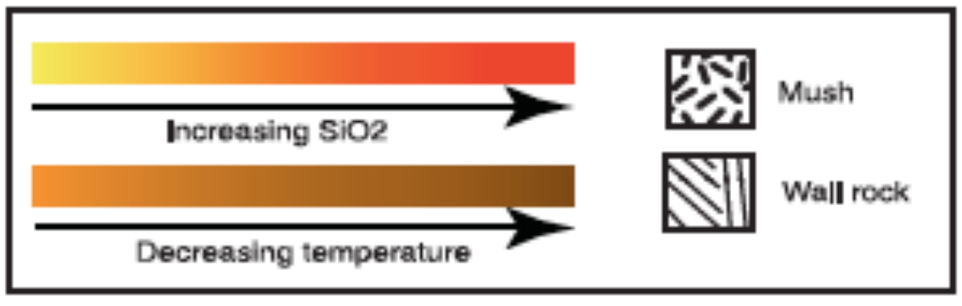




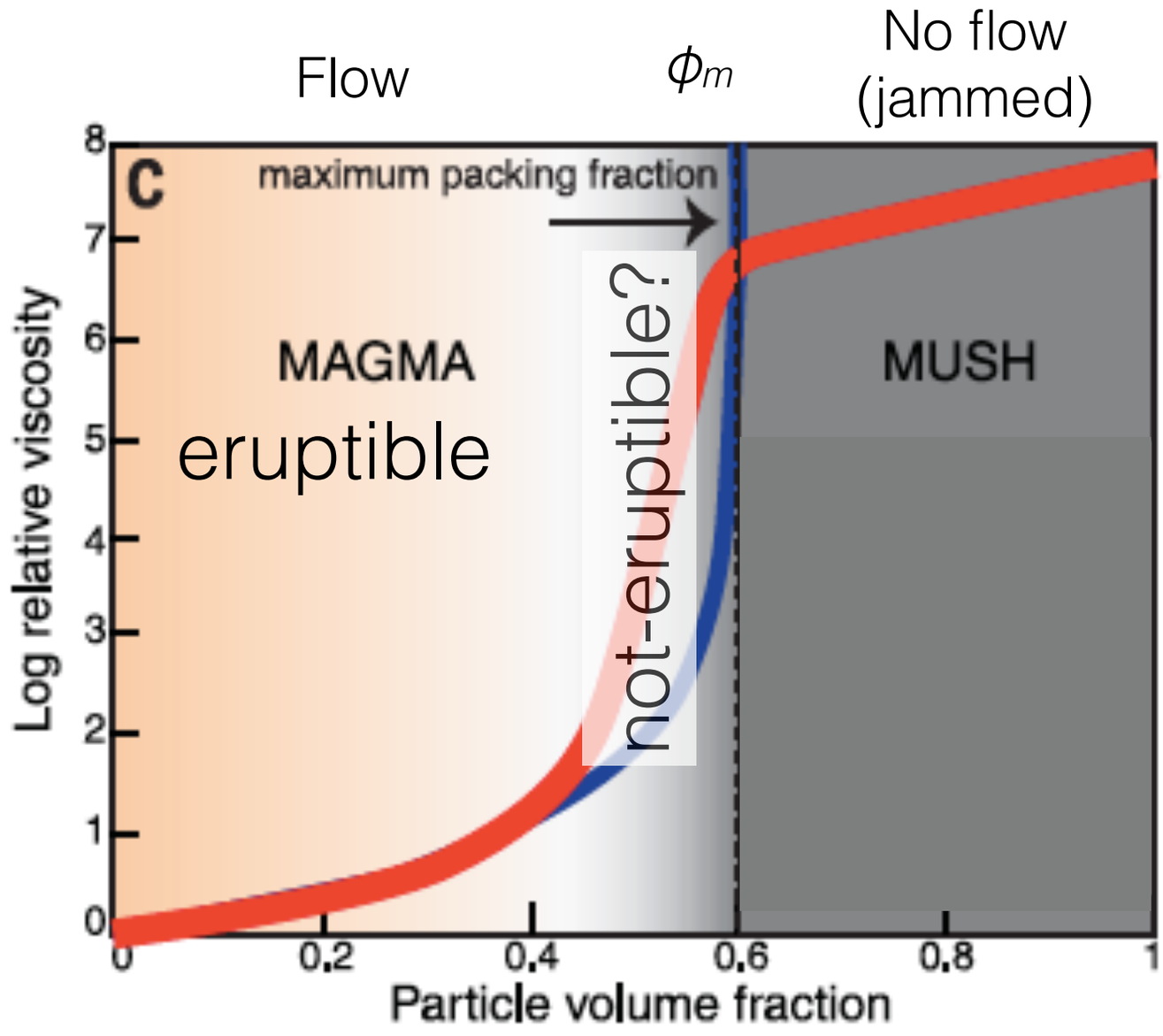
Cashman et al., Science, 2017

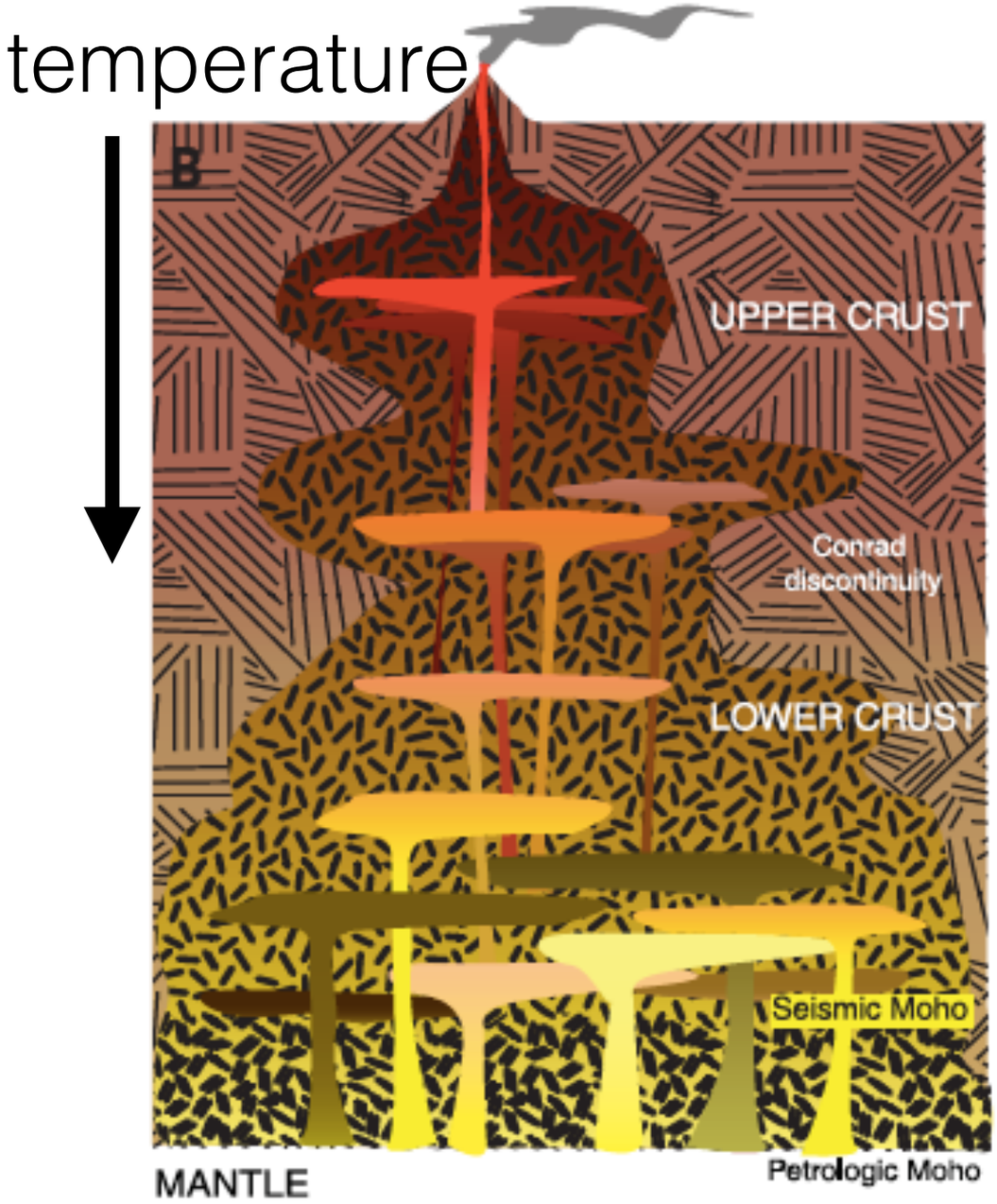
Produced at ~70-100 km depth, buoyant, ascend to 0 km

