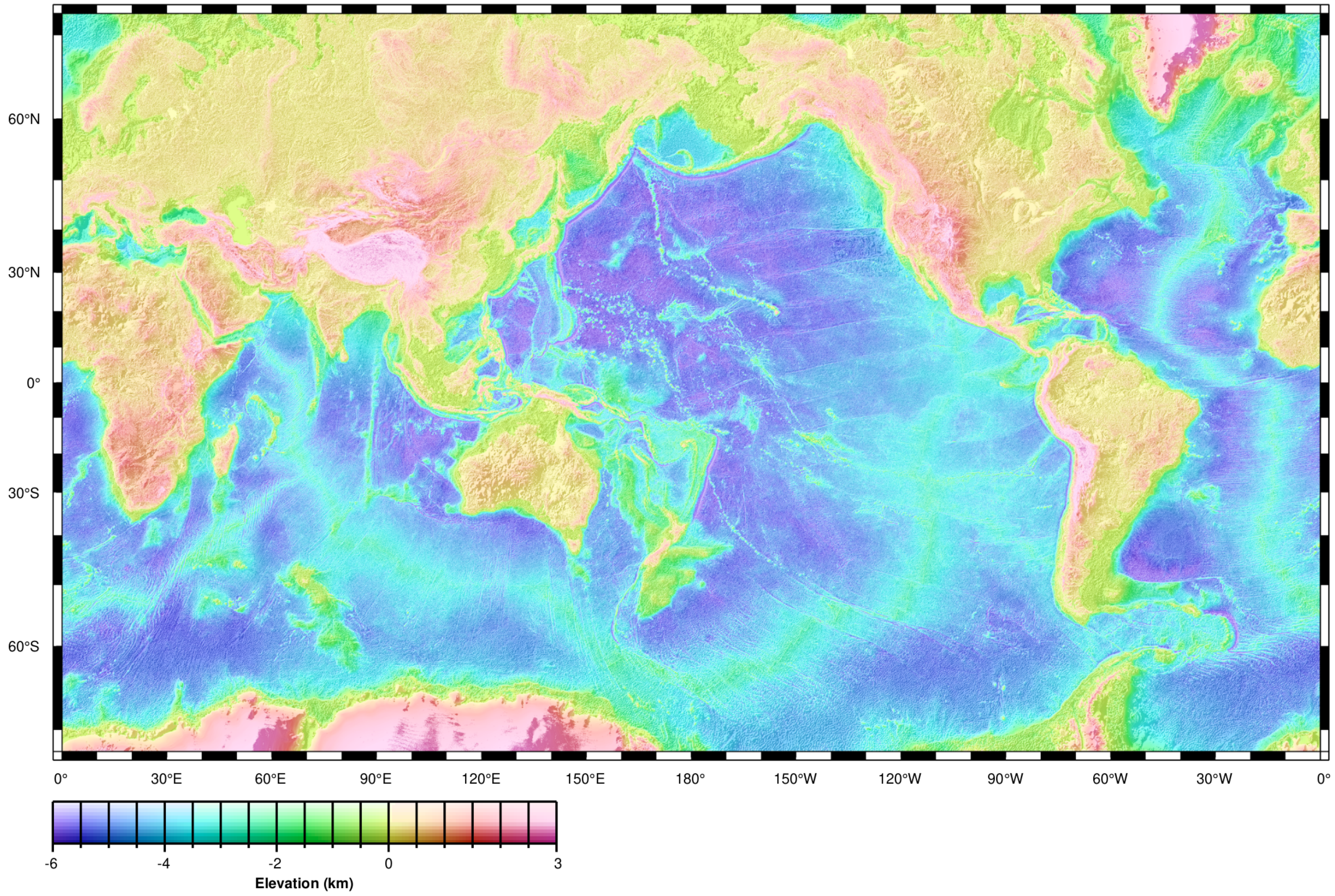
Lectures 4-6: Hot spots and seamounts

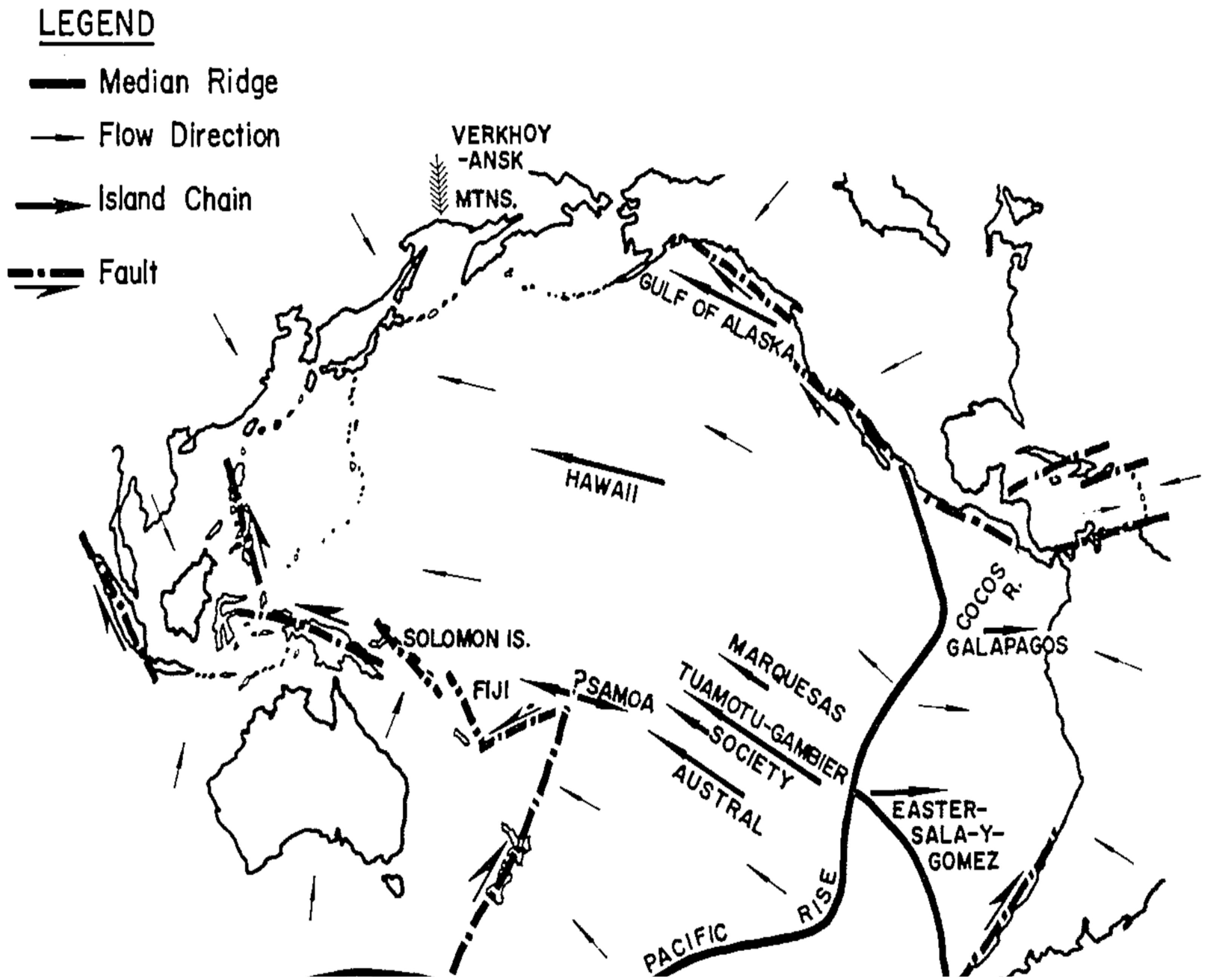
- Early ideas:
  - Origin of the Hawaiian Islands
  - Convective models of the mantle
  - Swells and depth anomalies
- Geochemistry weighs in:
  - Seafloor Basalt Geochemistry and Potential Temperature
  - Compatibility and decay systems
  - The fate of slabs
  - Large igneous Provinces and Plumes

We acknowledge and respect the lək̓ʷəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

Features of the seafloor



A possible origin of the Hawaiian Islands (Tuzo Wilson, 1963)



"It is less obvious why a stream of volcanoes should arise like a series of bubbles from a point beneath the island of Hawaii which is far from the rising current."
Tuzo Wilson, *A possible origin of the Hawaiian Islands*, 1963

Possible convective models

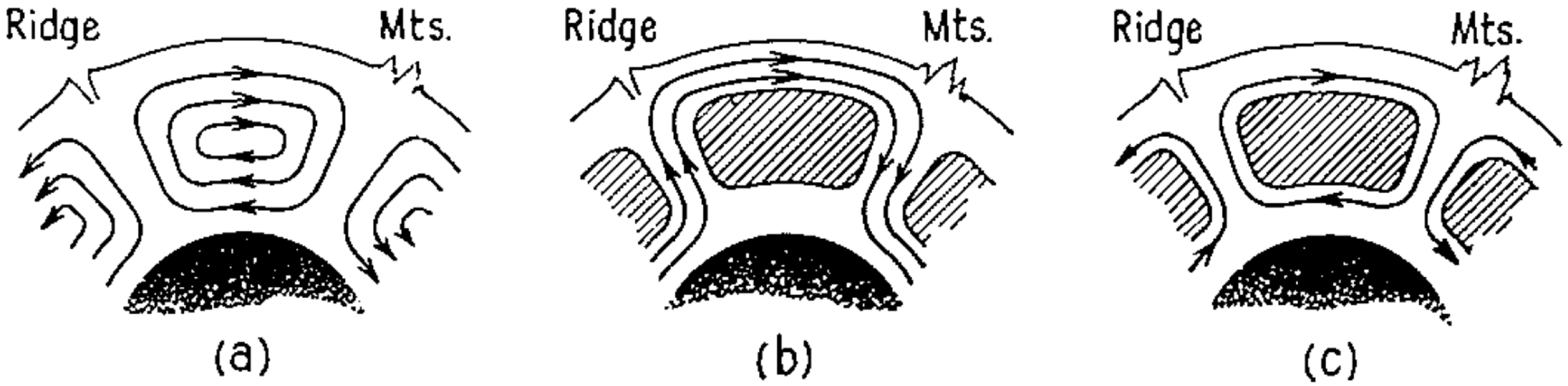


FIG. 2. Three possible modes of convection in the Earth's mantle.

The volcanic consequences of each convective model

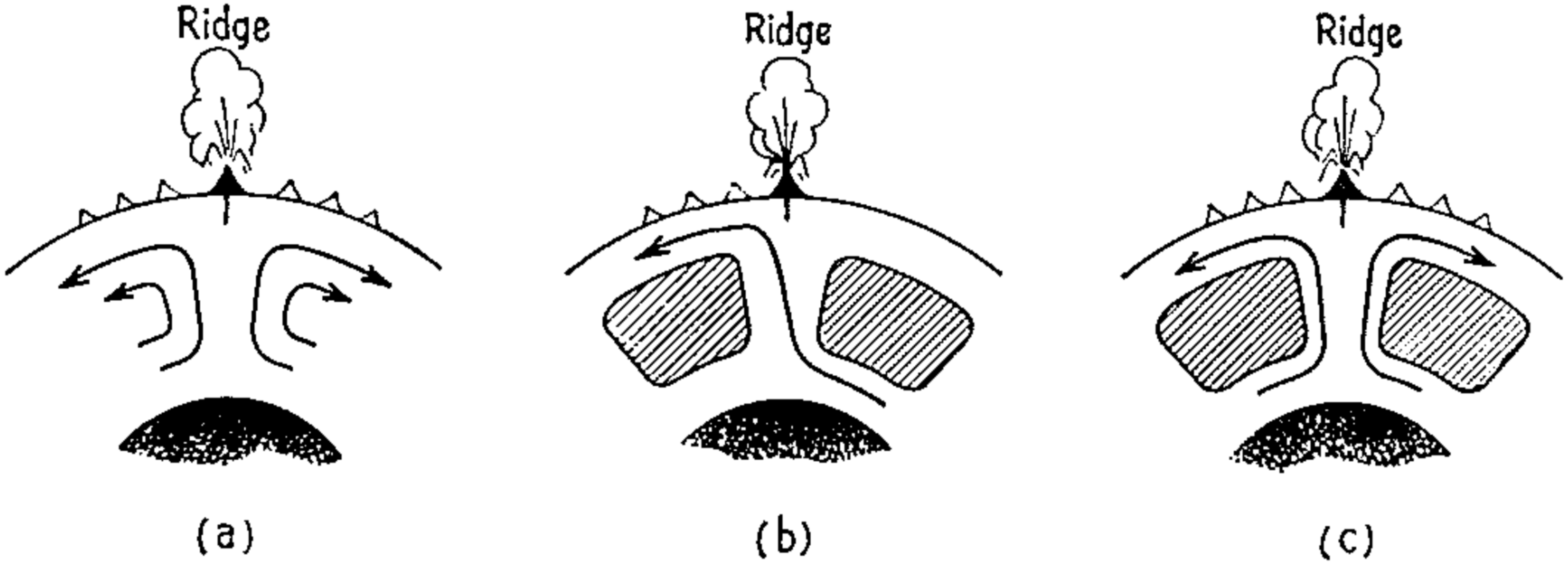


FIG. 3. Some possible patterns of convection, showing that, if active volcanoes form ovef rising vertical currents, chains of extinct volcanoes might be formed by the horizontal flow or the currents. The shaded areas represent stable cores of cells.

The volcanic consequences of each convective model

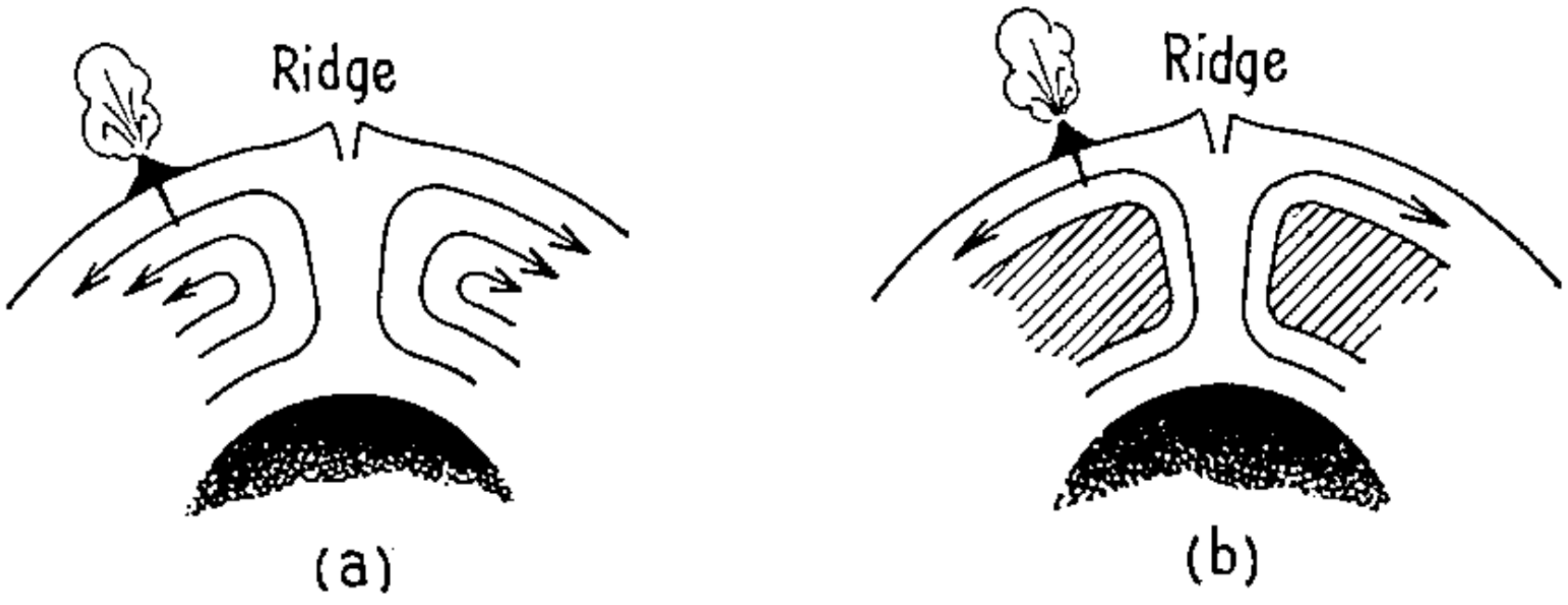


FIG. 4. Diagram to illustrate that in general if lava is generated at some other point of a convecting system than over a rising current, then only one volcano will be generated.

