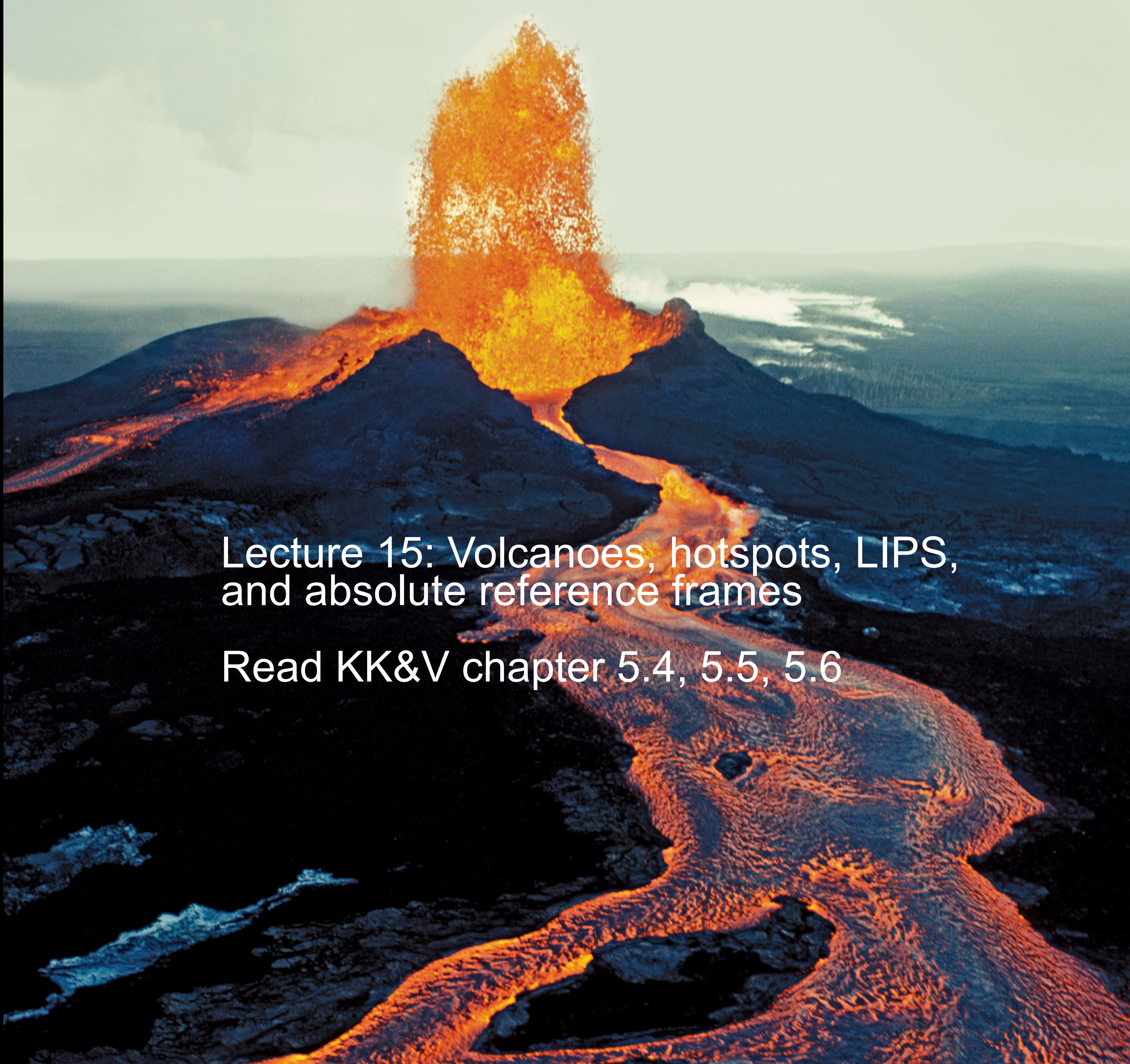
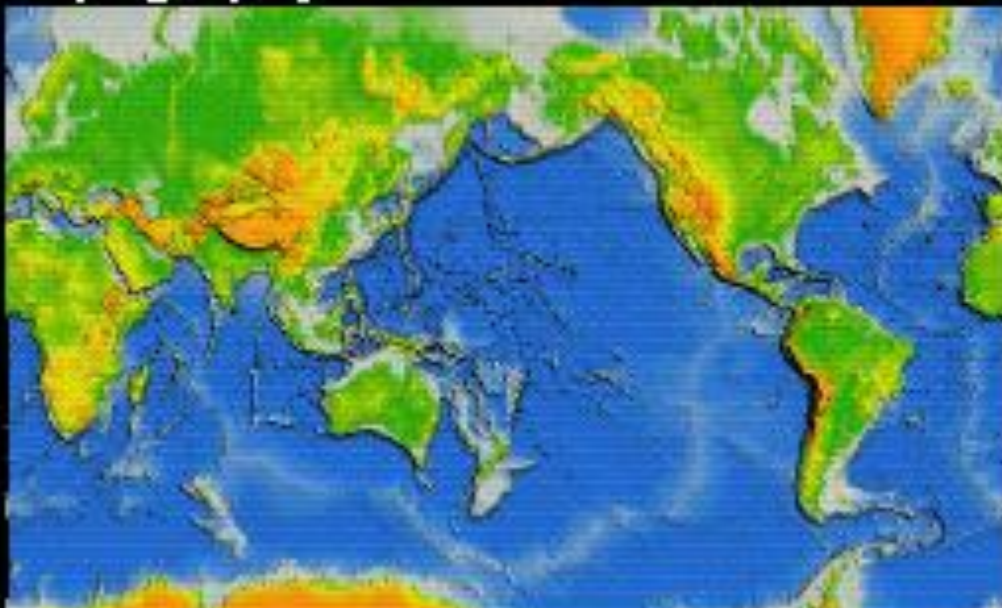


Lecture 15: Volcanoes, hotspots, LIPS, and absolute reference frames

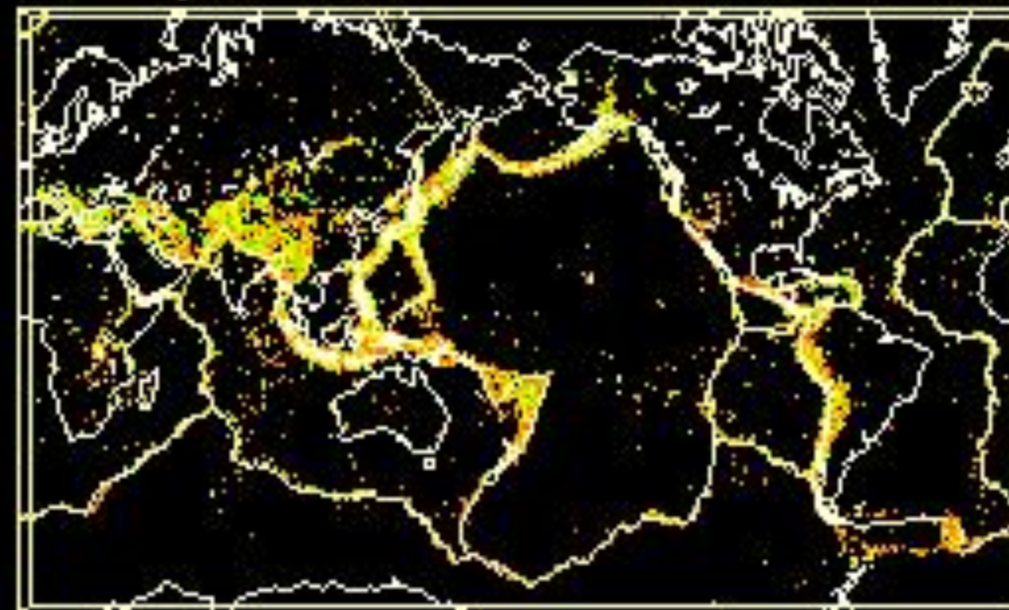
Read KK&V chapter 5.4, 5.5, 5.6

Manifestations of active tectonics

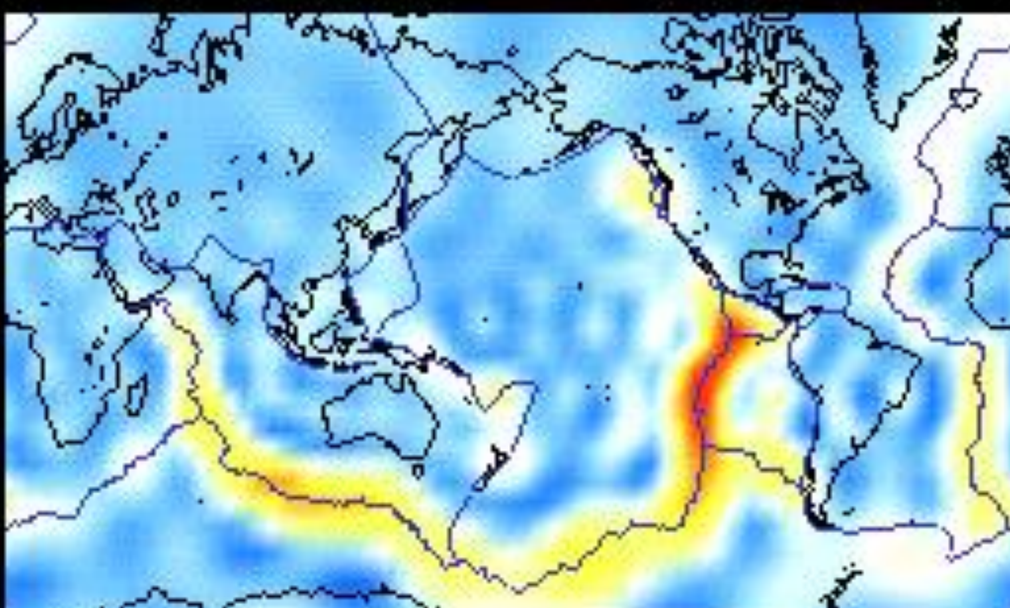
Topography



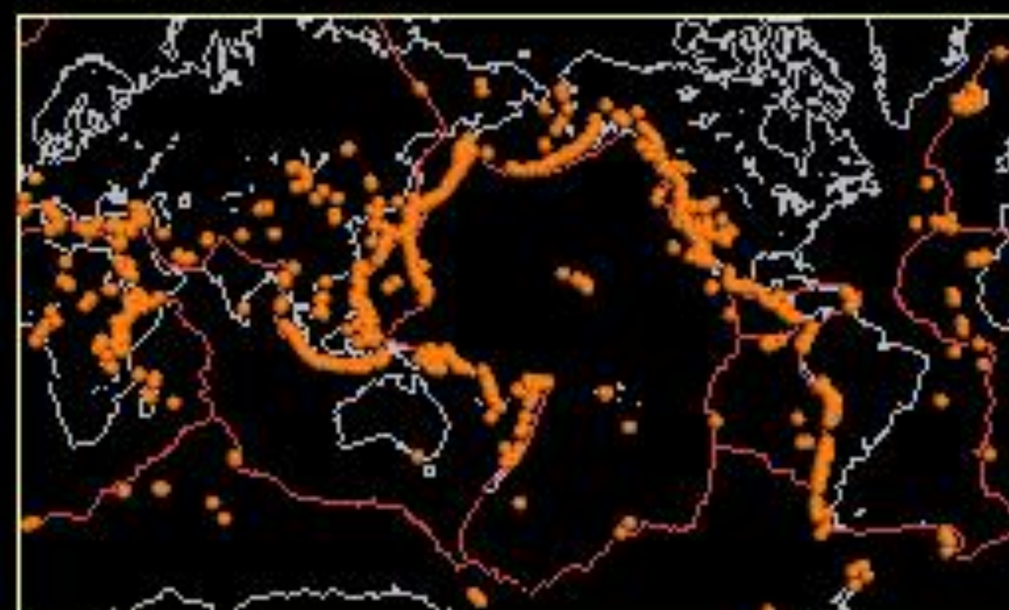
Earthquakes



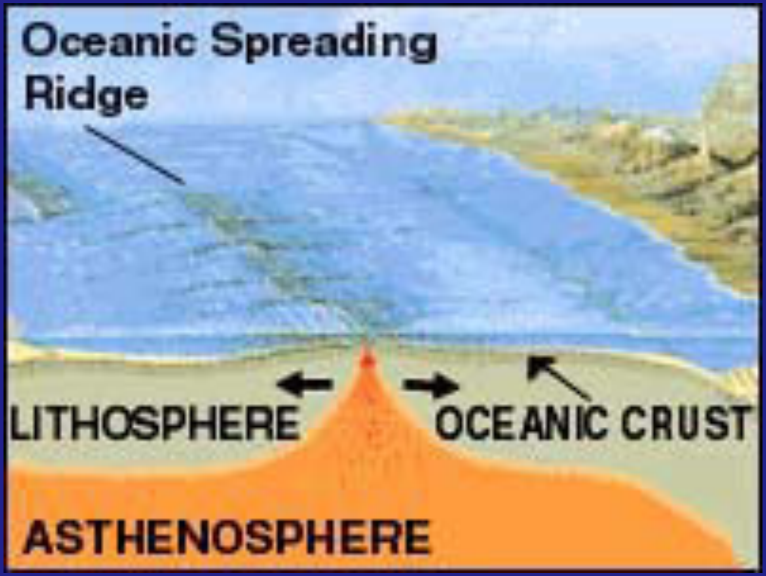
Heat flow

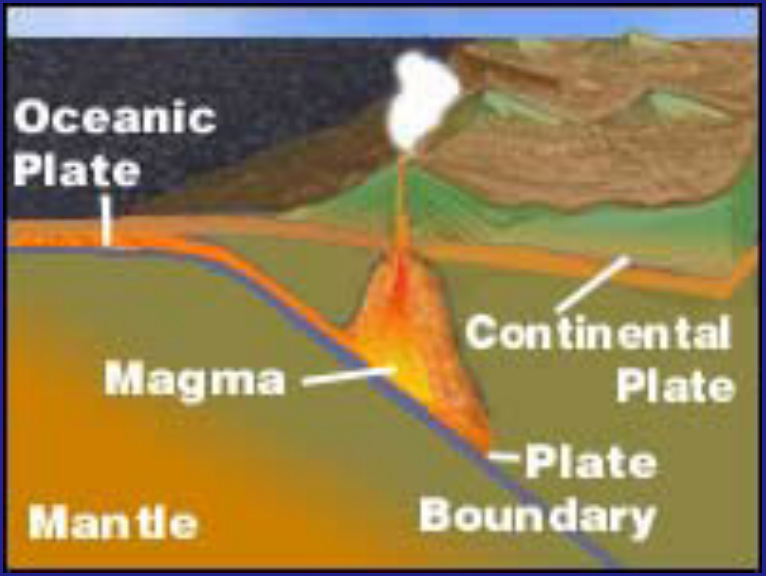


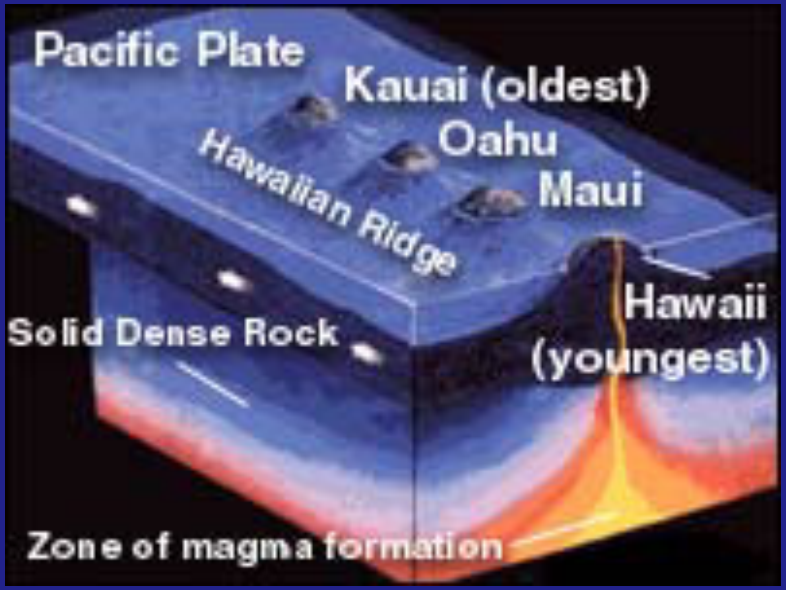
Volcanoes



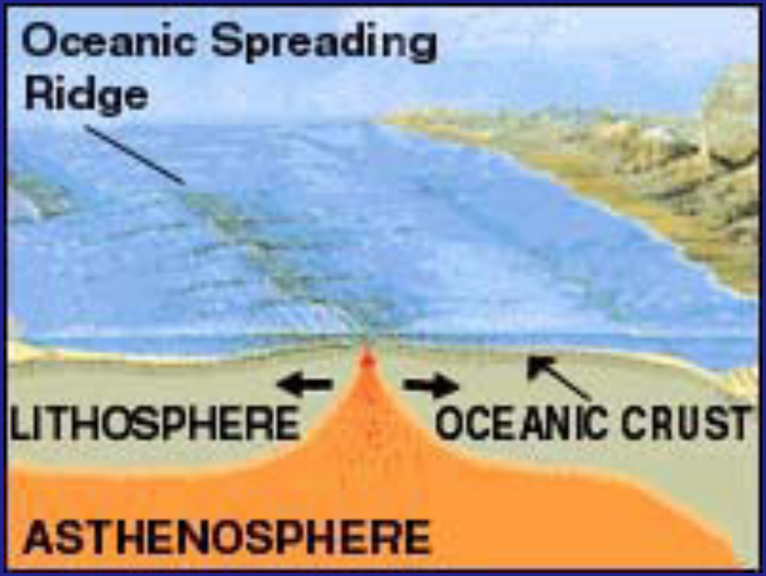
3 types of volcanic activity on Earth

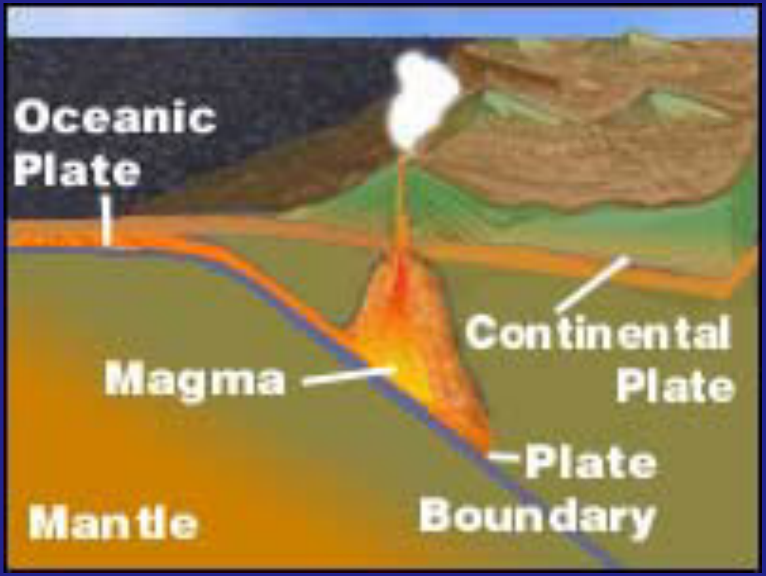


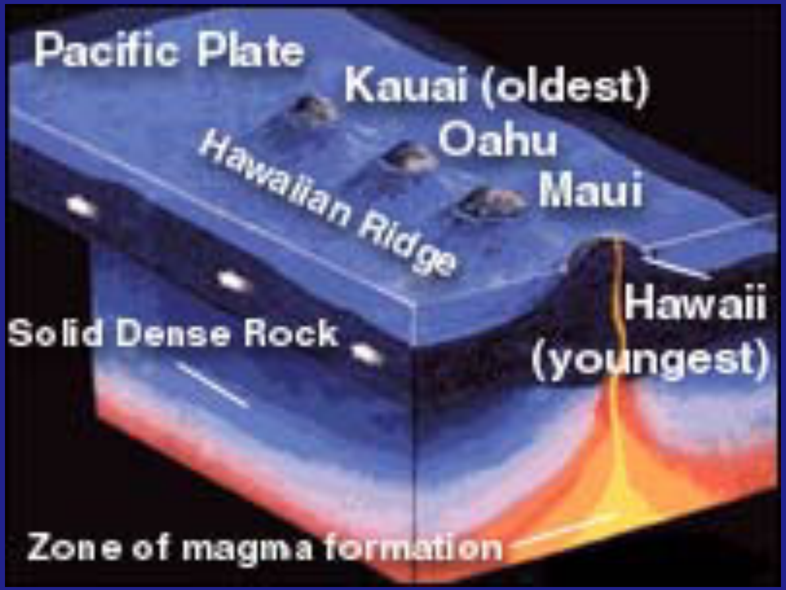




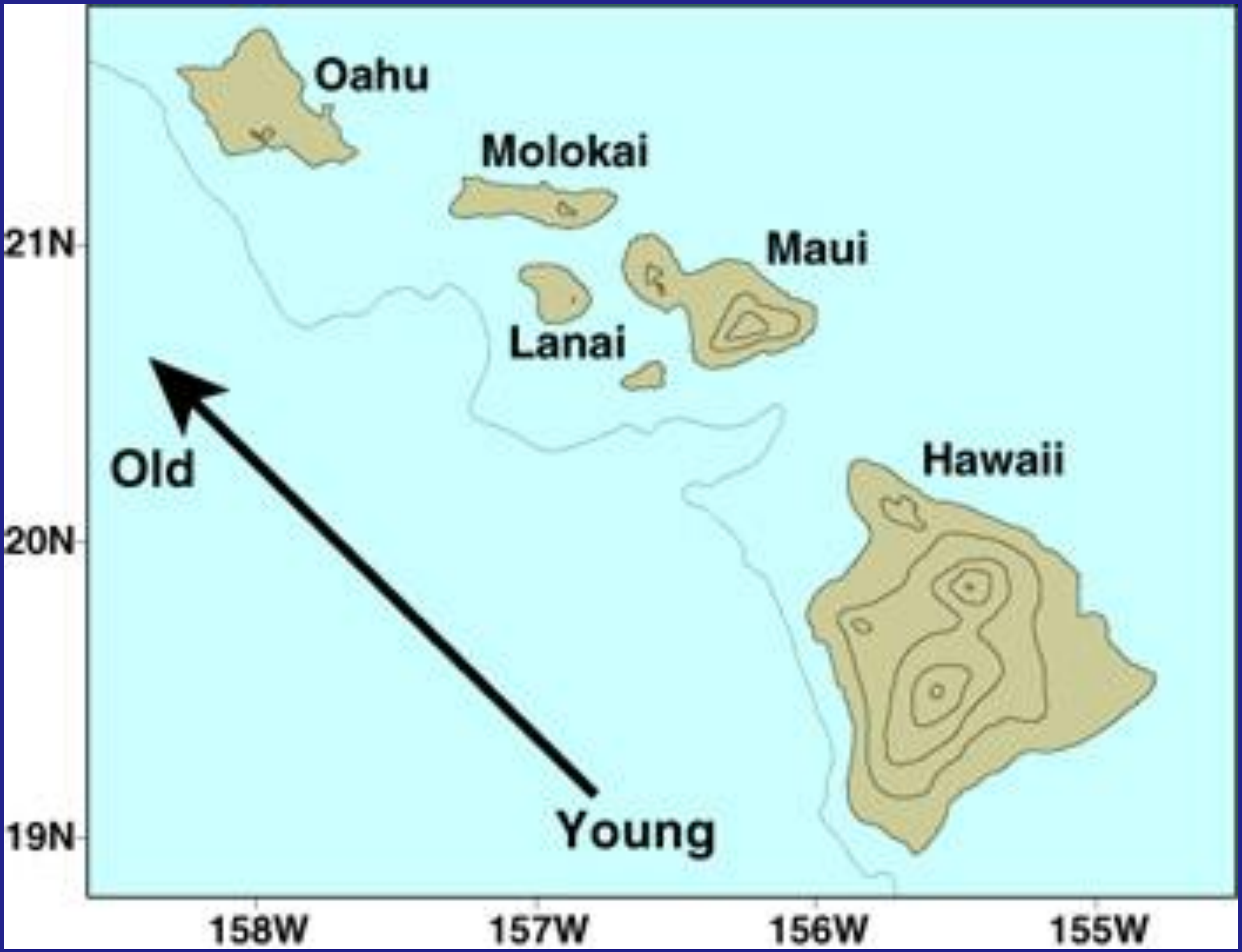
3 types of volcanic activity on Earth





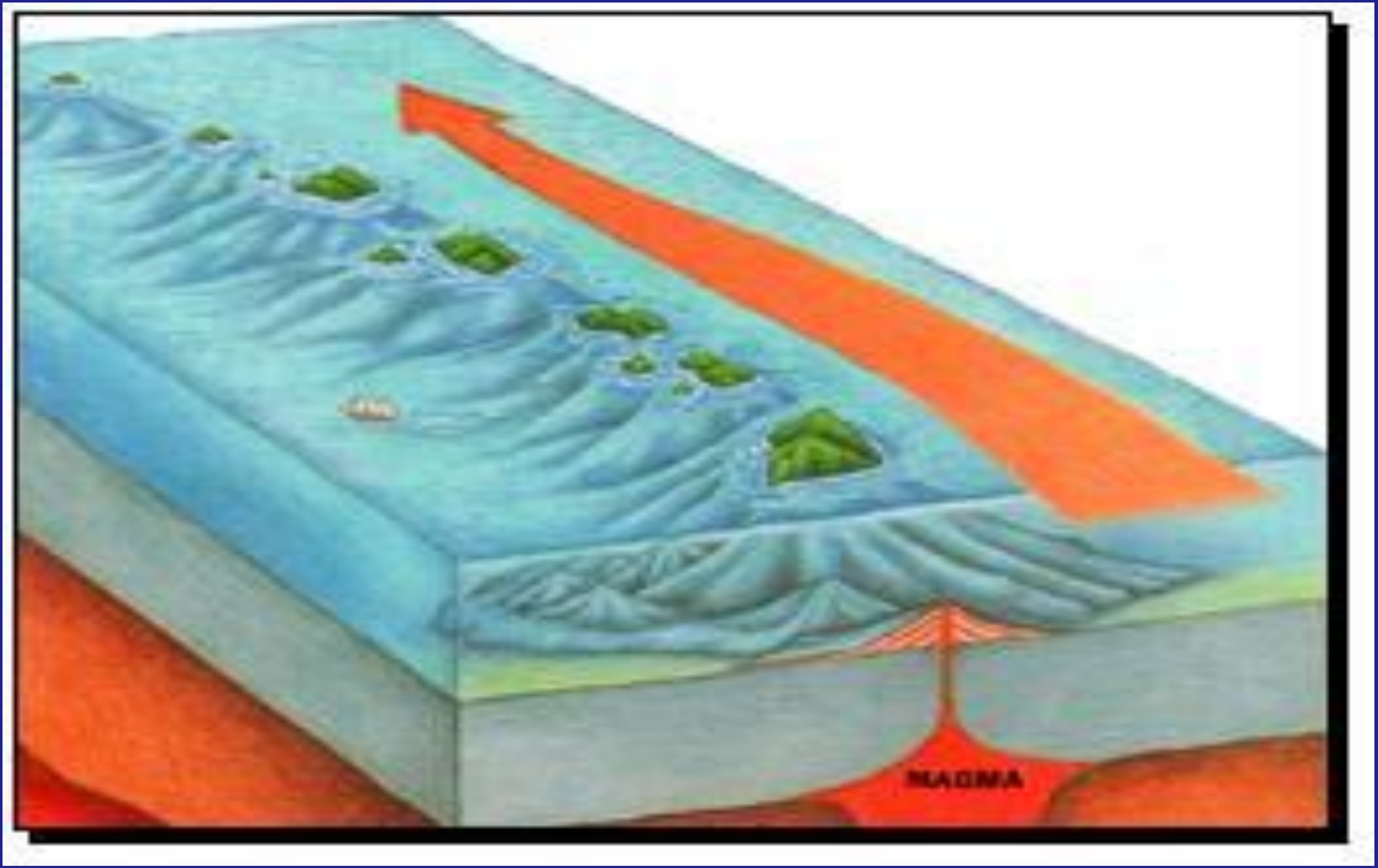


Hawaiian hotspot and its chain of volcanic islands



both emerged…..