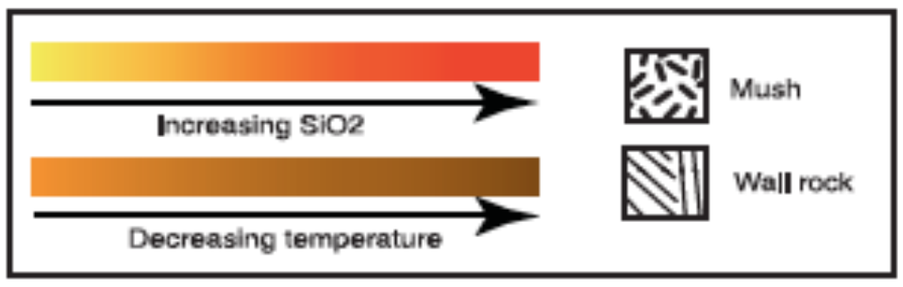




MUSH : $\phi \longrightarrow \phi_m$

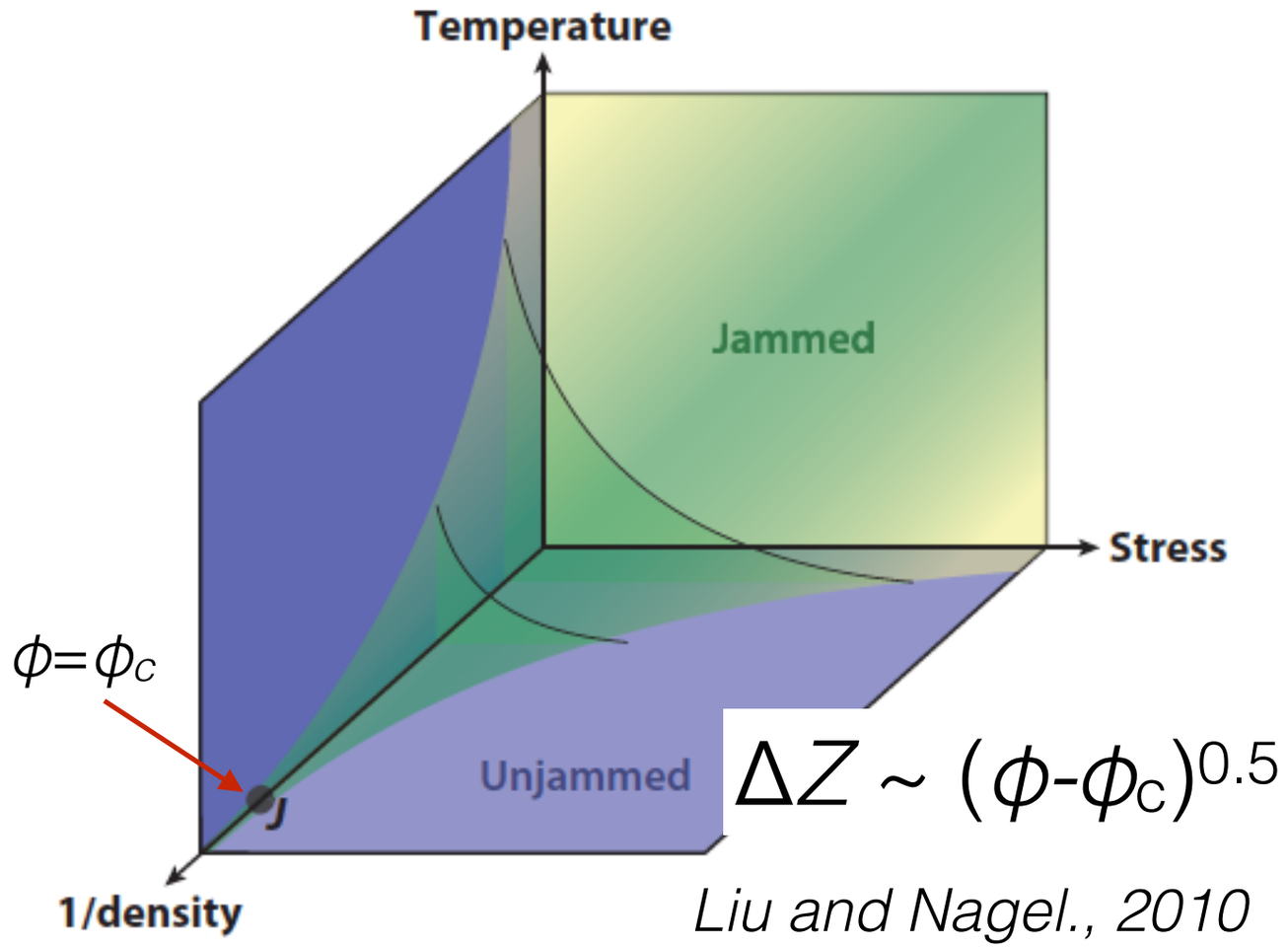






Cashman et al., Science, 2017

Open problem:
re-mobilization of mush —> magma

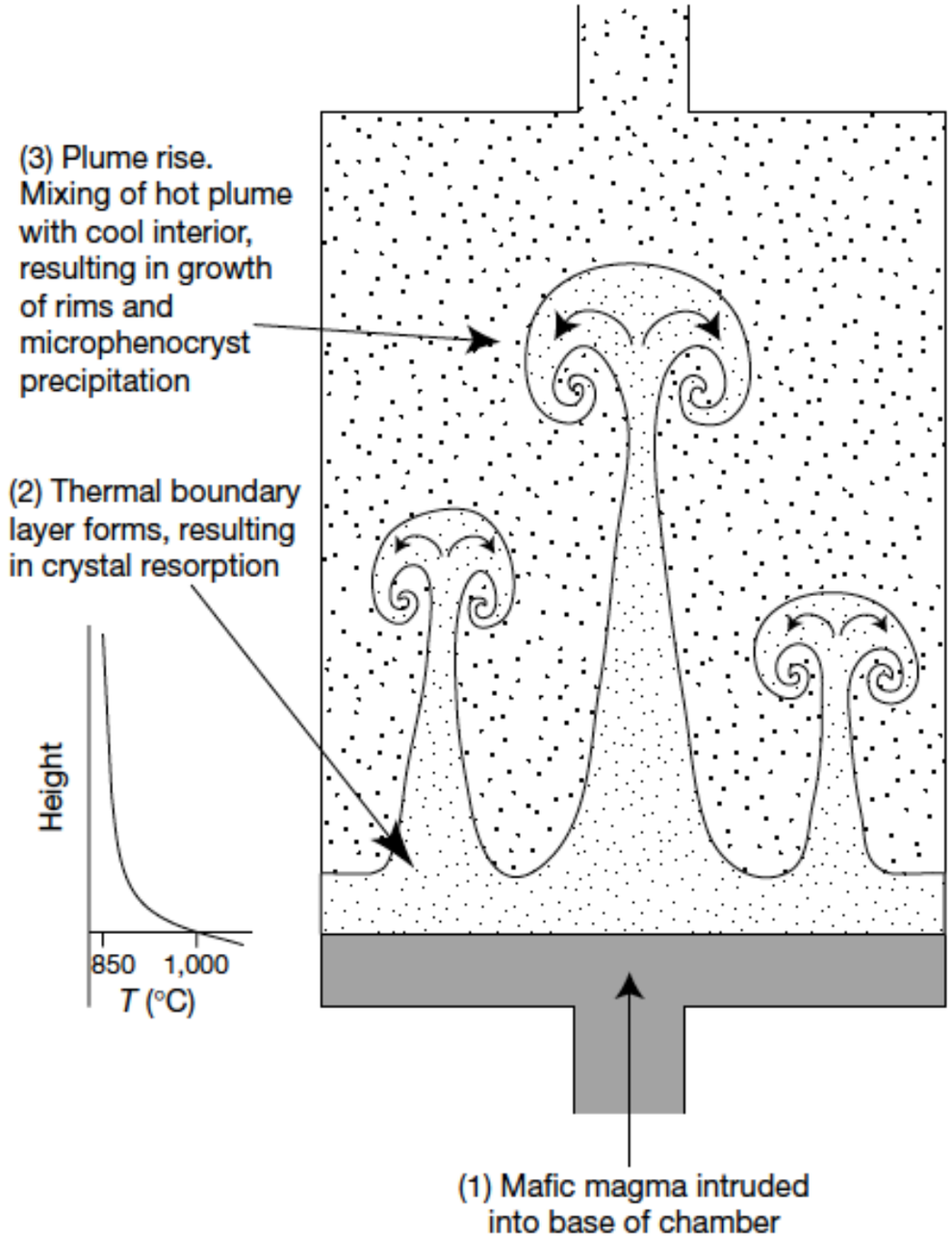


$\Delta Z \sim (\phi-\phi_C)^{0.5}$

Liu and Nagel., 2010

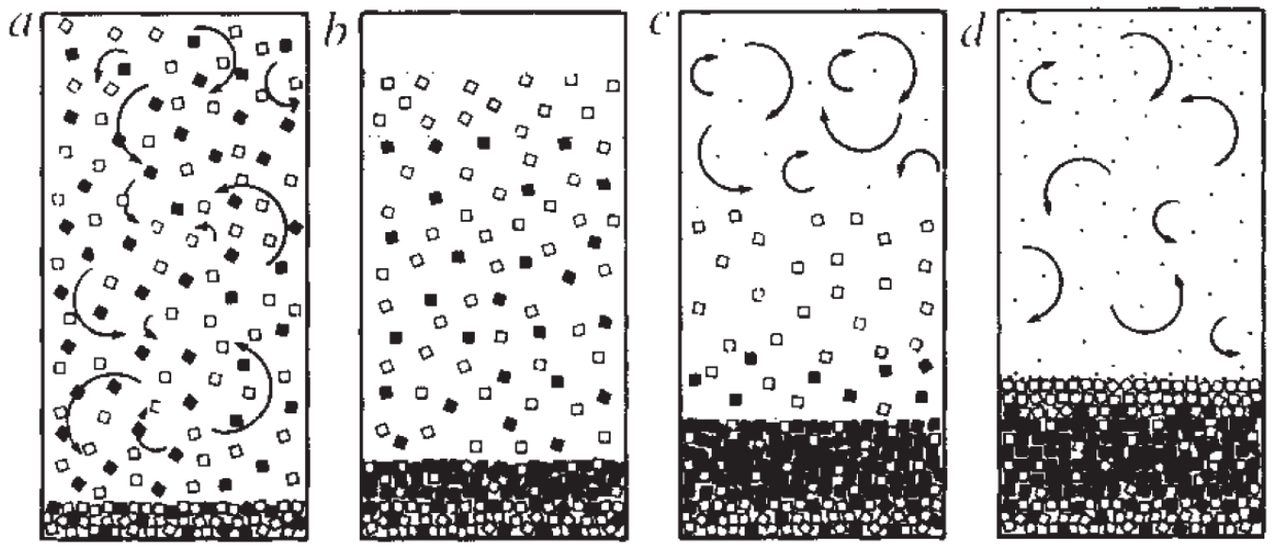
Forcing: changing ϕ, 'density'
Order parameter: Z
coordination number
(Z=0 for $\phi<\phi_C$, Z_C at ϕ_C)