The source of lavas must be deep

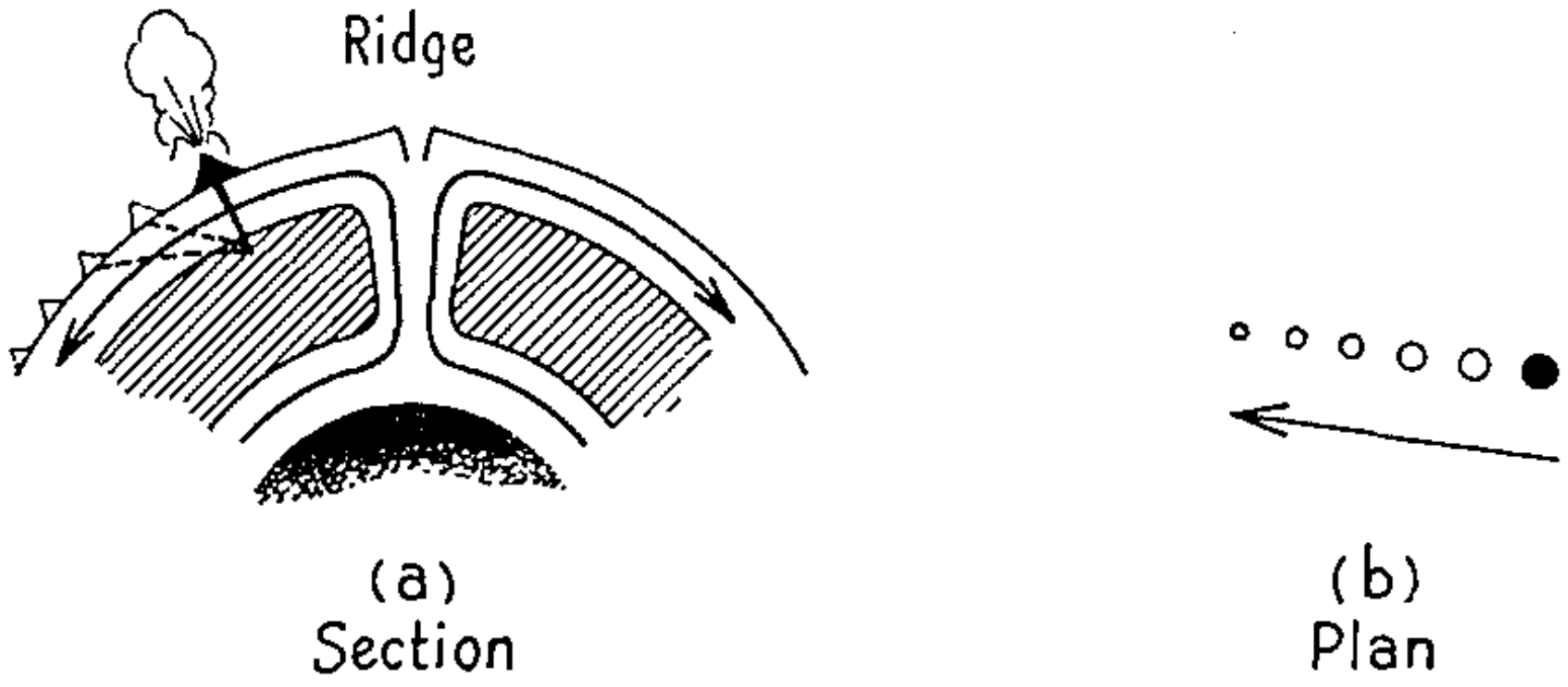


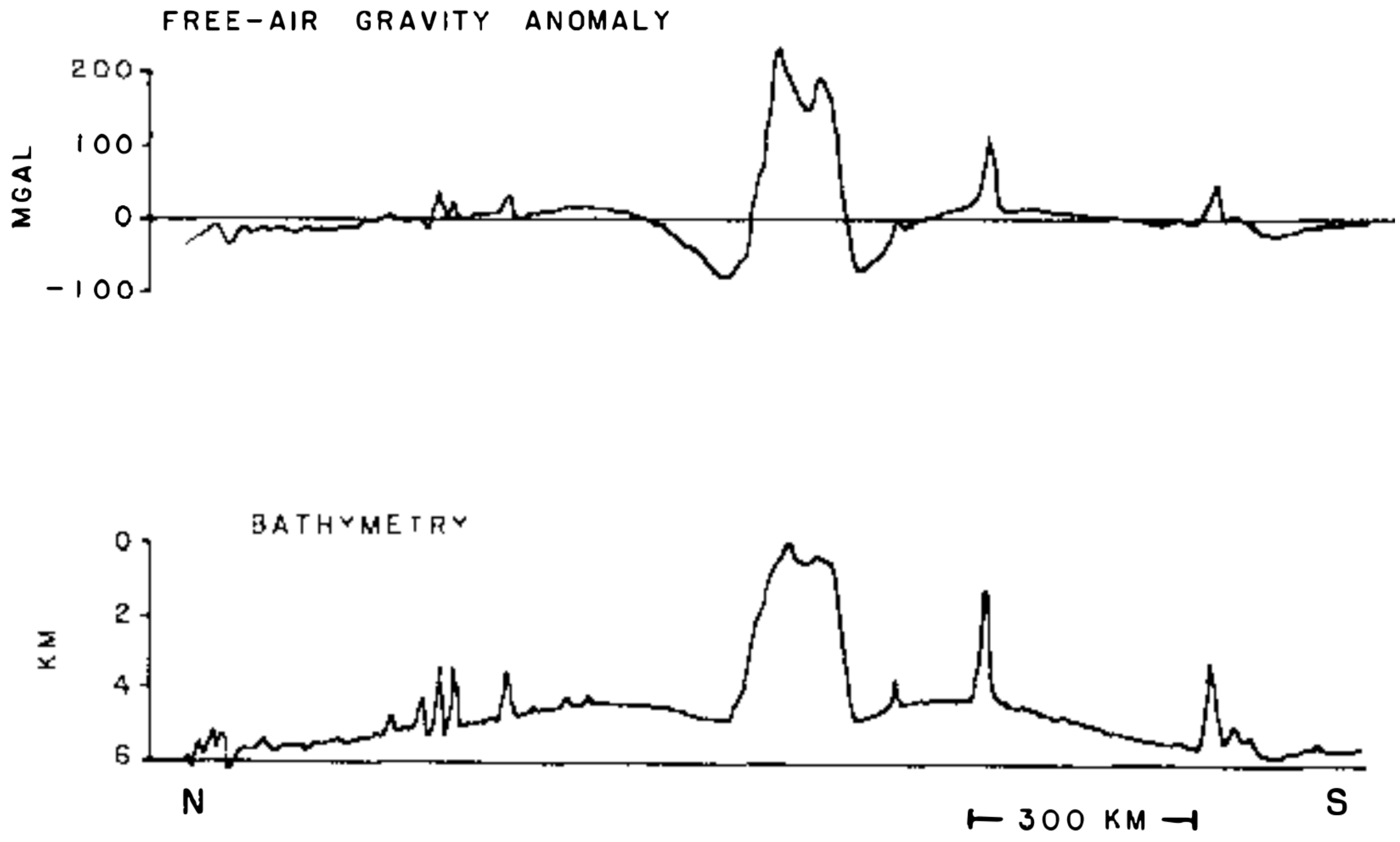
FIG. 5. Diagram to illustrate that if lava is generated in the stable core of a convection cell, and the surface is carried by the jet stream, then one source can give rise to a chain of extinct volcanoes even if the source is not over a rising current. This is proposed as a possible origin of the Hawaiian chain of islands.

The plume

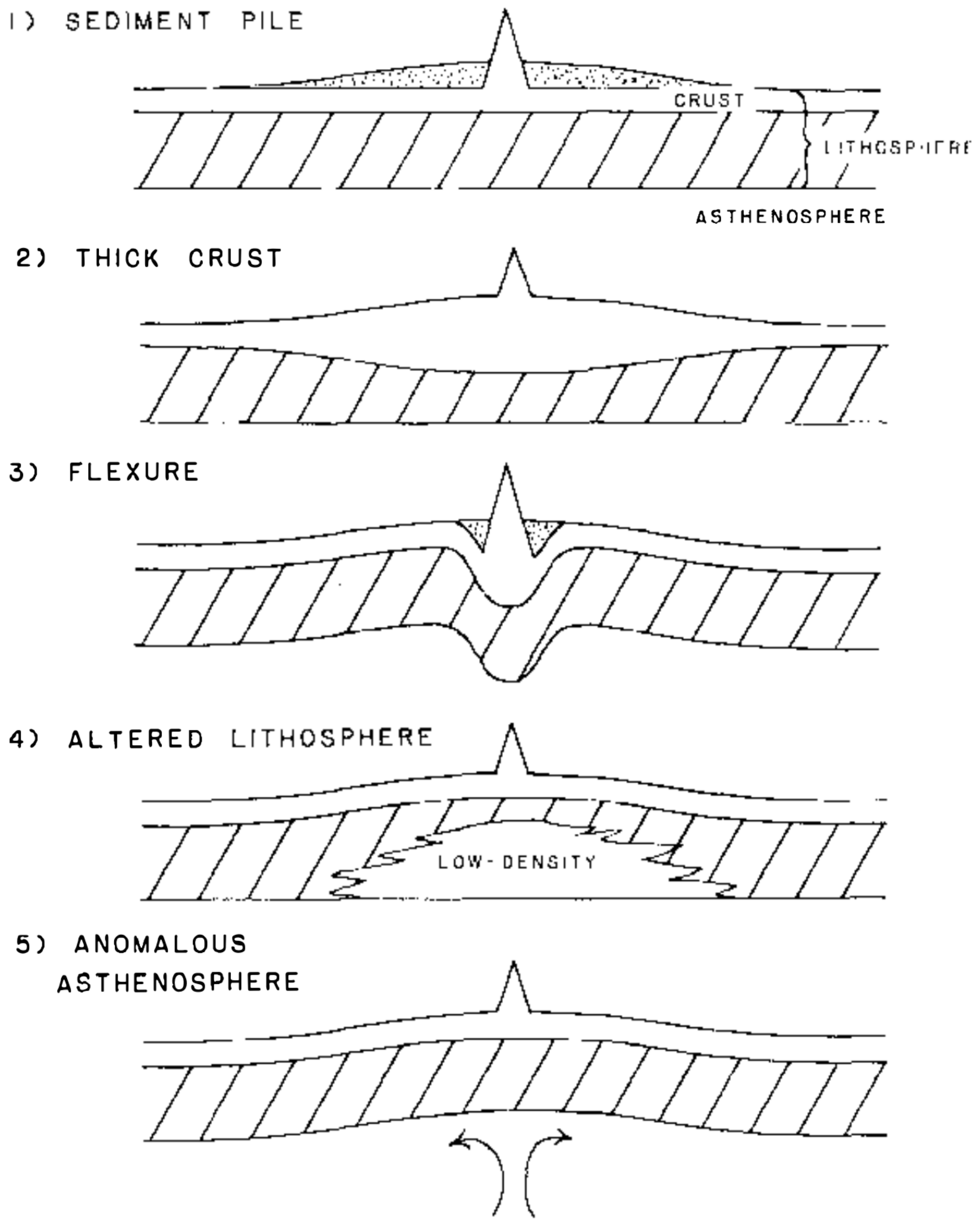
"In my model there are about twenty deep mantle plumes bringing heat and relatively primordial material up to the asthenosphere and horizontal currents in the asthenosphere flow radially away from each of these plumes..... This model is compatible with the observation that there is a difference between oceanic island and oceanic ridge basalts."

Jason Morgan, *Convection Plumes in the Lower Mantle*, 1971

Swells and depth anomalies



Supporting swells



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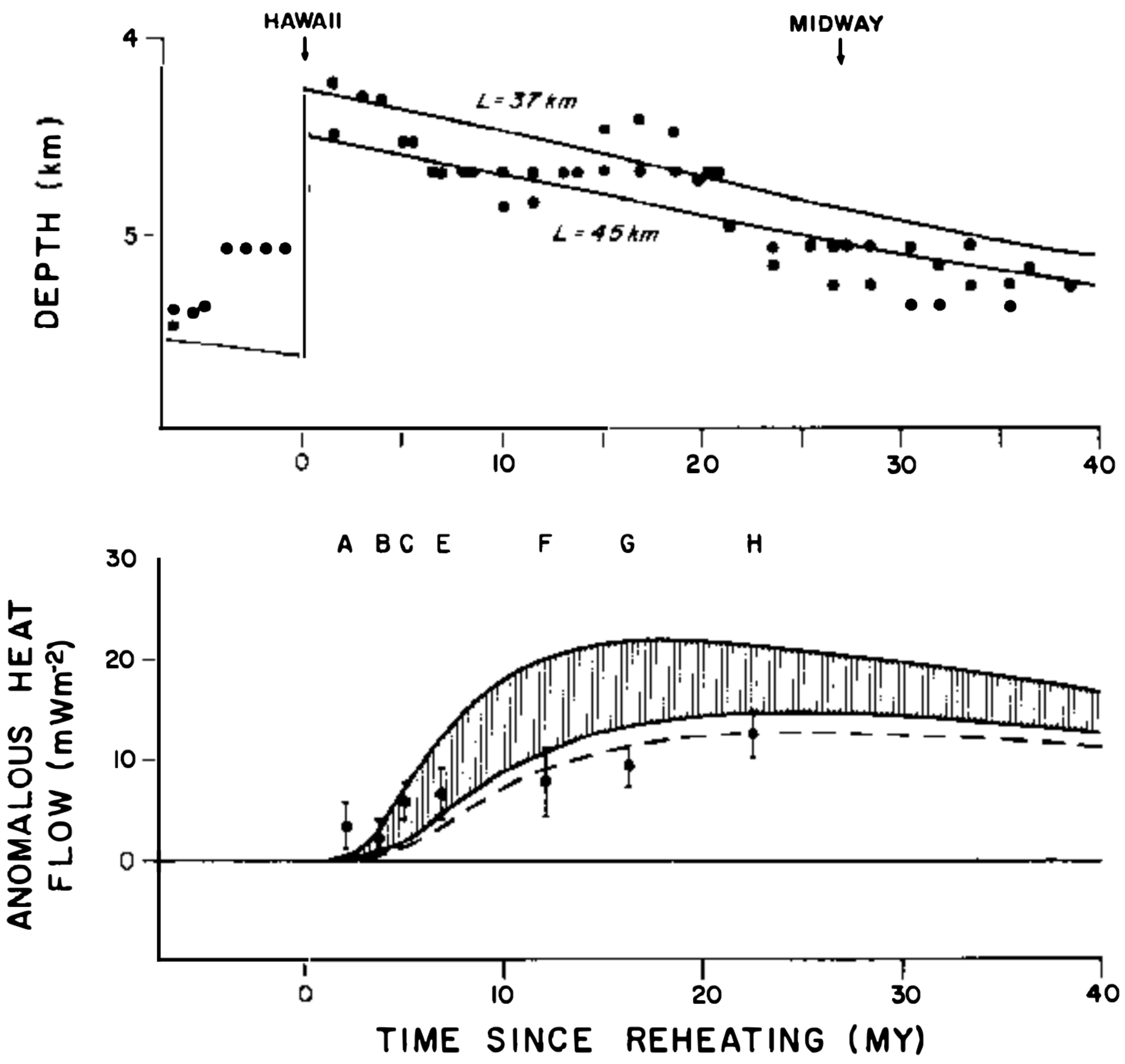
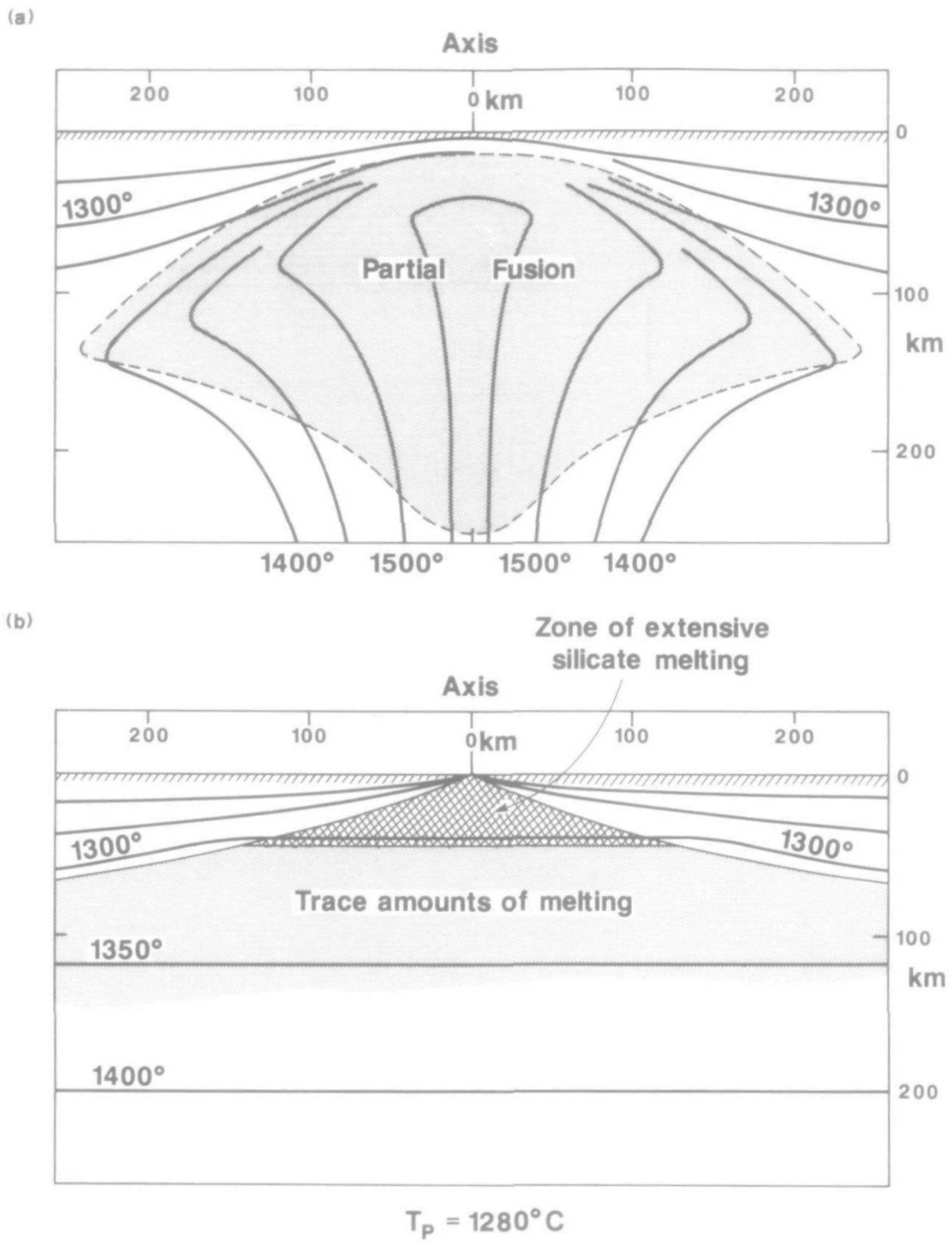