…. and submerged

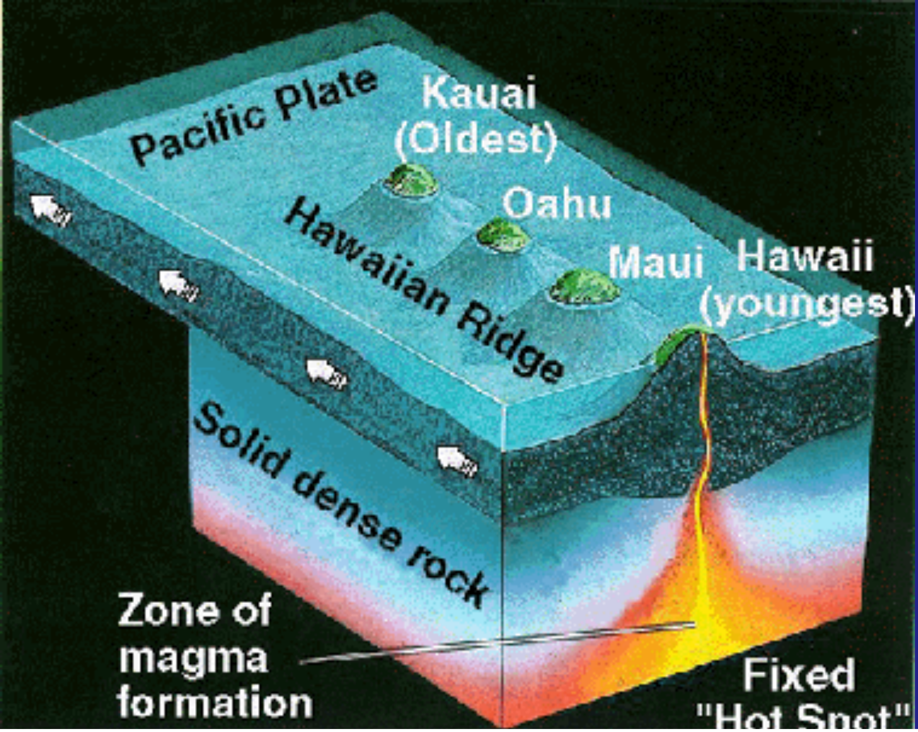


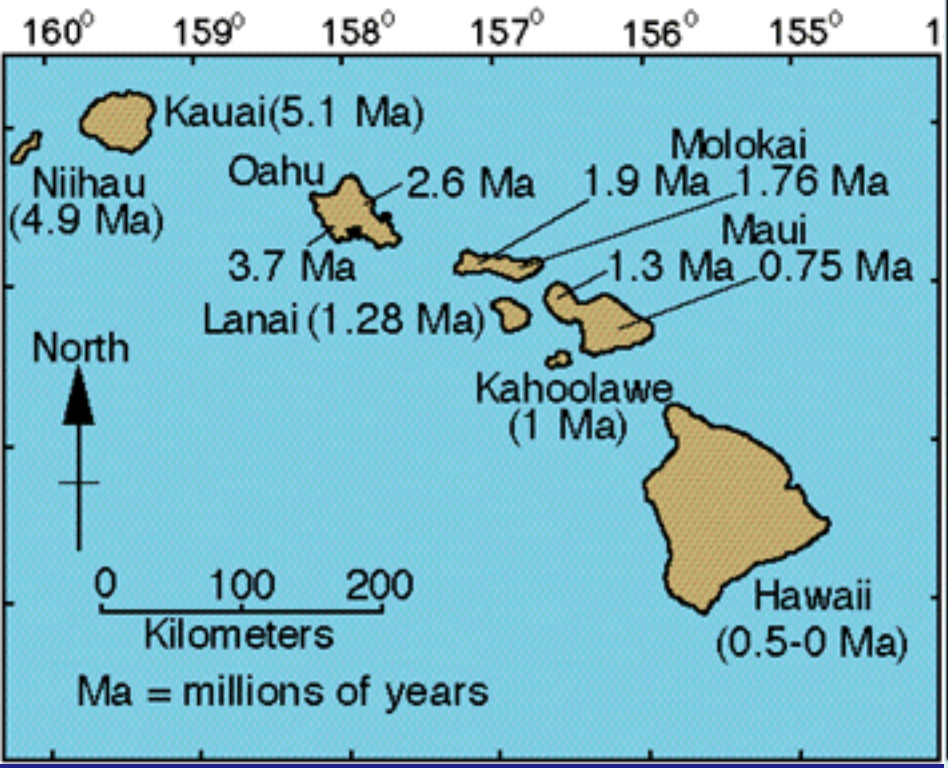
to leave the trace of a hot spot stable in the mantle and beneath the northwestward moving Pacific Plate

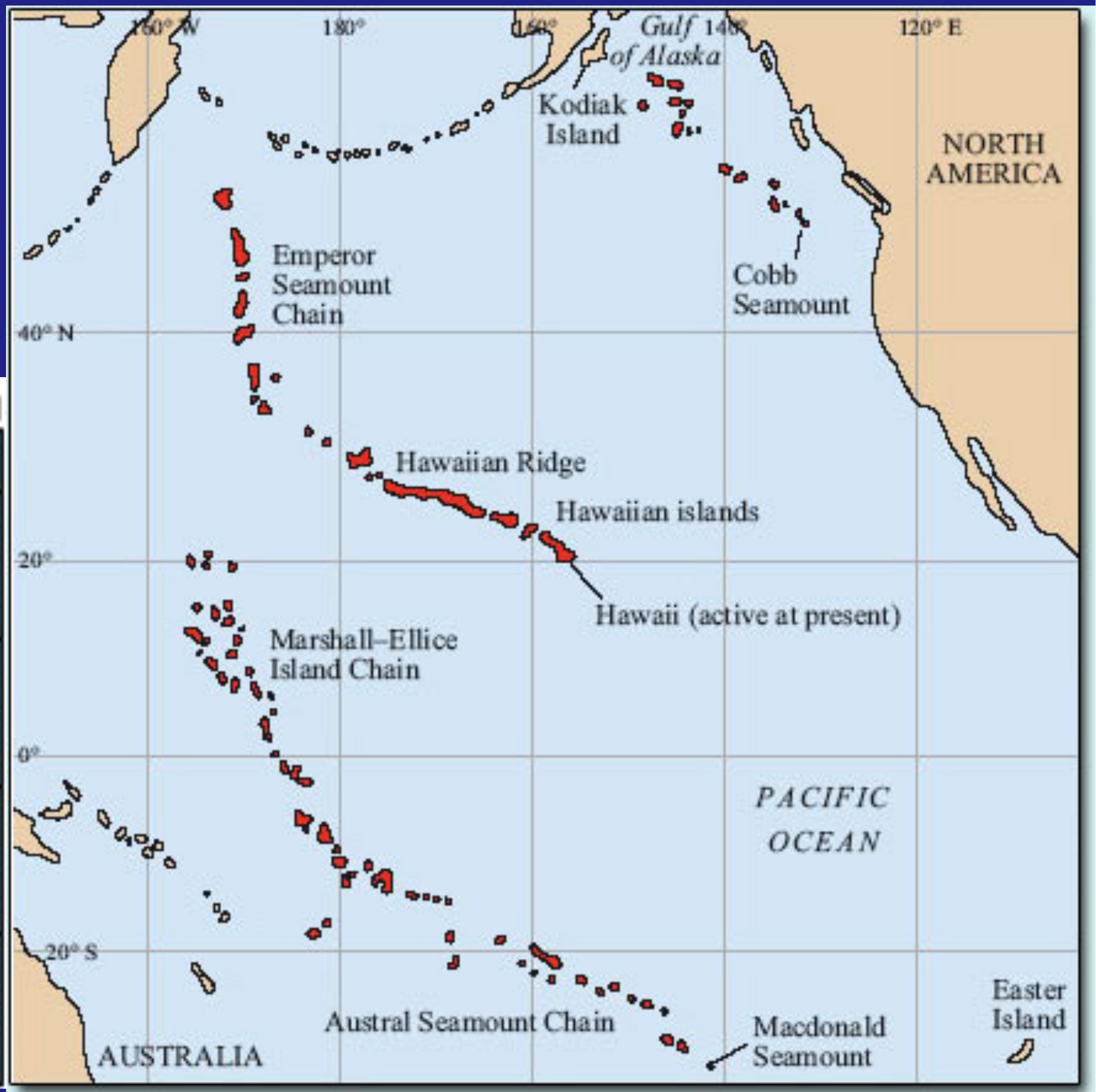
Volcanic chains like Hawaii form by motion of the Pacific plate over magma plumes embedded in the mantle

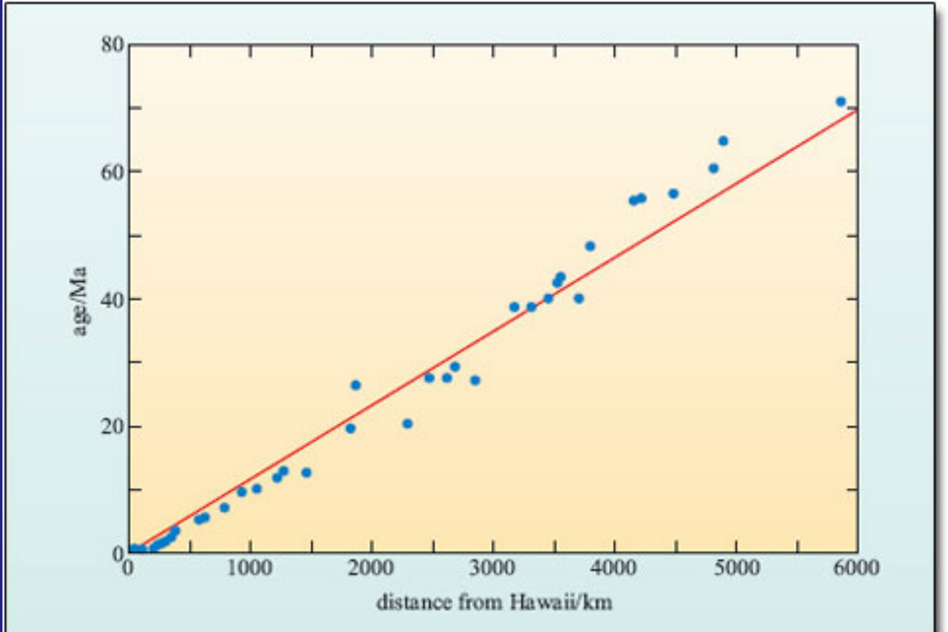
Islands and seamounts get progressively older off to NW

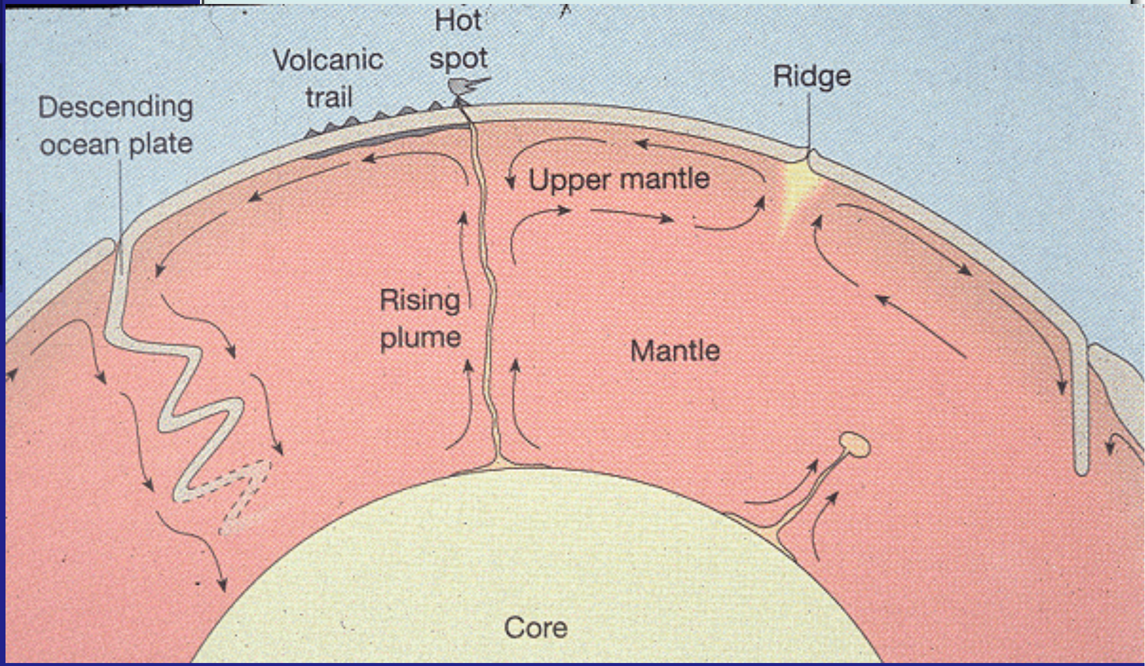
Several chains of volcanic features show similar progression





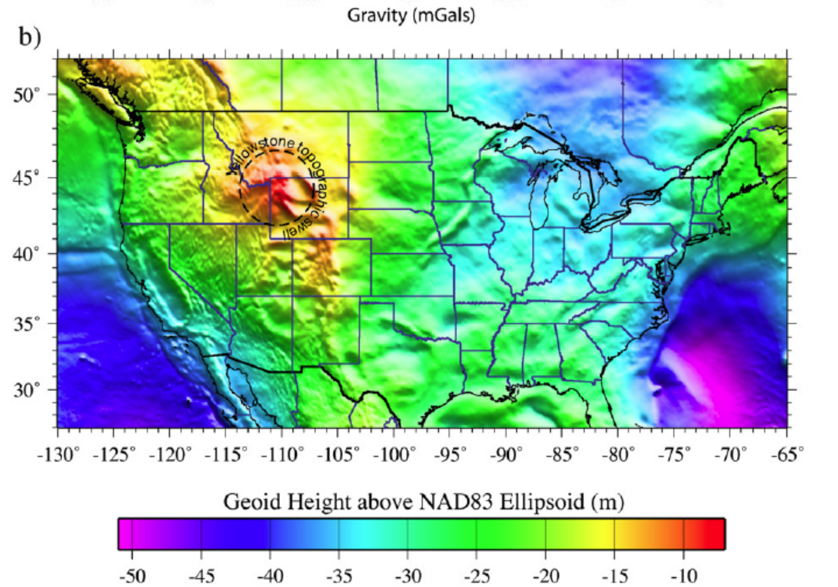






Seamounts along the Hawaii-Emperor chain are roughly 50 m.y. old at the Bend and 80 m.y. old at the far end. To first order, roughly a constant rate of motion

Lots of drilling, dredging



Yellowstone hotspot

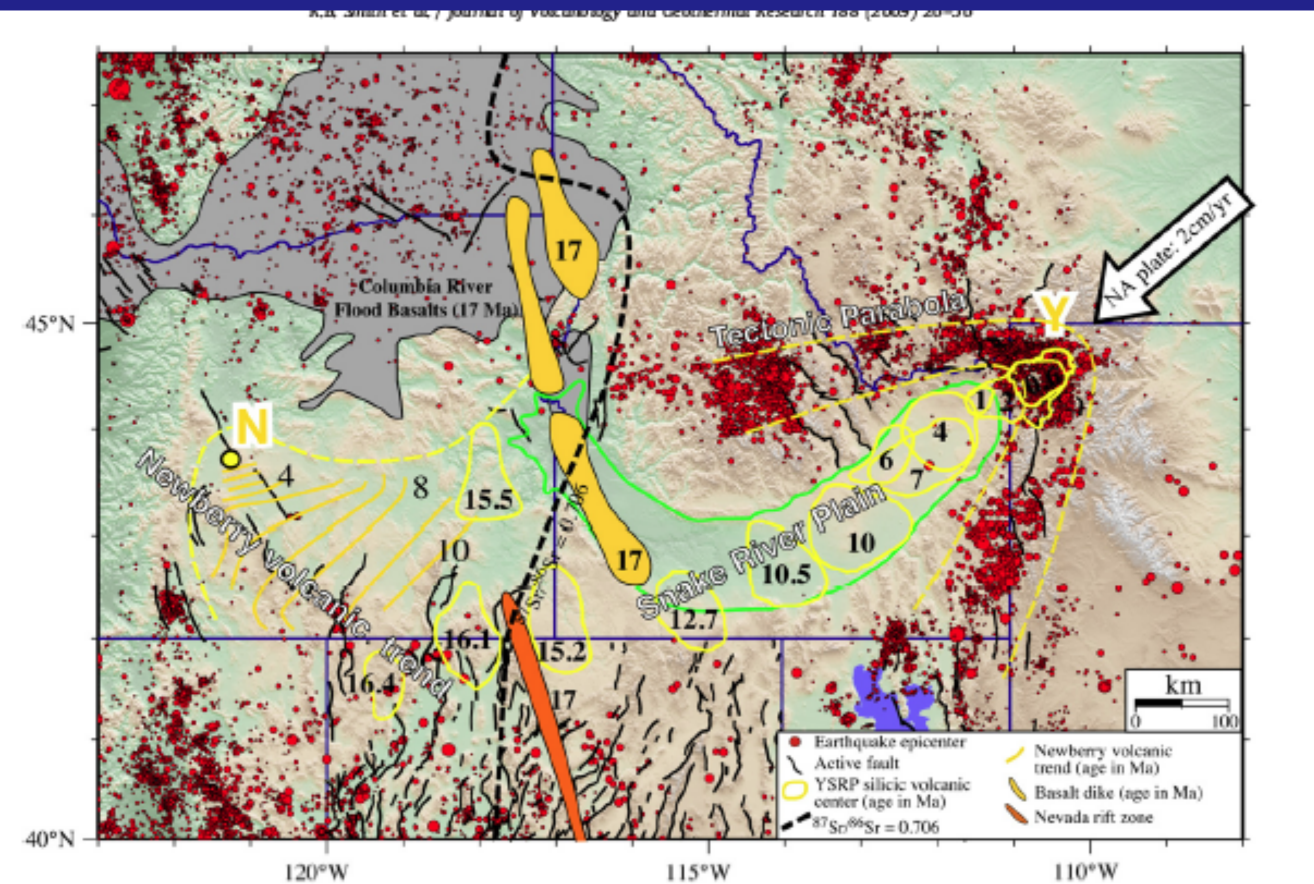
Prominent Geoid anomaly

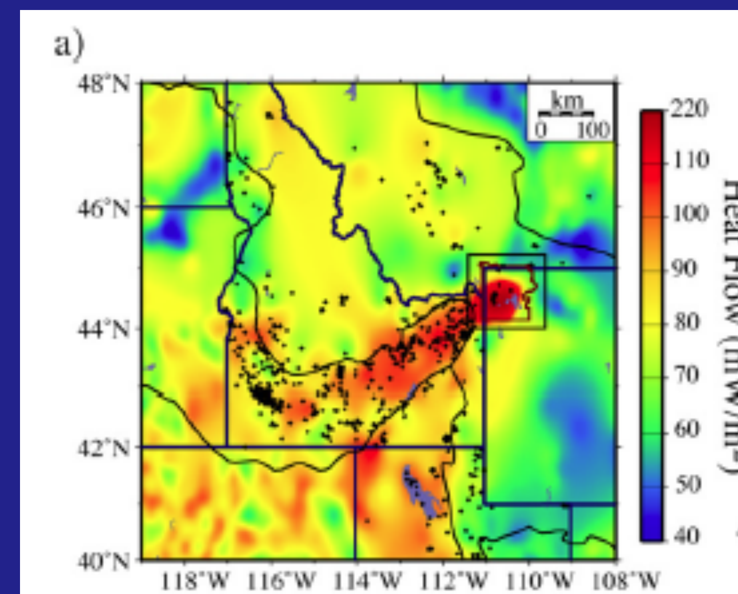
Has a 500 km wide topographic swell

A large heat flow anomaly

And a track going back 17 Ma to the Columbia river flood basalts

Heatflow



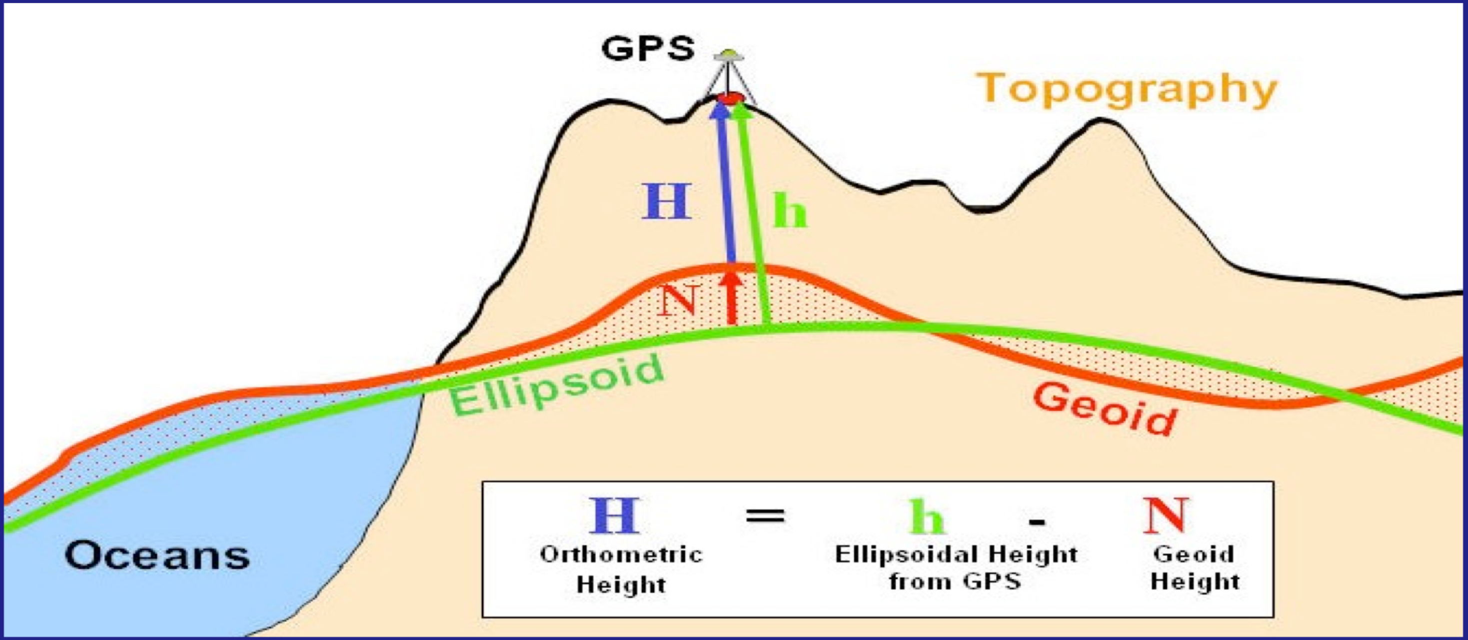


Smith et al. (2009)

The Geoid is:

The shape a fluid Earth would have if it had exactly the gravity field of the Earth

Corresponds to level of water if narrow channels were cut through continents

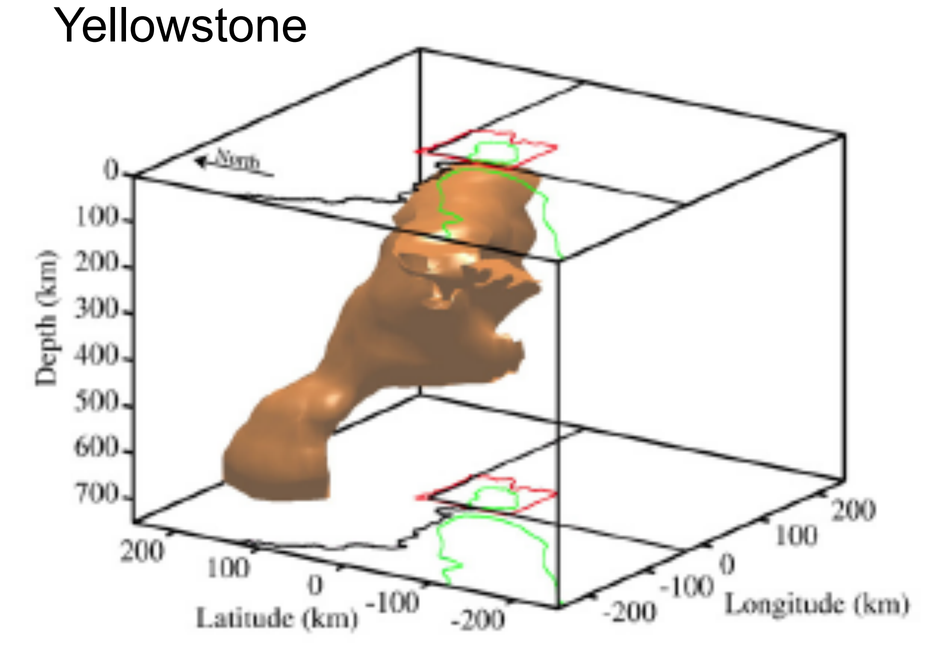


Geoid anomalies often reflect “dynamic topography”

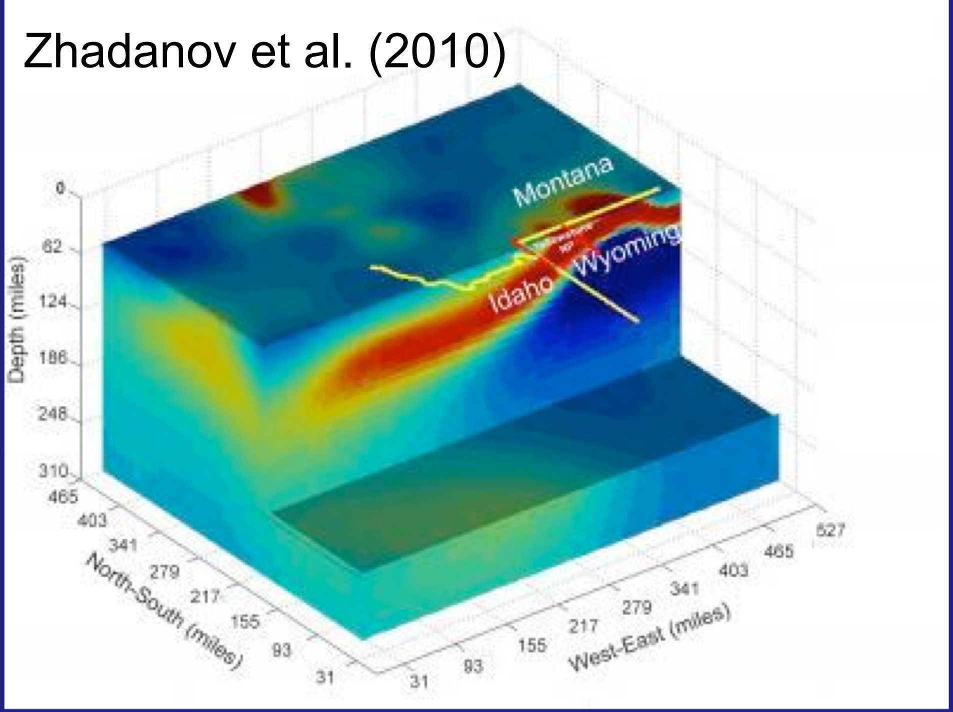
Dynamic topography is a region where the high topography is supported by upwelling hot material

Dynamic topography is the reason why the geoid is high over regions of low-density mantle. If the mantle were static, these low-density regions would be geoid lows. However, these low-density regions move upwards in a mobile, convecting mantle

http://principles.ou.edu/earth_figure_gravity/geoid/



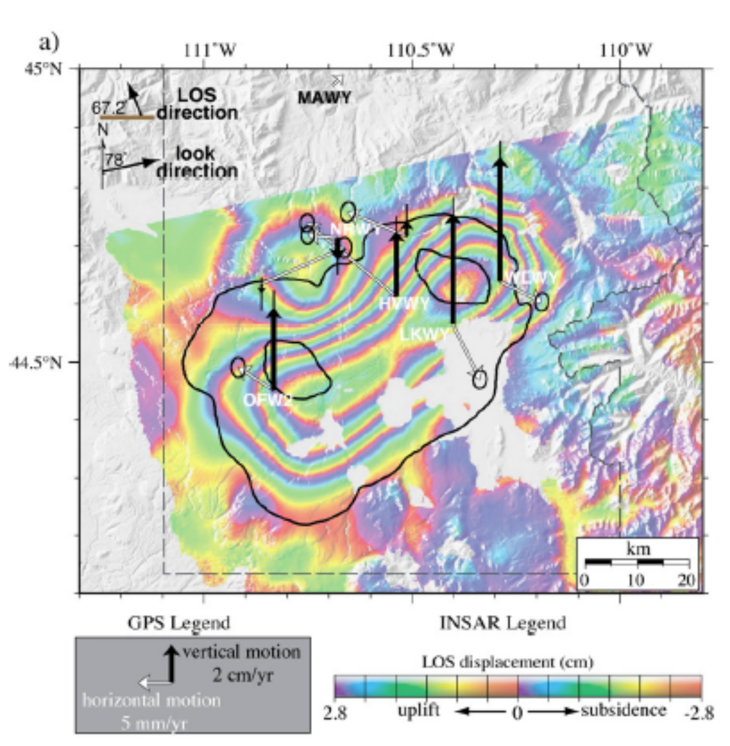
Plume as imaged from seismic P waves



Magma plume as mapped by electrical conductivity variations

Shows plume 400 miles across , dipping 40 ° to the west; less tilt than in seismics

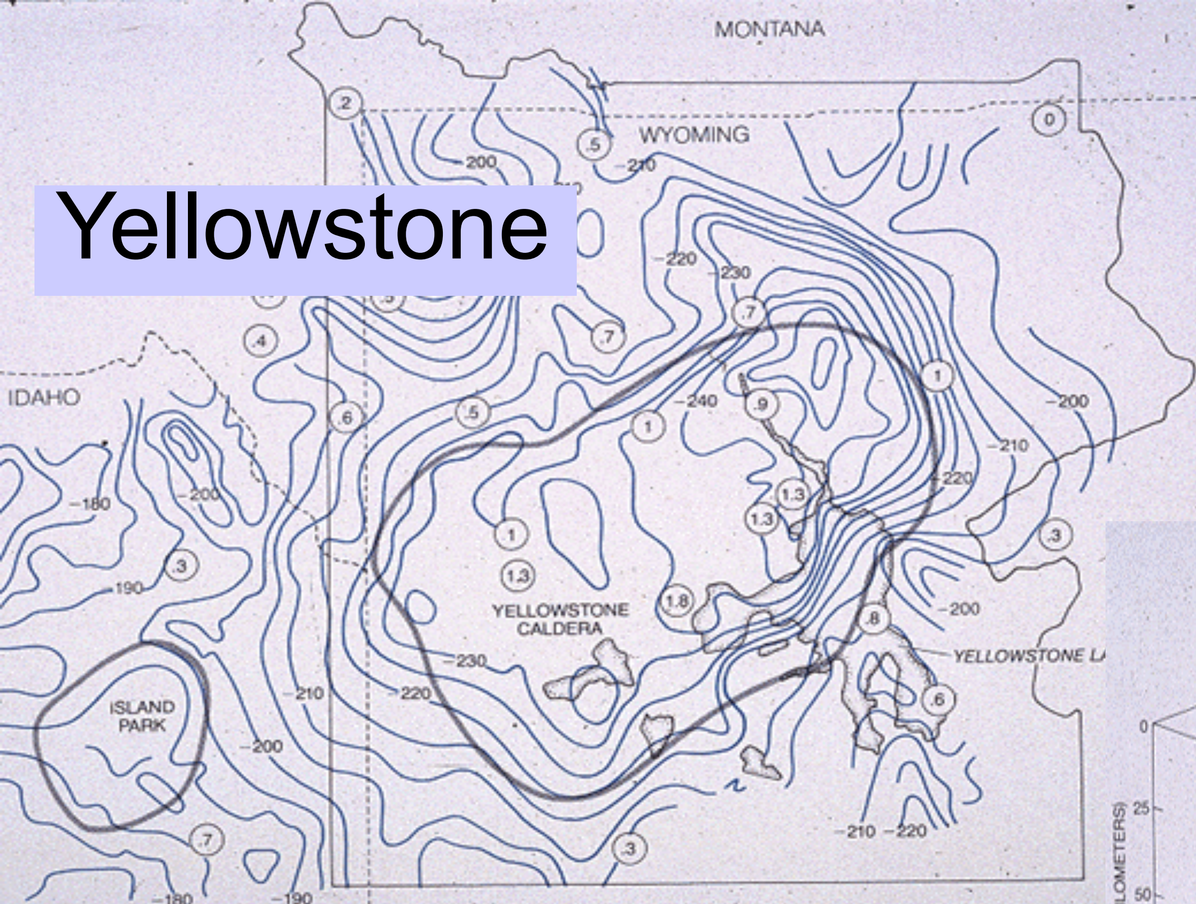
Can only see to 200 miles depth but defines the zone as bigger than only seen in seismics