Re-mobilization of mush —> magma



Couch et al., Nature, 2001

Sparks et al., Nature, 1993



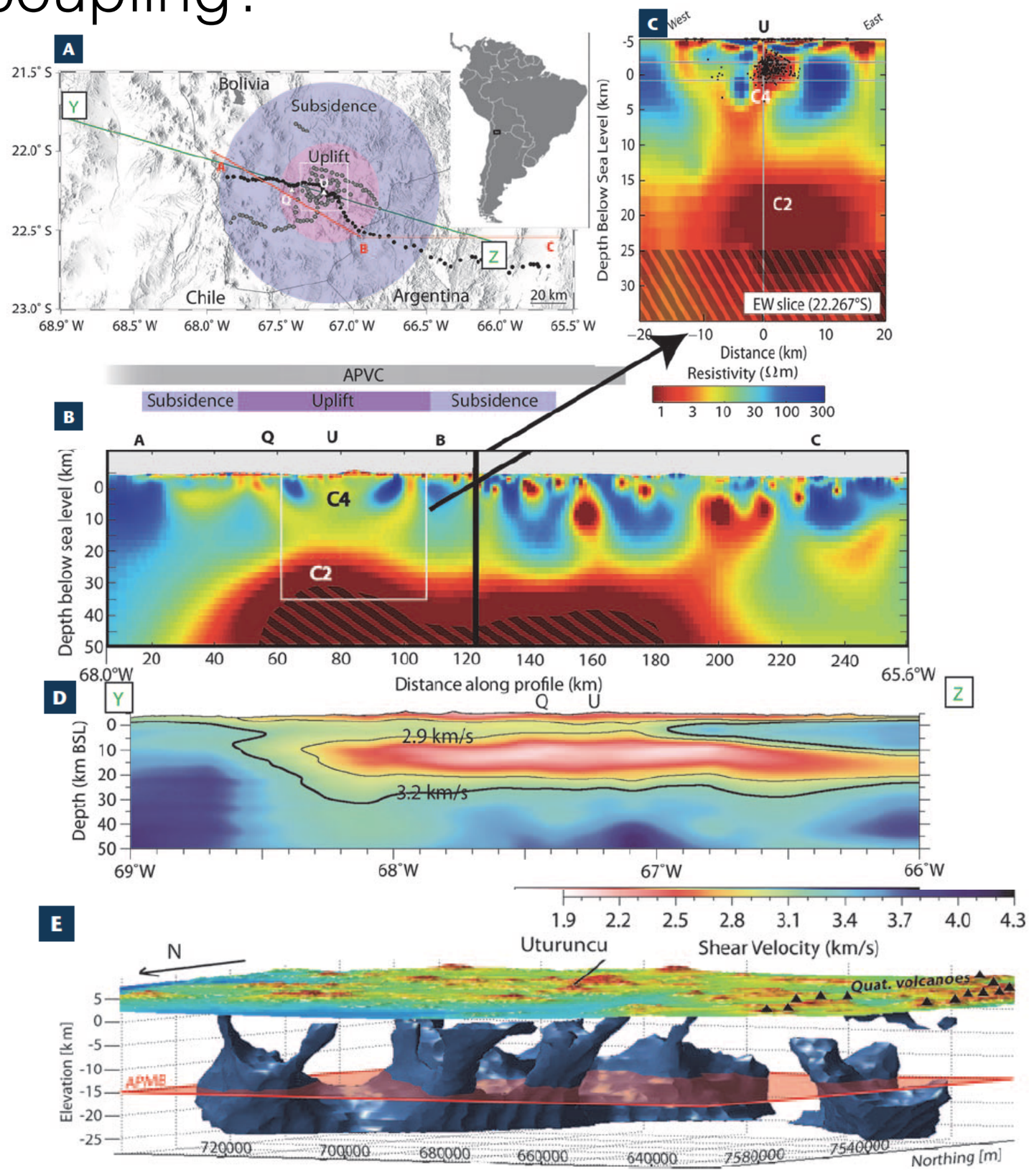
Critical crystal fraction—settling

dense vs less dense

- Convective mixing by heating from below
- Viscosity reduction by settling

Volcano coupling?

Pie in the Sky



Pritchard and Gregg, 2016

Why should we care about deformation on fault systems?

Tang Shan, China, 1976 – m. 7.8 followed by a 7.1 (15 minutes later) 240,000 killed