Are ridges passive or active?



- Ridges move with respect to a reference frame (what reference frame??)
- What happens when a ridge is offset by a transform fault?
- Challenges posed by these questions are solved if the ridge system is the result of spreading plates
- Melting is a passive process driven by spreading, not driven by hot sheets of rising mantle

Potential temperatures

In our daily lives we have an intuitive understanding that a hot object generally has more heat content (enthalpy) than the same object after it cools. This intuition is less useful when considering materials on Earth (rocks, air, water) that are moving quickly across pressure gradients.

The *first law of thermodynamics* can be stated as:

$$\begin{array}{ccccc} dQ & = & dU & + & PdV \\ change\ in\ heat & = & change\ in\ internal\ energy & + & work\ done\ on\ the\ environm \end{array}$$

where dV is the change in volume, and P is the pressure. When considering **adiabatic** processes, where there is no change in *heat*, $dQ = 0$, we find that the temperature of a material changes due to work done by the system.

$$\begin{array}{ccccc} dQ & = & dU & + & PdV \\ 0 & = & C_v dT & + & PdV \\ & & C_v dT & = & -PdV \end{array}$$

Potential temperatures

$$\begin{aligned} dQ &= dU + PdV \\ 0 &= C_v dT + PdV \\ C_v dT &= -PdV \end{aligned}$$

So when the volume change is positive (expansion), dT must be negative (cooling). Alternatively if we considered the case of constant volume, using $PdV = -\frac{VdP}{\gamma}$, then decreases in pressure lead to decreases in temperature (γ is a positive ratio of the specific heat for the material at constant pressure and constant volume).

The potential temperature, T_p, is the temperature defined at a reference pressure, and it allows us to use our intuition about temperature when considering the energy (heat content) in a parcel of rock, water, or air. Potential temperatures of the mantle control the starting point for melting during adiabatic decompression.

Basalt chemistry tells us about process at depth: example from MORB

"The temperature and flow regime of the mantle should, in part, control the extent of partial melting that the mantle undergoes as it ascends beneath ocean ridges. The extent of melting should, in turn, govern both the chemistry of ocean ridge basalts and the thickness of the oceanic crust. Crustal thickness, to first order, should be related through isostatic compensation to the zero-age depth of ocean ridges. <u>Thus, variations in ocean ridge basalt chemistry, axial depth, and crustal thickness should correlate with each other and with mantle temperature variations.</u>"

Klein and Langmuir, *Global Correlations of Ocean Ridge Basalt Chemistry with Axial Depth and Crustal Thickness*, 1987

- Why would zero-age depth and chemistry correlate?
- Geochemistry review:
    - What trends in FeO content of melt do you expect with increasing melt fraction? (think about minerals in peridotite)
    - What trends in NaO content of melt do you expect with increasing melt fraction? (sodium behaves like an **incompatible** trace element)

Axial depth, crustal thickness, and melting

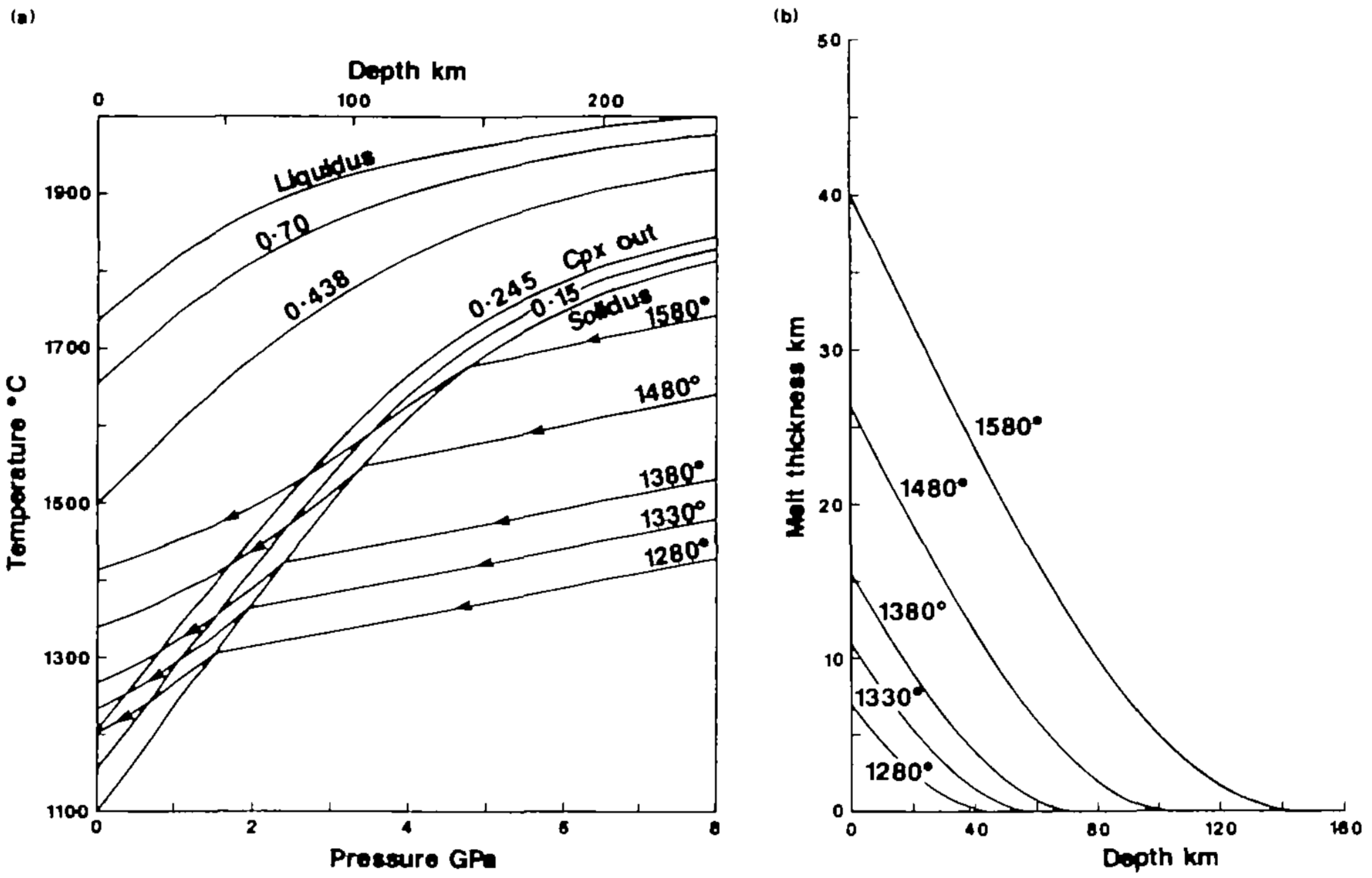
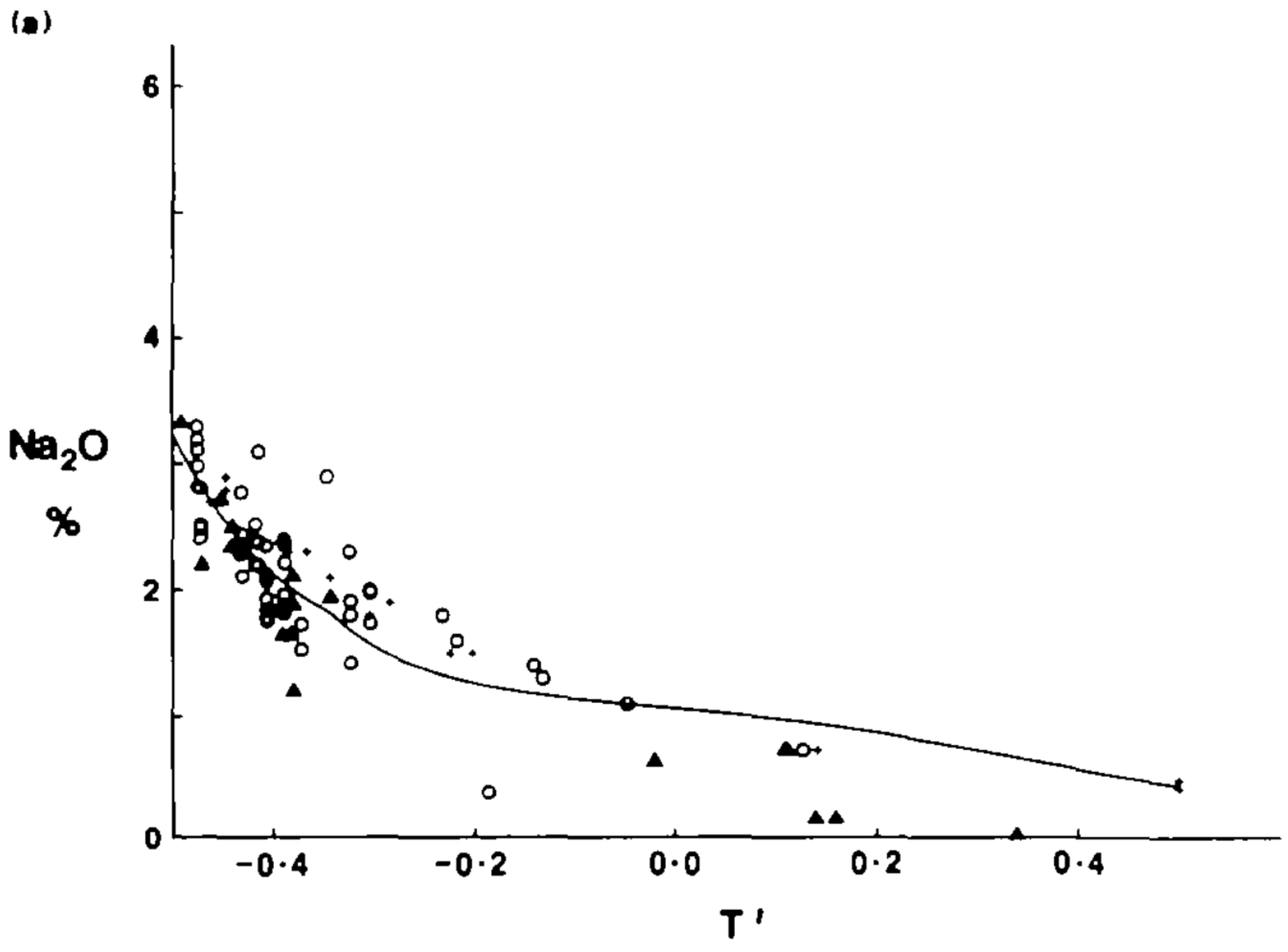


FIG 7 (a) Adiabatic decompression paths calculated using the equations given by McKenzie (1984*a*) Appendix D, a fourth order Runge–Kutta scheme and