Uplift map from GPS and InSAR data

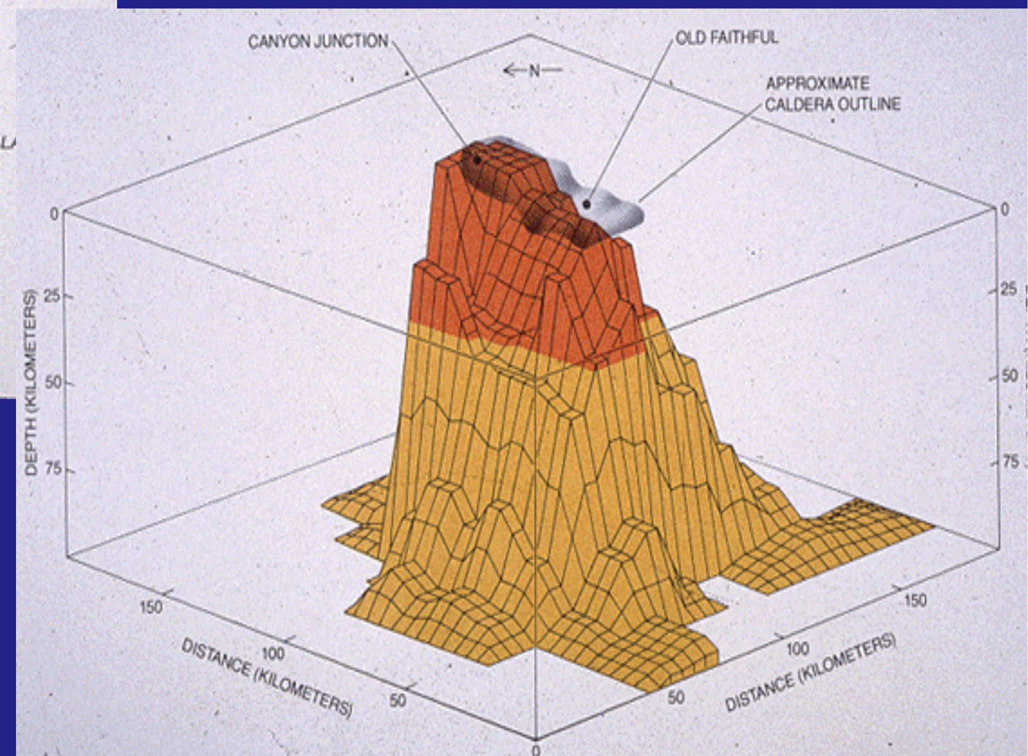
Smith et al. (2009)

Yellowstone



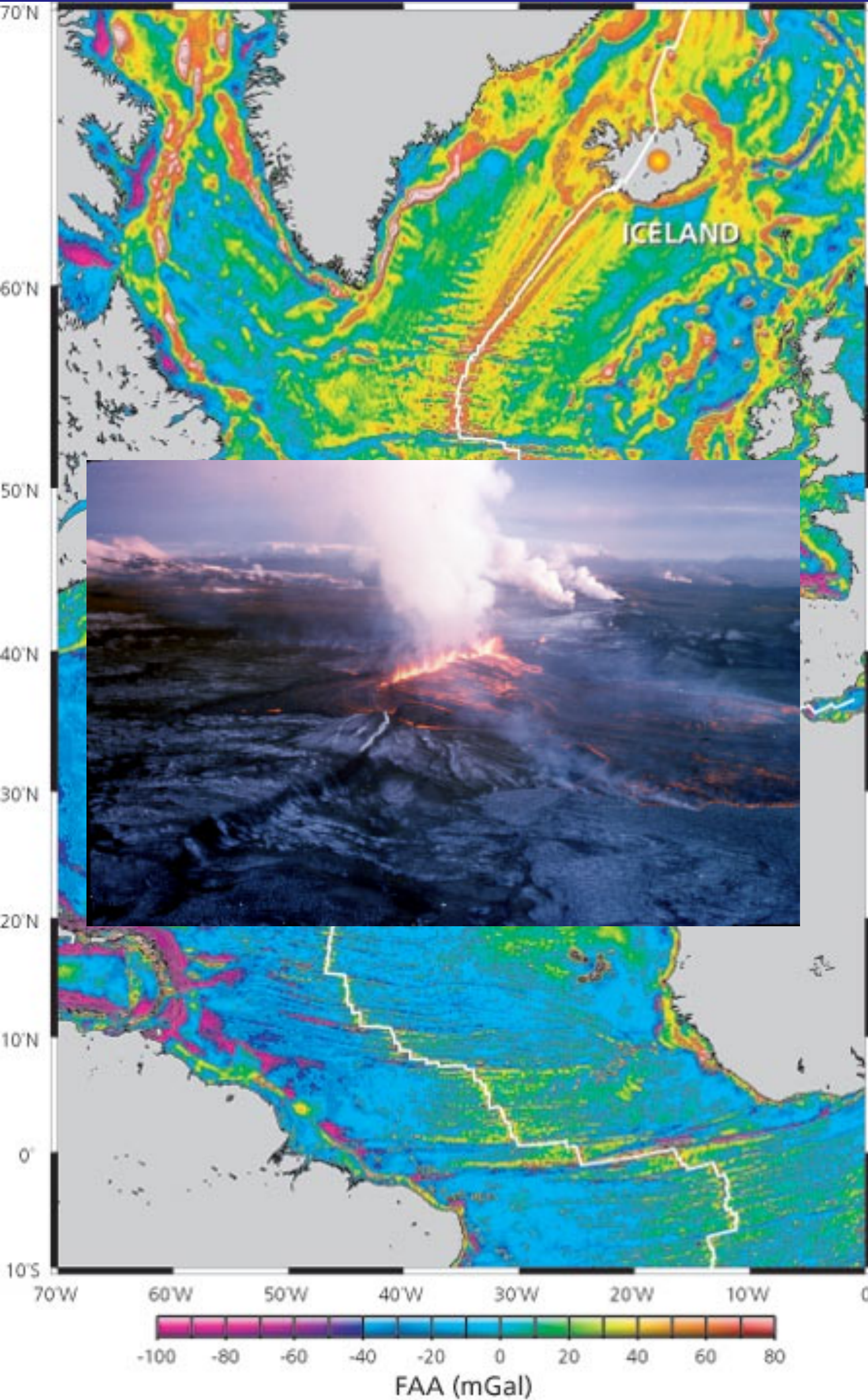
Last super-eruption
(Yellowstone caldera) ~640 kyr
1000 x ash with Mt. St. Helens

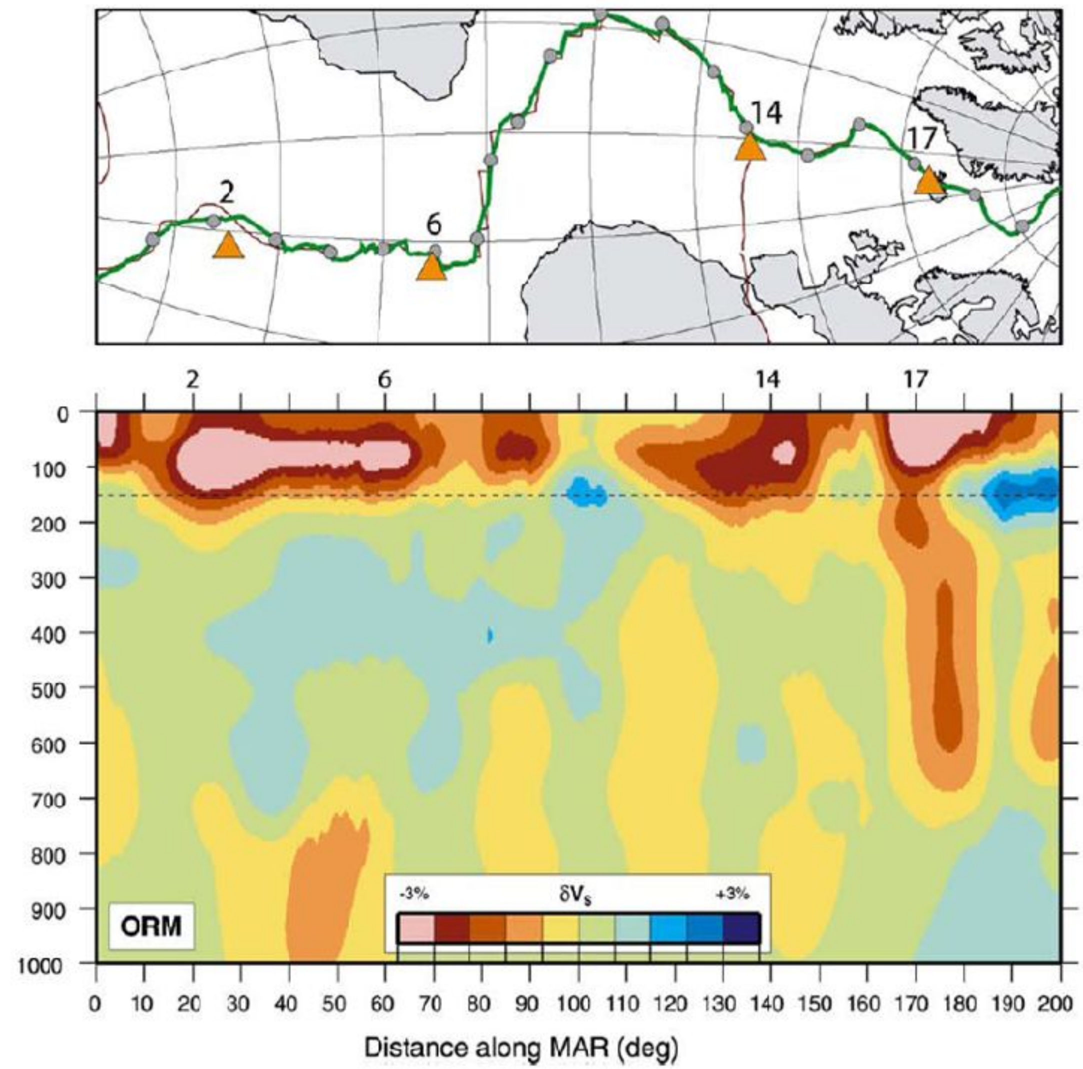
Last large lava flows ~70 kyr
Last small eruptions ~10 kyr



with an imaged volcanic conduit centered beneath the surface caldera holding Yellowstone Lake

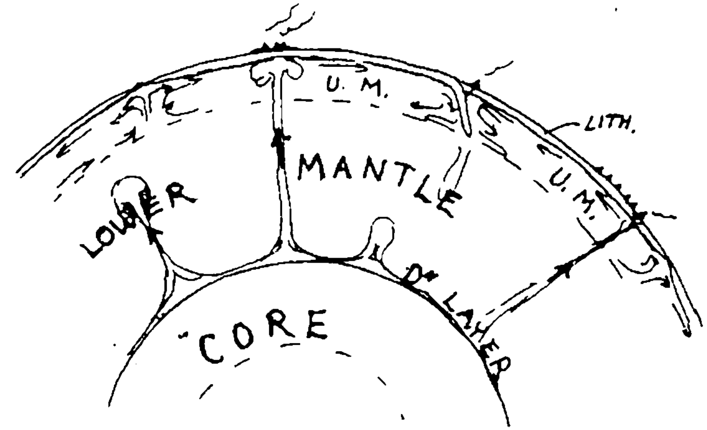
Iceland: image conduit to 400 km





LIKELY MODEL FOR HOT SPOTS: MANTLE PLUMES

Mantle is heated from below at the core mantle boundary.
Hot, buoyant material collects and rises as a diapir, with a "plume head" at the top - like a "mushroom cloud" - and forming a pipe (or tail) through which hot material can continue to rise.



When the plume head reaches the surface its melt erupts as a flood basalt, forming a Large Igneous Province ("L.I.P.") and a massive dike swarm.

The pipe continues to deliver hot mantle and melt to the surface as the plate moves over it, creating a "hot-spot track" of volcanoes.

from Thompson GSA Today April 1998

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Examples of giant dike swarms

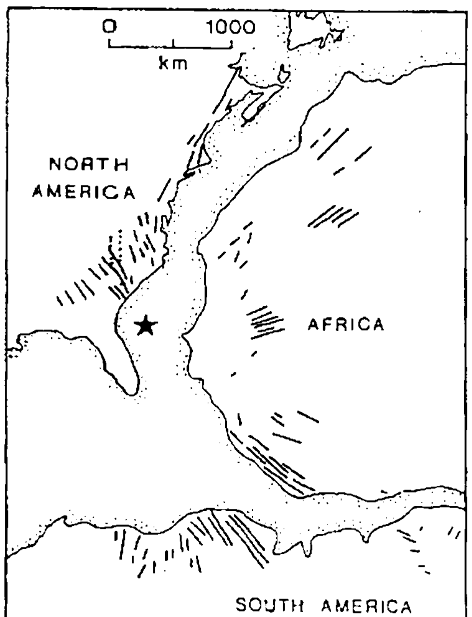


Figure 18. Giant swarm of Early Jurassic dikes radiating from offshore eastern North America (star) into the three continents before breakup. From Ernst et al. (1995).

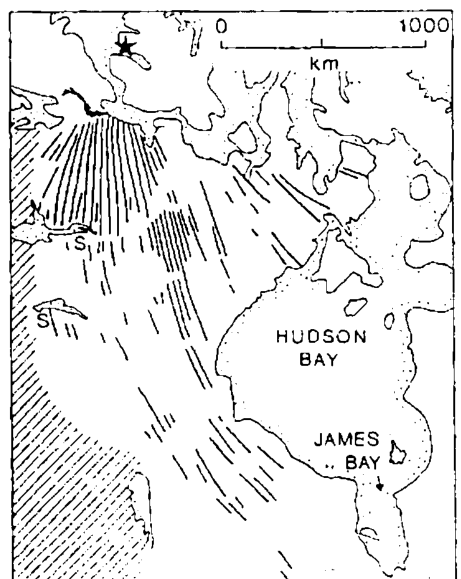


Figure 7. Simplified map of the Mackenzie giant radiating dike swarm (1.265 Ga) of northern Canada. S marks coeval sills: black area indicates coeval Coppermine volcanics. From Ernst et al. (1995).

Columbia river flood basalts ~17 Ma

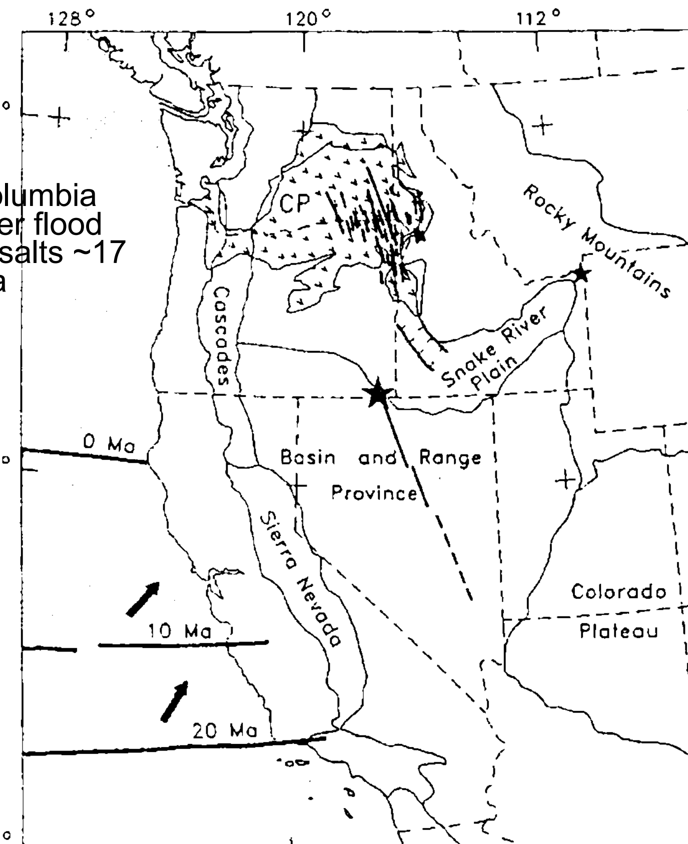
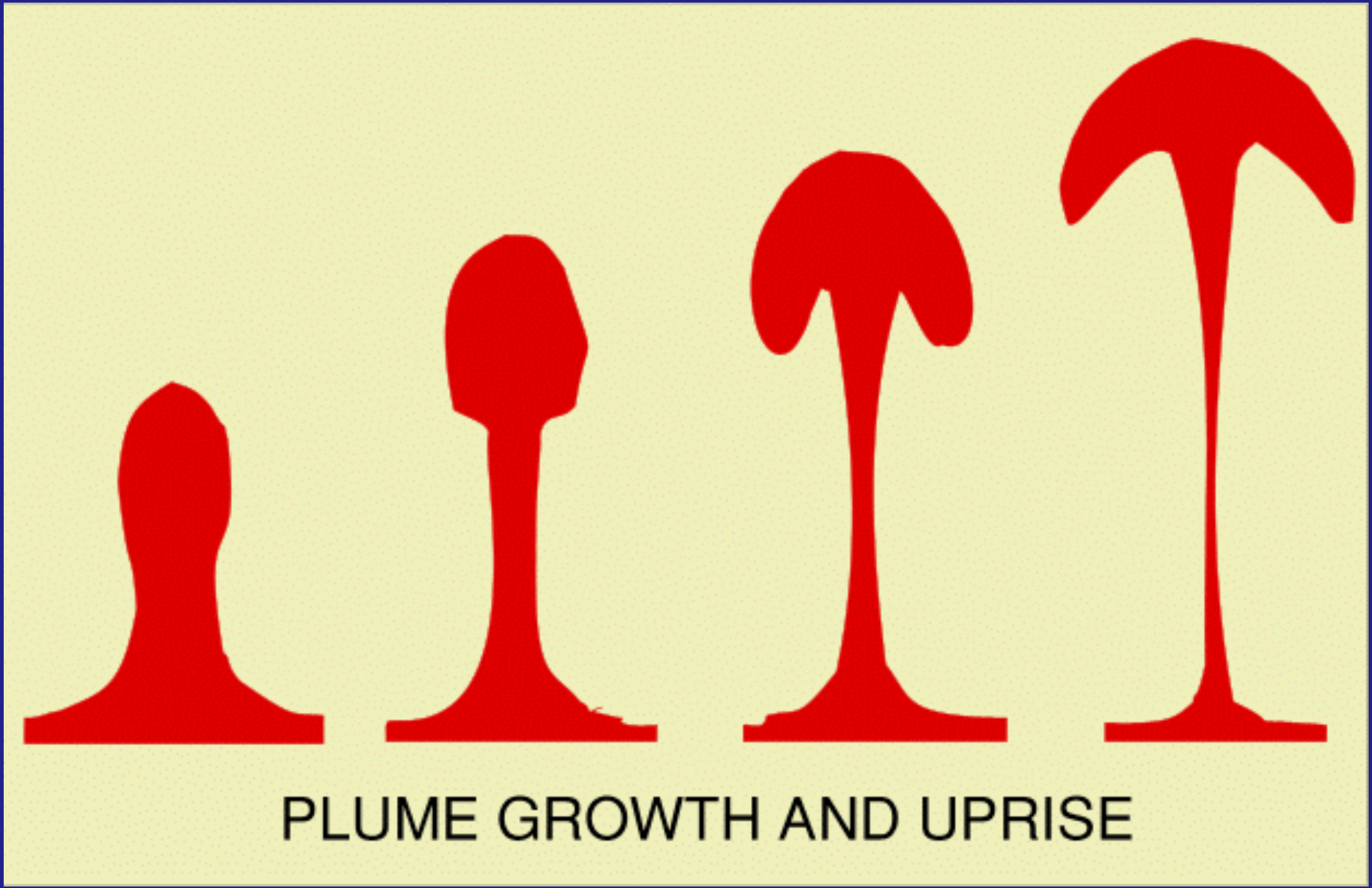


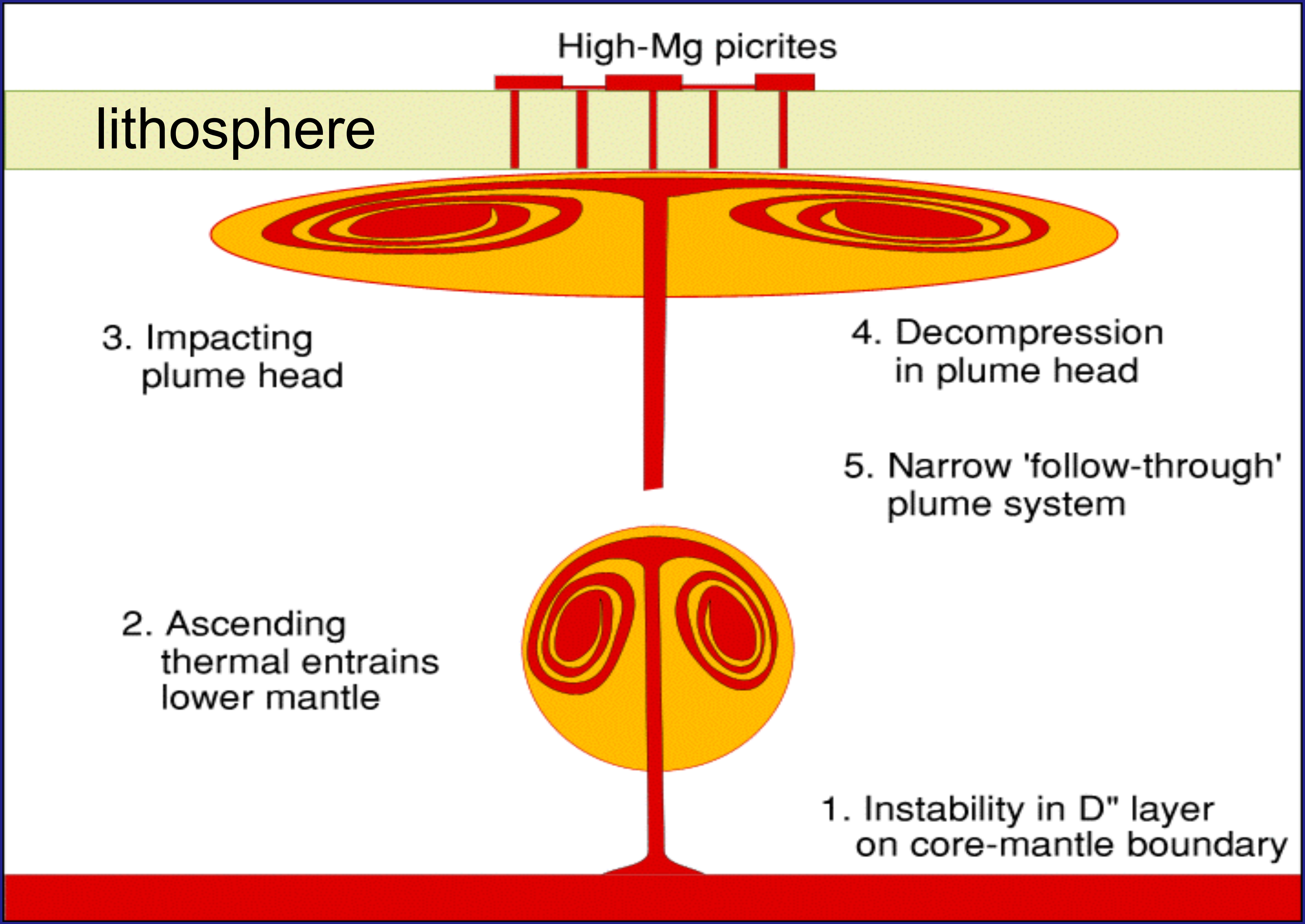
Figure 10. Emergence point of Yellowstone plume (large star), its track on the Snake River Plain, and its present position at Yellowstone (small star). The line extending south from the large star indicates dike swarms of the northern Nevada rift. To the north are shown the Columbia River flood basalts (CP) and their feeder dikes. Heavy lines at left indicate the position of the Mendocino fracture zone at three time intervals. From Zoback et al. (1994).

Mantle plumes come in various shapes and sizes and can be modeled based on assumptions of mantle viscosity and layering….

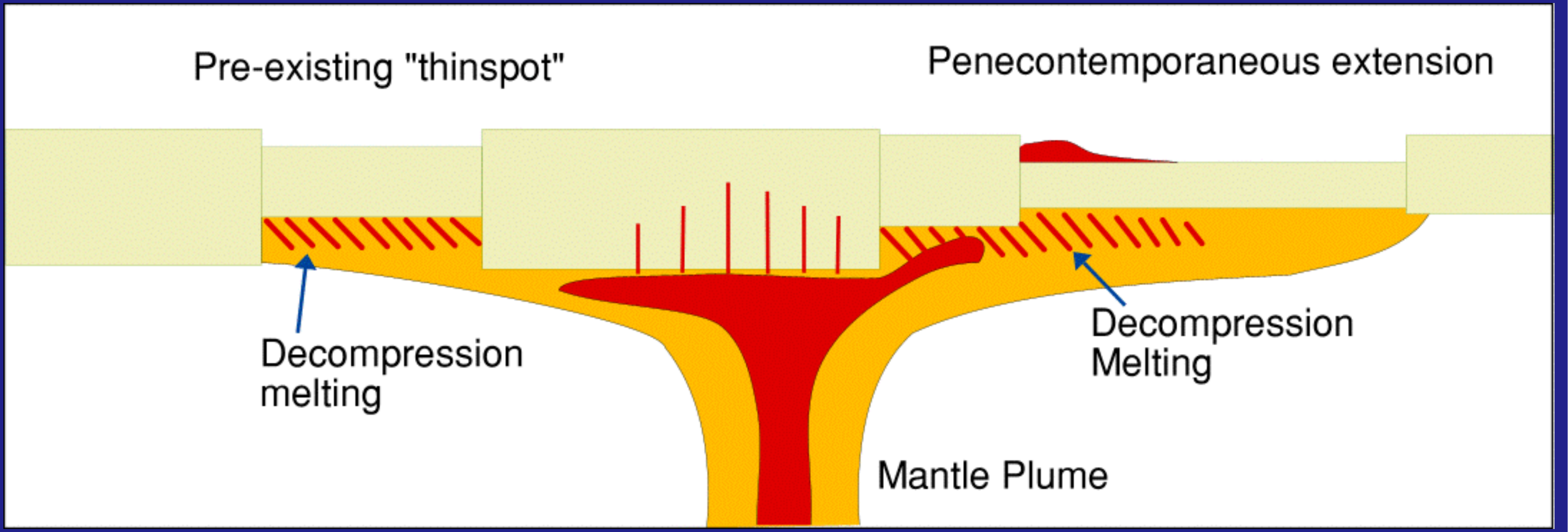


characteristic of most models are broad plume heads

Ascending plumes interact with the rigid, strong lithosphere producing a number of phenomena



Decompression is generally only possible in the uppermost mantle. Thus if the lithosphere is exceptionally thick as under continents, melting by adiabatic decompression is limited.



Consequently we tend to observe the surface manifestation of plume volcanism in areas of thin crust, such as in the oceans or in stretched continental margins.

ORIGIN OF HOT SPOT MAGMAS, "O.I.B."

MAGMA COMES FROM PARTIAL MELT OF MANTLE (BASALT)

BUT IS DISTINCT FROM "M.O.R.B."
IN MINOR & TRACE ELEMENTS
AND IN ISOTOPIC CONTENT

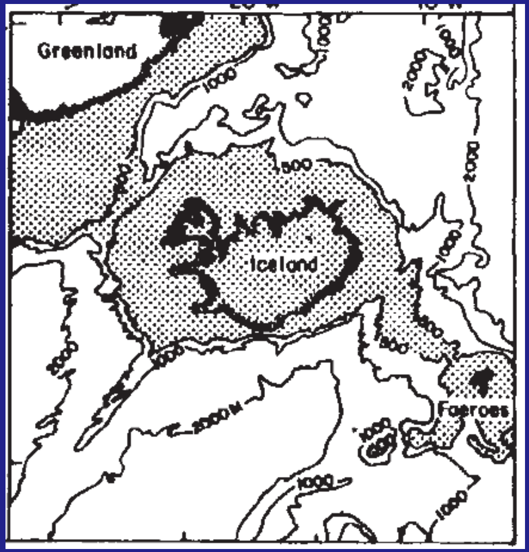
LARGE-ION LITHOPHILE ELEMENTS "L.I.L.s"
La, Rb, Cs, Ba, Sr, K, P, Ti

THESE TEND TO CONCENTRATE
INTO PARTIAL MELT

SO IF MELT MANTLE SEVERAL
TIMES THEY ARE CONCENTRATED
IN FIRST MELT, DEPLETED
IN LATER MAGMAS.

Classic model
Schilling (1973)
Based on dredging along
Reykjanes ridge near Iceland

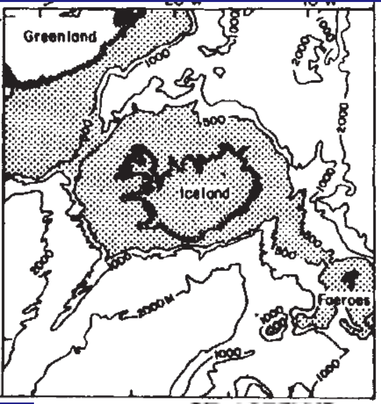
O.I.B. = Ocean Island basalts

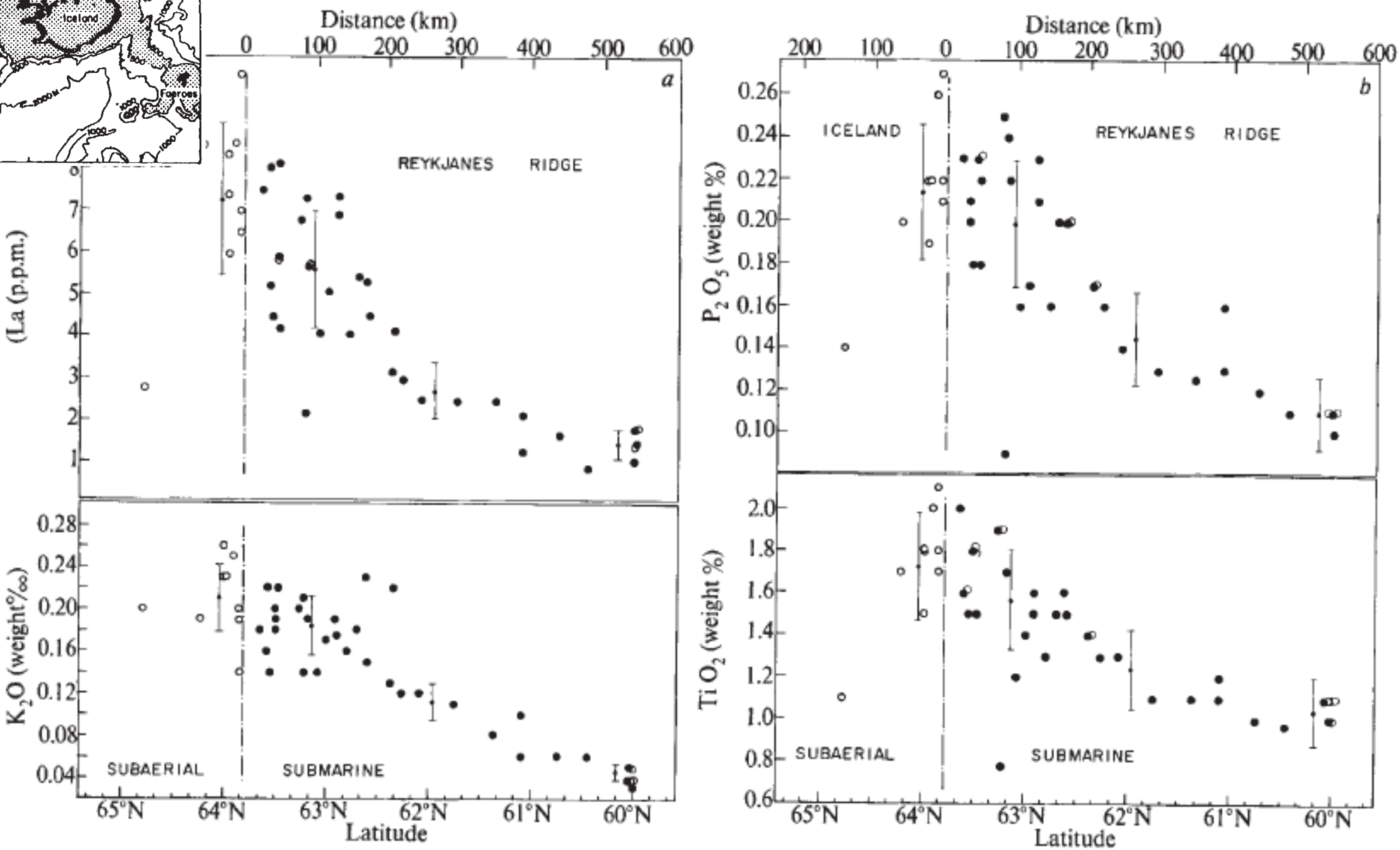


Normal MORBs have been recycled repeatedly through the mantle and are “depleted” in LILs.