http://west.pima.edu/~jmiller/TANGSHAN.HTML

Hazards
Fundamental science

1960, Chile, m. 9.5 – largest recorded last century

Isla Chiloe, Chile

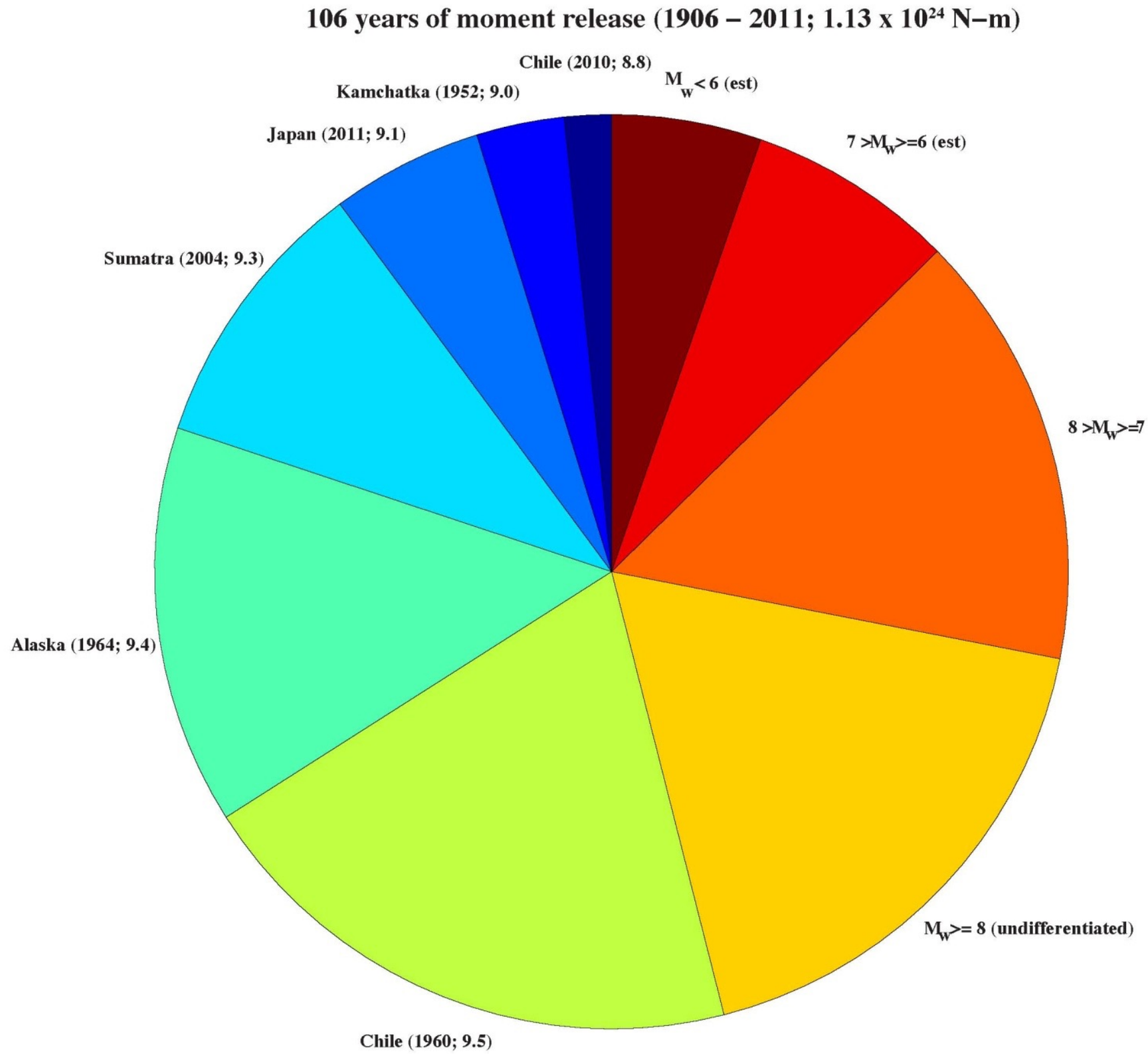
Hilo, Hawaii

Magnitude 9.0 NEAR THE EAST COAST OF HONSHU, JAPAN

Friday, March 11, 2011 at 05:46:23 UTC

The moment magnitude scale is designed to give an accurate characterization of the true size of an earthquake, but be tied to the original description of magnitude that was developed by Charles Richter. Moment magnitude accounts for earthquake size by looking at all the energy released.

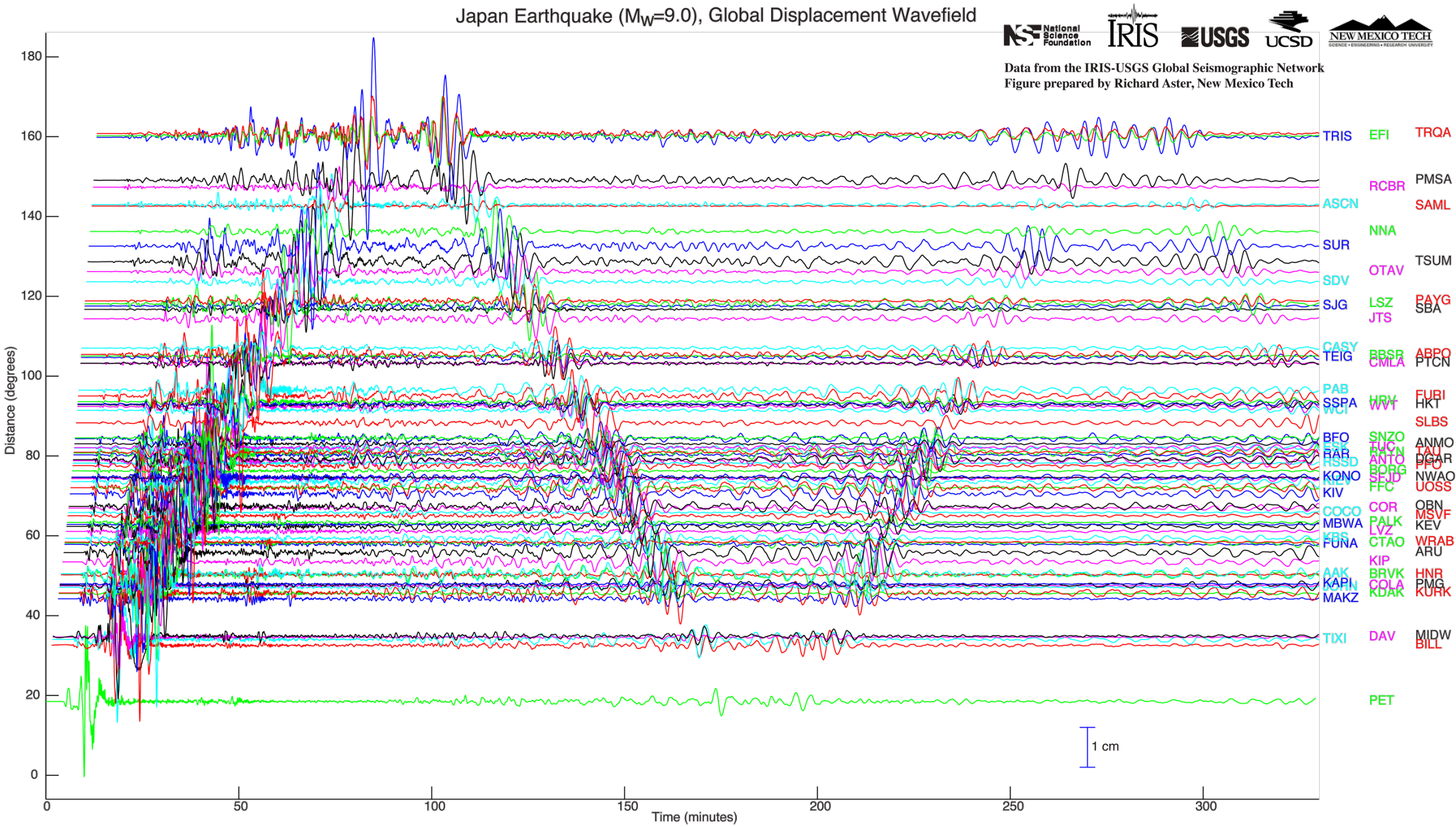
It is striking that only 6 earthquakes over the last 106 years account for over half of the energy released during that time.



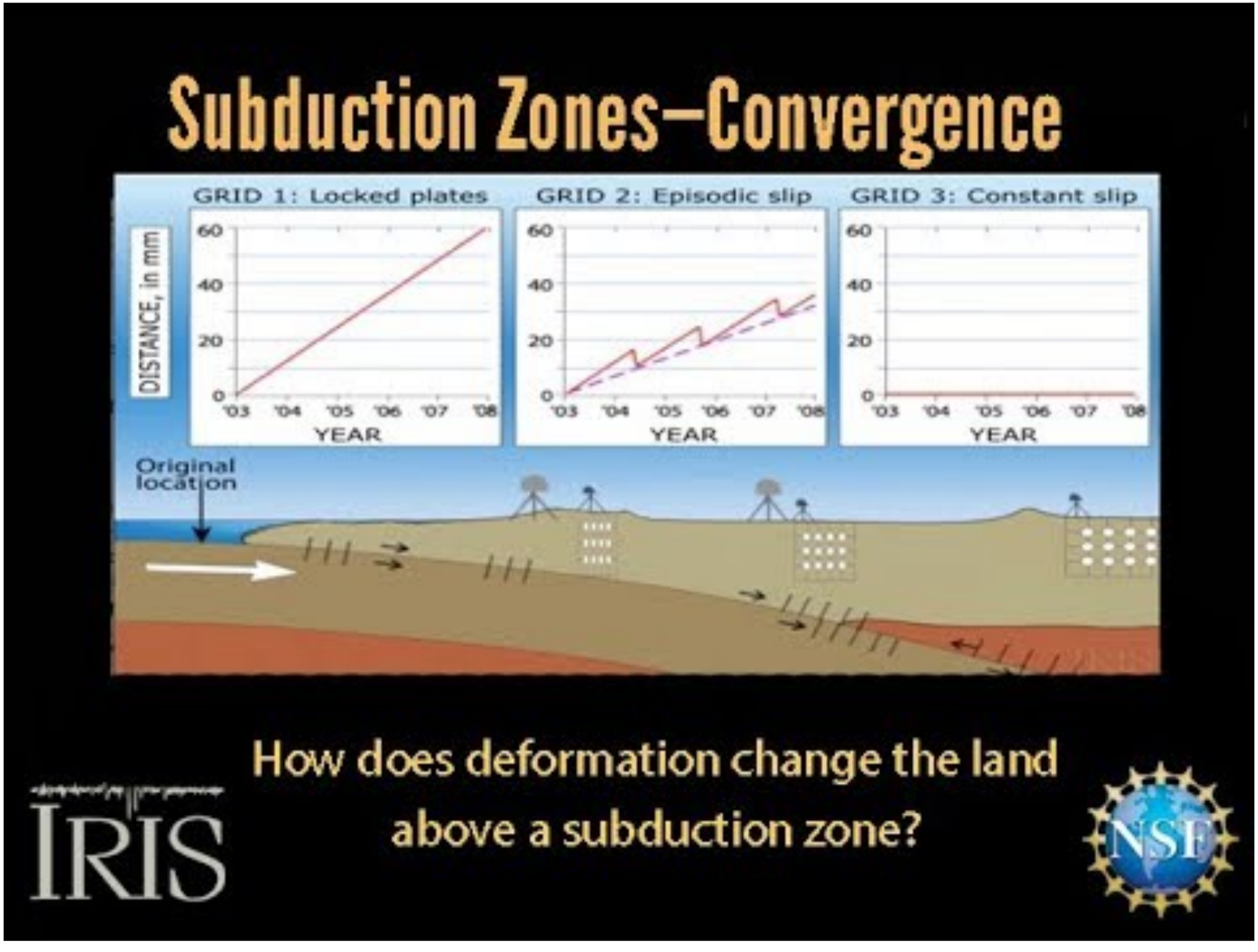
Magnitude 9.0 NEAR THE EAST COAST OF HONSHU, JAPAN

Friday, March 11, 2011 at 05:46:23 UTC

Seismic waves recorded around the world.