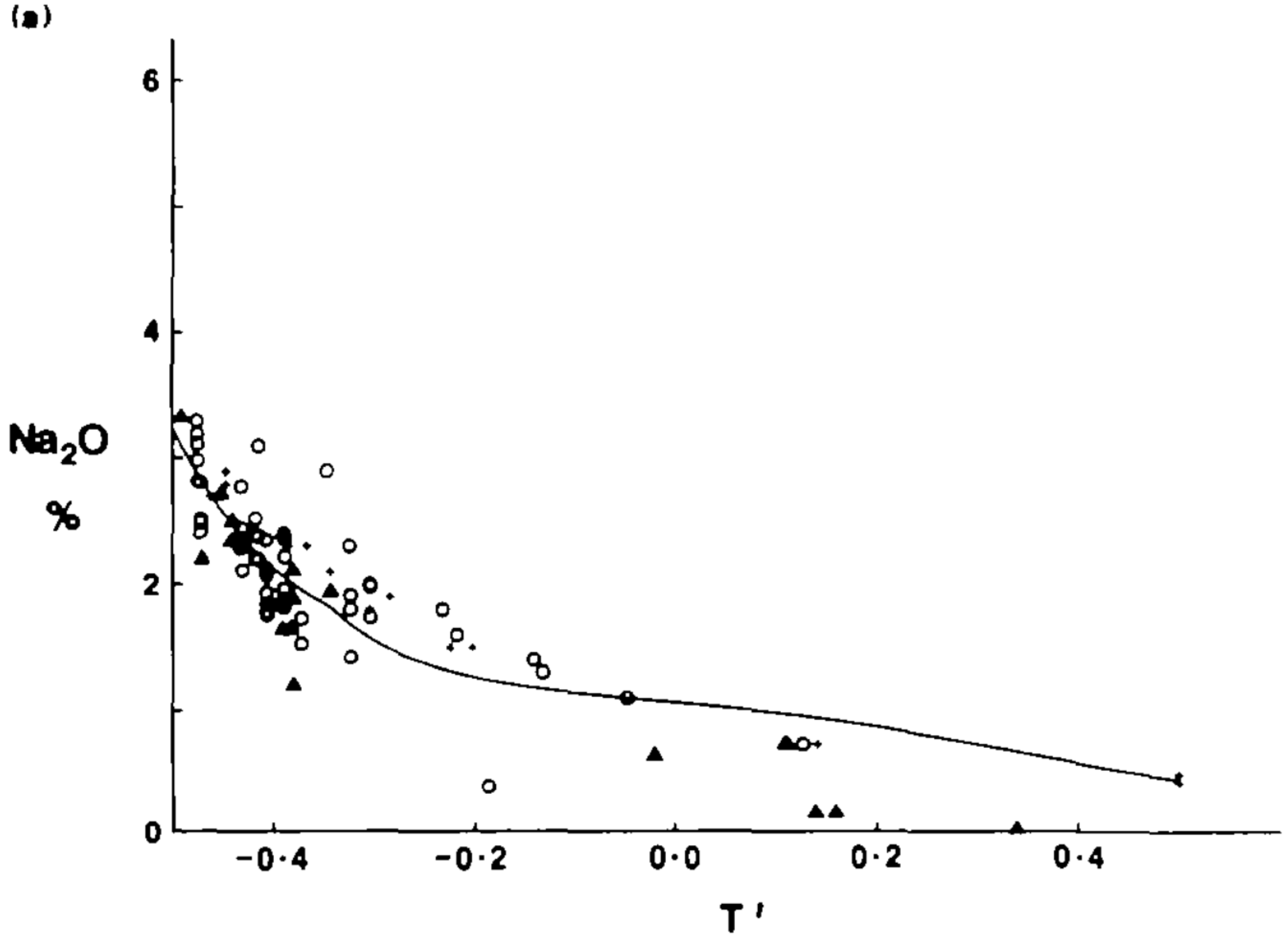
$$\Delta S = 250\ \mathrm{J\ kg^{-1}\ ^\circ C^{-1}}.$$

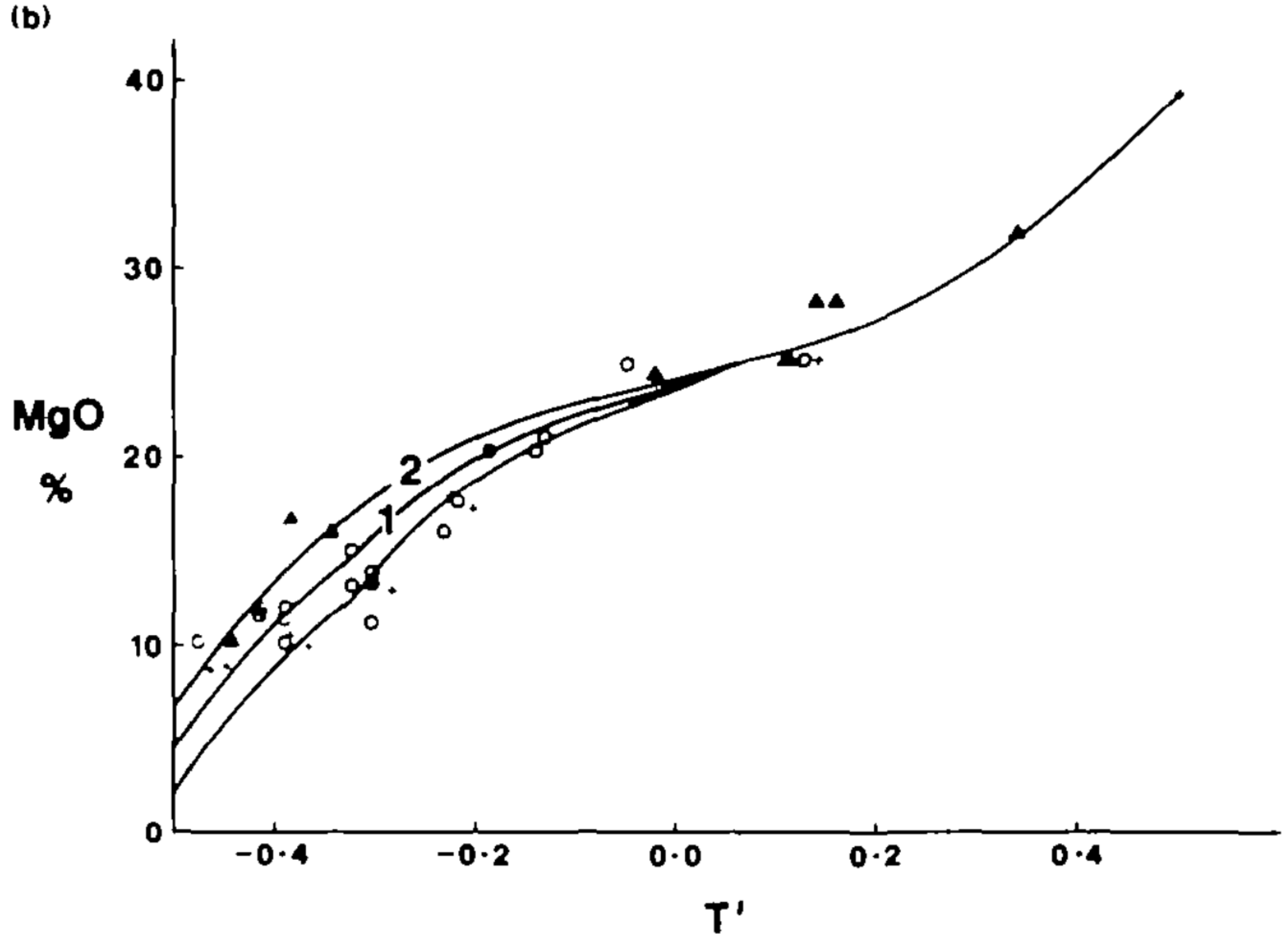
The curves are labelled with their potential temperatures, and entropy is conserved to 1 part in 10^4 during the numerical integration. The curves between the solidus and the liquidus are labelled with the melt fraction by weight. (b) The total thickness of melt present below a given depth plotted as a function of depth, calculated by integrating the volume of melt present in (a).