Deep mantle plumes have not gone through this process and are “enriched” in LILs

L.I.L.'s have greatest concentration near Iceland ("enriched"), gradually fall off to south ("depleted")





Schilling (1973)

O.I.B.s ARE HIGH IN L.I.L.S

M.O.R.B. IS DEPLETED

ALSO LEAD ISOTOPE STUDIES SUGGEST HOT SPOT MAGMA HAS BEEN ISOLATED FROM REST FOR 1 – 2 BILLION YR.

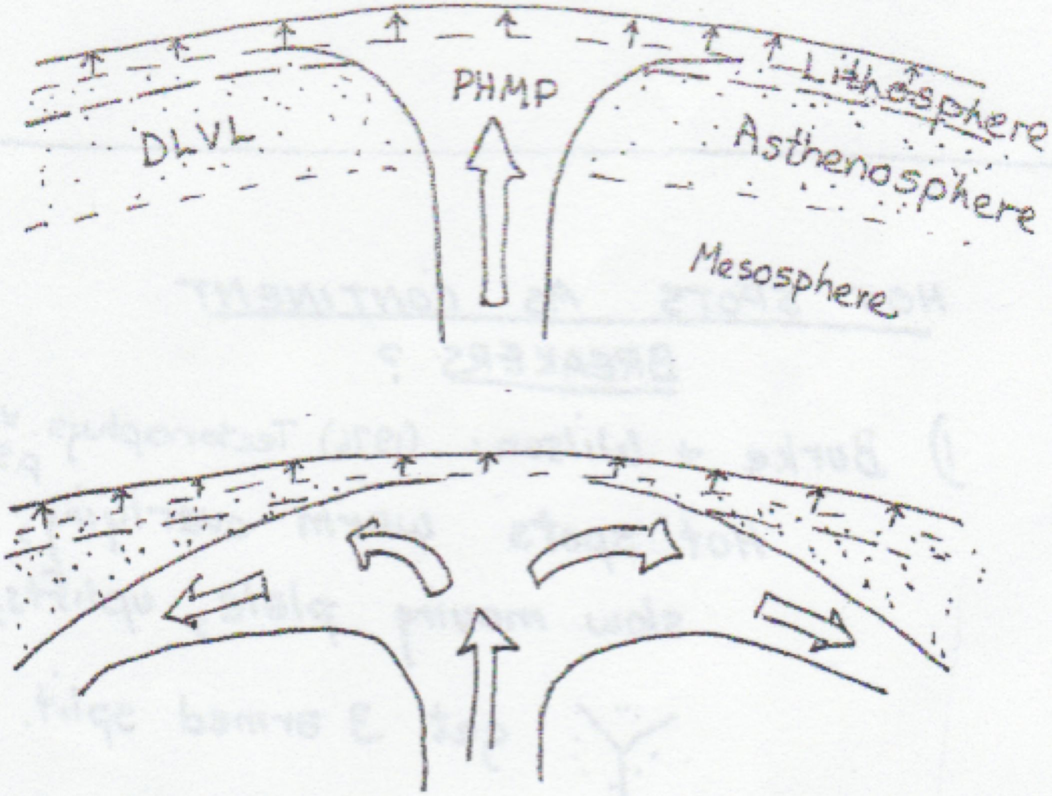
SO O.I.B. FROM DEEP IN MANTLE ?

Controversial, alternative source:

FROM ISOLATED BLOBS IN UPPER MANTLE ?

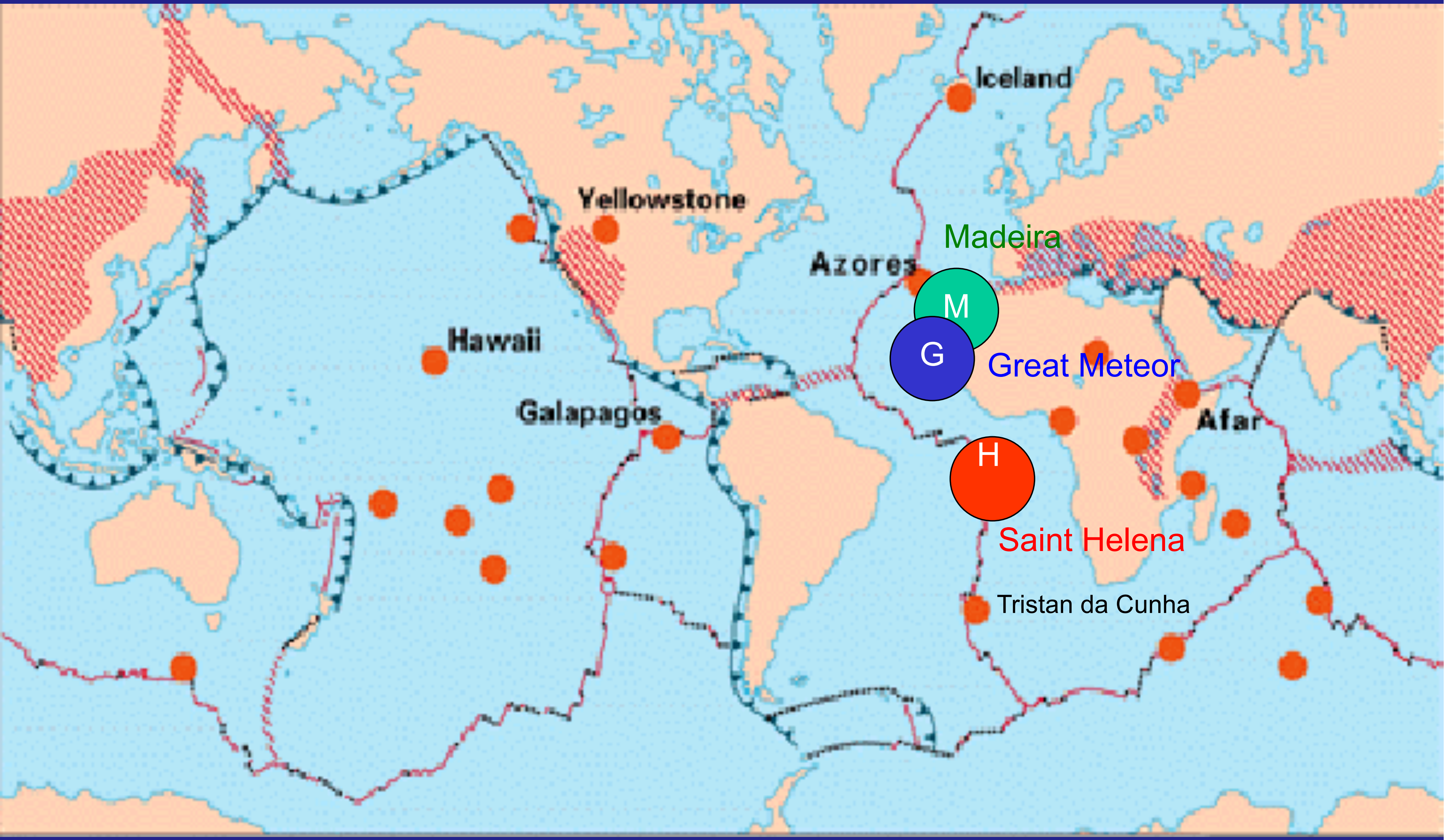
P.H.M.P. "Primordial Hot Mantle Plume"

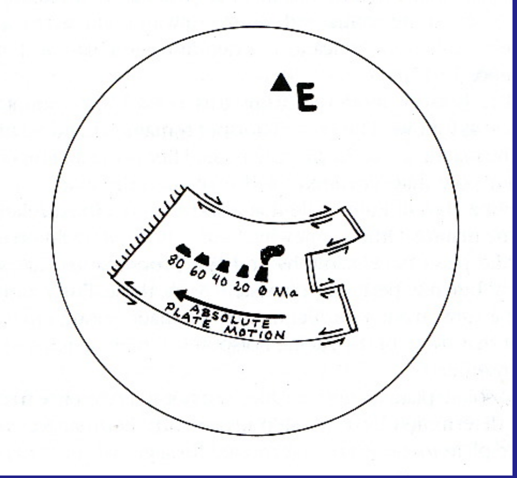
D.L.V.L. "Depleted Low Velocity Layer"



Two mantle plume models by Schilling (1973) to account for chemical gradients along the Reykjanes Ridge (so. Iceland).

Here are some of the more prominent hotspots





Hotspot trails constrain the location of Euler poles that give the motion of a plate relative to the mantle

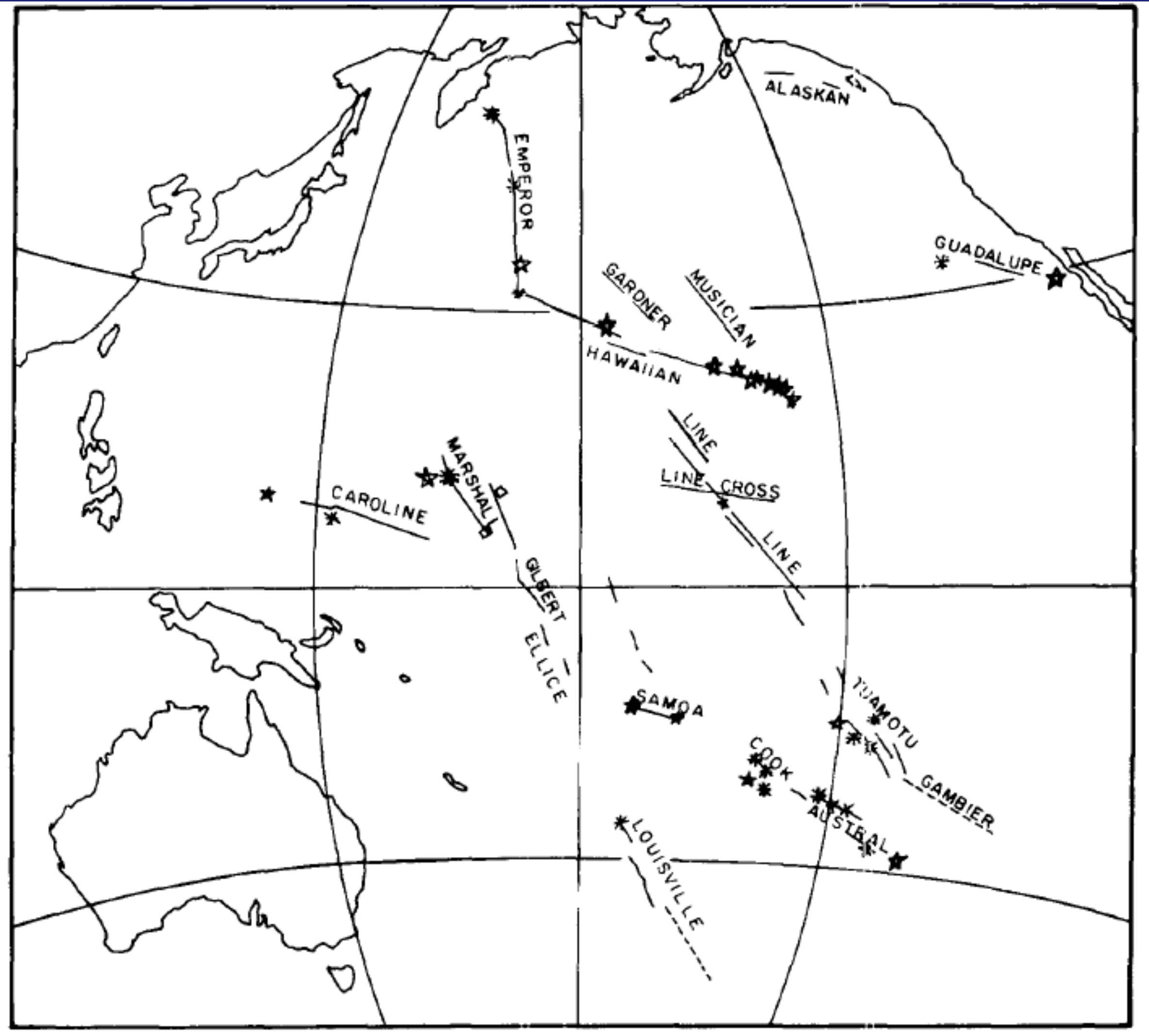
They generate small circles about the Euler pole

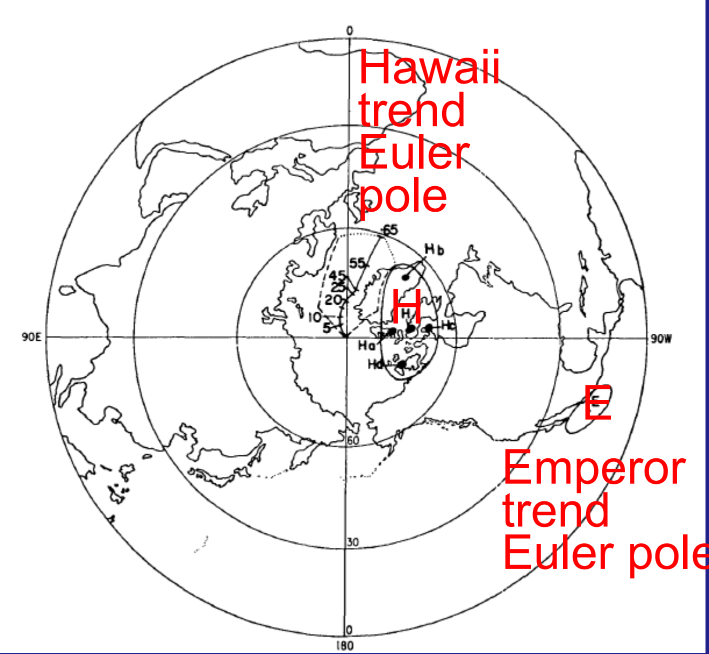
Can define an “absolute reference frame” based on present day motion of plates relative to many hotspots

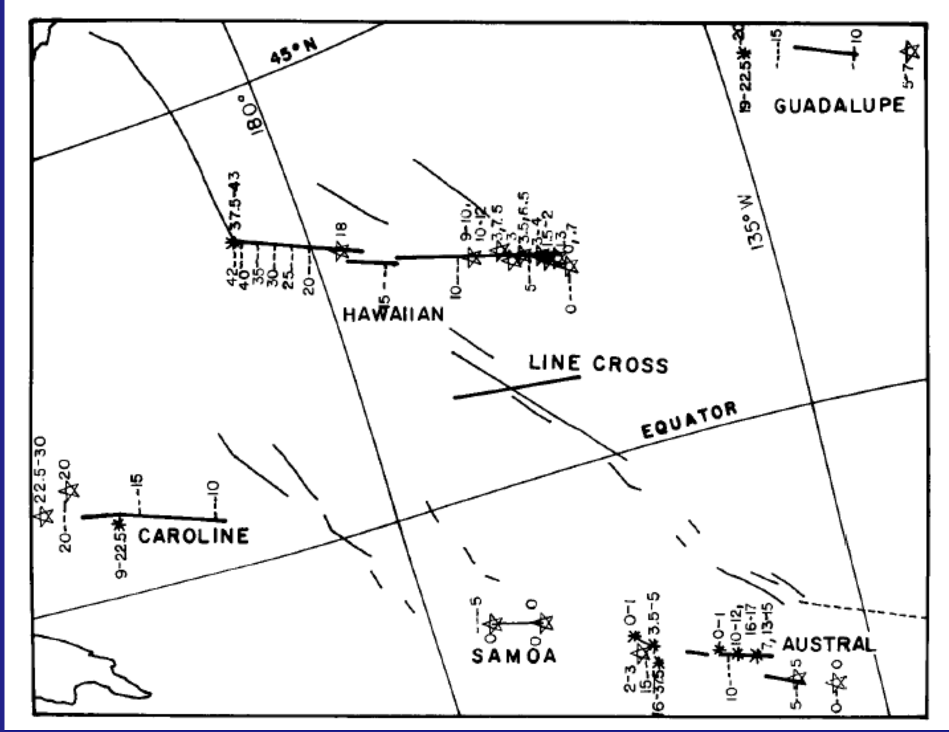
Classic study:
Clague & Jarrard (1973) identified two trends to the Pacific Island chains

A younger trend (~45 Ma to present) matching Hawaii and other young chains

An older trend (~80 To 45 Ma) matching the Emperor chain and a few other chains



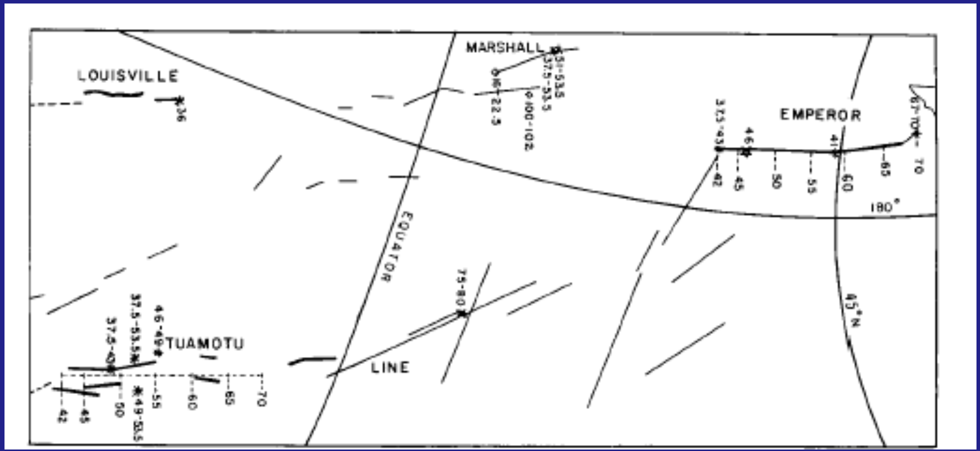




Oblique Mercator Projection!

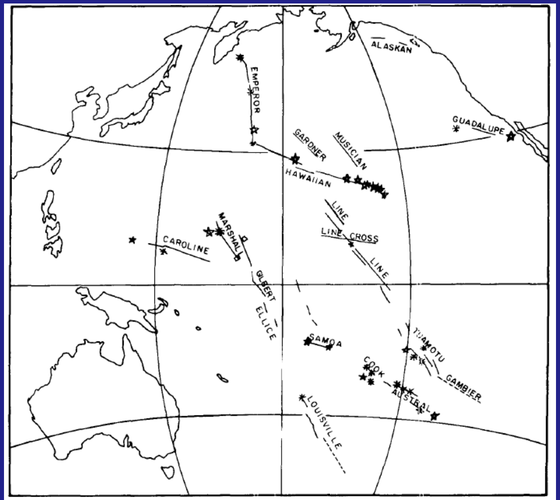
Hawaii trend Euler pole

Clague & Jarrard found Euler poles that fit the two distinct trends, in the same way you fit Euler poles to transform fault trends (orthogonal lines)

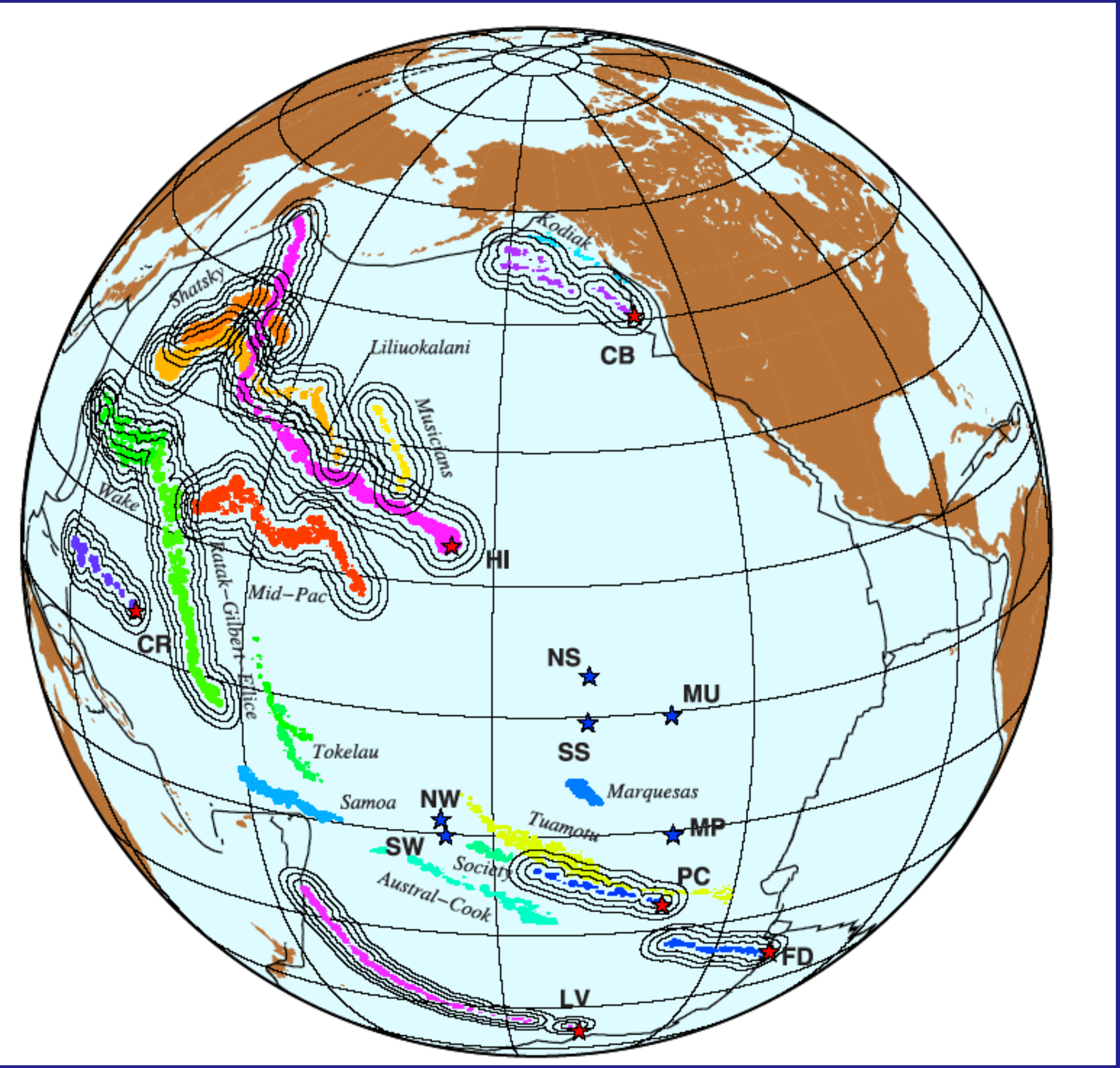


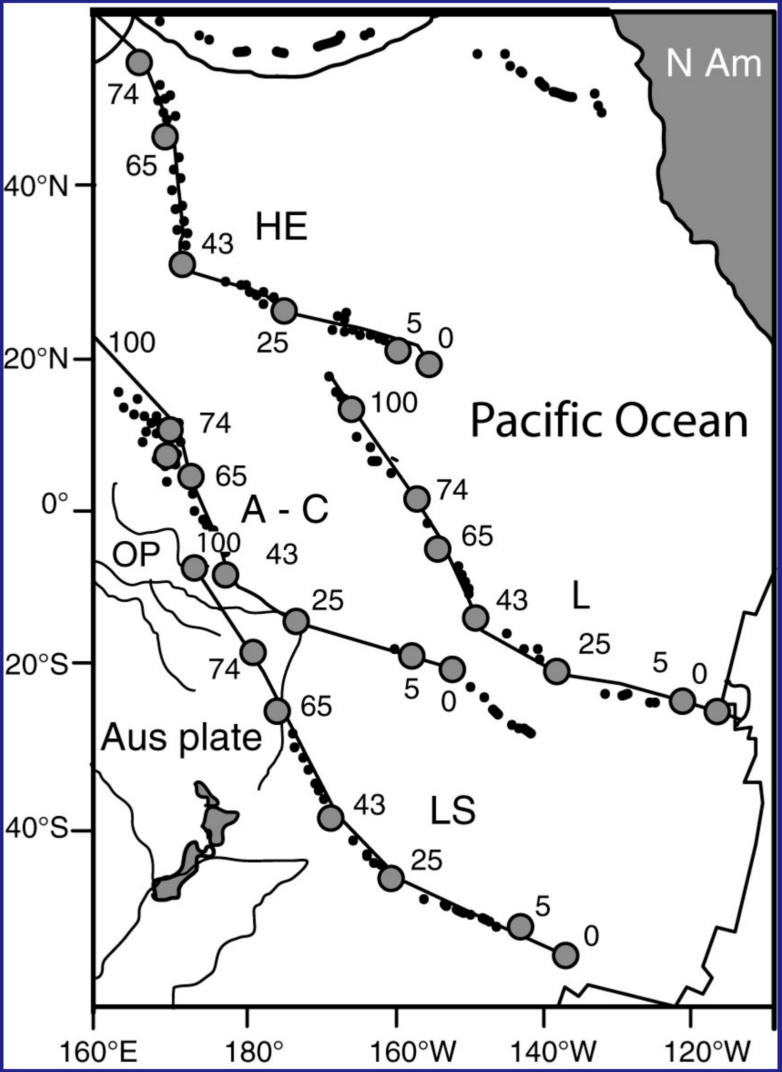
Oblique Mercator Projection!