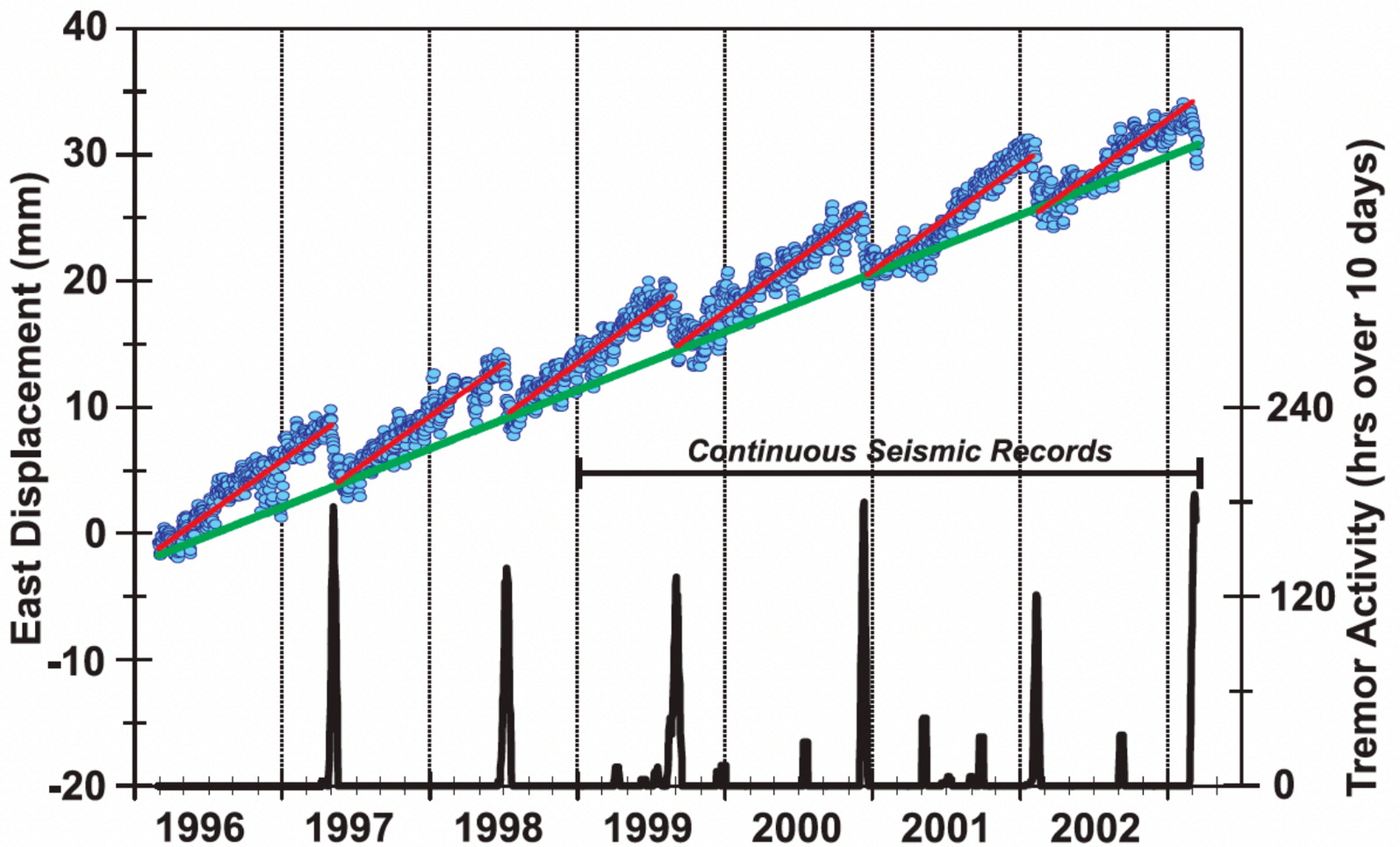


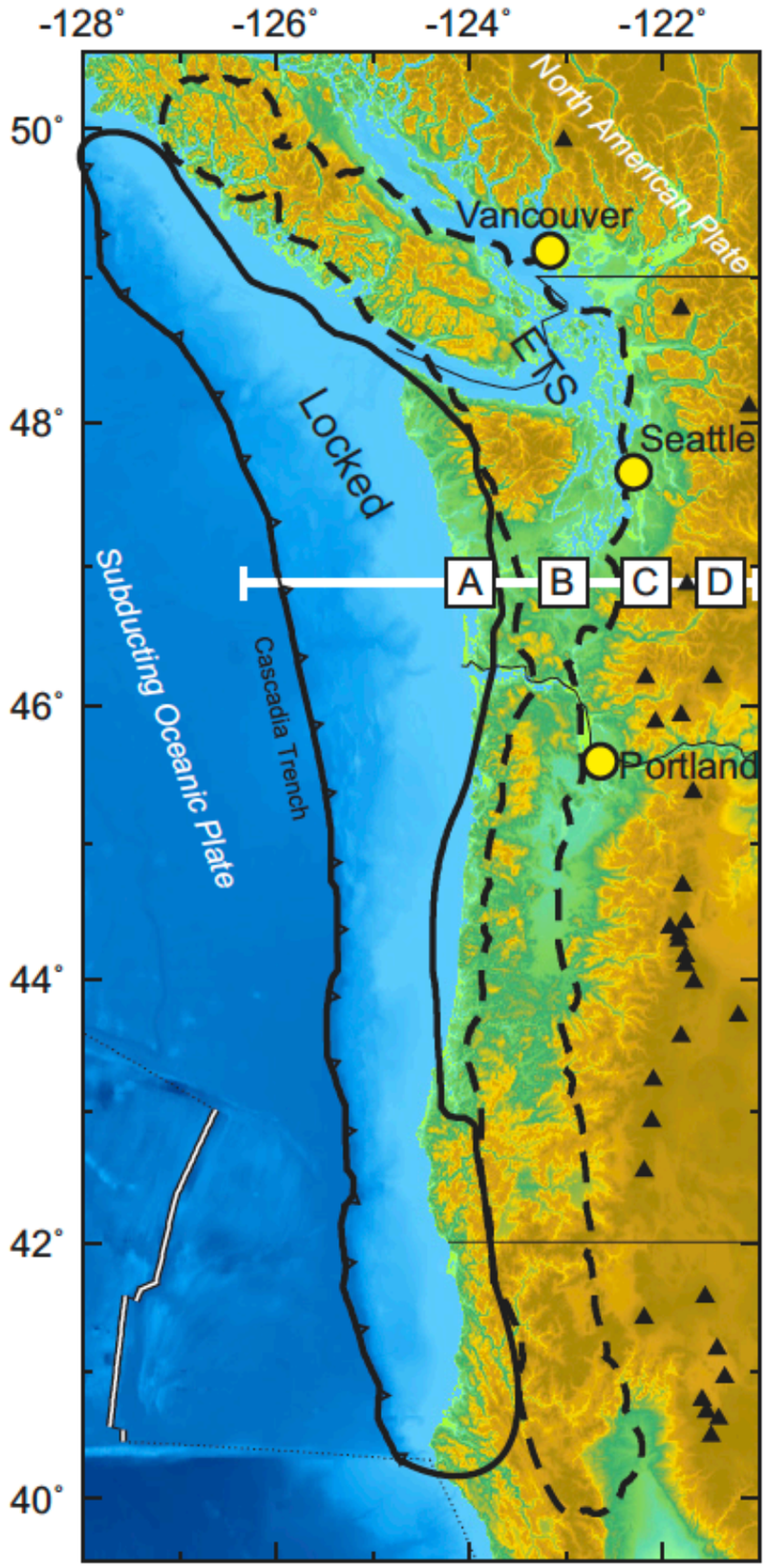
But wait, there's more…

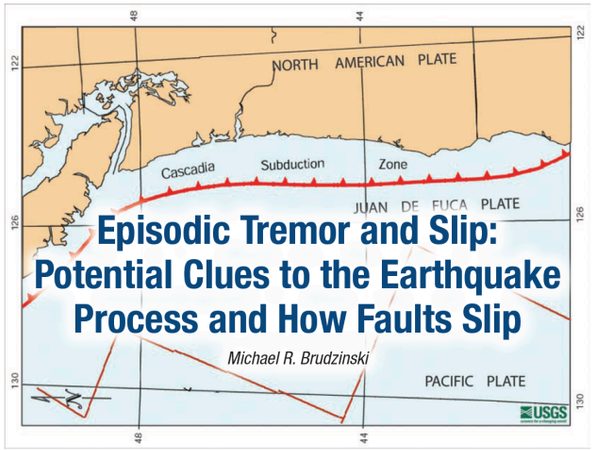