Peridotite melting experiments

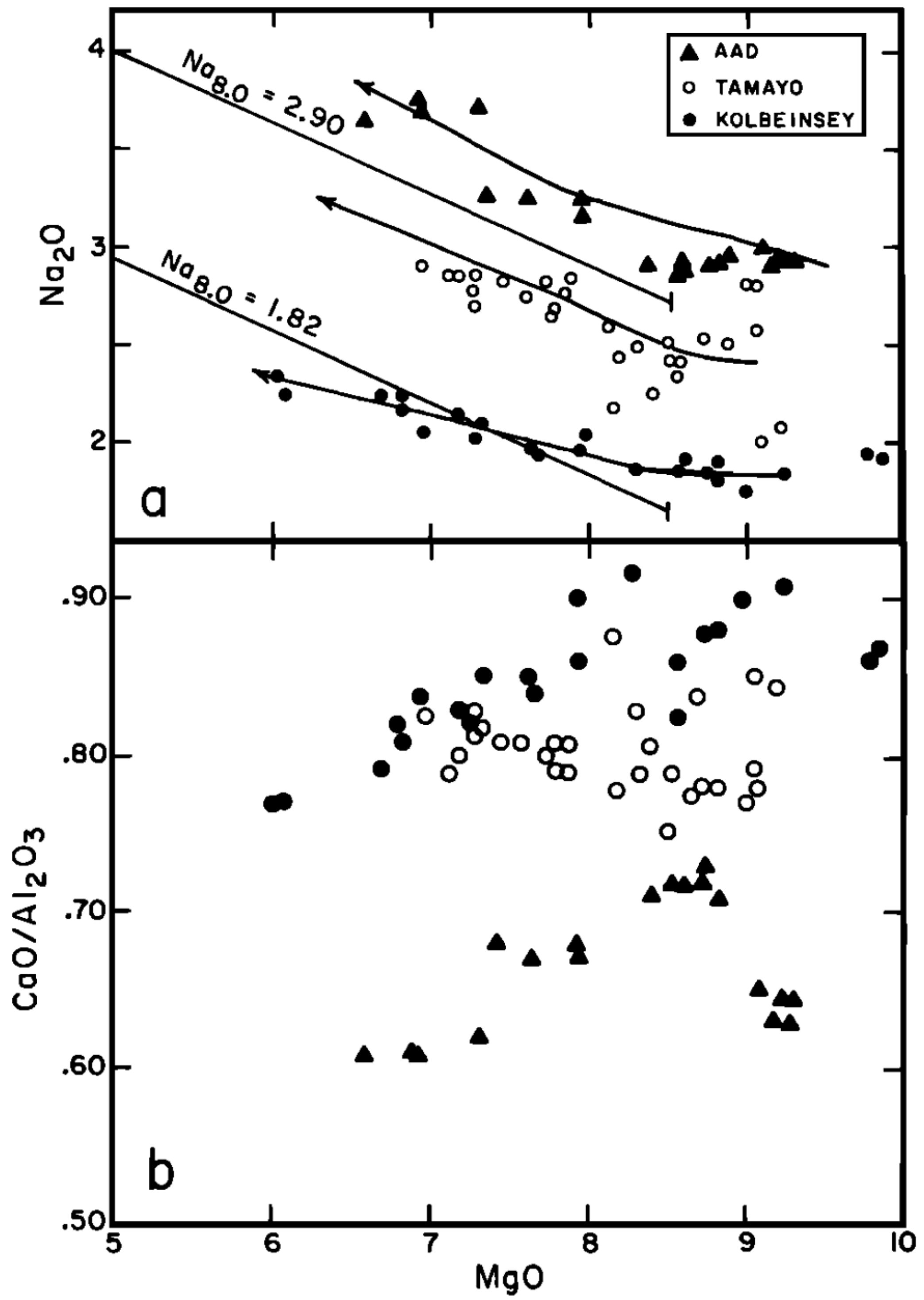


Peridotite melting experiments

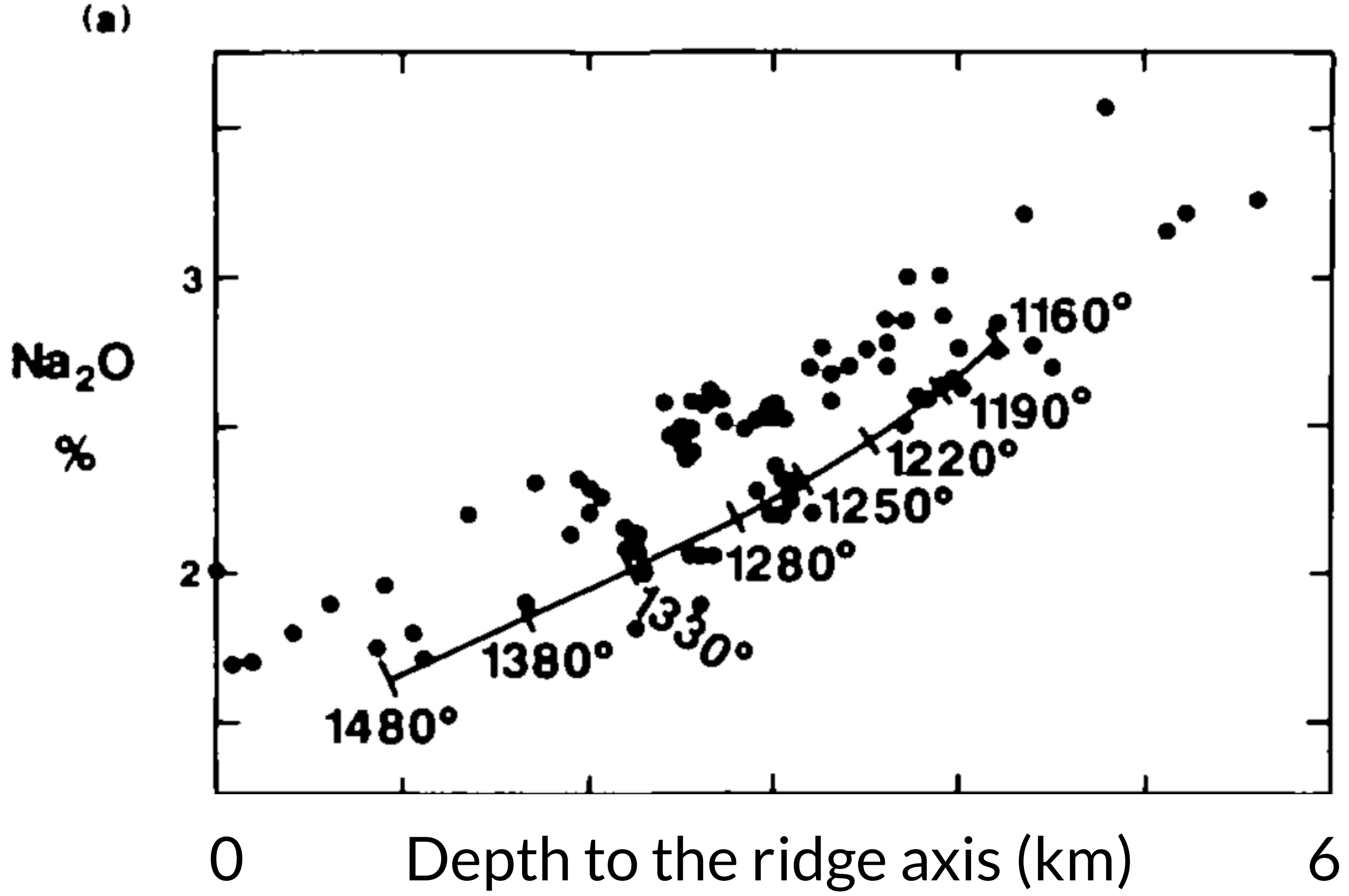


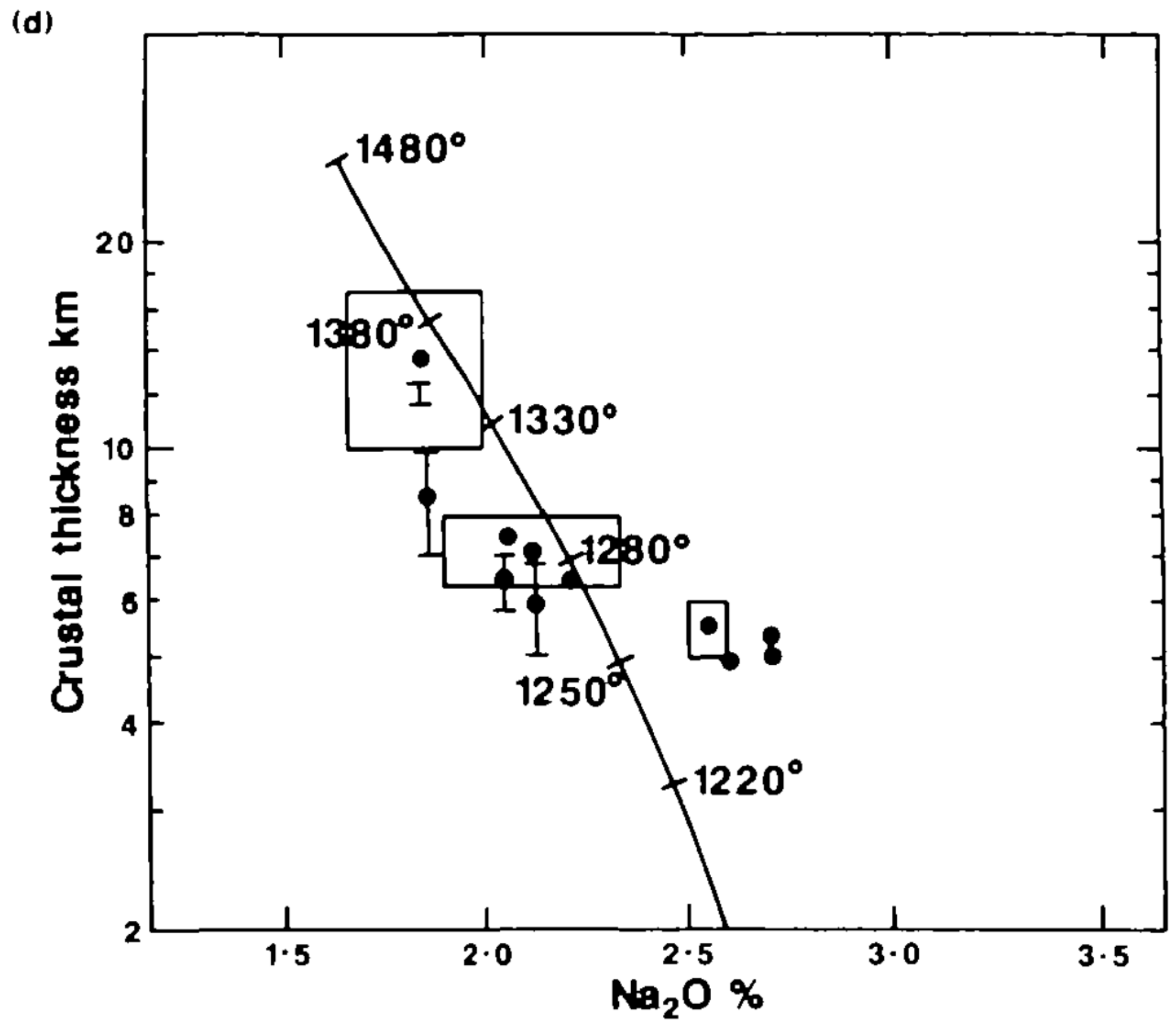


Na2O data from MORB

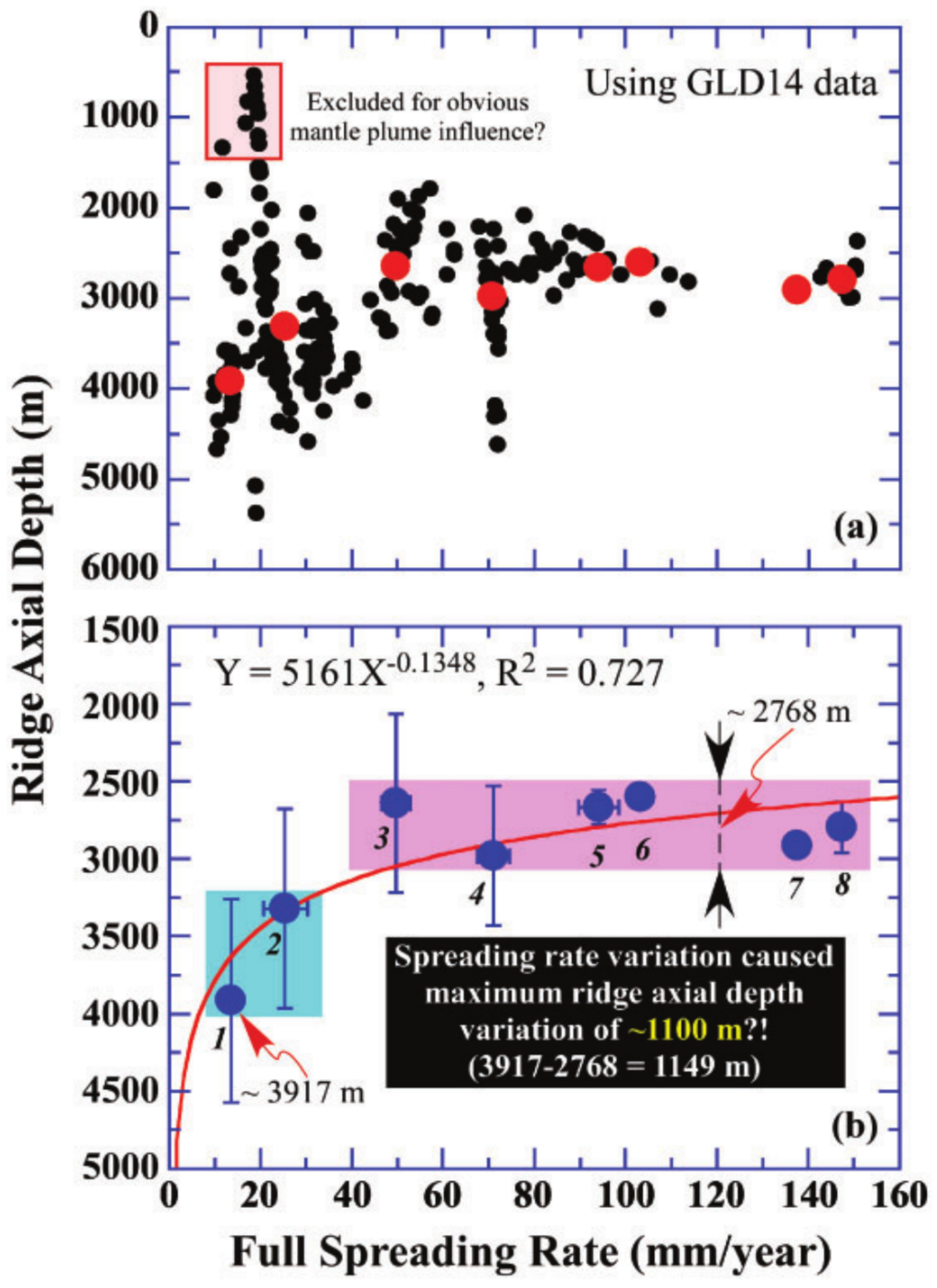


Normalized (MgO = 8%) Na_2O



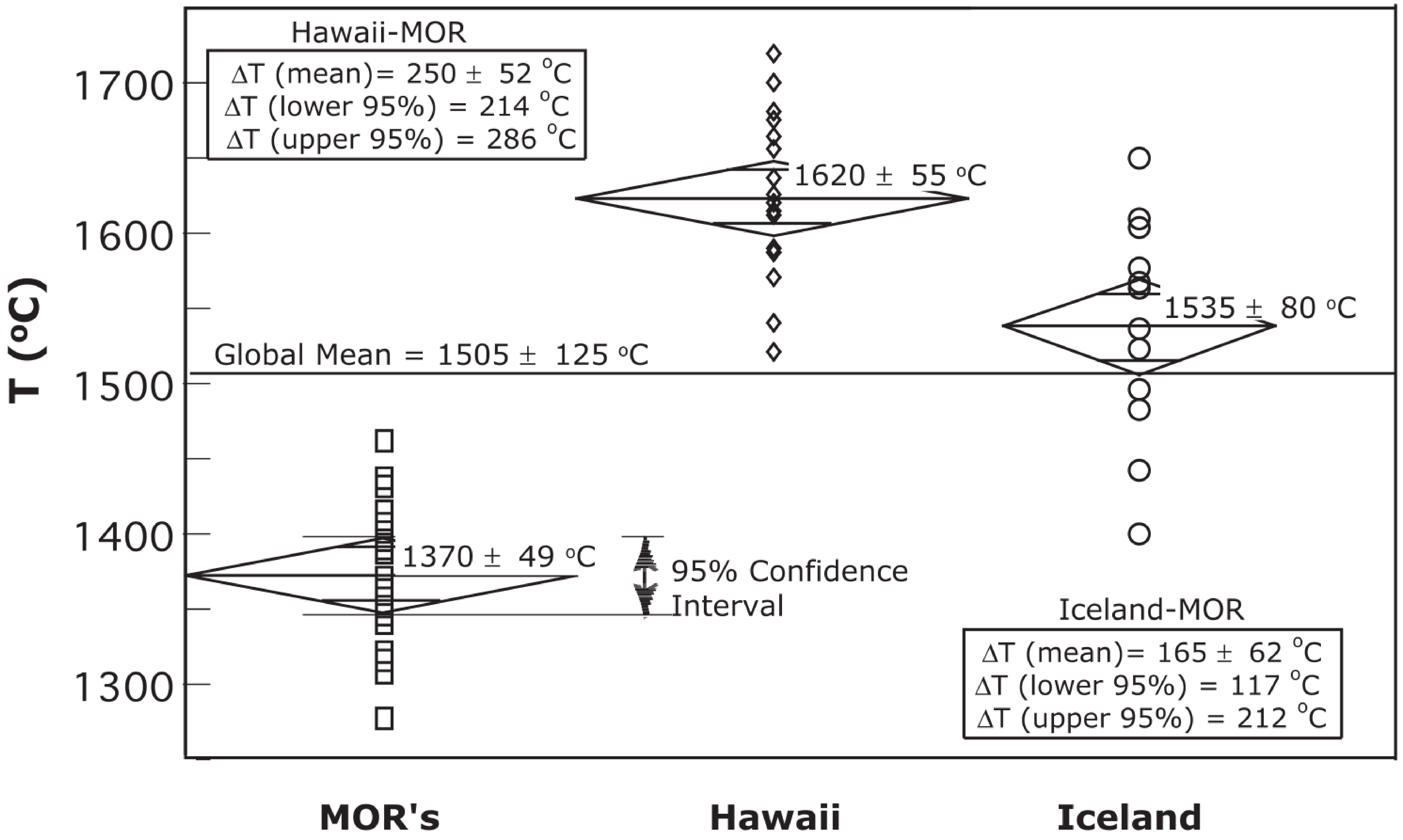


Variations in spreading rate?

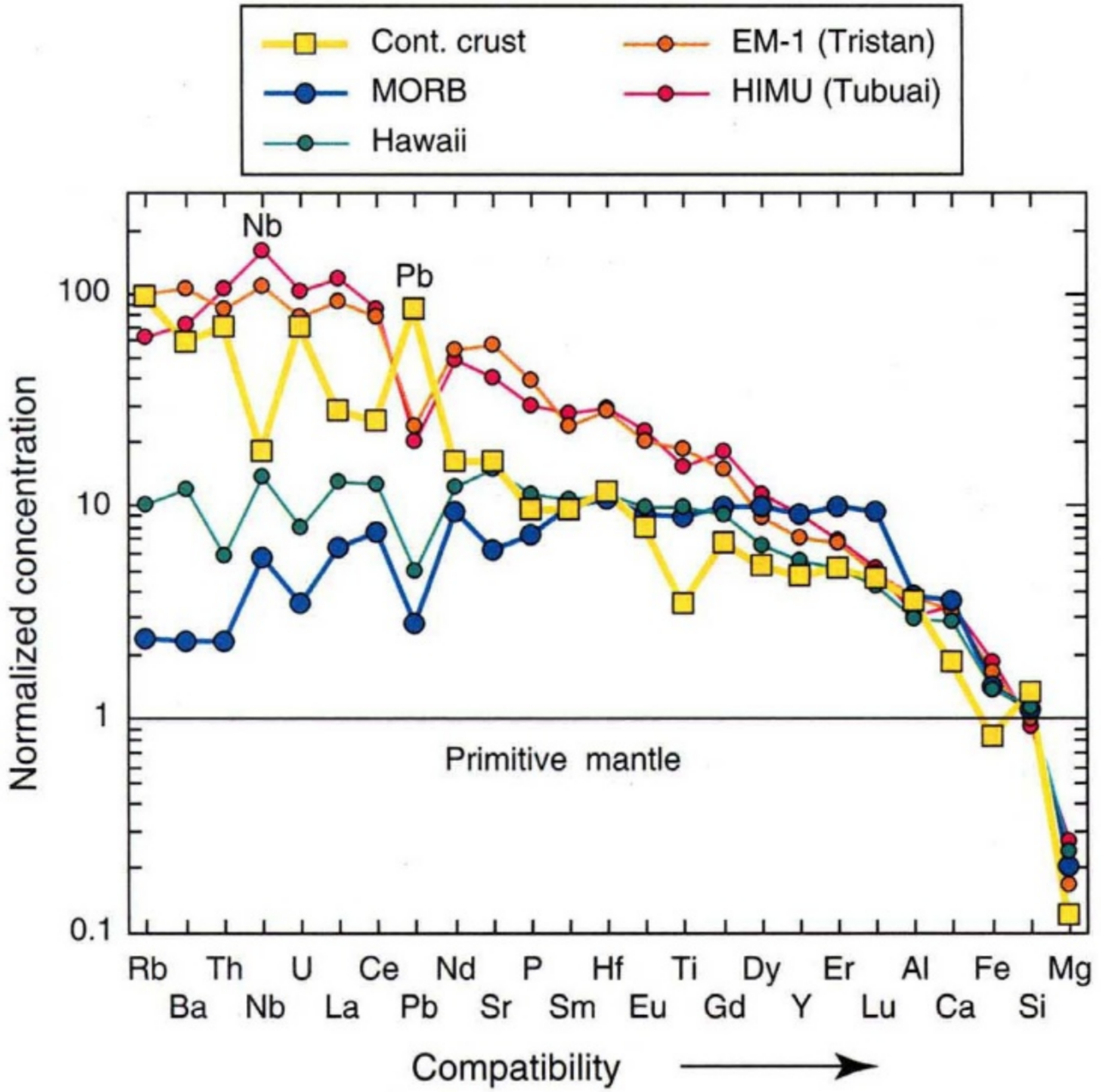


Potential temperatures beneath ridges and oceanic islands

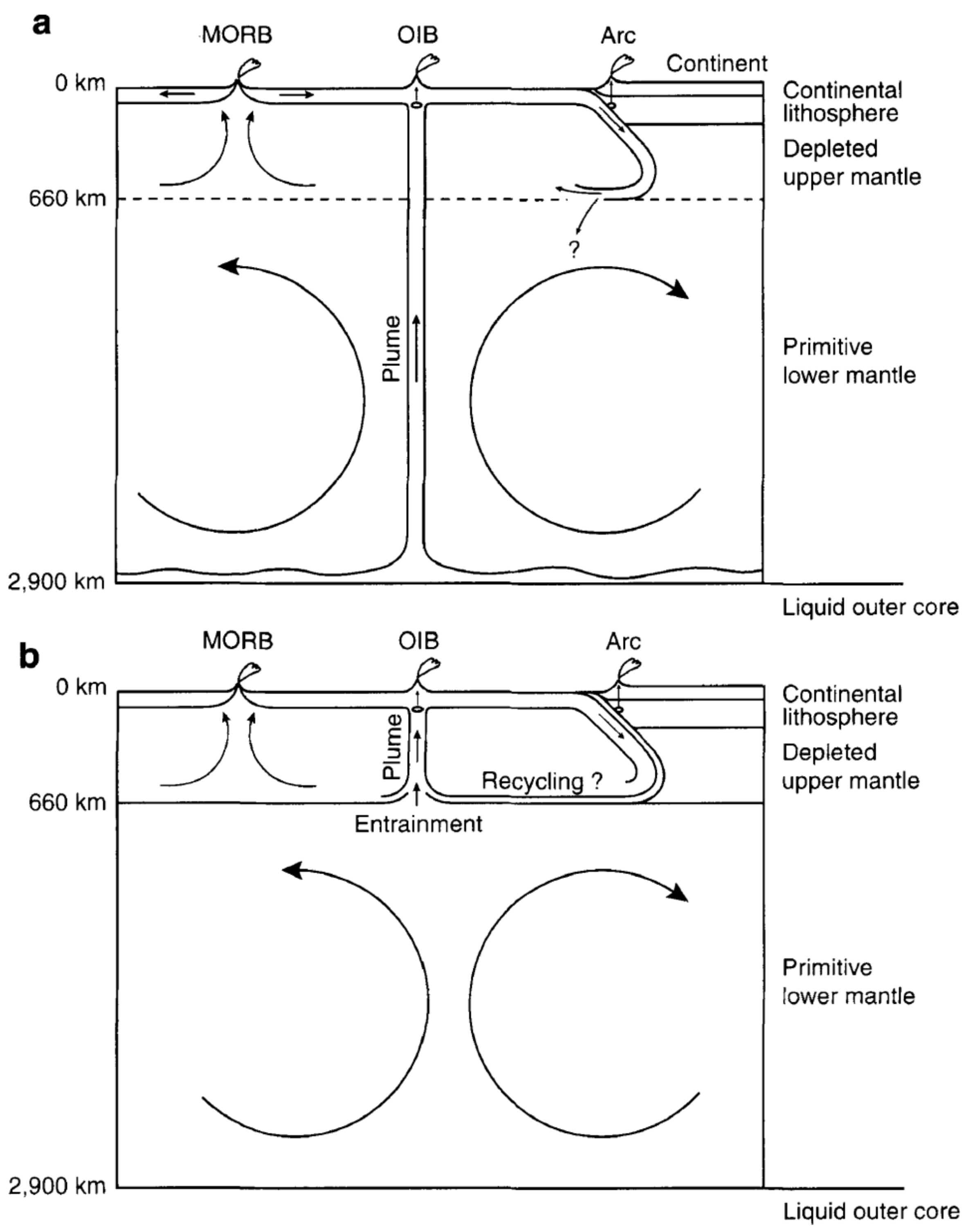
The partitioning of Mg in Olivine is sensitive to temperature while the Fe/Mg partitioning is not



Trace elements in MORB and OIB (review compatibility trends)



Models of the mantle



Sm and Rb

- $^{147}\text{Sm} \rightarrow {}^{143}\text{Nd}$
    - Sm more **compatible** than Nd
- $^{87}\text{Rb} \rightarrow {}^{87}\text{Sr}$
    - Rb highly **incompatible** (and more incompatible than Sr)

- What trends do you expect between primitive mantle, MORB, and continental crust?
    - If plumes sample primitive mantle, what should their radiogenic Nd and Sr look like?