Emperor trend Euler pole



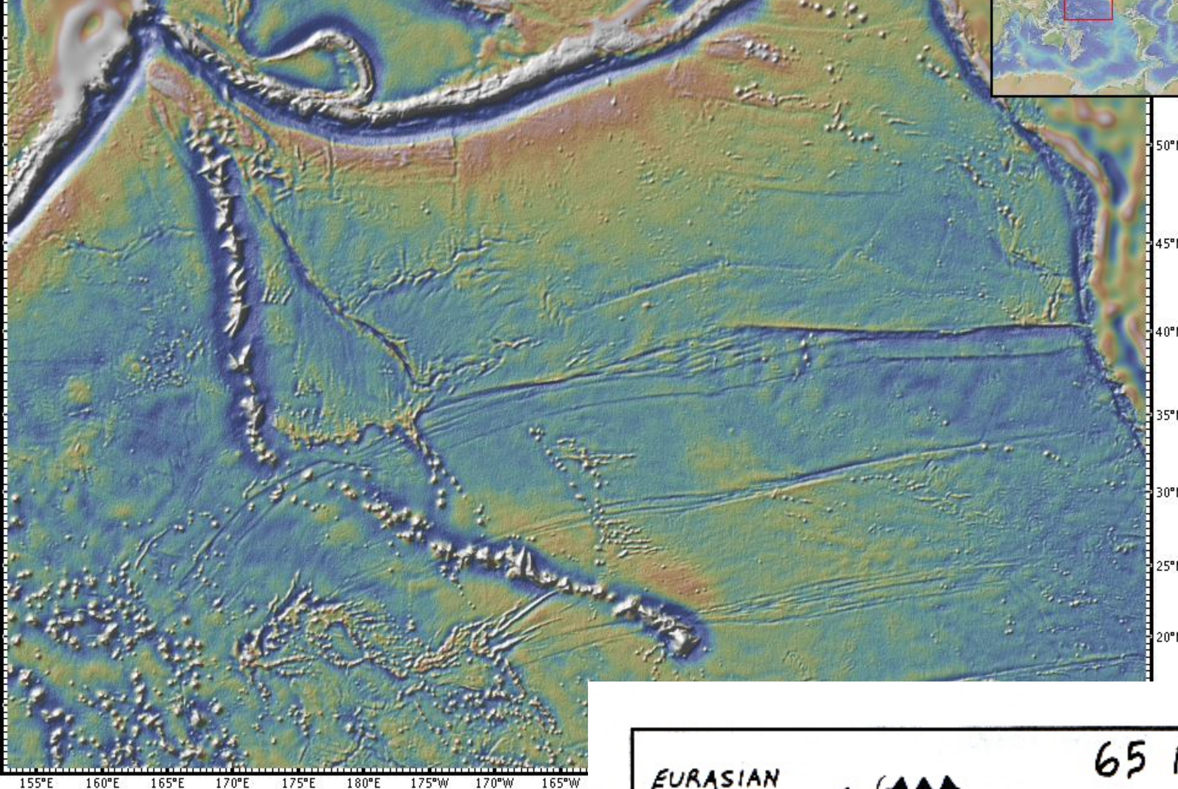
Now, 40 years later, lots more ages, but basic picture is abut the same … 2 or 3 longlasting trends over last 80 Ma





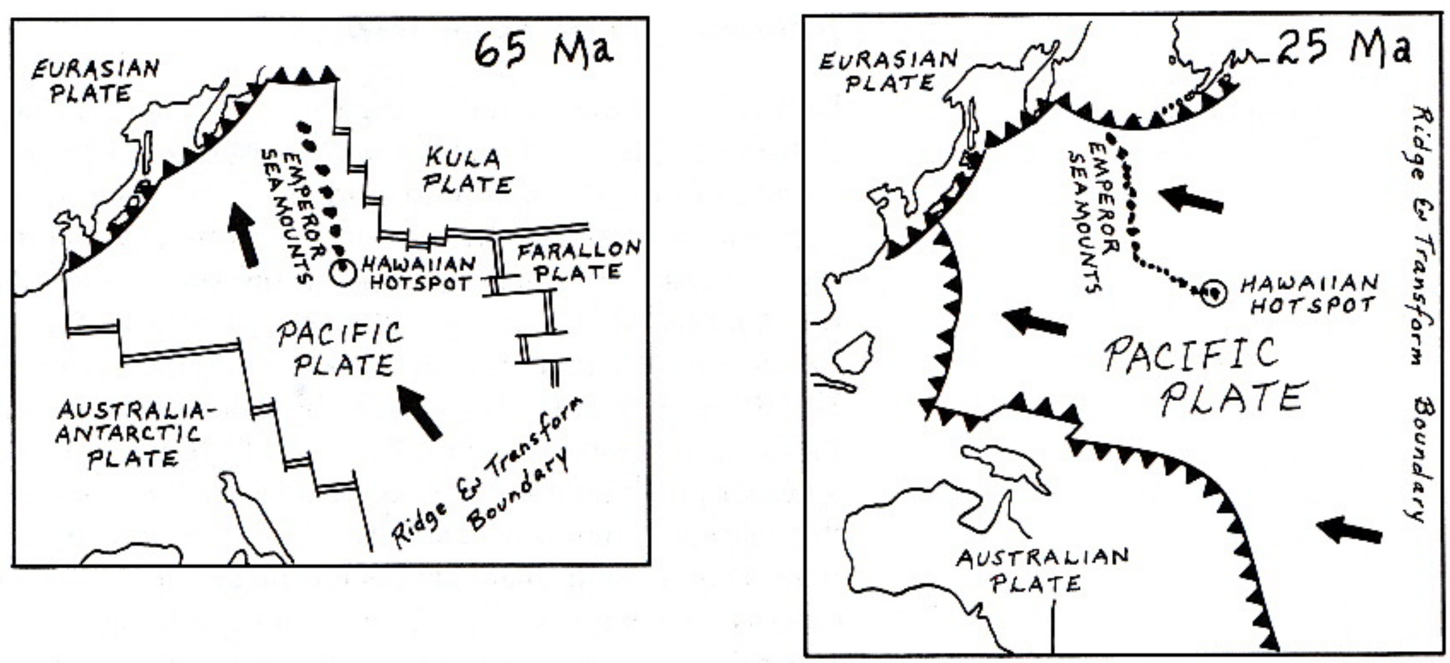
Wessel and Kroenke (2008)

KK&Vfig 5.7

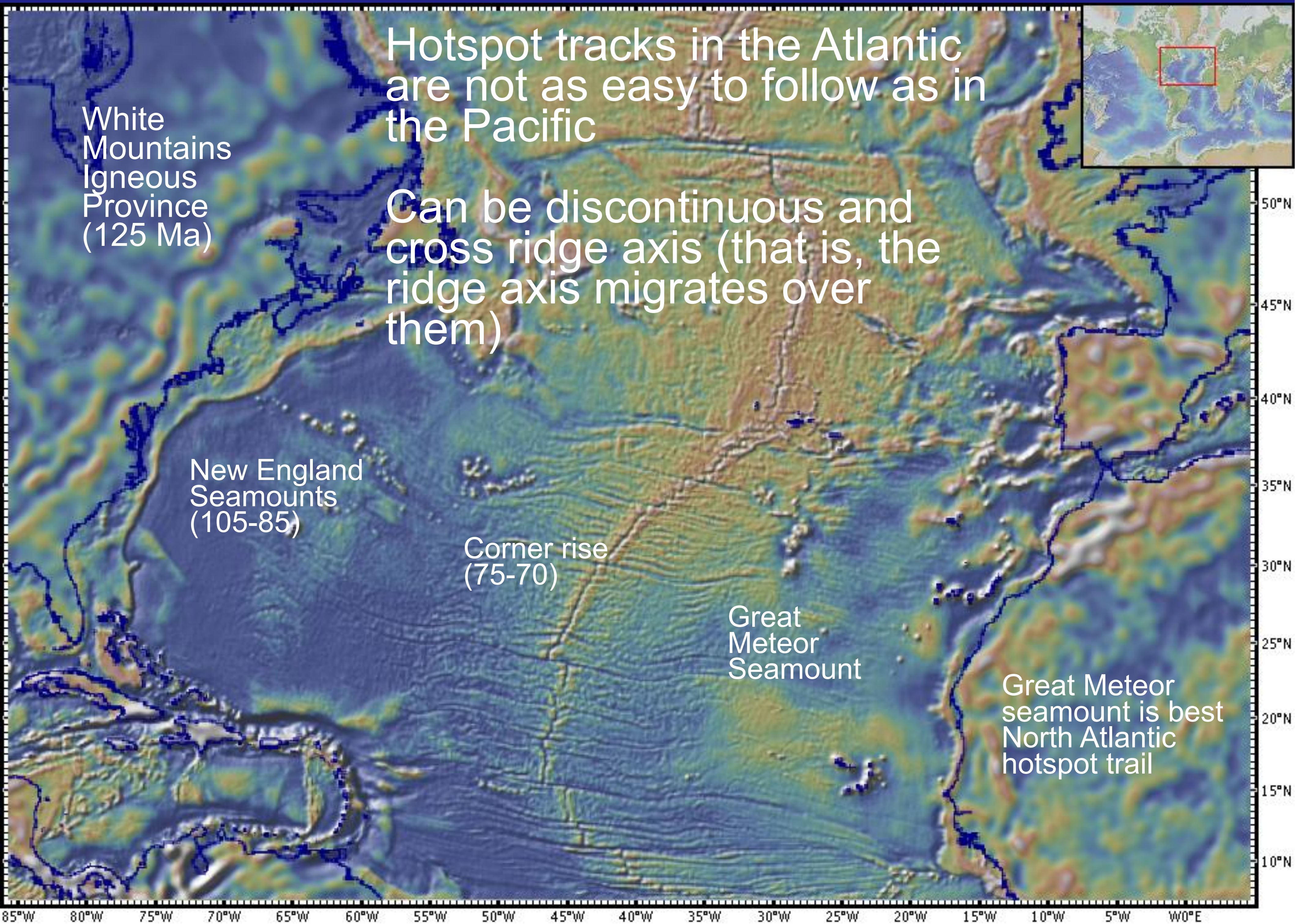


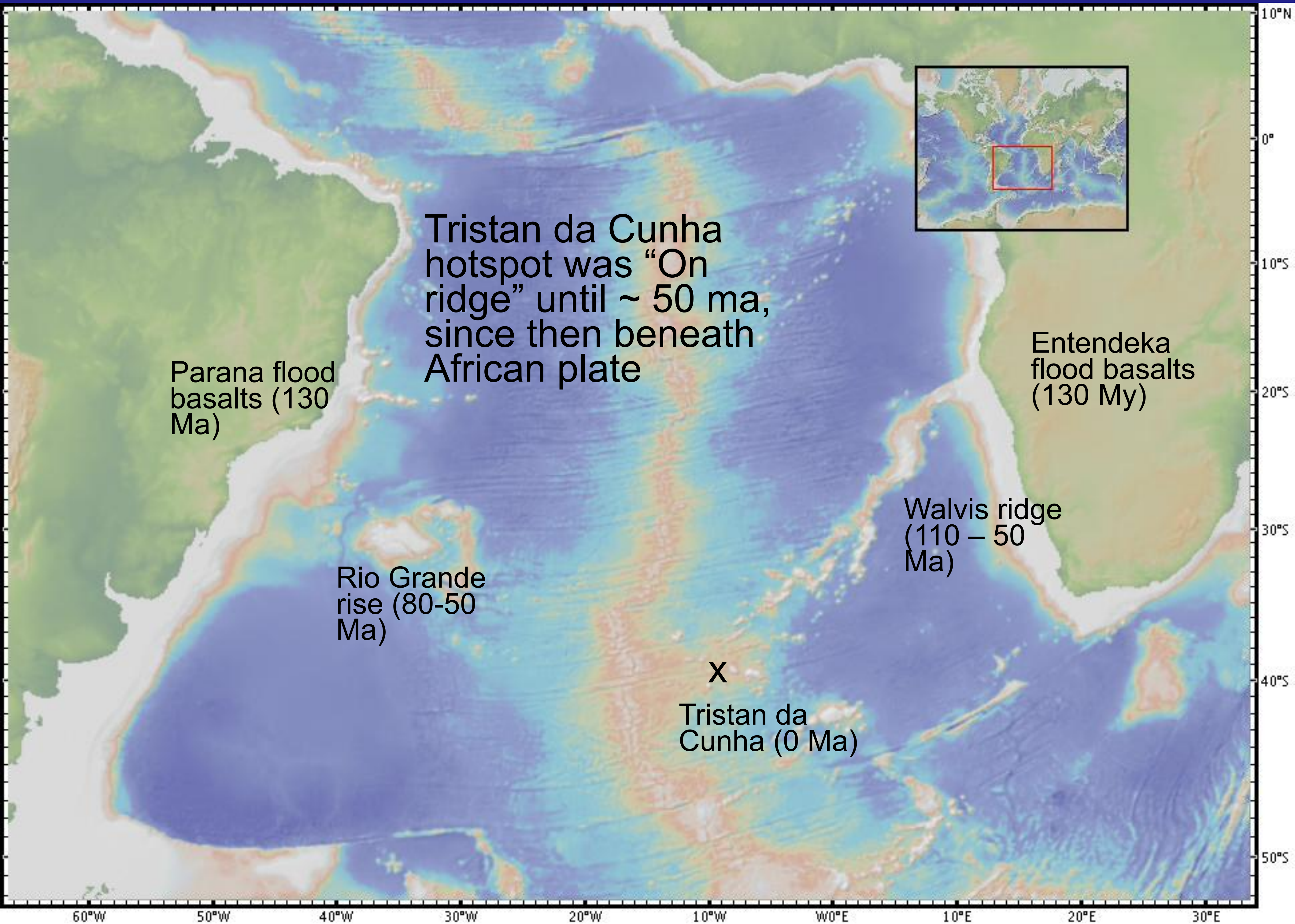
Originally attributed change of motion to change in geometry of trenches ("slab pull")

Now, believe hotspots sometimes drift



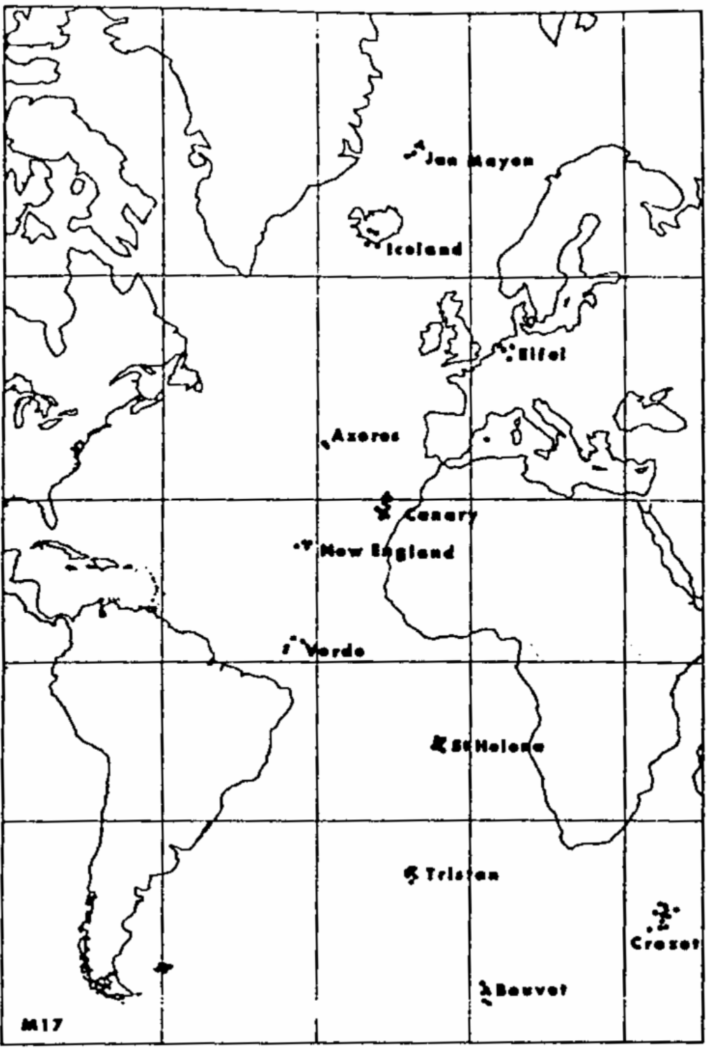
Cox and Hart

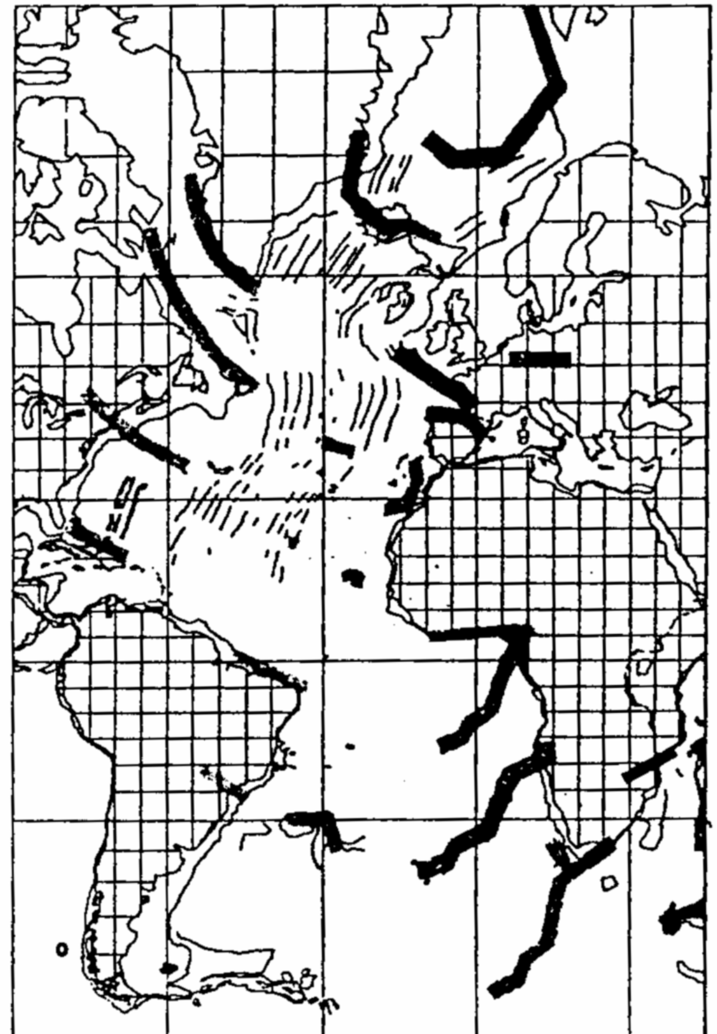

Hotspot tracks in the Atlantic are not as easy to follow as in the Pacific
Can be discontinuous and cross ridge axis (that is, the ridge axis migrates over them)
White Mountains Igneous Province (125 Ma)
New England Seamounts (105-85)
Corner rise (75-70)
Great Meteor Seamount
Great Meteor seamount is best North Atlantic hotspot trail
50°N
45°N
40°N
35°N
30°N
25°N
20°N
15°N
10°N
85°W
80°W
75°W
70°W
65°W
60°W
55°W
50°W
45°W
40°W
35°W
30°W
25°W
20°W
15°W
10°W
5°W
W0°E


Tristan da Cunha hotspot was "On ridge" until ~ 50 ma, since then beneath African plate
Parana flood basalts (130 Ma)
Entendeka flood basalts (130 My)
Walvis ridge (110 – 50 Ma)
Rio Grande rise (80-50 Ma)
x
Tristan da Cunha (0 Ma)
10°N
0°
10°S
20°S
30°S
40°S
50°S
60°W
50°W
40°W
30°W
20°W
10°W
W0°E
10°E
20°E
30°E

Atlantic Ocean hotspots a-la Jason Morgan

Morgan generated a set of ages/positions for Atlantic hotspots
Fuzzy hotspots on left shows slop in fit





Classic study:

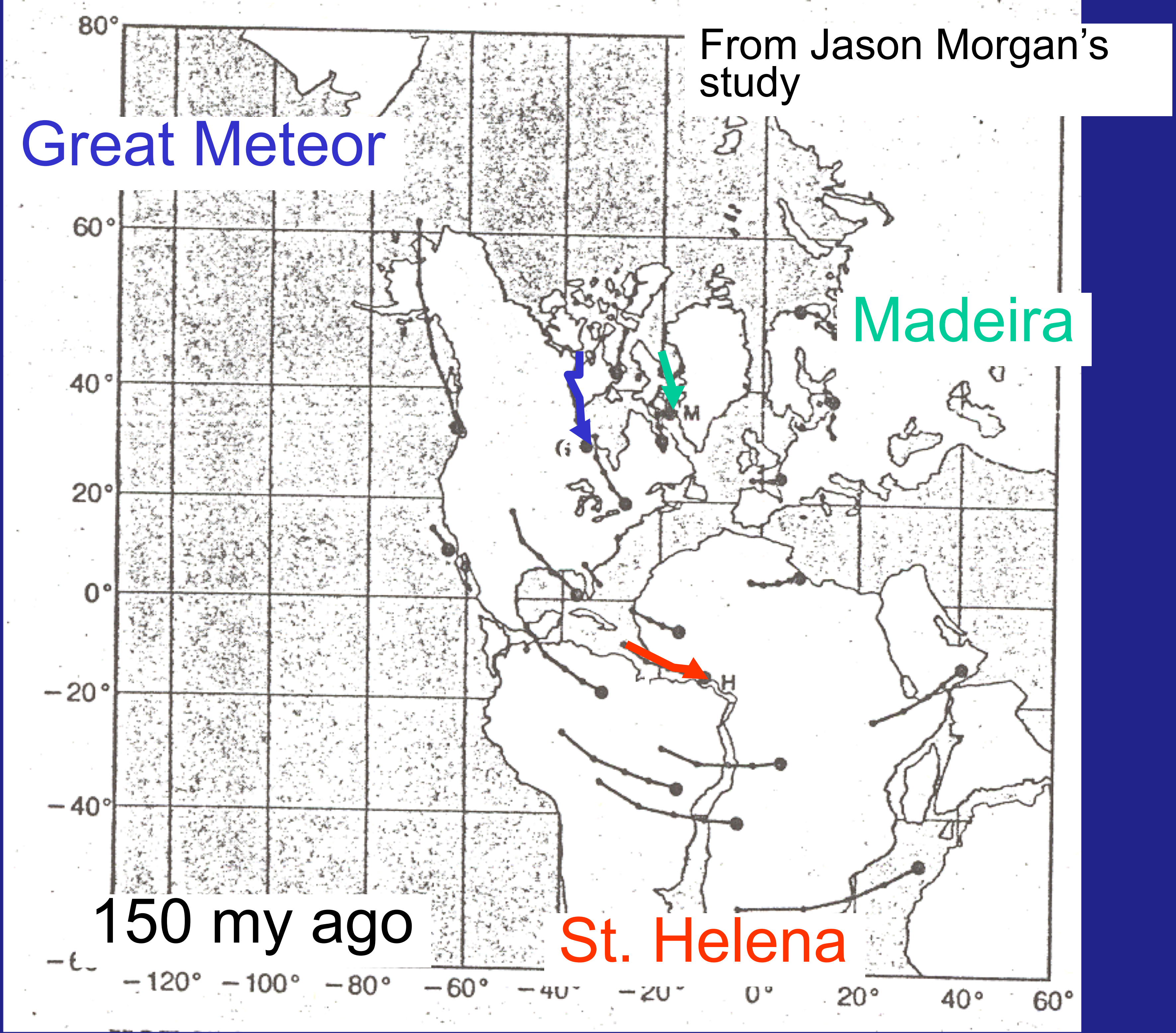
Tricky – find set of rotations that fit all of the hotspots at the same time you are reconstructing the relative motions of the plates

Problem: the age progression on many of the hotspot tracks are poorly defined.

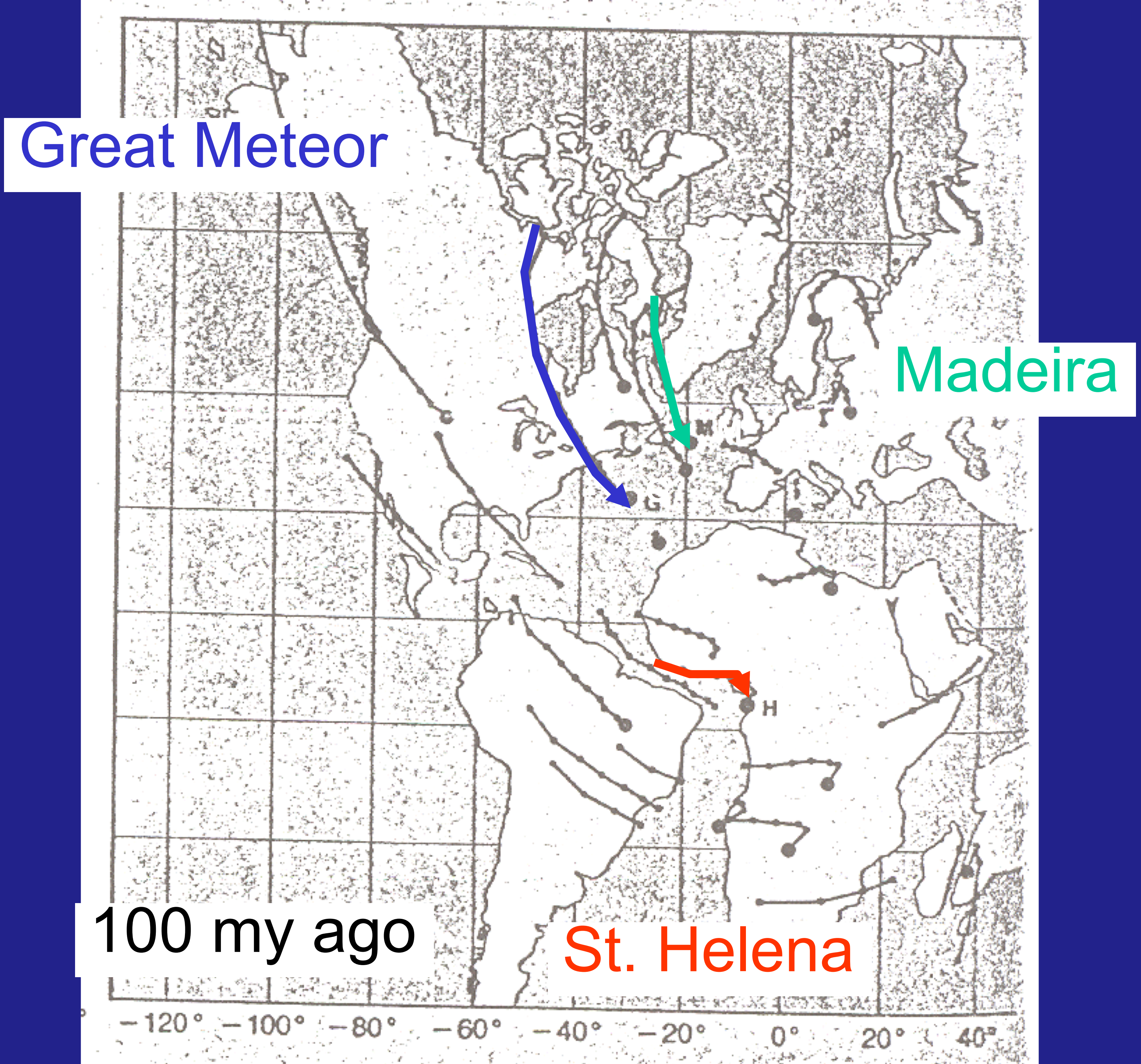
Morgan (1977)

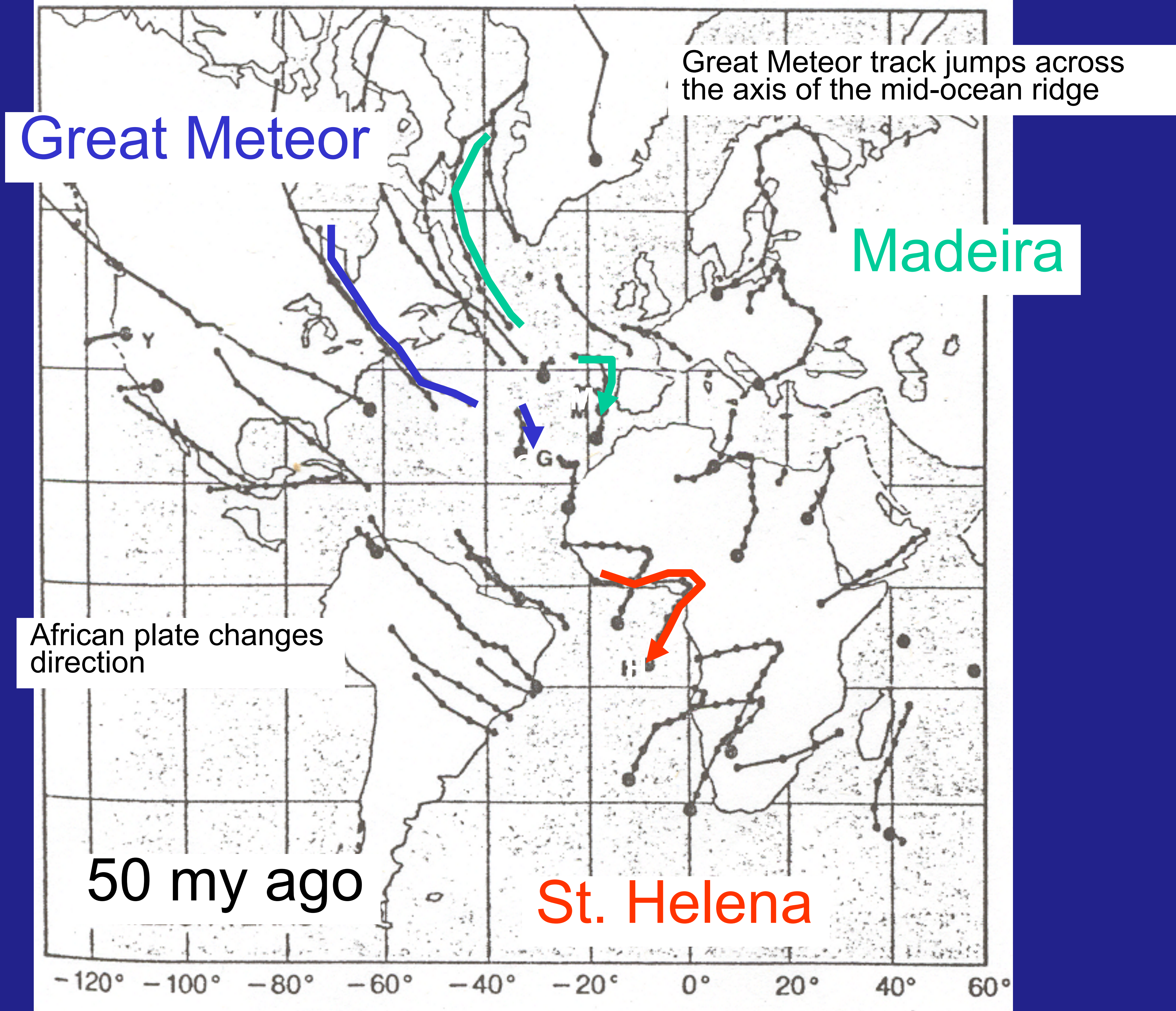
Torch tectonics: where continents later rifted after passing over hotspots

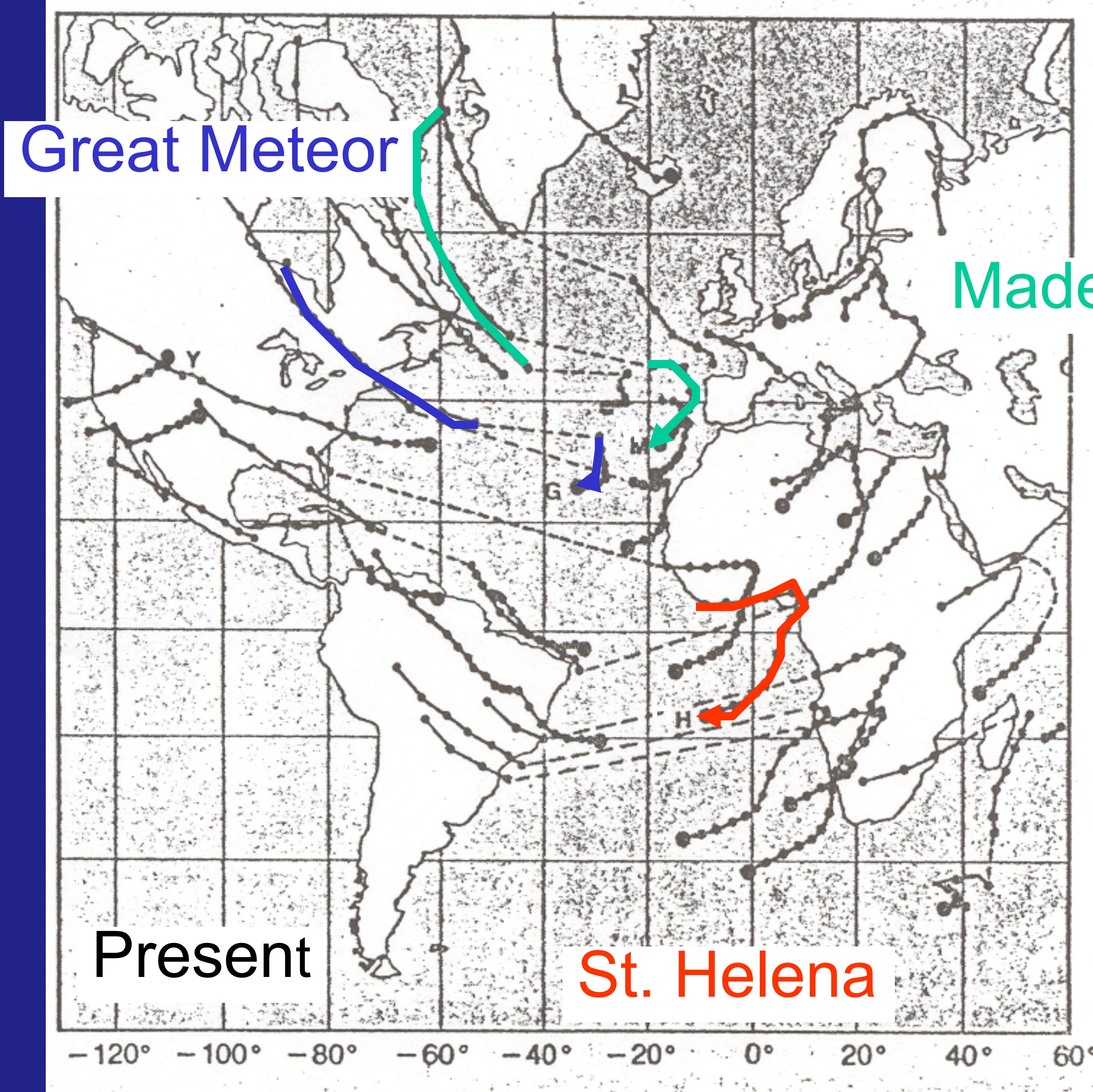
Note: - "pre-weakening" of continental rifts
- crossing of mid-ocean ridges