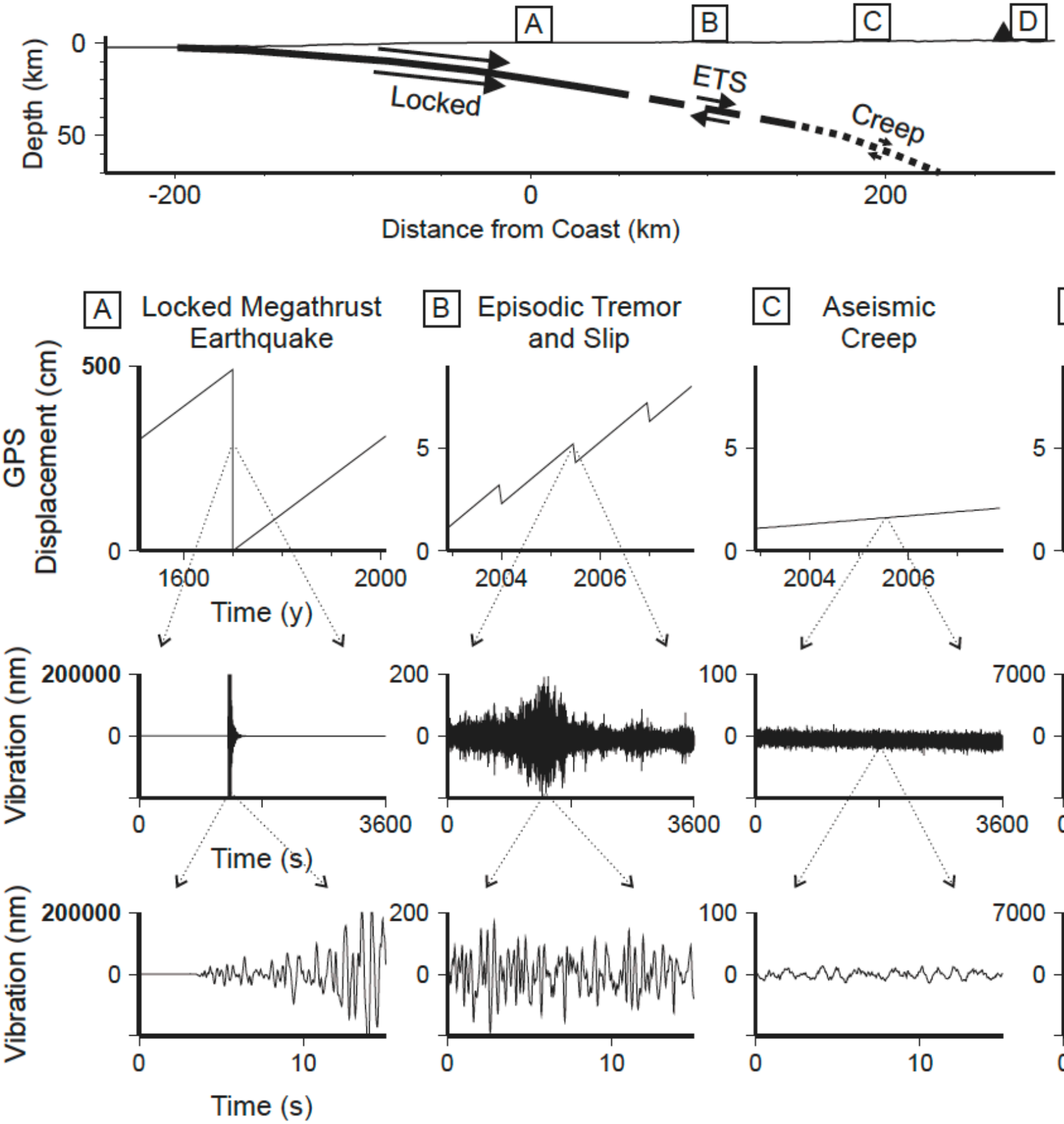
"There are more things in heaven and Earth, Horatio, Than are dreamt of in your philosophy…"