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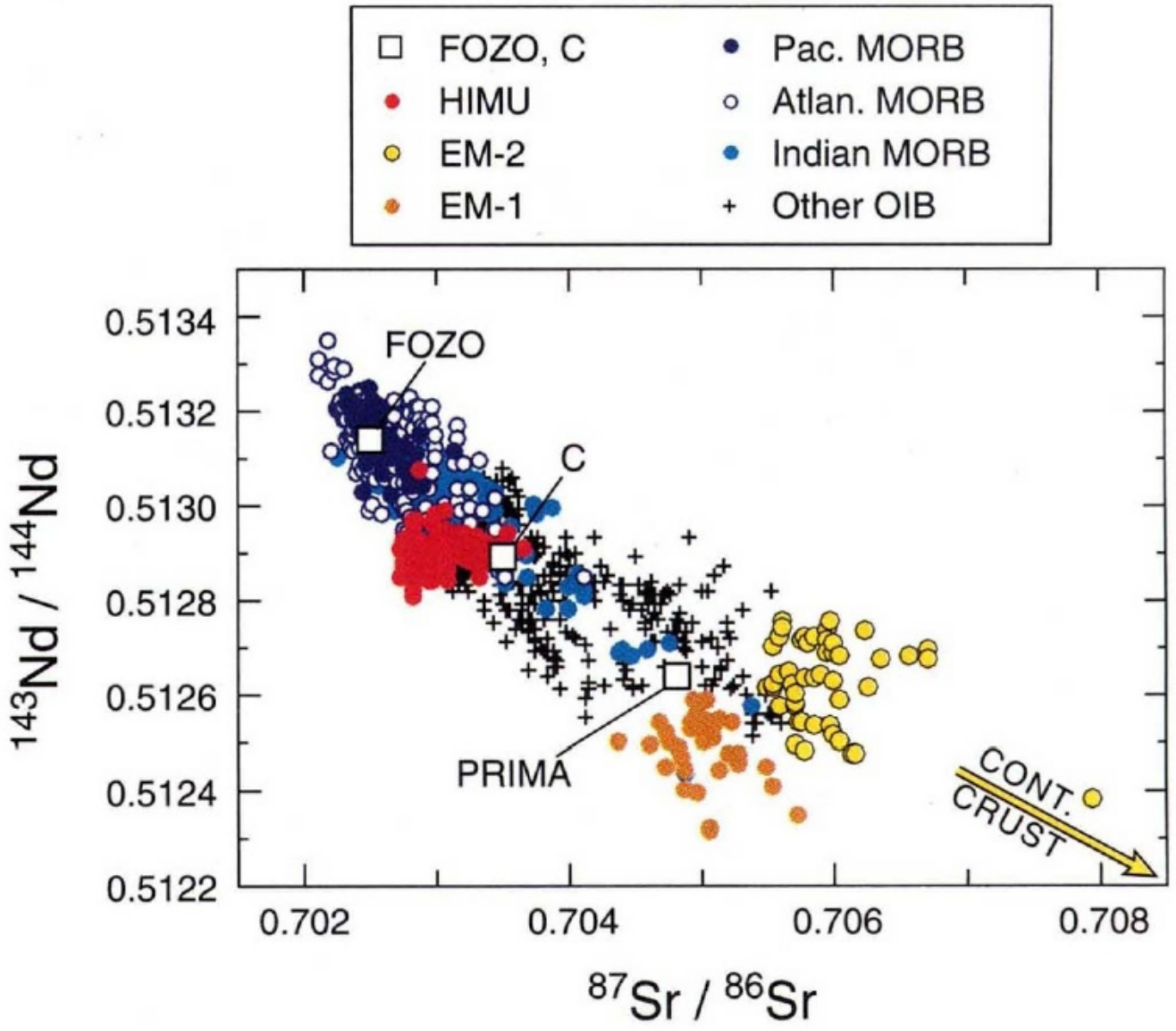

$^{3}He/^{4}He$

- atmospheric $^{3}He/^{4}He$ ratio = 1.4×10^{-6}
- continental crust has low ratios $^{3}He/^{4}He$ = 0.01 RA
- MORB have rather uniform values of 8 ± 1 RA
- OIB range from 5 to 30

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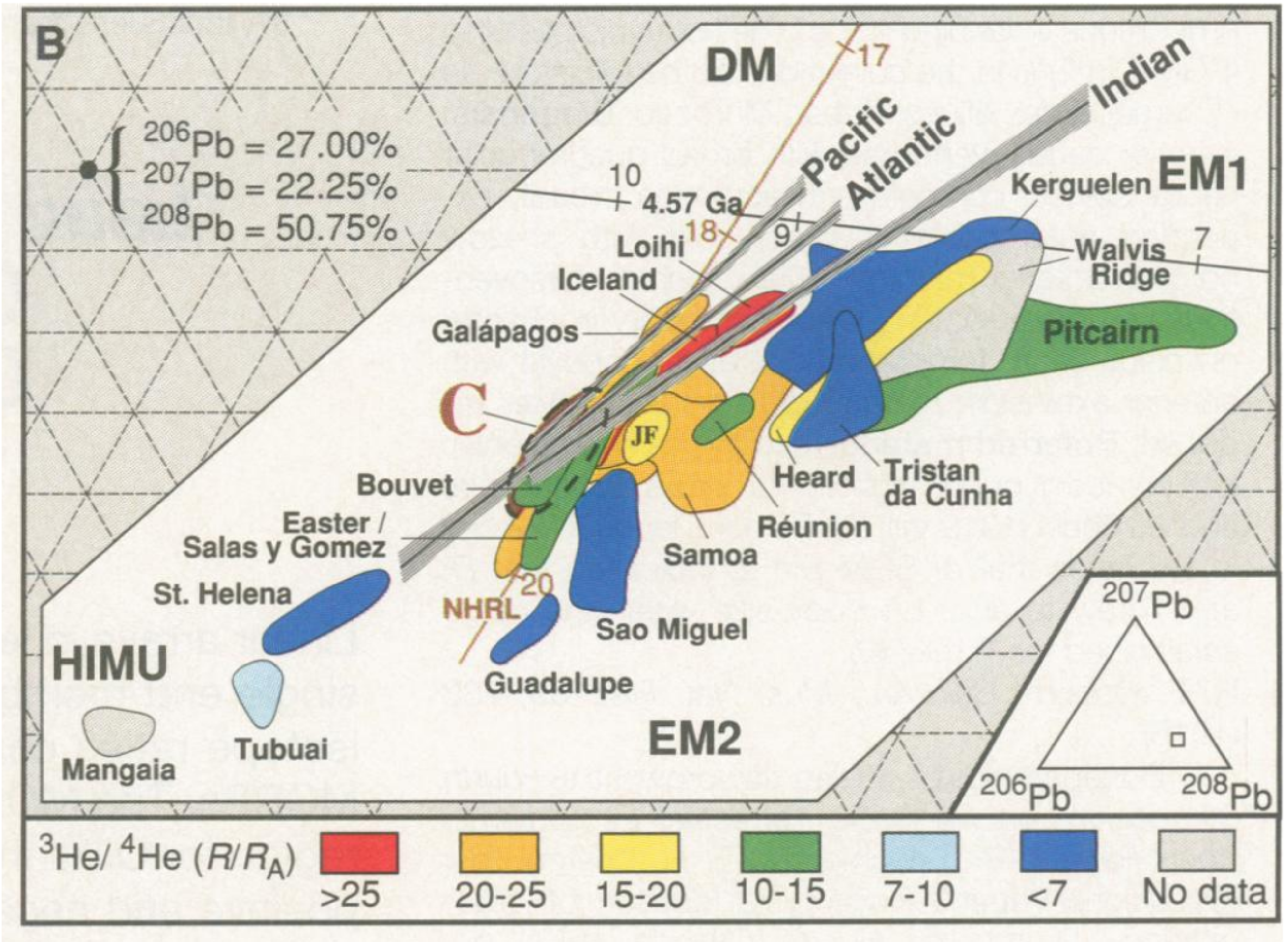
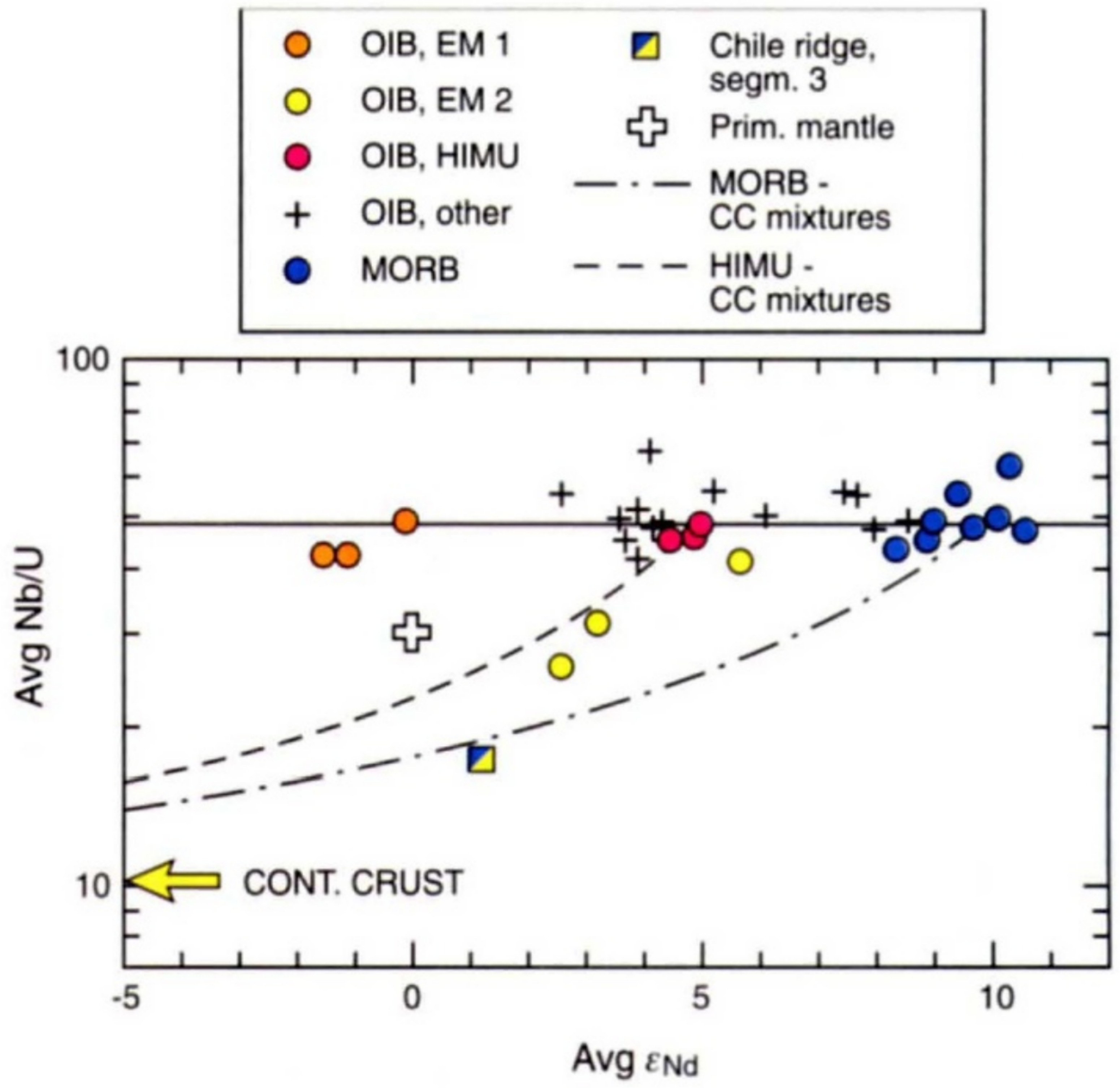
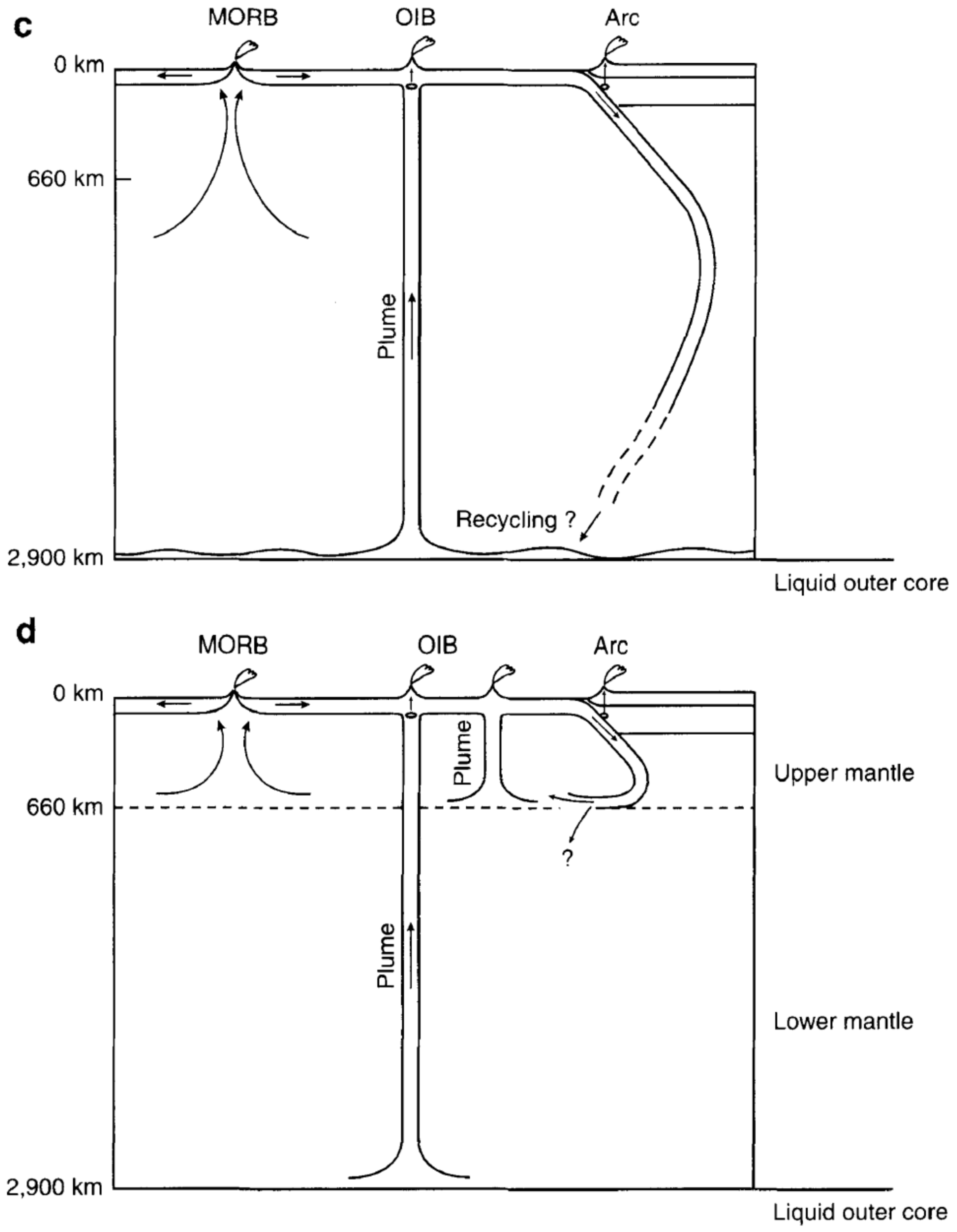