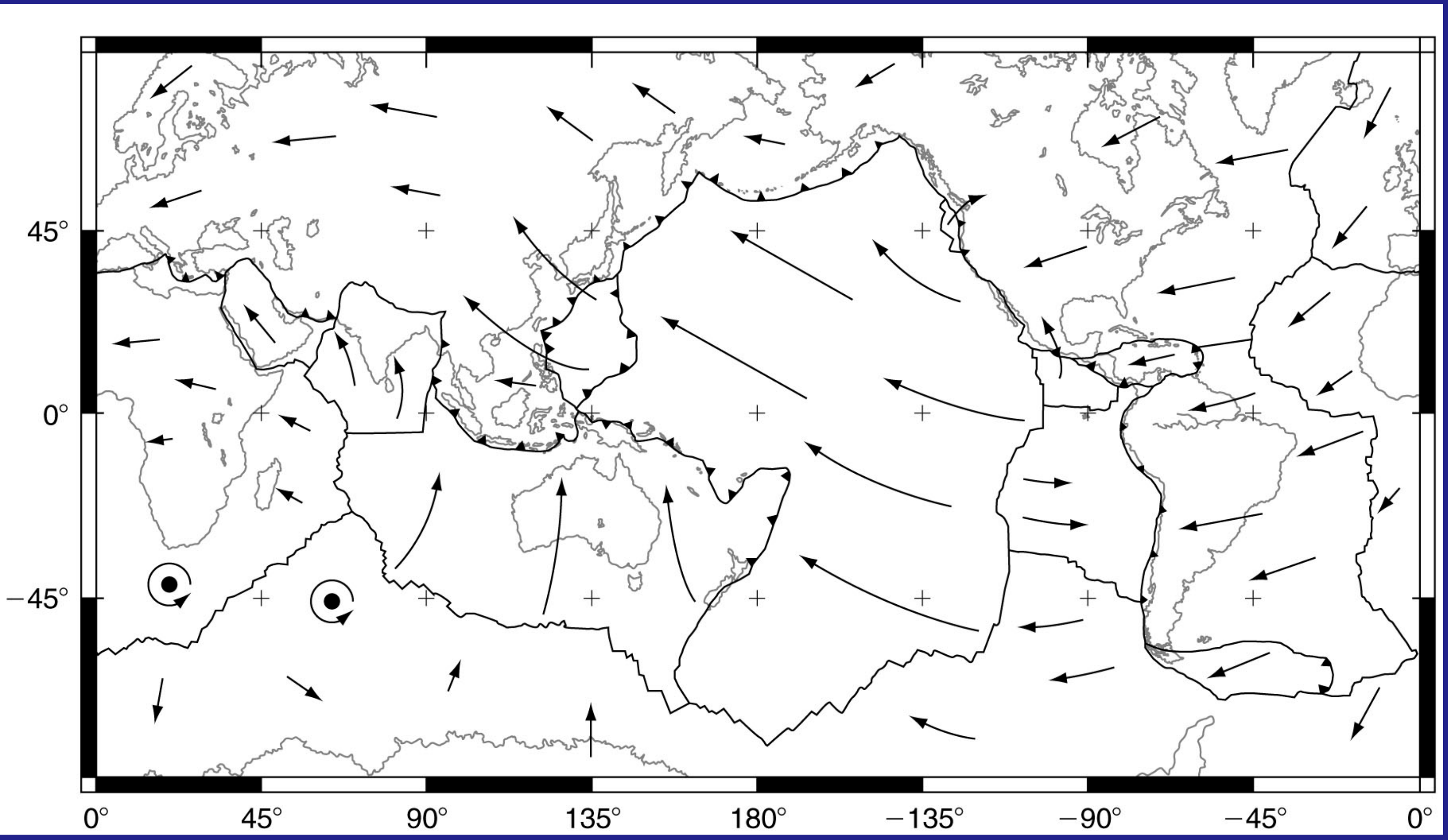


From Jason Morgan's study
Great Meteor
Madeira
150 my ago
St. Helena
80°
60°
40°
20°
0°
−20°
−40°
−120°
−100°
−80°
−60°
0°
20°
40°
60°
M
H


Great Meteor
Madeira
St. Helena
100 my ago
M
G
H
−120°
−100°
−80°
−60°
−40°
−20°
0°
20°
40°


Great Meteor track jumps across the axis of the mid-ocean ridge
Great Meteor
Madeira
African plate changes direction
50 my ago
St. Helena
M
G
Y
-120°
-100°
-80°
-60°
-40°
-20°
0°
20°
40°
60°


Great Meteor
Madeira
Present
St. Helena
Y
G
H
-120°
-100°
-80°
-60°
-40°
-20°
0°
20°
40°
60°



Like NUVEL1, can also make a global model for present day absolute plate motions

Here, recent absolute motion has been calculated for all plates and extrapolated forward 40 m.y.

See that Pacific plate moves quite fast relative to mantle

Other plates more slowly,

Africa, Eurasia and Antarctica the slowest

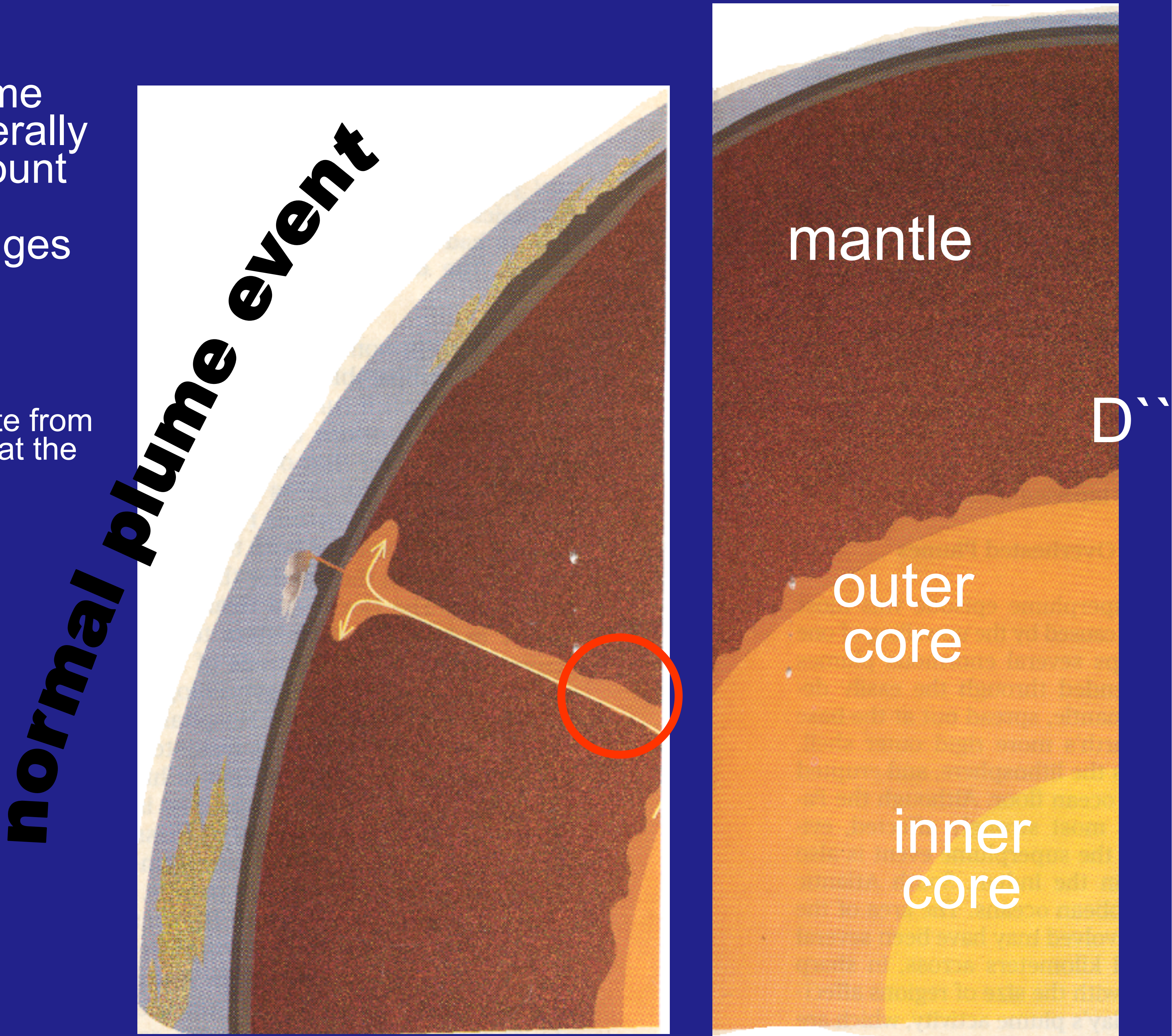
Present day absolute plate motions x 40 Ma

KK&V Fig. 5.6

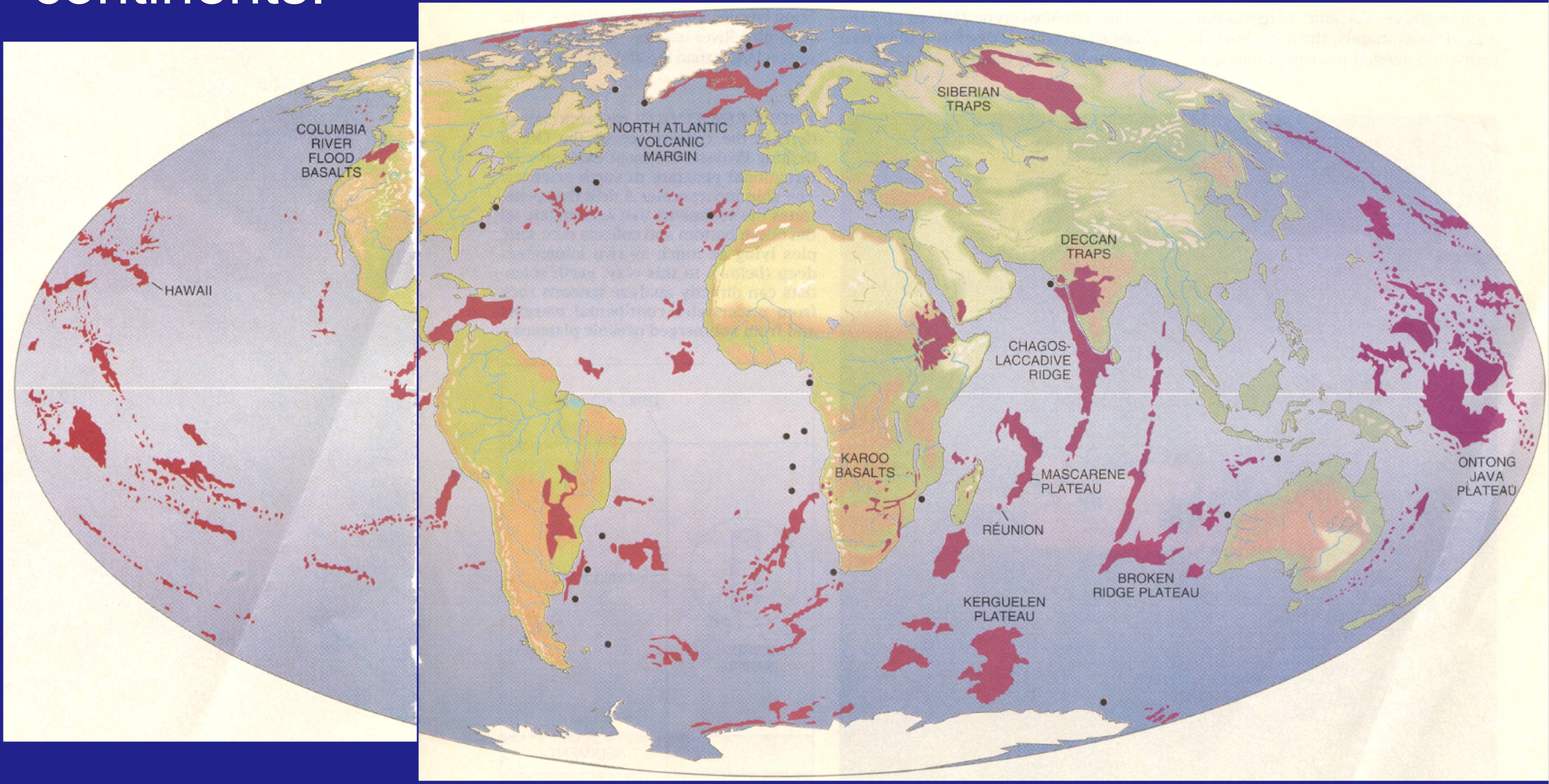
Gripp and Gordon (2002)

Normal plume events generally build seamount chains and aseismic ridges

Plumes initiate from the D`` layer at the core/mantle boundary



Volcanic plateaus and seamount chains (shown in red) are found worldwide in oceans and on continents.



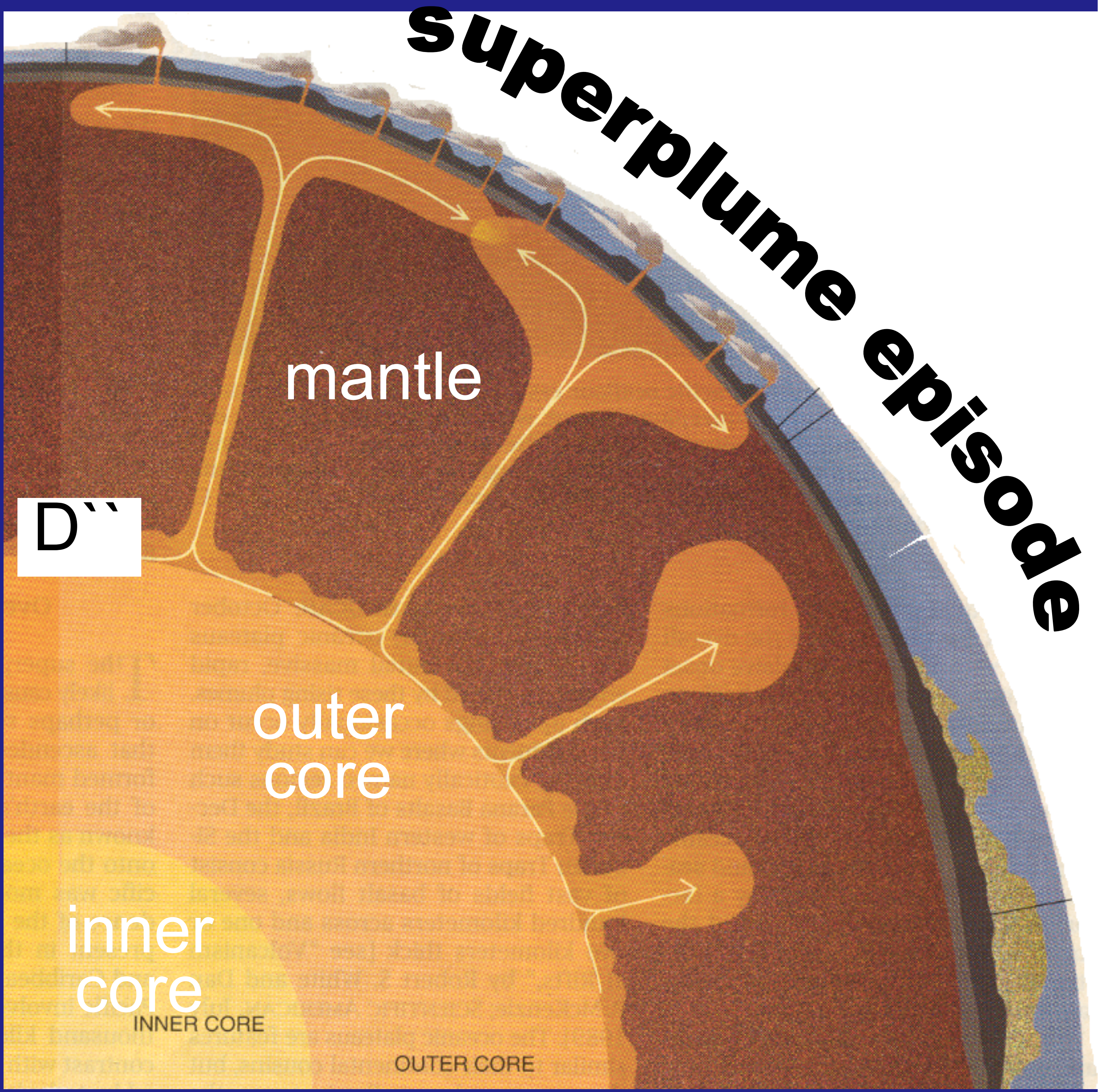
The plateaus are called Large Igneous Provinces (LIPs)

LARGE IGNEOUS PROVINCES

- Large igneous provinces (LIPs) are voluminous emplacements of predominantly mafic extrusive and intrusive rock whose origins lie in processes other than 'normal' seafloor spreading.

- LIPs include continental flood basalts and associated intrusive rocks, volcanic passive margins, oceanic plateaus, submarine ridges, seamount groups, and ocean basin flood basalts.

Some argue there are superplumes which build vast areas of oceanic plateaus and seamount clusters



The Mid-Cretaceous Superplume Episode

The earth has an erratic "heartbeat" that can release vast amounts of heat from deep within the planet. The latest "pulse" of the earth occurred 120 million years ago

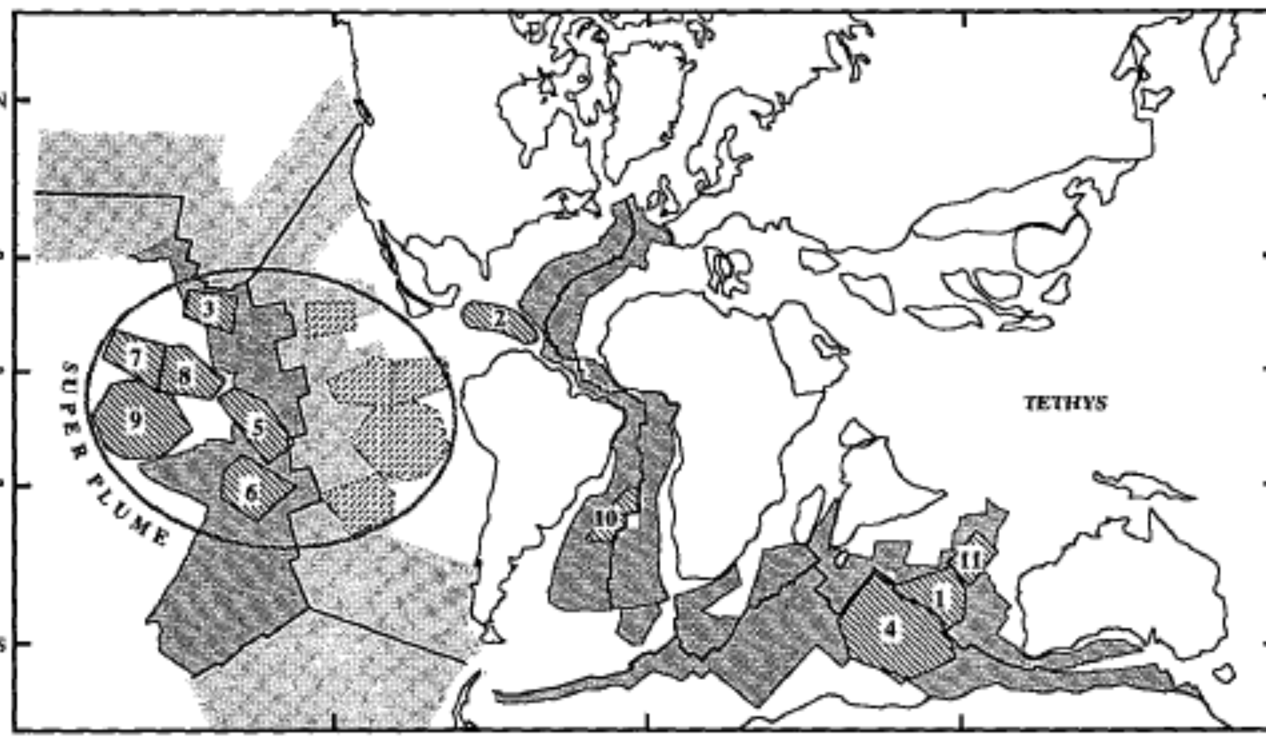
by Roger L. Larson

Larson's Mid-Cretaceous Superplume is perhaps the largest

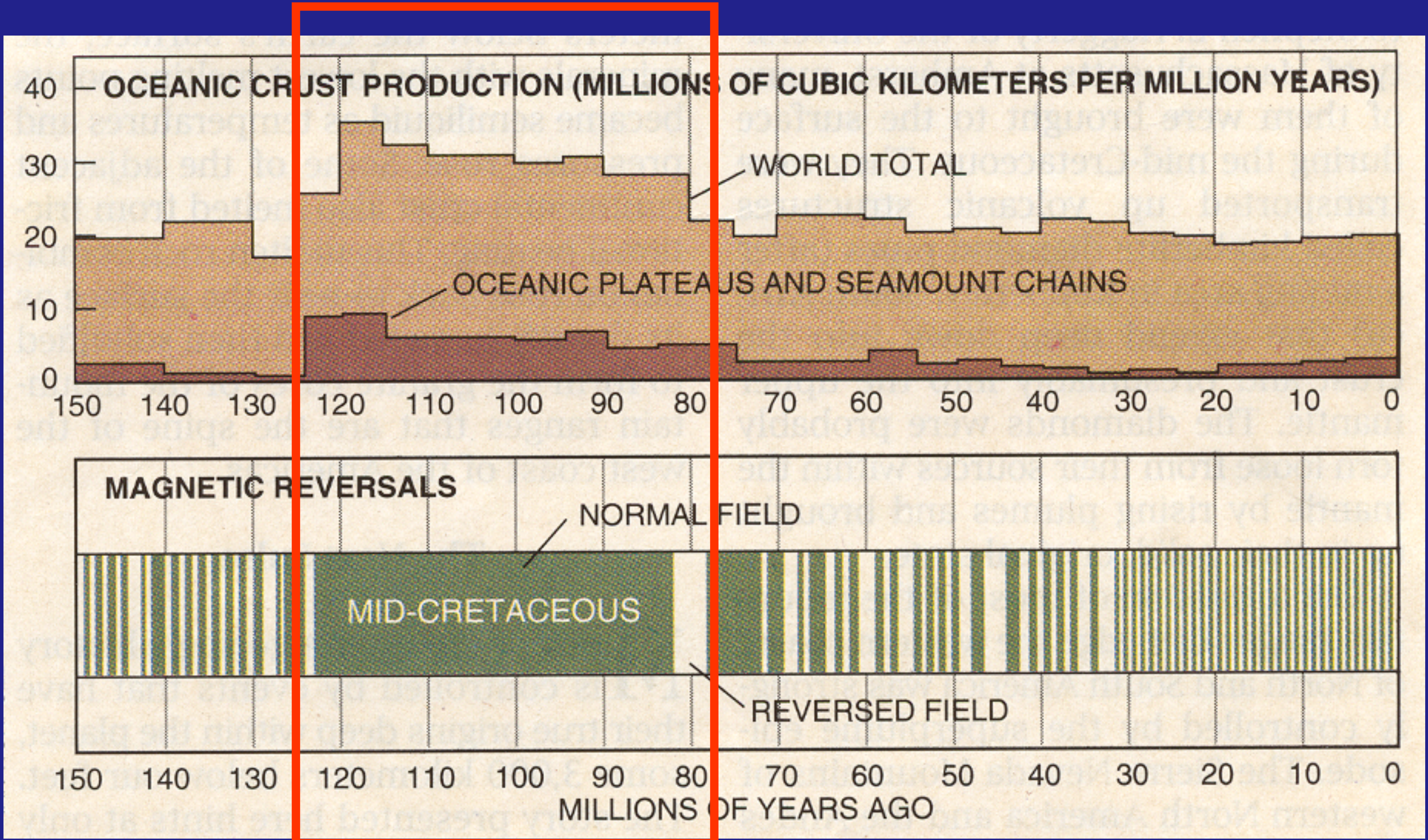
Reconstruction to anomaly 34

Dark areas = crust formed between M0 and 34

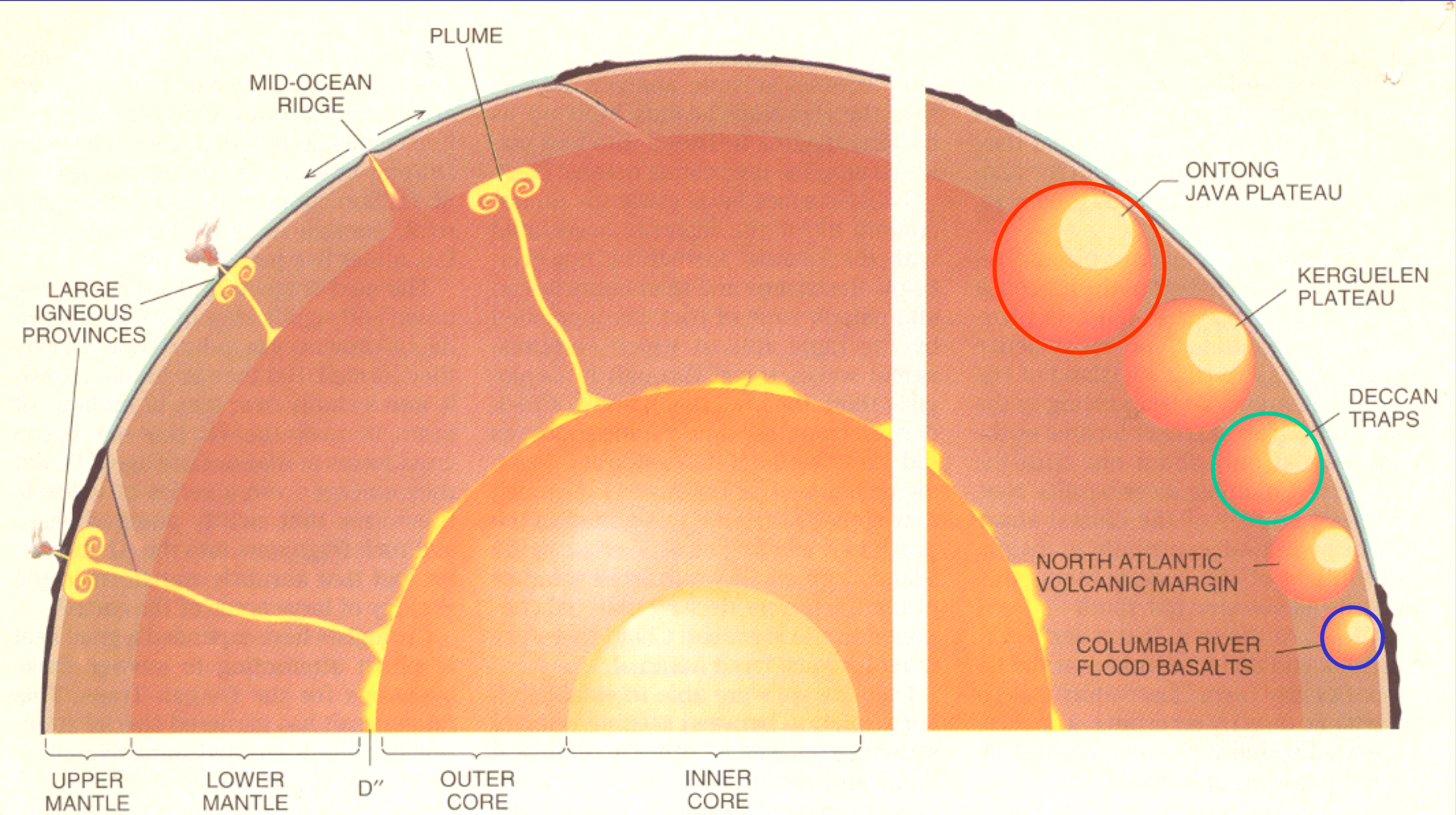
Polygons are aseismic ridges (and their conjugates) formed in this period



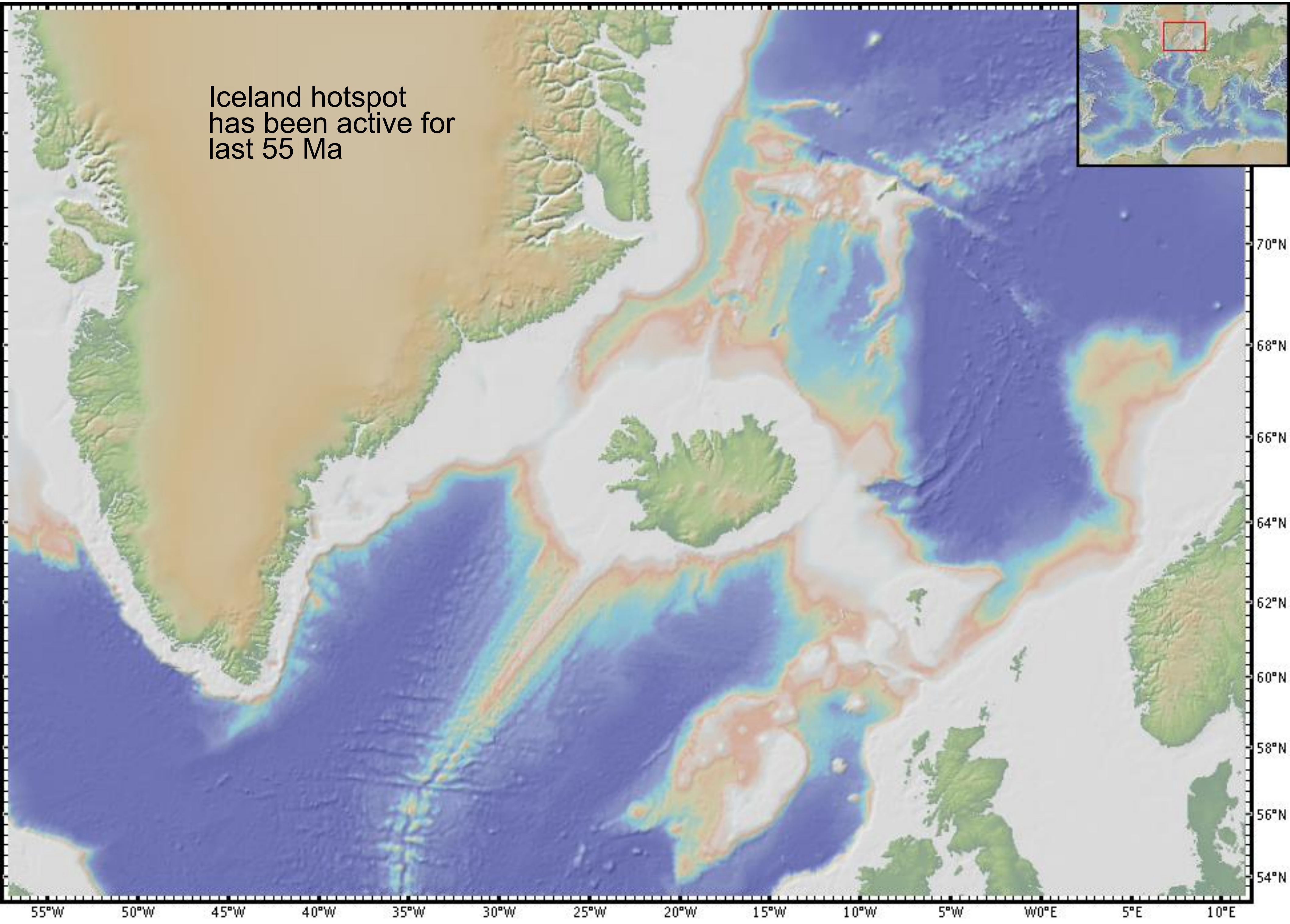
Some geologic consequences of the mid-Cretaceous superplume event



- Increase in the world-wide rate of oceanic crust production
- Shutdown in reversals of the earth's magnetic field



The largest LIPs are therefore in the oceans such as the Ontong Java Plateau in the Pacific and smaller LIPs are on the continents such as the Columbia River Flood Basalts with those in between at continental margins such as the Deccan Traps



Iceland hotspot
has been active for
last 55 Ma
70°N
68°N
66°N
64°N
62°N
60°N
58°N
56°N
54°N
55°W
50°W
45°W
40°W
35°W
30°W
25°W
20°W
15°W
10°W
5°W
W0°E
5°E
10°E

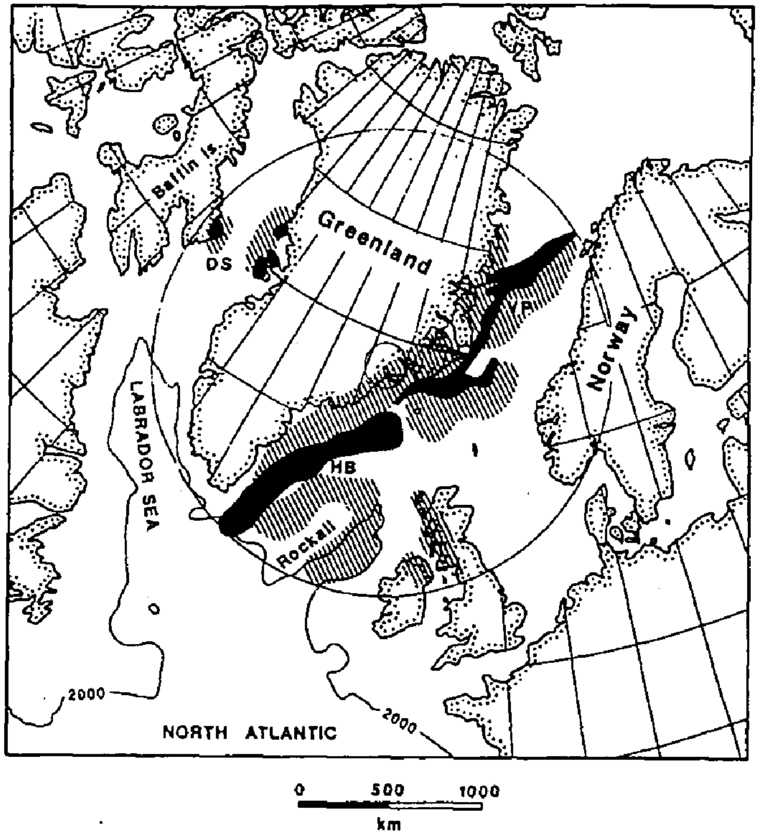


Fig. 8. Reconstruction of the northern North Atlantic region at magnetic anomaly 23 time, just after the onset of oceanic spreading. Position of extrusive volcanic rocks is shown by solid shading, with hatching to show the extent of early Tertiary igneous activity in the region. The inferred position of the mantle plume beneath east Greenland at the time of rifting and the extent of the mushroom-shaped head of abnormally hot asthenosphere are superimposed. Projection is equal area centered on the mantle plume.