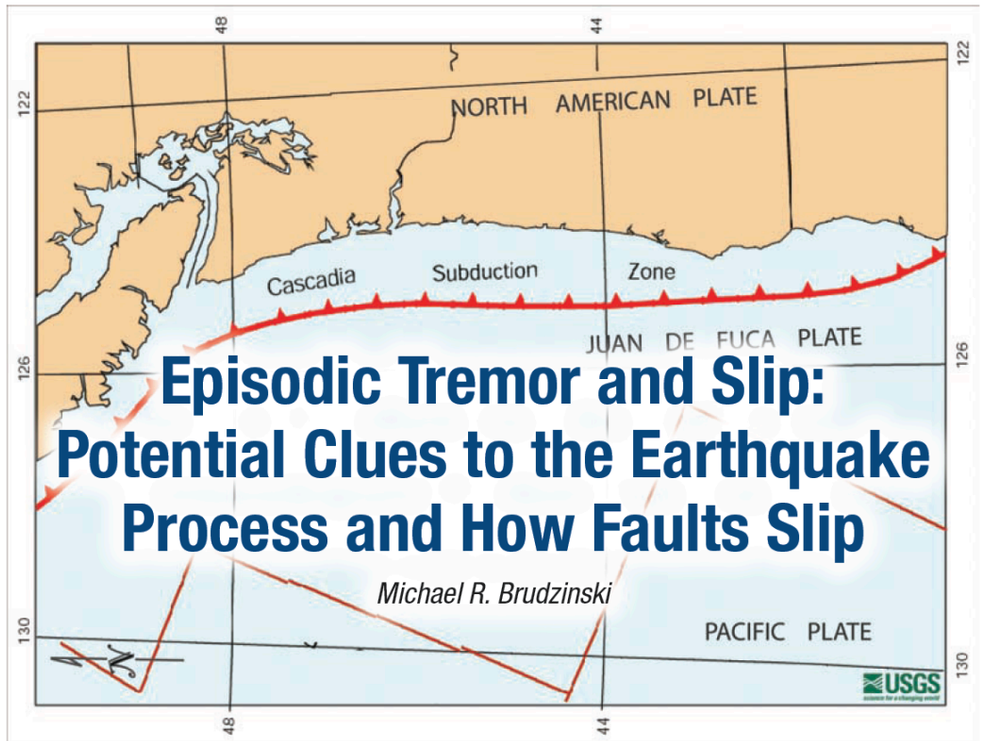
Rogers & Dragert, 2003





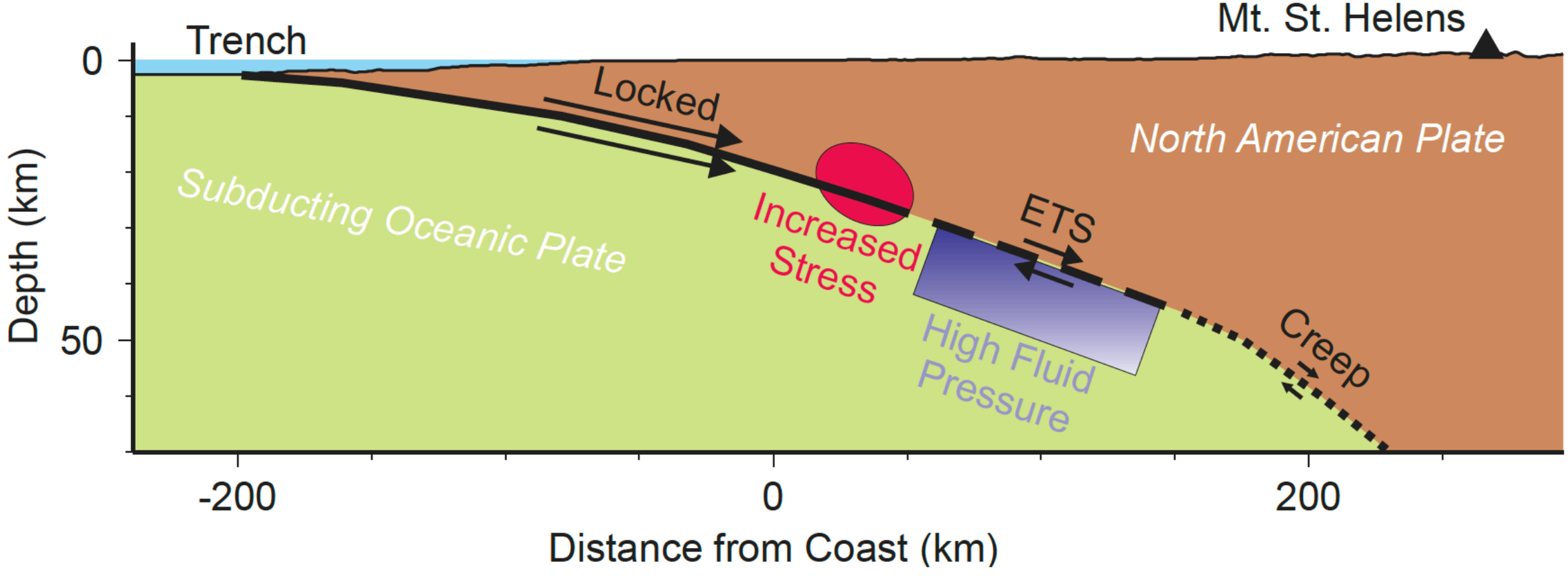

NORTH AMERICAN PLATE
Cascadia
Subduction
Zone
JUAN DE FUCA PLATE
Episodic Tremor and Slip:
Potential Clues to the Earthquake
Process and How Faults Slip
Michael R. Brudzinski
PACIFIC PLATE
USGS


A
B
C
D
Depth (km)
0
50
Locked
ETS
Creep
-200
0
200
Distance from Coast (km)
A Locked Megathrust Earthquake
B Episodic Tremor and Slip
C Aseismic Creep
D Volcanic Tremor
GPS Displacement (cm)
500
0
5
0
1600
2000
2004
2006
Time (y)
Seismic Vibration (nm)
200000
200
100
7000
0
3600
Time (s)
10
Time (s)

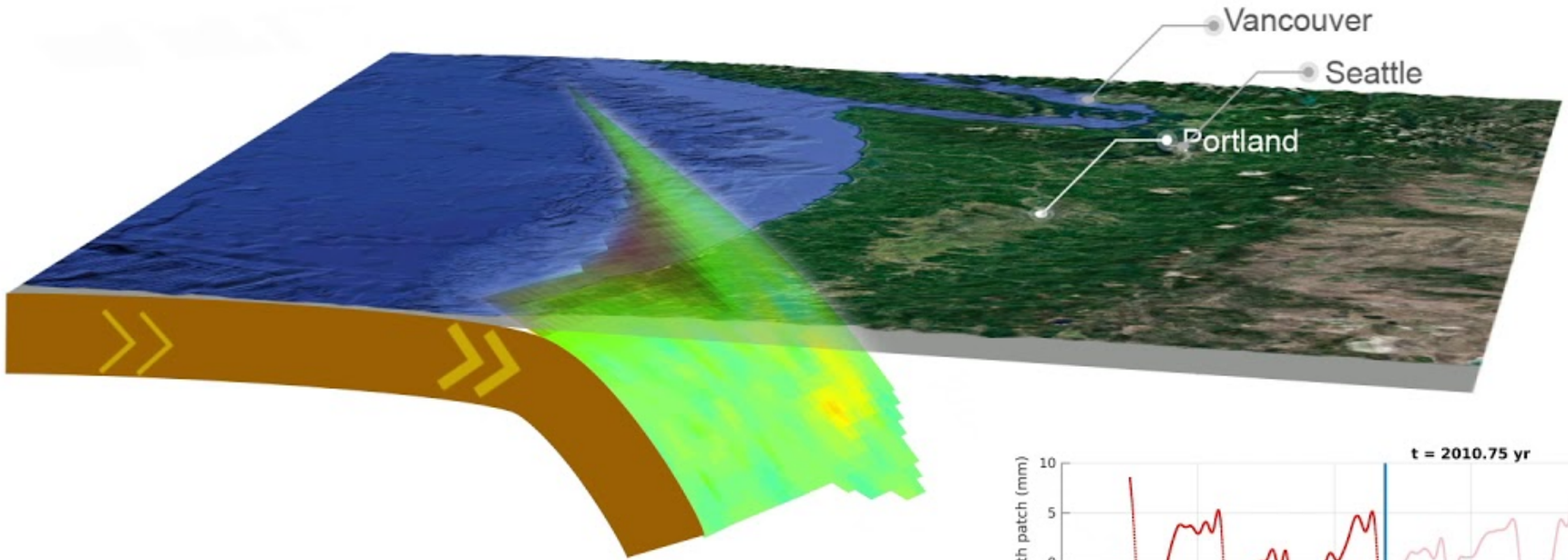


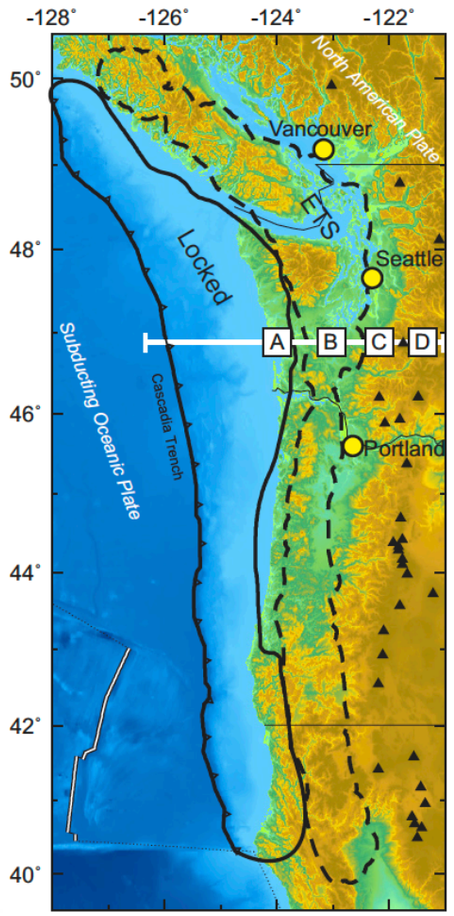
Episodic Tremor and Slip: Potential Clues to the Earthquake Process and How Faults Slip

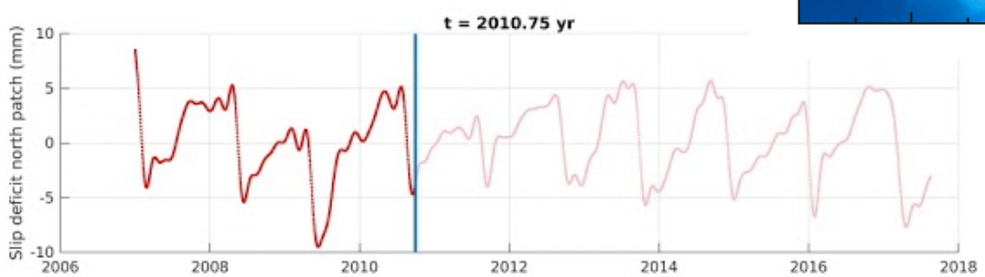
Michael R. Brudzinski

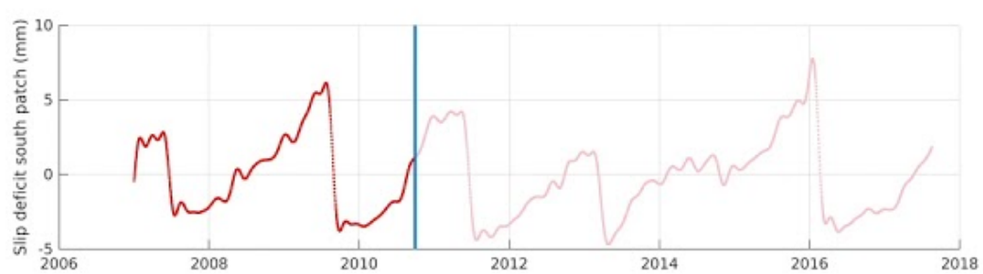


Where (on the plate interface) do these ETS events happen?