Nb/U should trace continental material

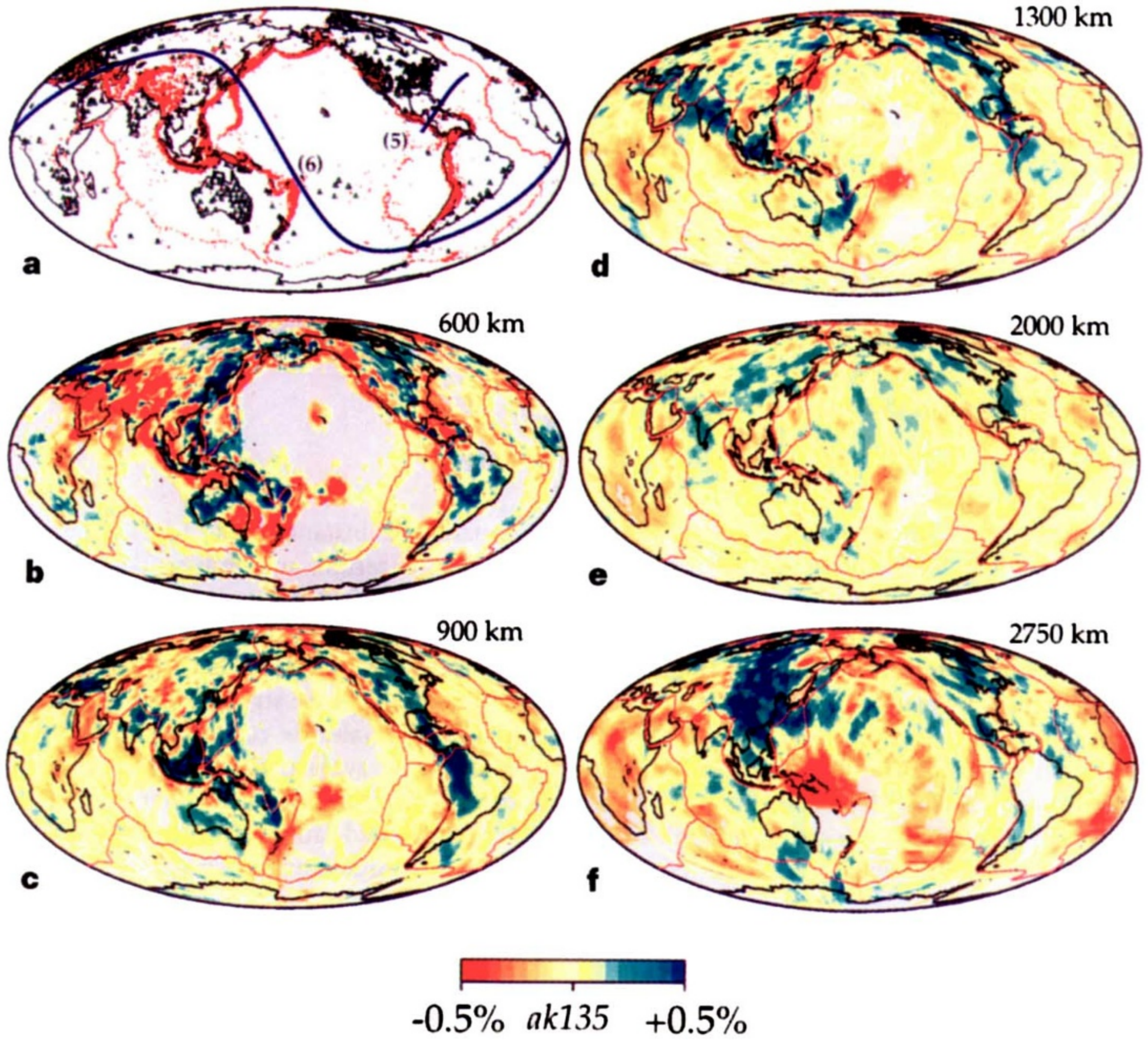
- OIBs have MORB-like Nb/U ratios, suggesting that they sample the same recycled source material
- $^3He/^4He$ ratios **can** be high in some ocean island basalts, hard to reconcile with a common source for MORB and OIB



Models of the mantle



The fate of slabs



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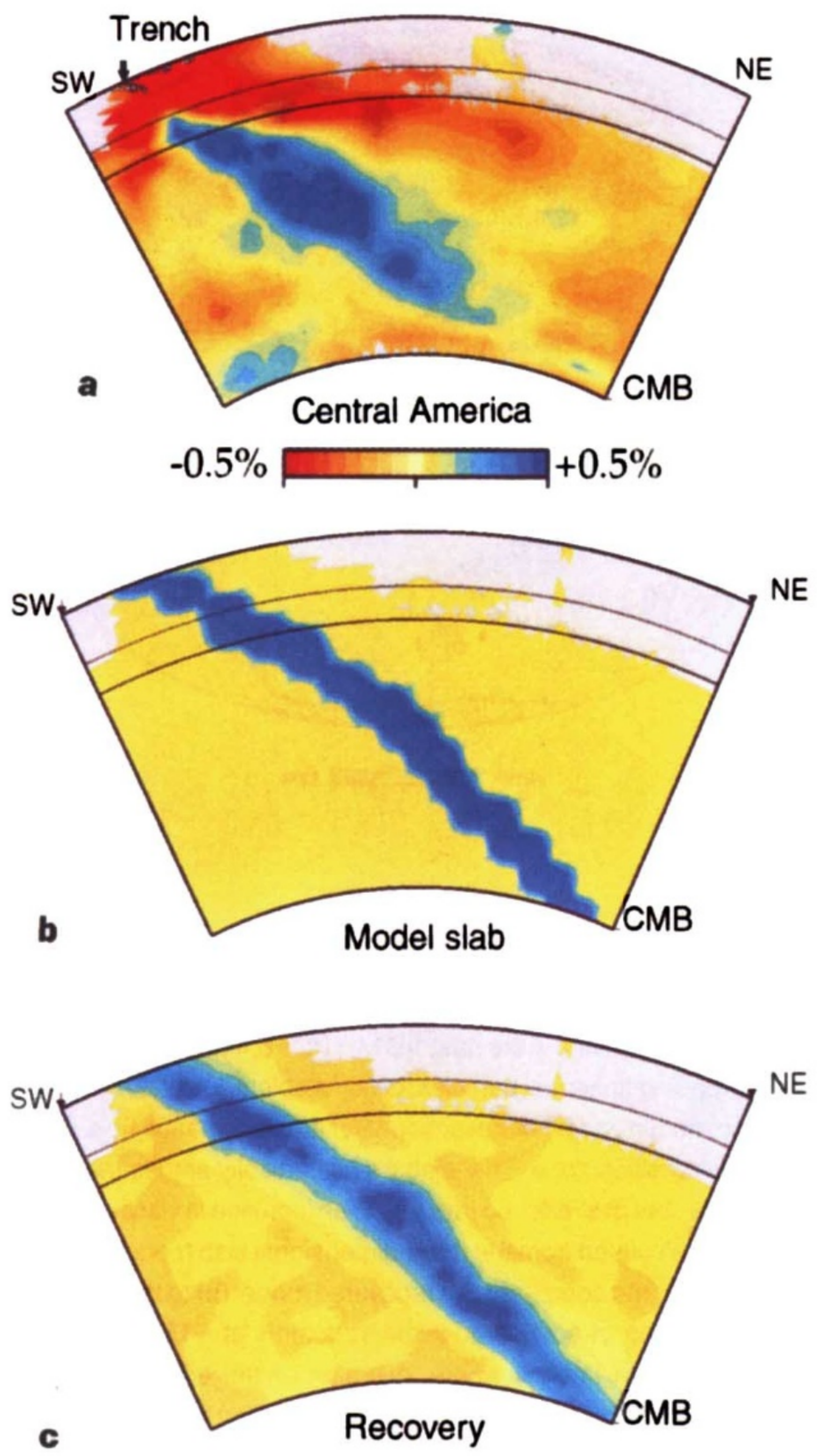
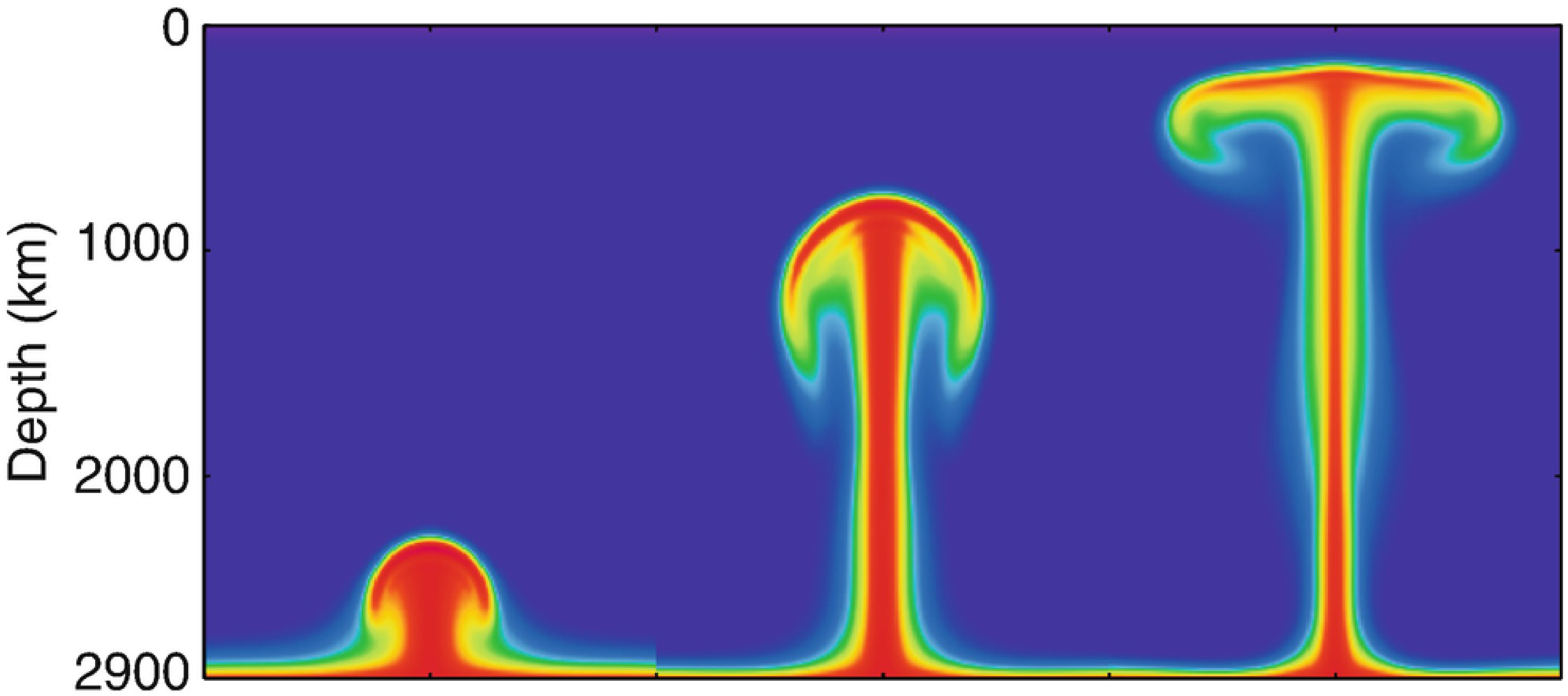
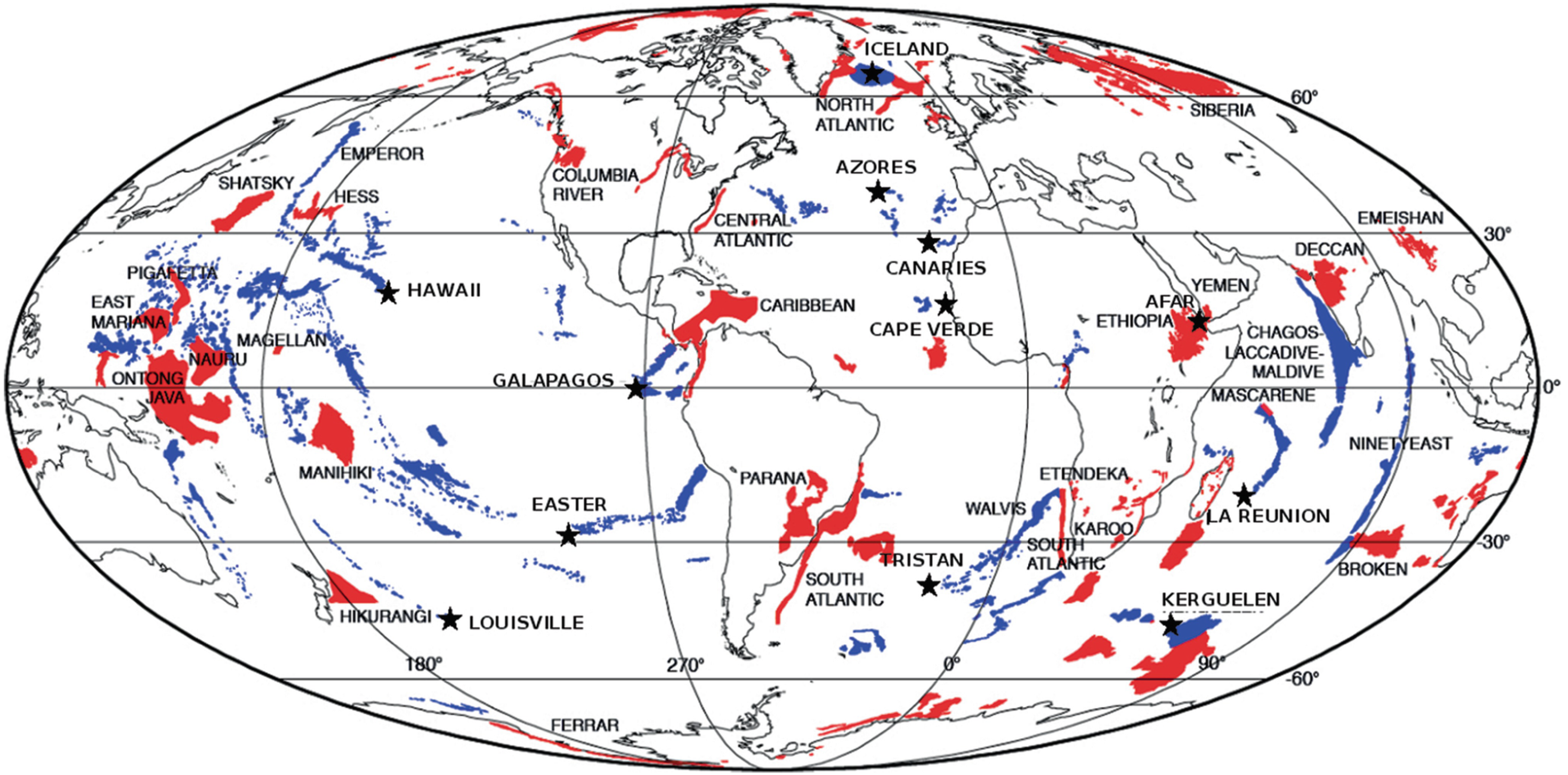