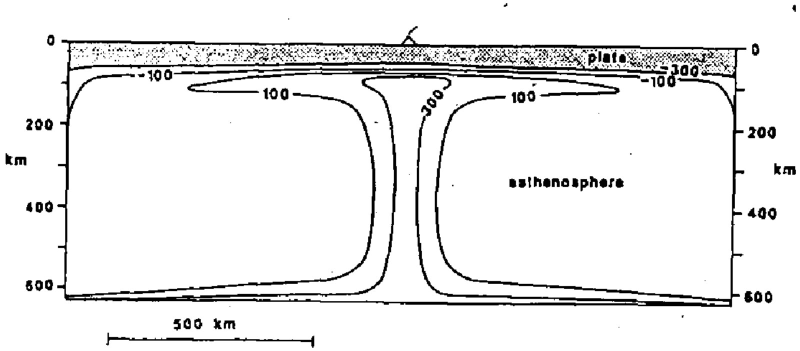


Fig. 2. Temperature variations seen in cross-section through the Cape Verde swell from the best fitting axisymmetric convection model of *Courtney and White* [1986]. Temperature anomalies are labeled in degrees Celsius with respect to the mean asthenosphere temperature. Note the narrow central rising plume and the broad mushroom-shaped head of hot material deflected laterally by the overlying plate.

Reconstruction of North Atlantic at 55 Ma

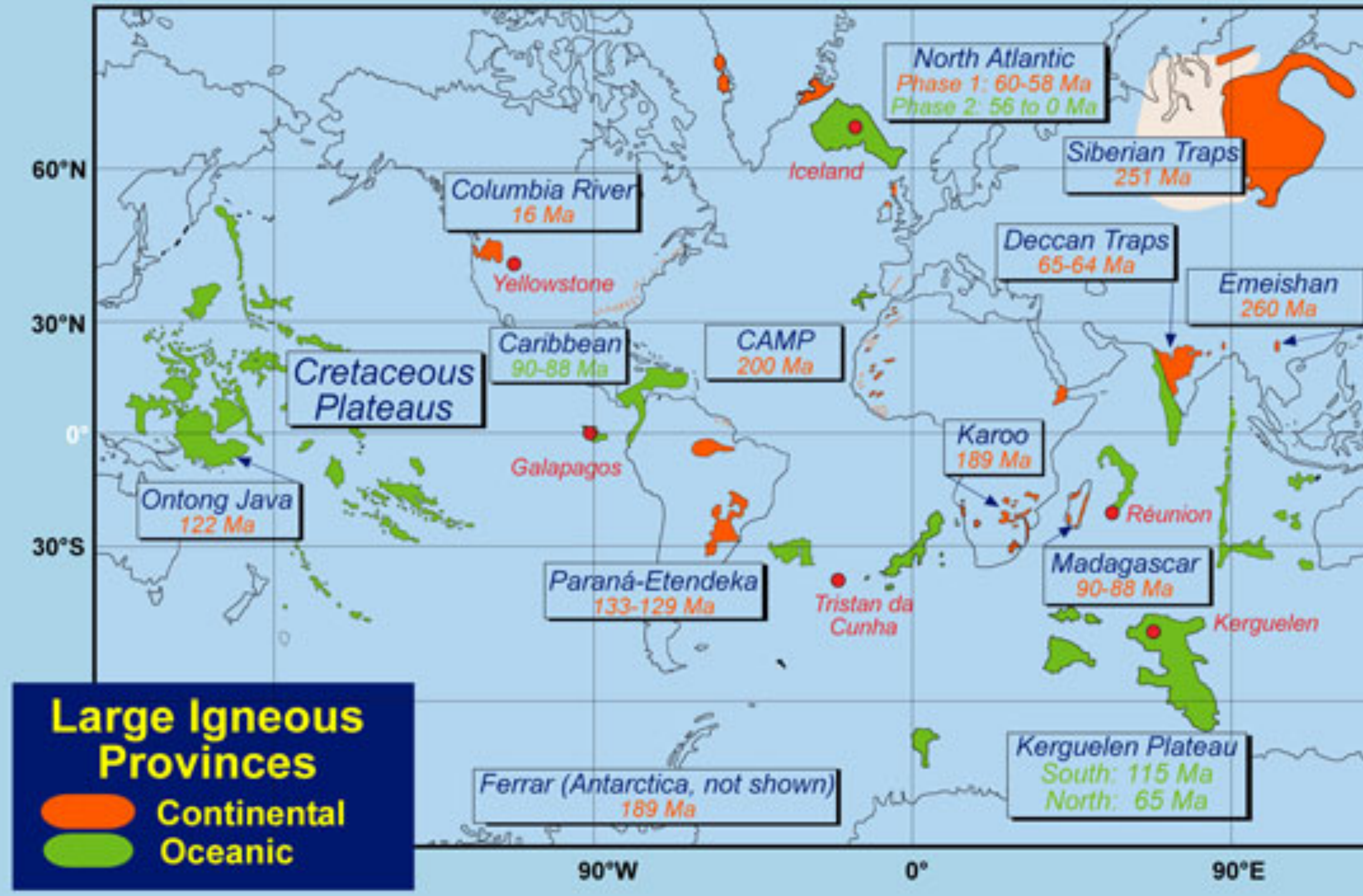
Rifting of Greenland and Norway in Early Tertiary (55 Ma) was associated with voluminous flood basalts (hatched areas)

Attributed to decompression melting of hot asthenosphere in a mantle plume (White and McKenzie)

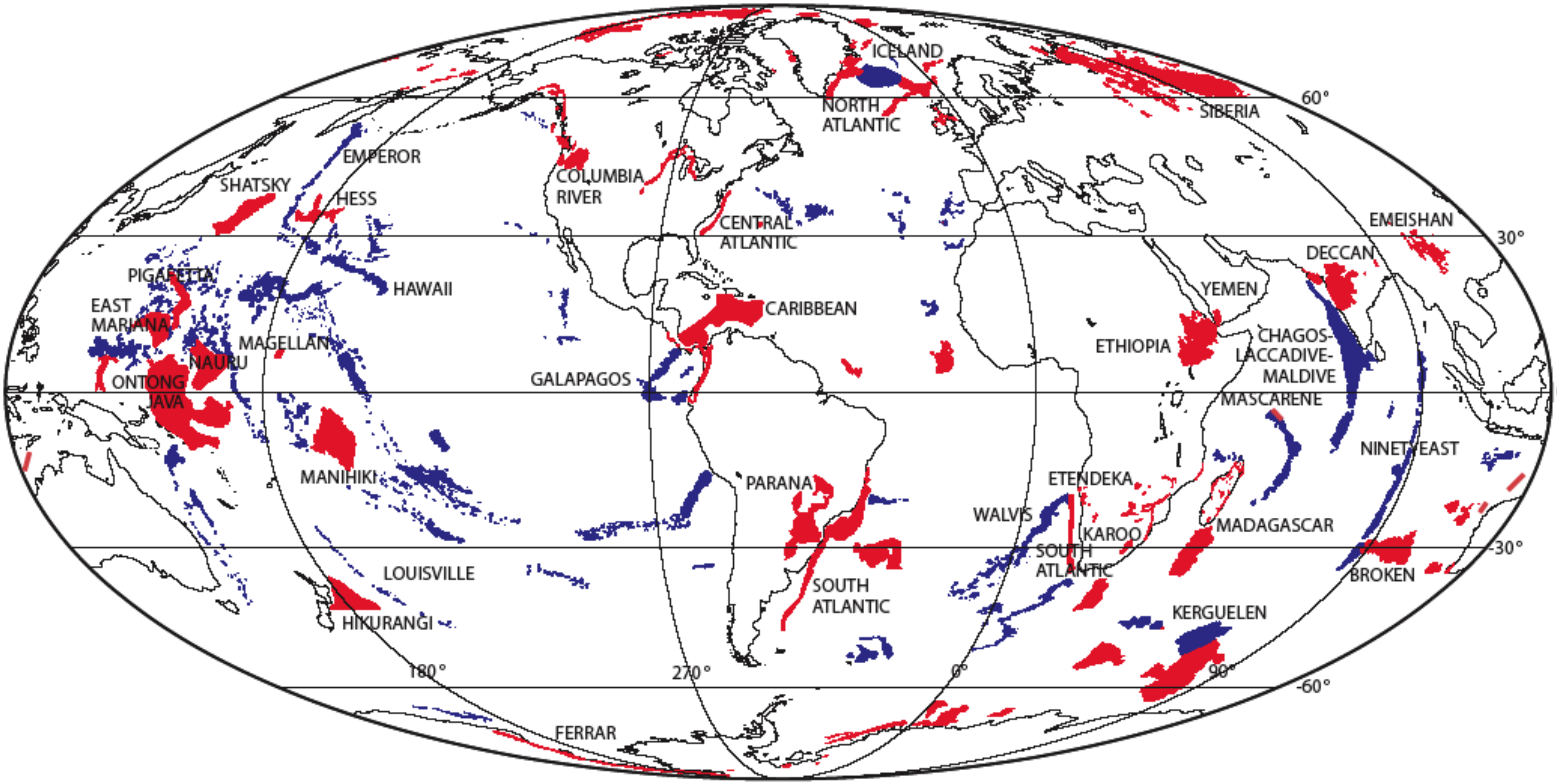
Plume head: 2000 km wide

Note that plume head volcanism mainly penetrated the thinned continental margin of Greenland

Other examples: Deccan Traps in India,
Parana/Etendeka in Brazil/Angola
Afar triple junction



Large Igneous Provinces
Continental
Oceanic
North Atlantic
Phase 1: 60-58 Ma
Phase 2: 56 to 0 Ma
Siberian Traps
251 Ma
Iceland
Columbia River
16 Ma
Yellowstone
Deccan Traps
65-64 Ma
Emeishan
260 Ma
Caribbean
90-88 Ma
CAMP
200 Ma
Cretaceous Plateaus
Galapagos
Karoo
189 Ma
Ontong Java
122 Ma
Réunion
Paraná-Etendeka
133-129 Ma
Tristan da Cunha
Madagascar
90-88 Ma
Kerguelen
Kerguelen Plateau
South: 115 Ma
North: 65 Ma
Ferrar (Antarctica, not shown)
189 Ma
60°N
30°N
0°
30°S
90°W
0°
90°E



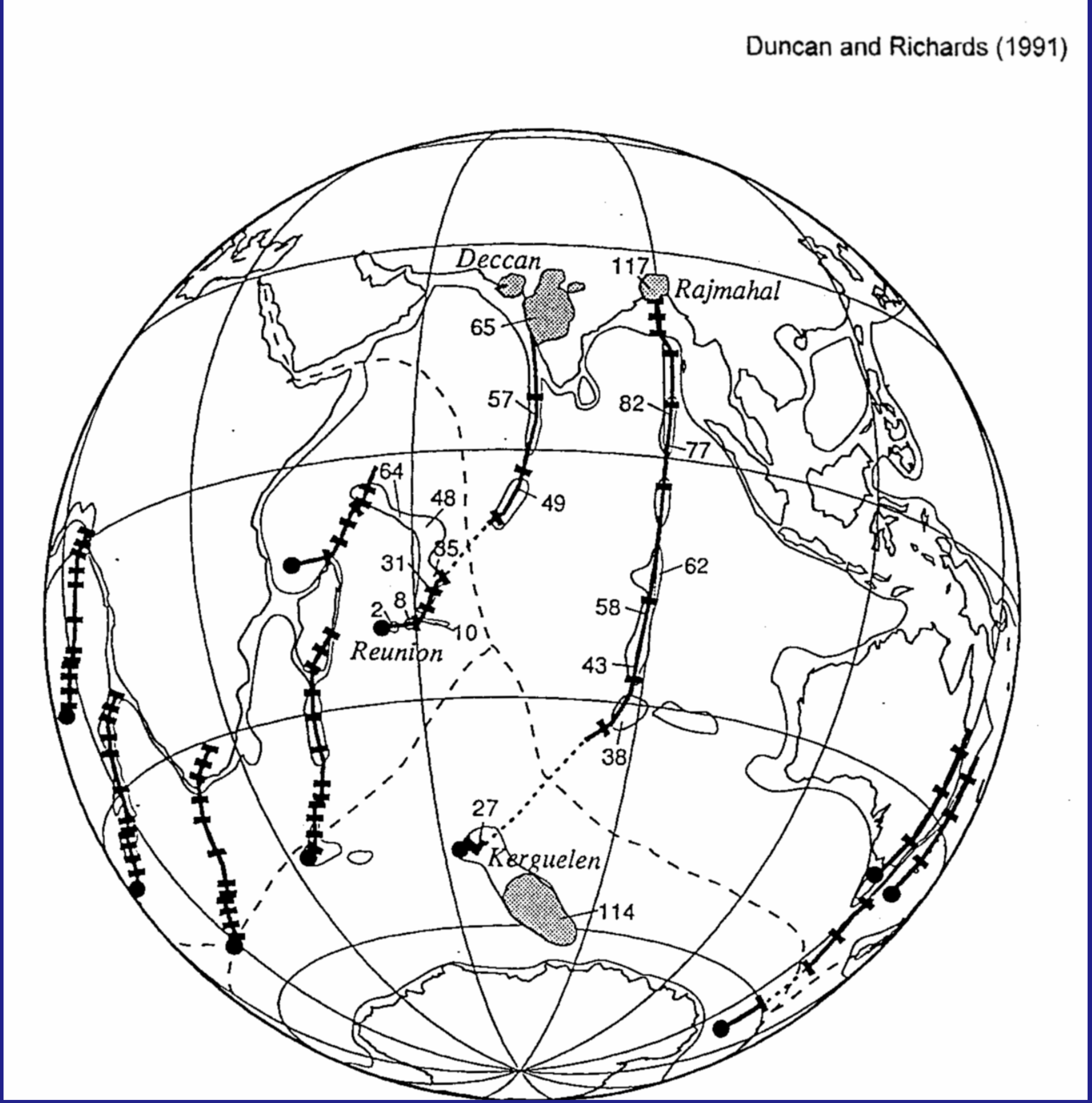
Another way of dividing them up:
Red = transient (plume head) LIPs;
Blue = persistent (plume tail) LIPs

Coffin 2006

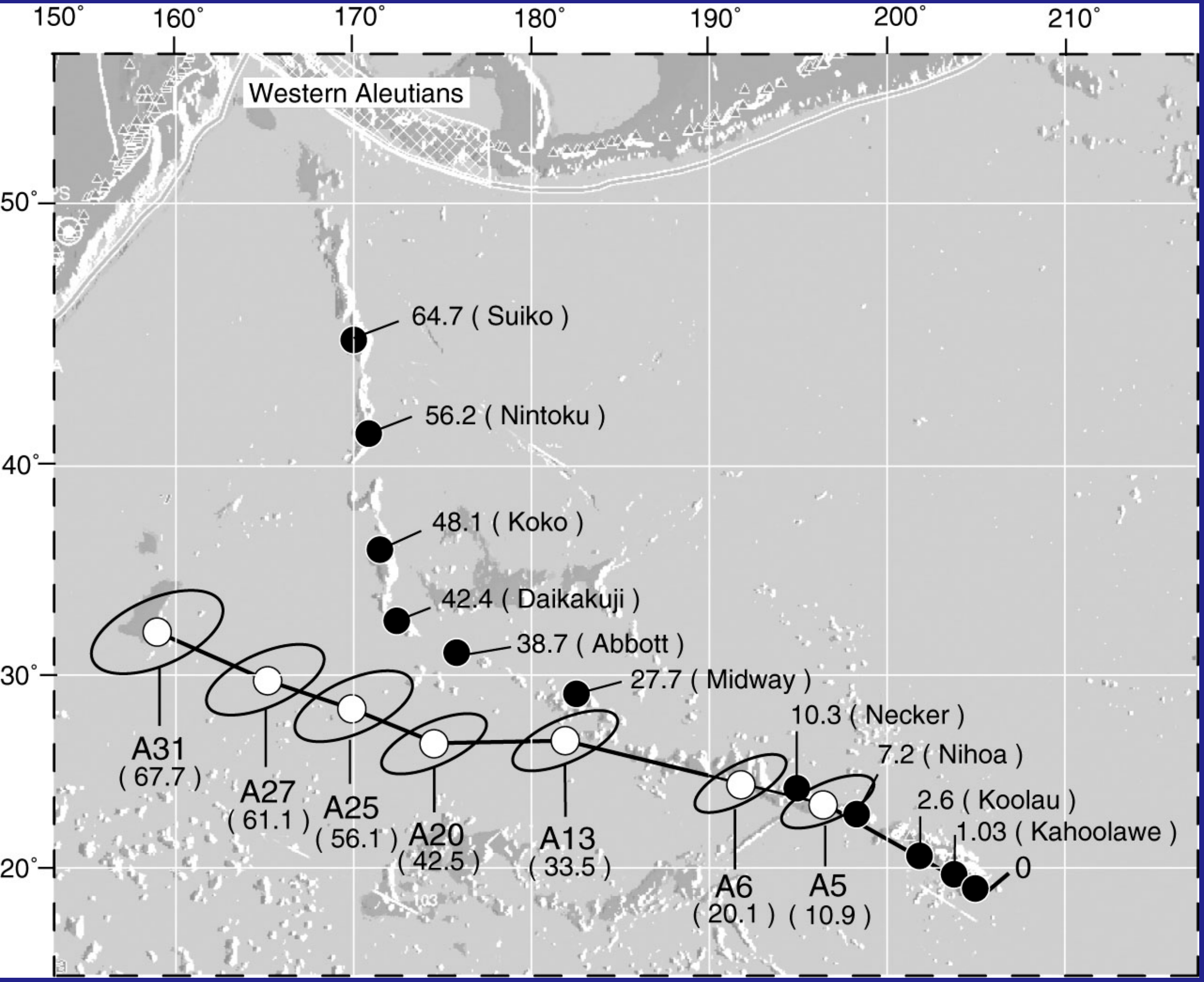
Two classic flood basalt provinces (LIPs) linked to hotspot track

Deccan/Chagos-Laccadive/Reunion

Rajmahal/90East Ridge/Kerguelen



Do hotspots form a fixed global reference frame?



White = predicted motion of Hawaii hotspot based on Indo-Atlantic hotspots and plate circuit

Initially constructed separate Indo-Atlantic and Pacific reference frames

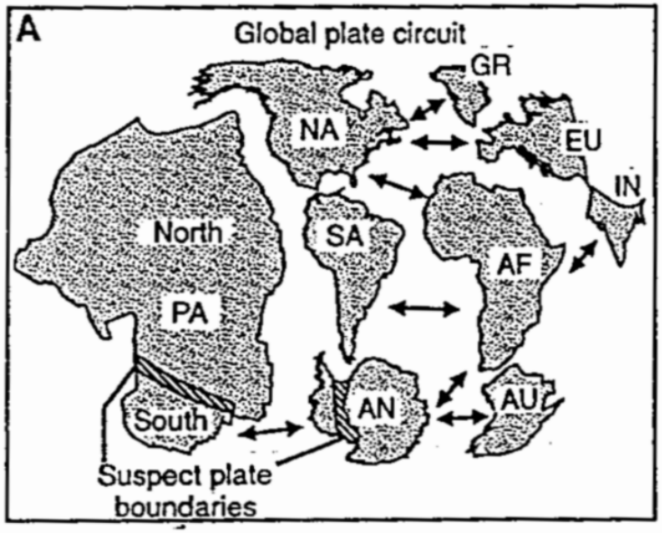
If global, should be able to predict motion of Hawaii hotspot based on Indo-Atlantic hotspot reference frame

Reconstructions failed to do this

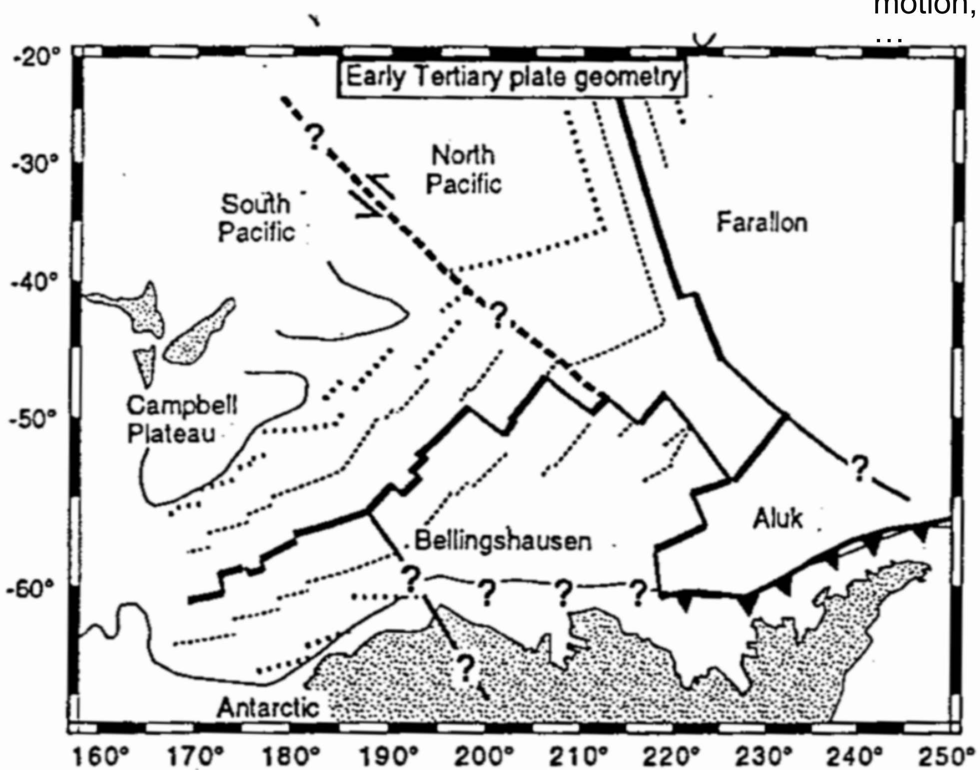
Major global tectonic puzzle

Why?

KK&V 5.10



Studied Antarctica margin, found some motion, but not enough …



Perhaps due to a missing plate boundary in plate circuit

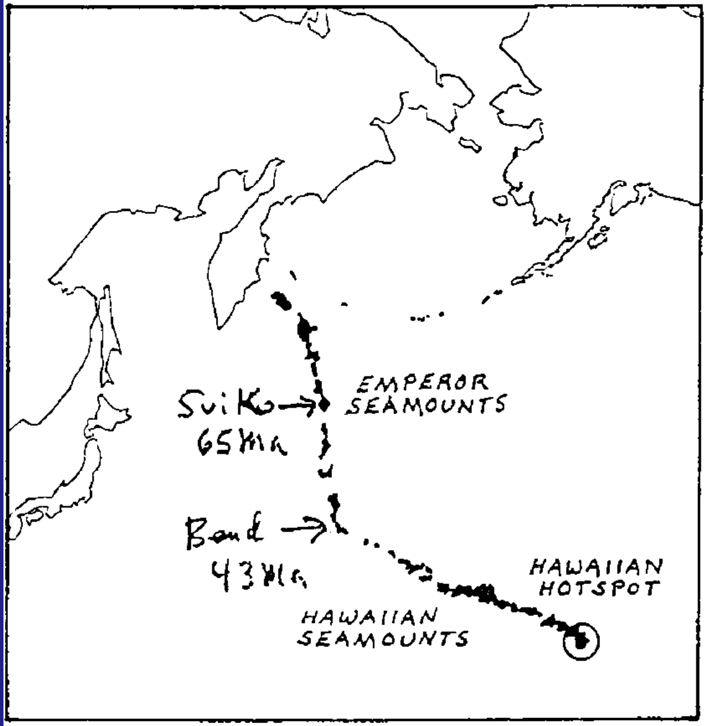
Most likely candidate: missing a boundary within Antarctica

This would lead to a bad plate circuit model

Or perhaps hotspots have drifted.

How can you test whether Hawaii has been “fixed” relative to mantle?

Paleomagnetics constrain drift of Hawaiian hitspoit



Latitude of Kilauea = 19°
Paleo-latitude of "Bend" = 19°
Paleo-latitude of Suiko Smt = 27°
(Based on paleo-inclinations of drilled rocks)

So – Hawaii Hotspot "drifted" 8° south between 65 and 43 Ma

Confirmed during ODP Leg 197
Drift of 30 to 50 mm/yr between 80 and 43 Ma.

If "fixed" relative to spin axis, hotspots should always be at the same paleomagnetic latitude

Why do hotspots drift?