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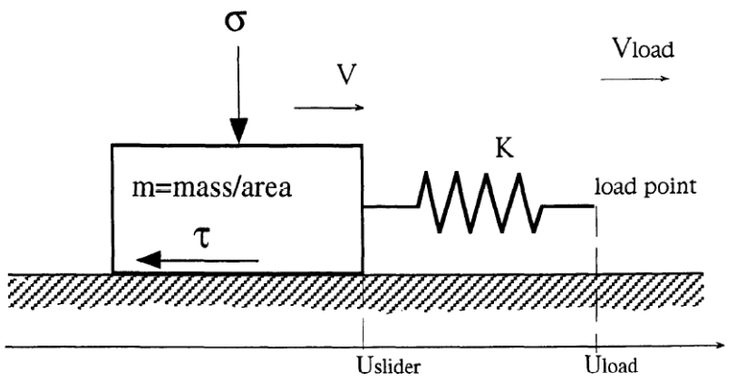
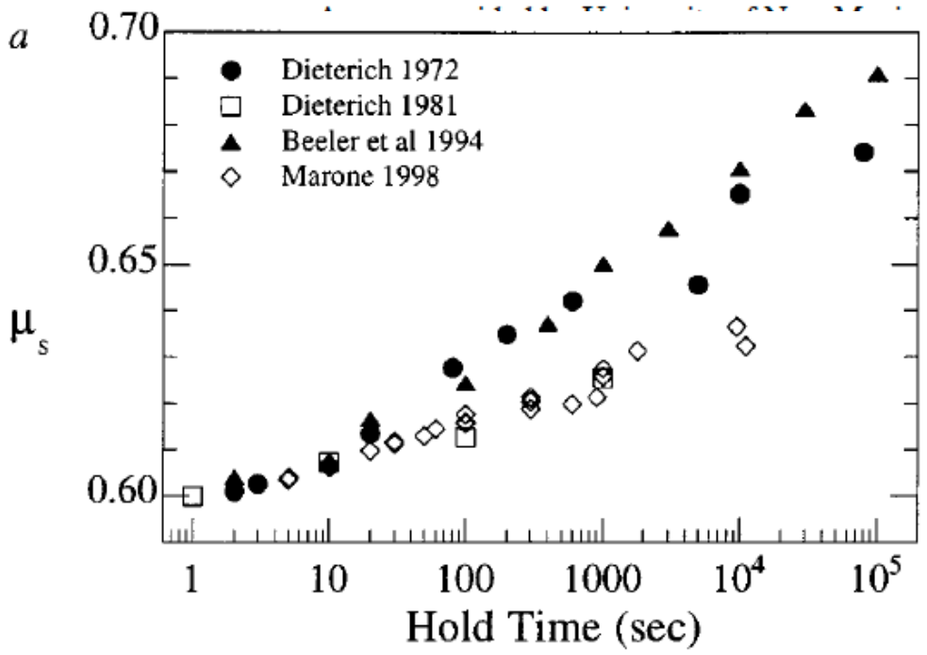
The surprising physics of friction

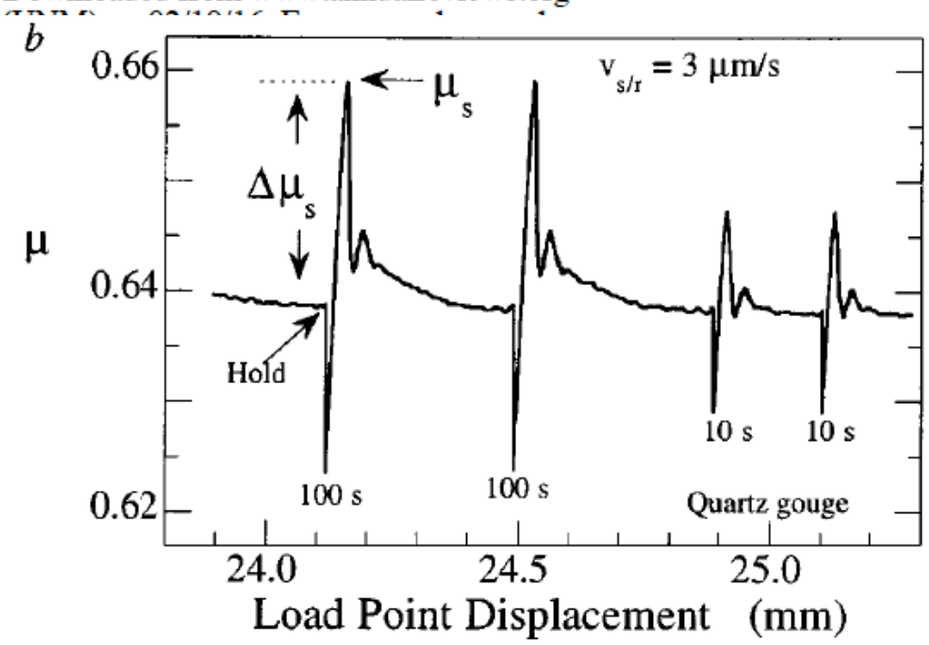


Roy and Marone, 1996

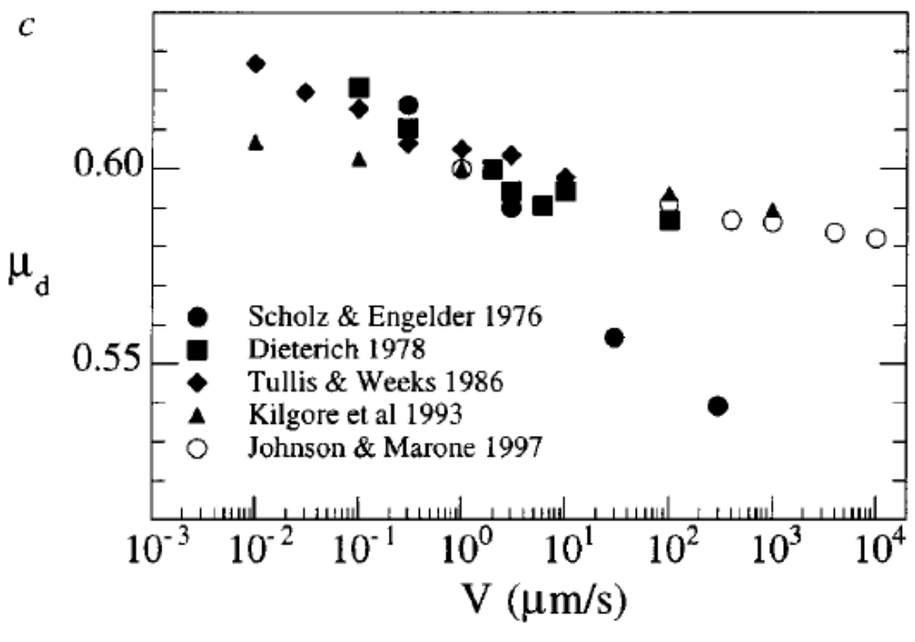
Marone, 1998

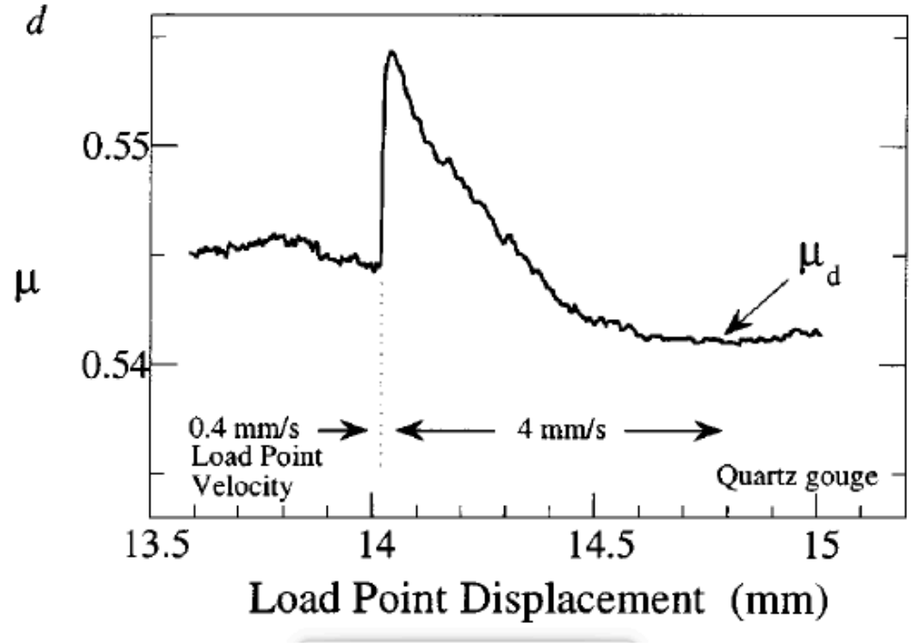
Annu. Rev. Earth Planet. Sci. 1998.26:643-696. Downloaded from www.annualreviews.org





"State"-dependence





Rate-dependence

Conclusions

1. We need to be able to deal with interdisciplinary observations —> large datasets
    - novel instrumentation, processing, integration (e.g., machine learning)

2. The Earth continues to surprise us and we need to learn how to “listen” and derive meaning from observations —> better physical models

END