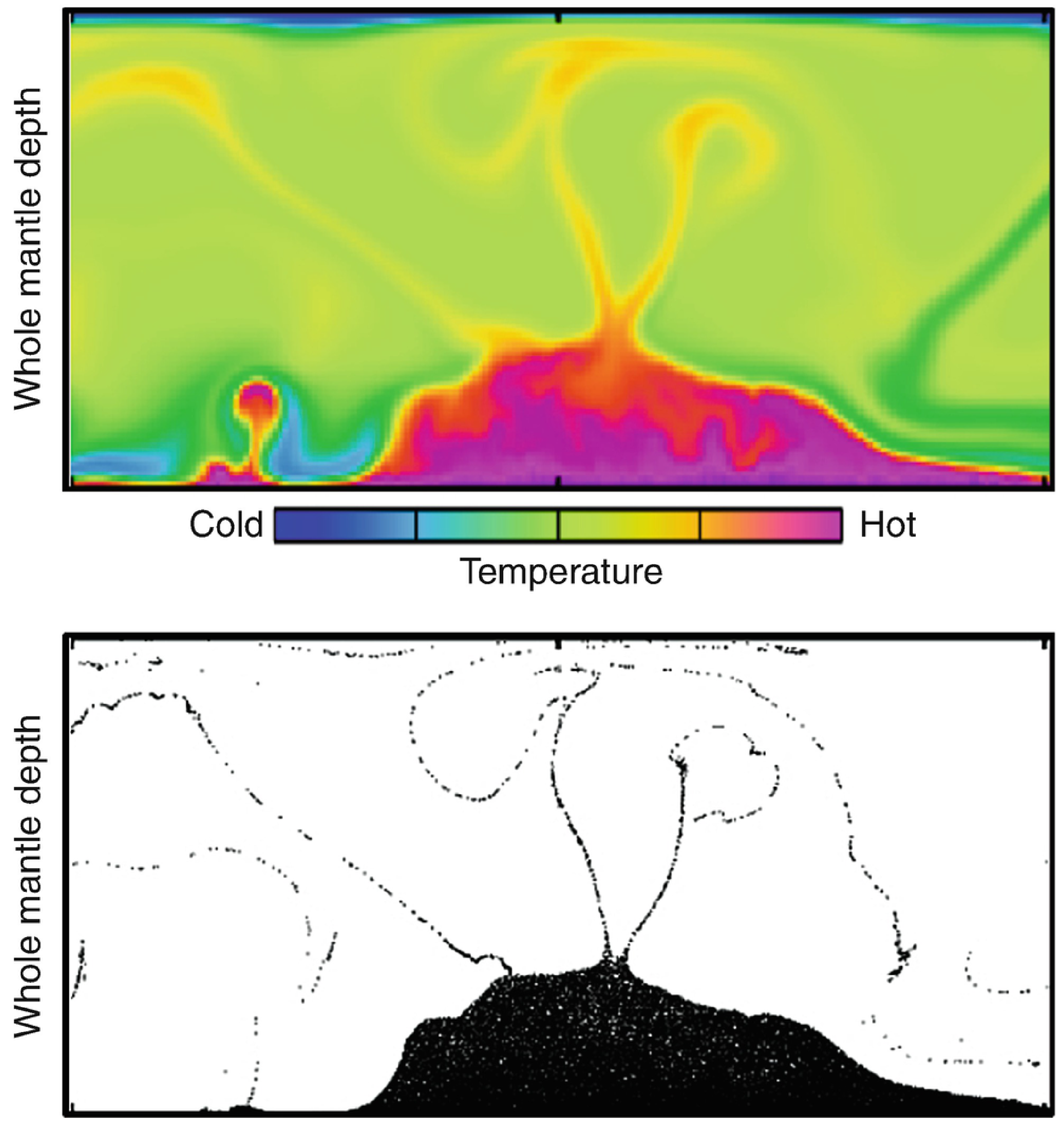
Thermal Plume simulations



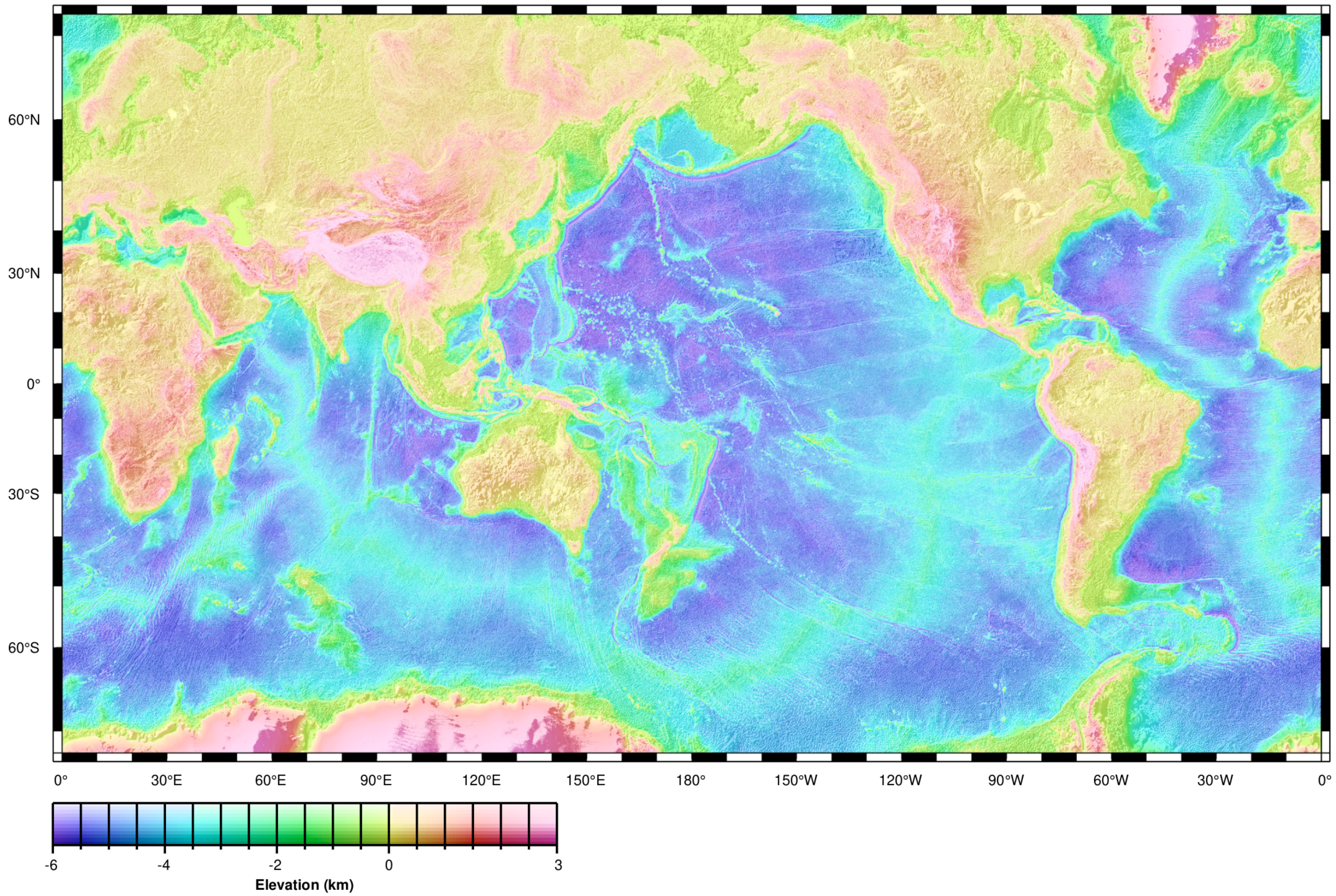
Large igneous provinces and flood basalts



Thermochemical plumes



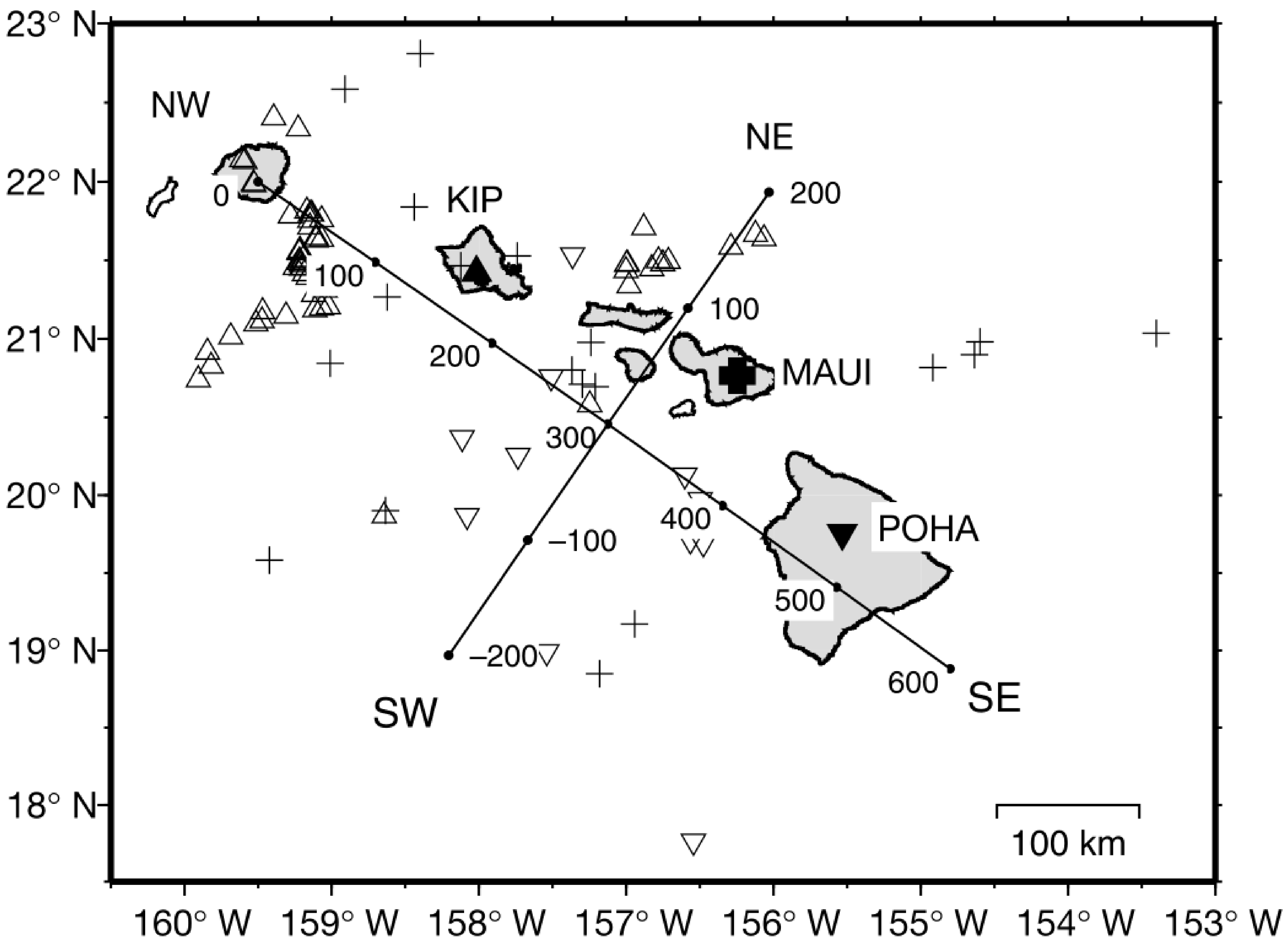
Breaking the mold



Breaking the mold

- Ages:
  - Bioko: active
  - Pricipe: ~6 Ma
  - Sao Tome: ~1-3 Ma
  - Continental volcanos: ~1-3 Ma

Are swells actually supported by thinner lithosphere?



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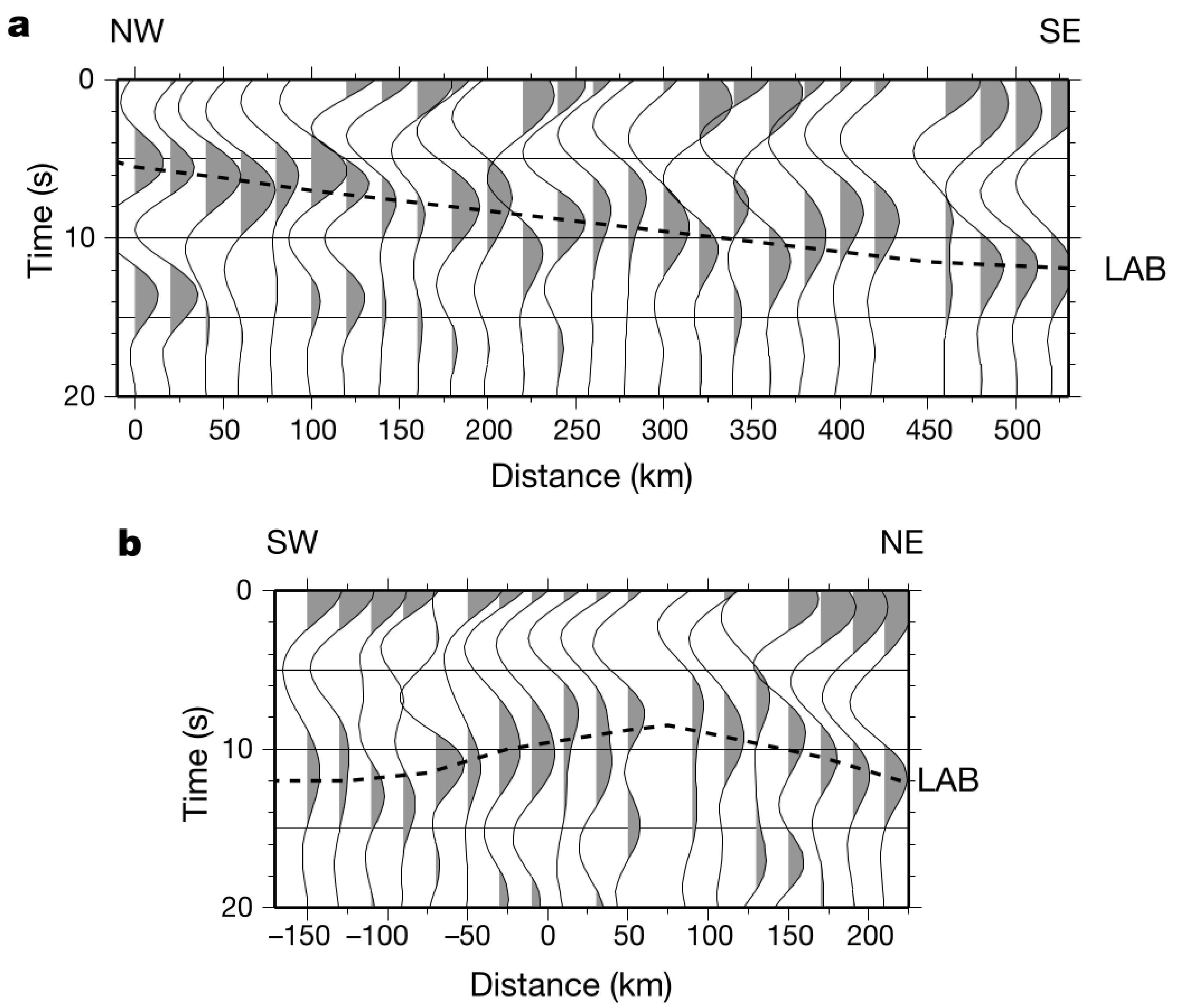

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