Perhaps deep mantle plumes are deflected by mantle flow .
Why shouldn't they drift? Computer models suggest that they do – but these models are very dependent on the viscosity structure of the lower mantle – which is poorly known …

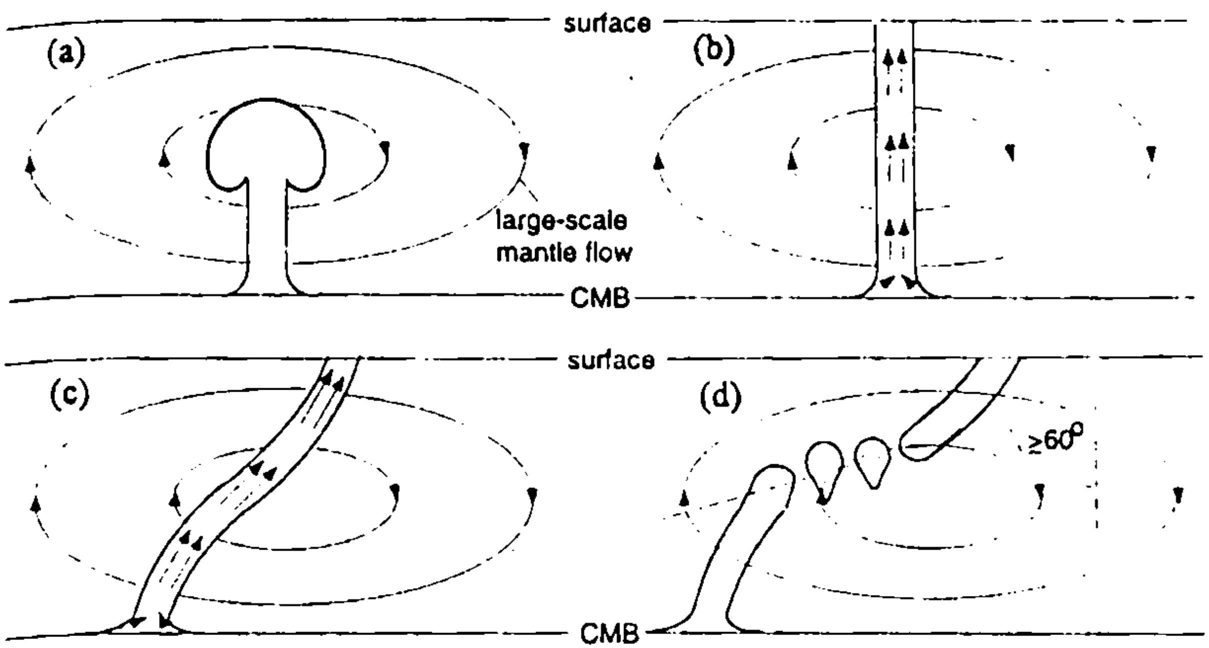
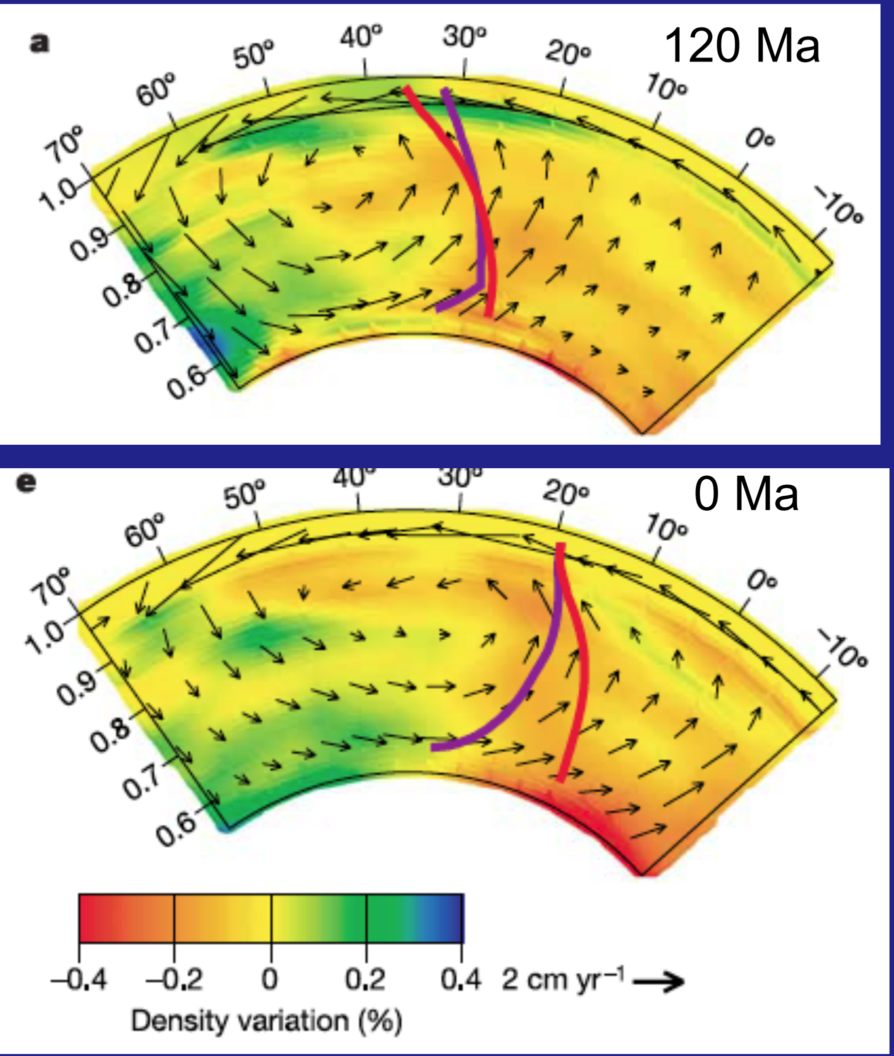


Figure 2. Four stages in the life of a mantle plume. (a) A rising plume consists of a plume head and a conduit. (b) After the plume head is erupted, the conduit is left behind. (c) A plume conduit gets distorted by mantle shear flow. (d) It splits up into several drops once the distortion gets too strong.

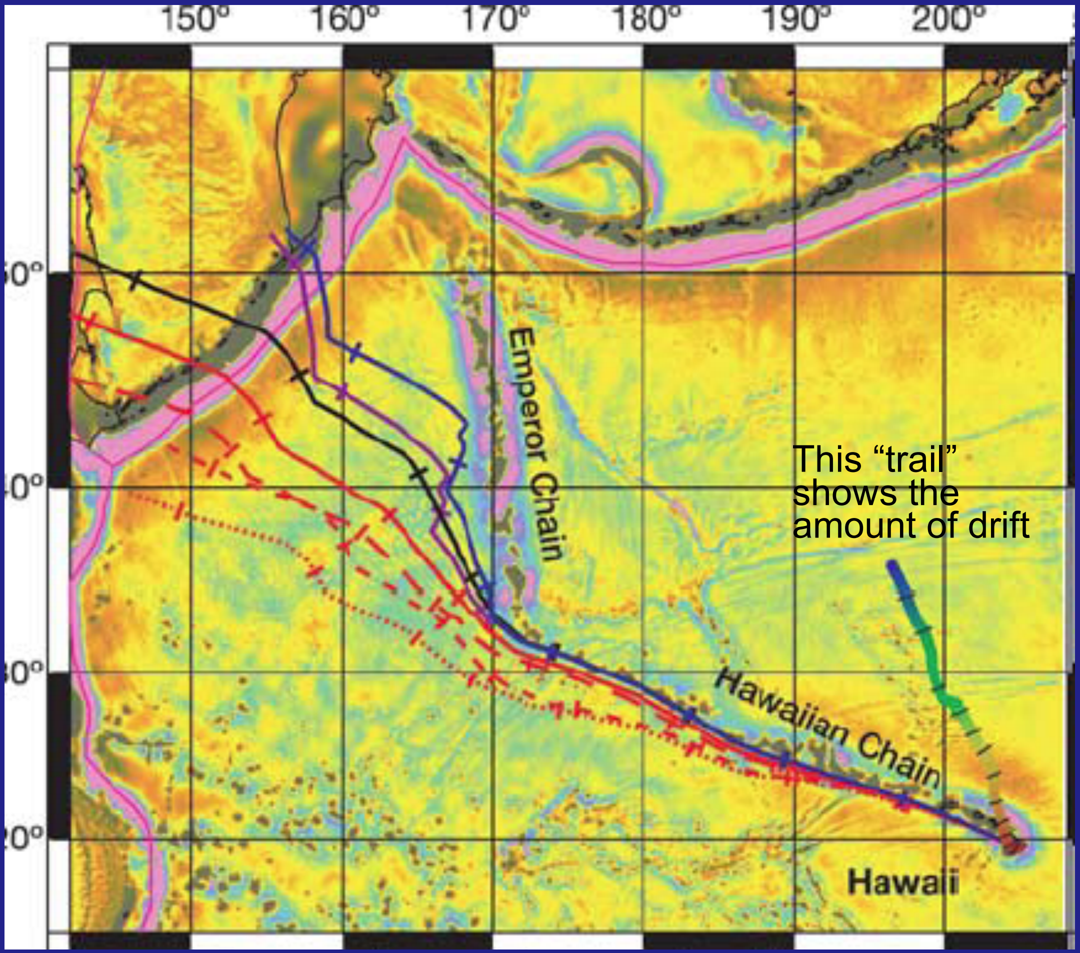
Steinberger and O'Connell (1998)



Note shift in latitude from 35° to 20°
In the red conduit, the source moves with flow

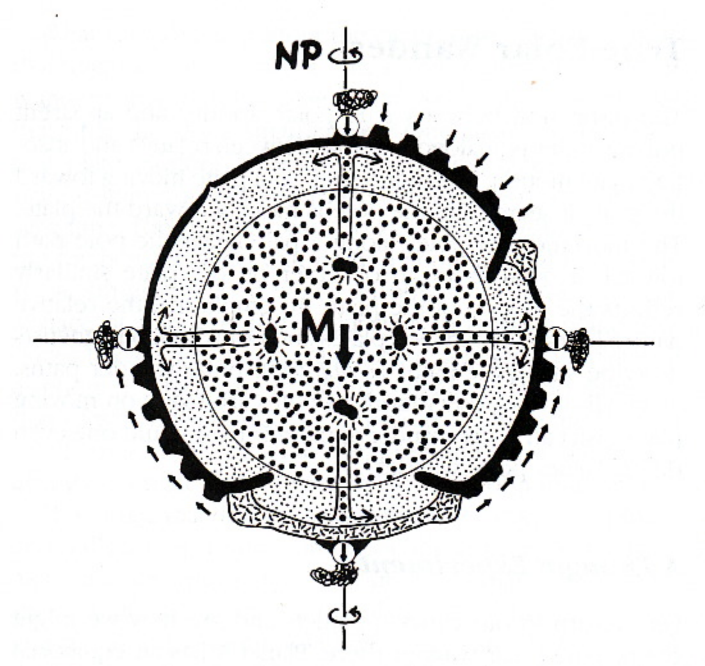
But why did it stop drifting at 45 Ma?

Predicted motion of Hawaiian hotspot based on mantle convection model



A little circular since viscosity in lower mantle is unknown and is manipulated until you get get the answer you like

Steinberger et al. (2004)

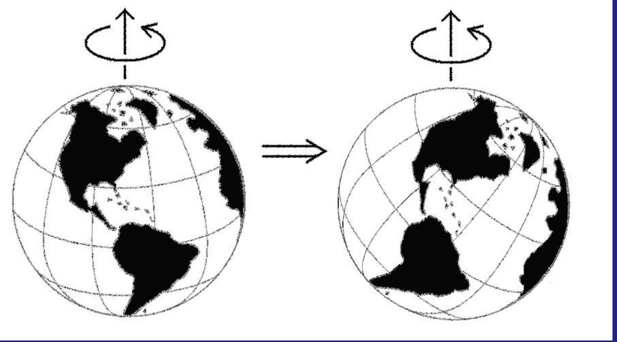


Another possibility:

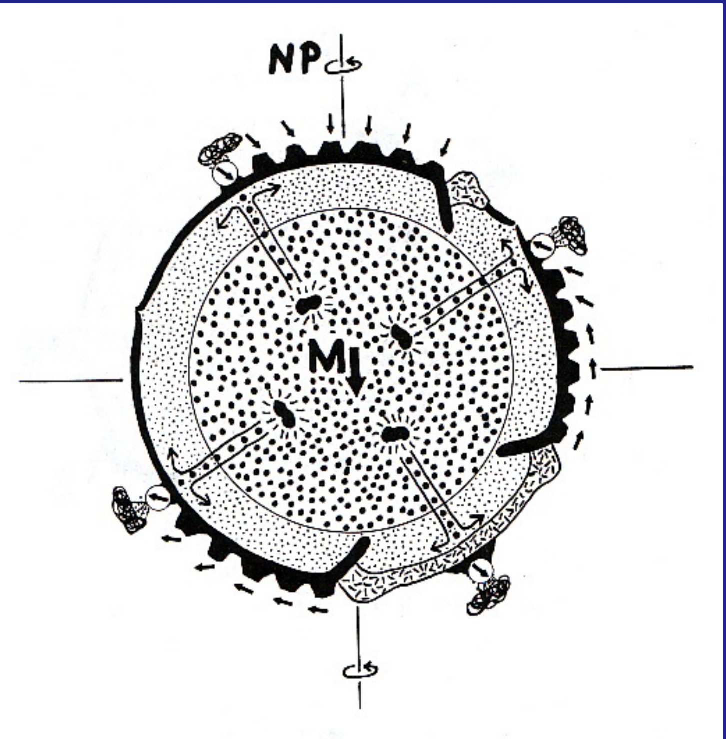
True polar wander (TPW): Does the spin axis shift with respect to the solid earth?

Normally the mantle and hotspots, on average, do not move with respect to spin axis

Magnetic inclination as recorded by seamounts, on average, do not change over time



Andrews (1985)

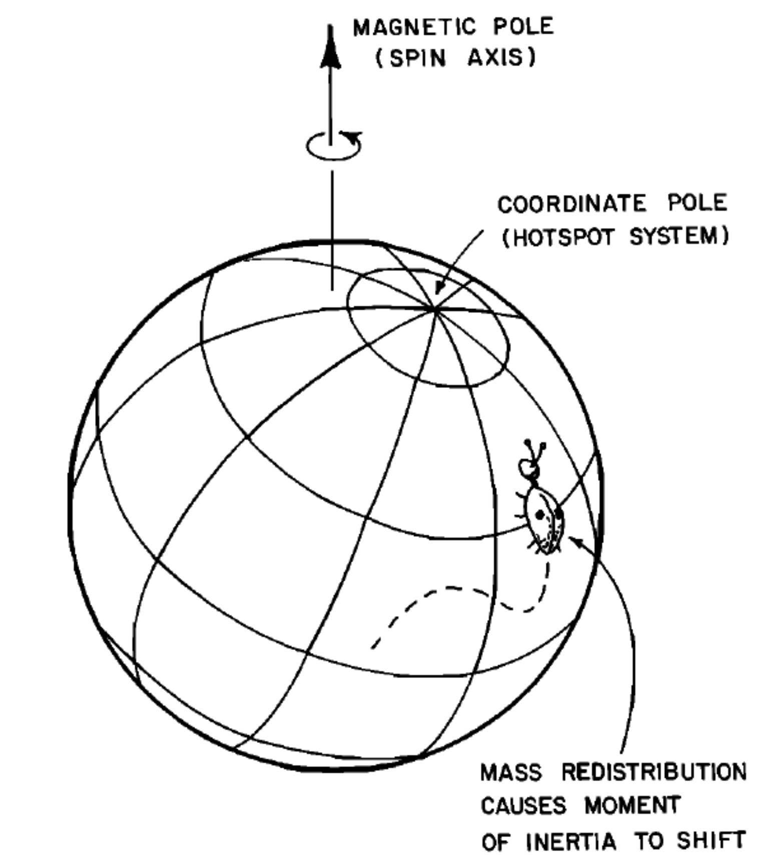


True polar wander:

Entire solid earth gradually (~1° /m.y.) shifts with respect to spin axis.

The earth's magnetic field stays aligned with the spin axis

The inclinations of hotspots will record this shift in the spin axis.



Cox and Hart

So, perhaps change in inclination of Hawaiin hotspot reflects shift in mantle w.r.t. spin axis

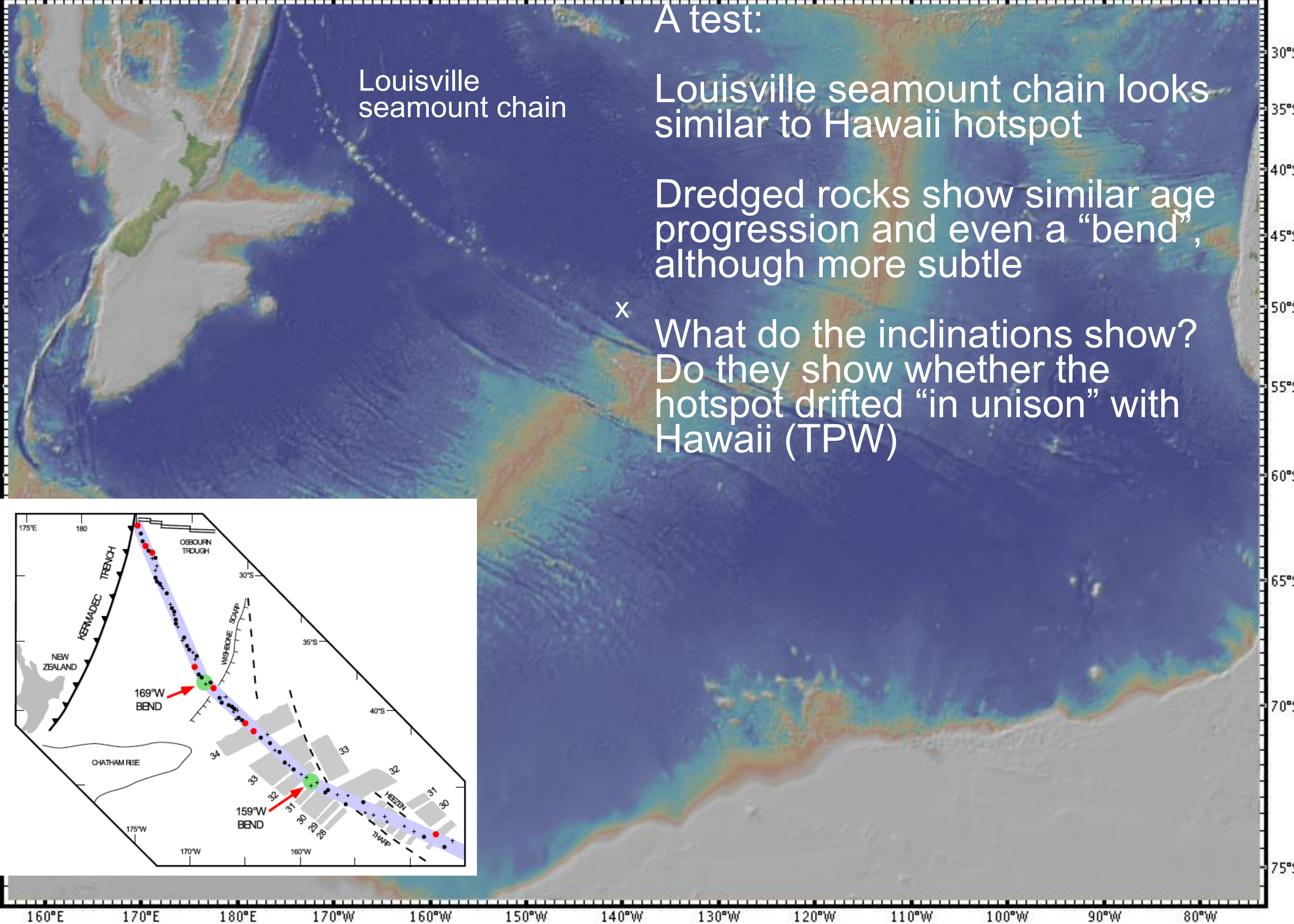
Test?

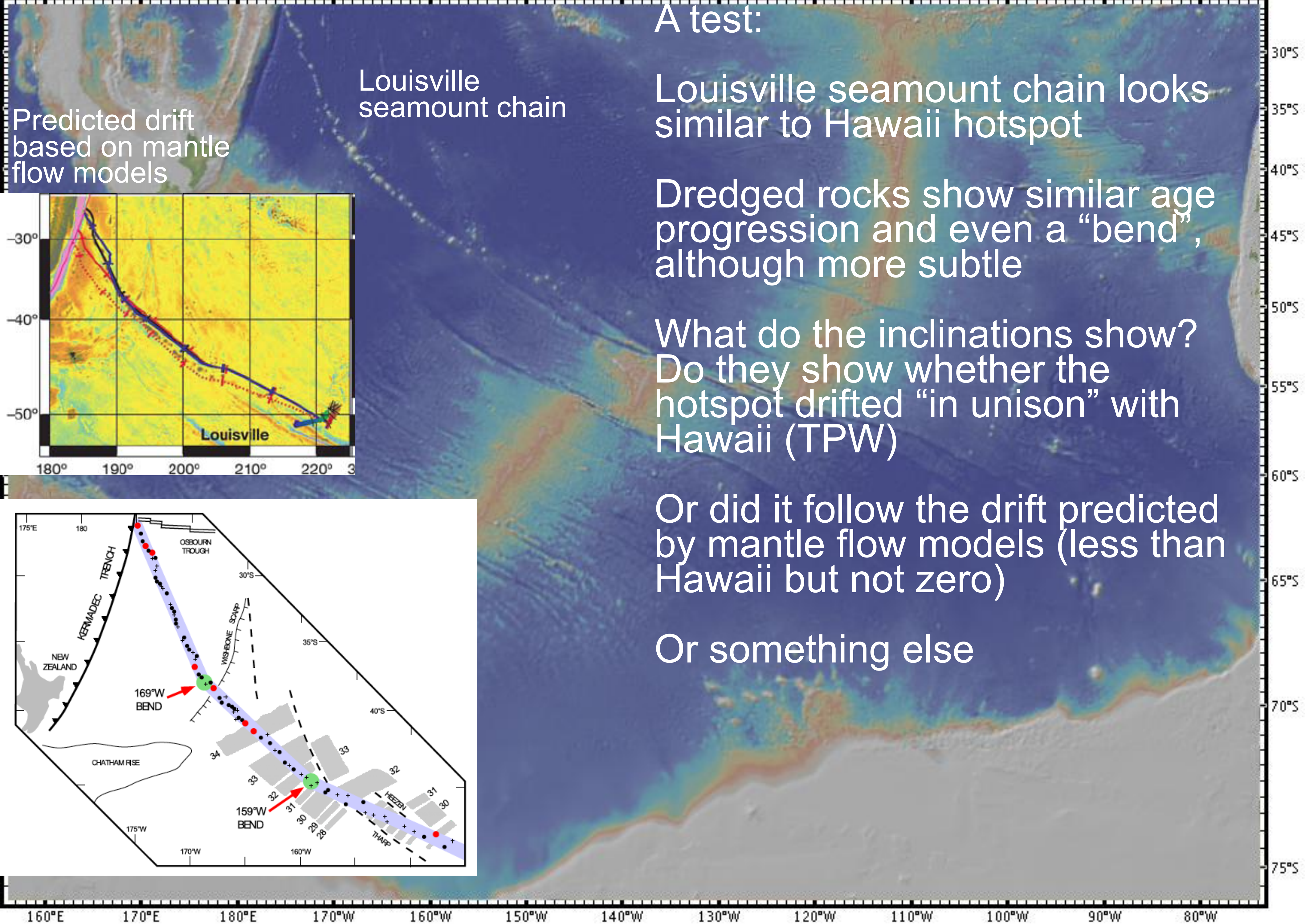
A test:

Louisville seamount chain looks similar to Hawaii hotspot

Dredged rocks show similar age progression and even a “bend”, although more subtle

What do the inclinations show? Do they show whether the hotspot drifted “in unison” with Hawaii (TPW)





A test:

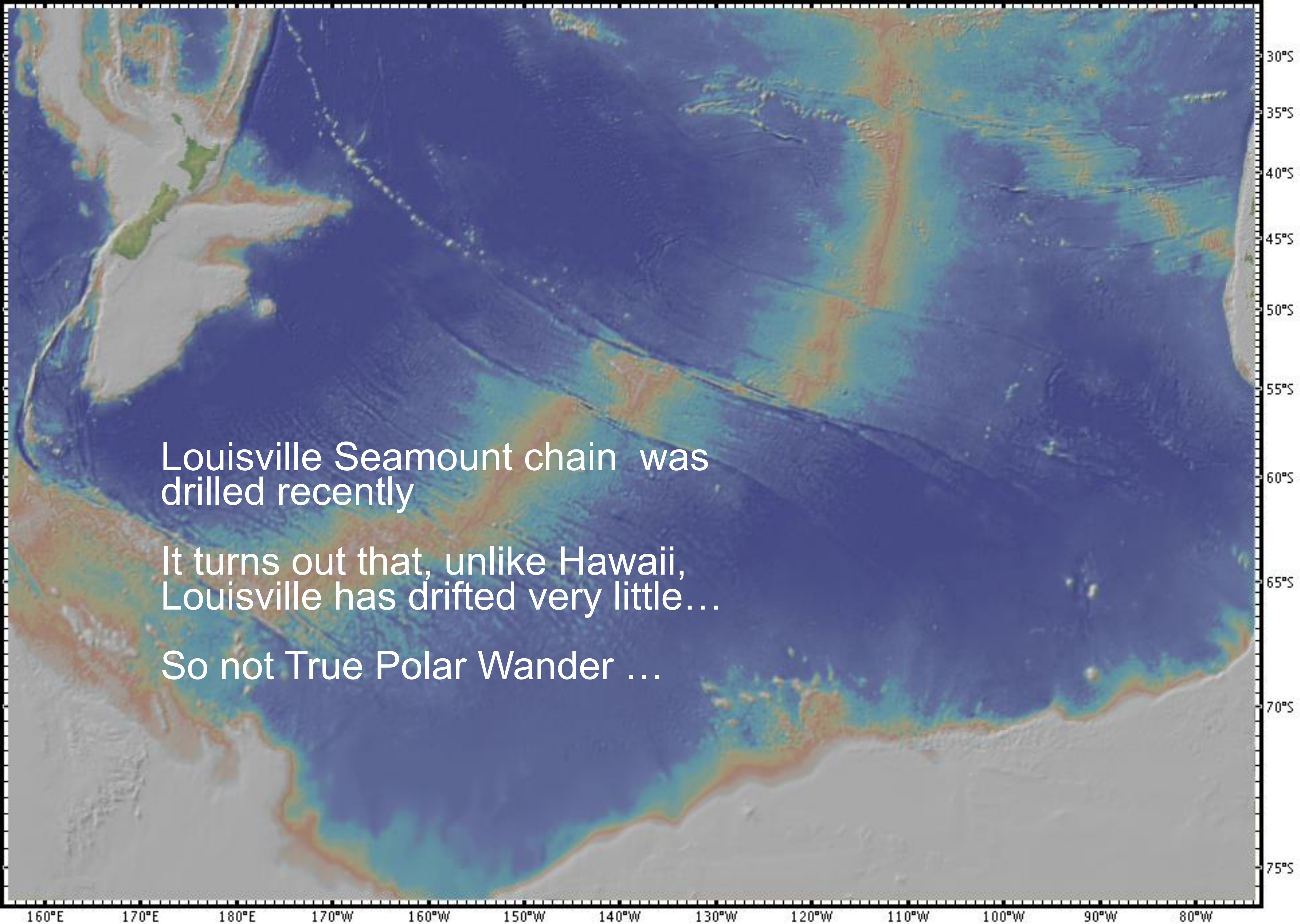
Louisville seamount chain looks similar to Hawaii hotspot

Dredged rocks show similar age progression and even a "bend", although more subtle

What do the inclinations show? Do they show whether the hotspot drifted "in unison" with Hawaii (TPW)

Or did it follow the drift predicted by mantle flow models (less than Hawaii but not zero)

Or something else

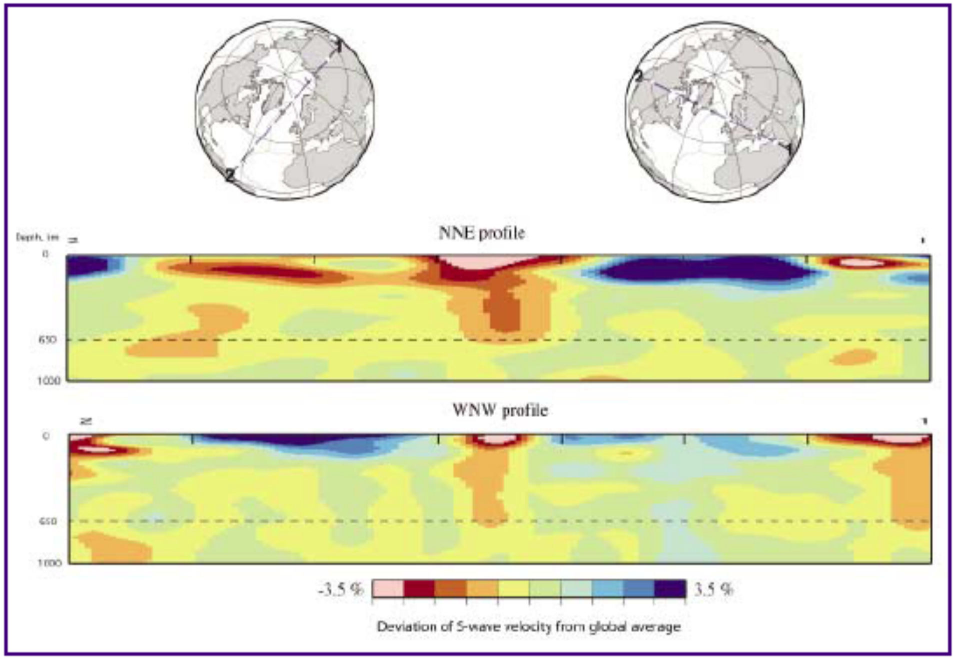


Louisville Seamount chain was drilled recently

It turns out that, unlike Hawaii, Louisville has drifted very little…

So not True Polar Wander …

So, are hotspots Deep Mantle plumes?
There are some who are skeptical.
MantlePlumes.org web site of Gillian Foulger



4: Cross sections through a whole-mantle tomography model (Ritsema *et al.* 1999) showing structure in the top 1000 km of the mantle at Iceland. (Courtesy of J Ritsema.)

Plume conduits should go down to Core Mantle boundary

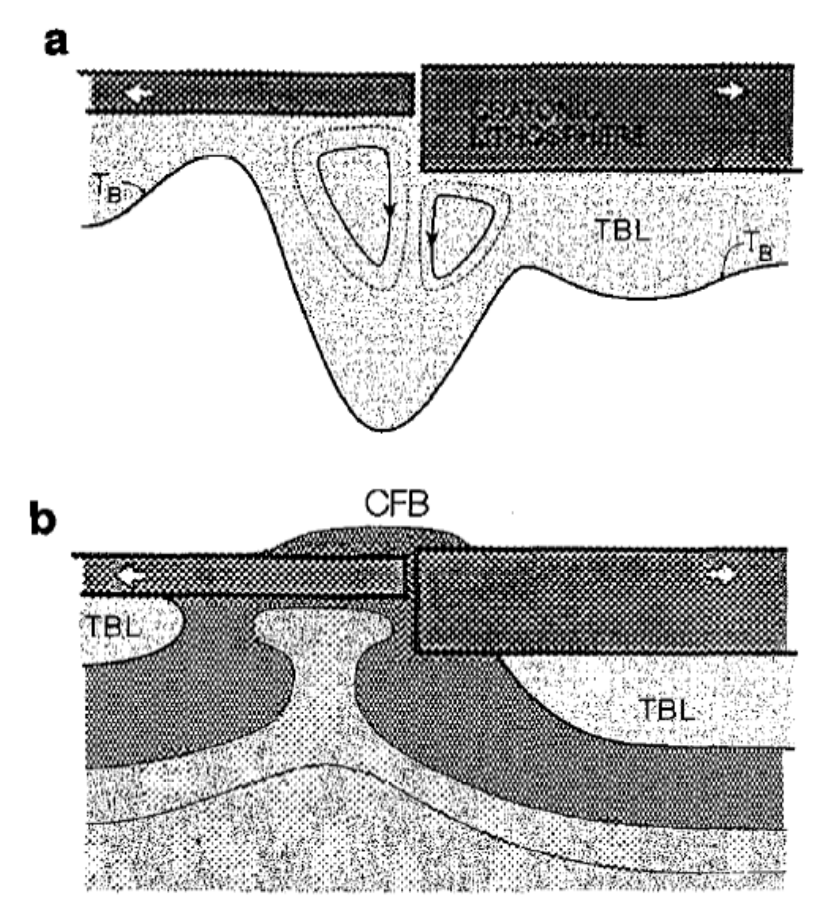
But only see them down to 400 km (limitation of method; conduits are too small to by imaged by normal mantle tomography)

Hotspots have distinctive chemistry: “enriched”, primitive mantle so skeptics have to come up with odd scenarios to explain

Foulger: Iceland due to passage of ridge over ancient suture zone

The excessive melt production at the Iceland volcanic province can be explained by high mantle fertility associated with an ancient subduction zone – the Caledonian suture, where it is crossed by a spreading ridge. This has given rise to locally excessive melting and consequential thick crust and complex, unstable tectonics. This interpretation of Iceland attributes

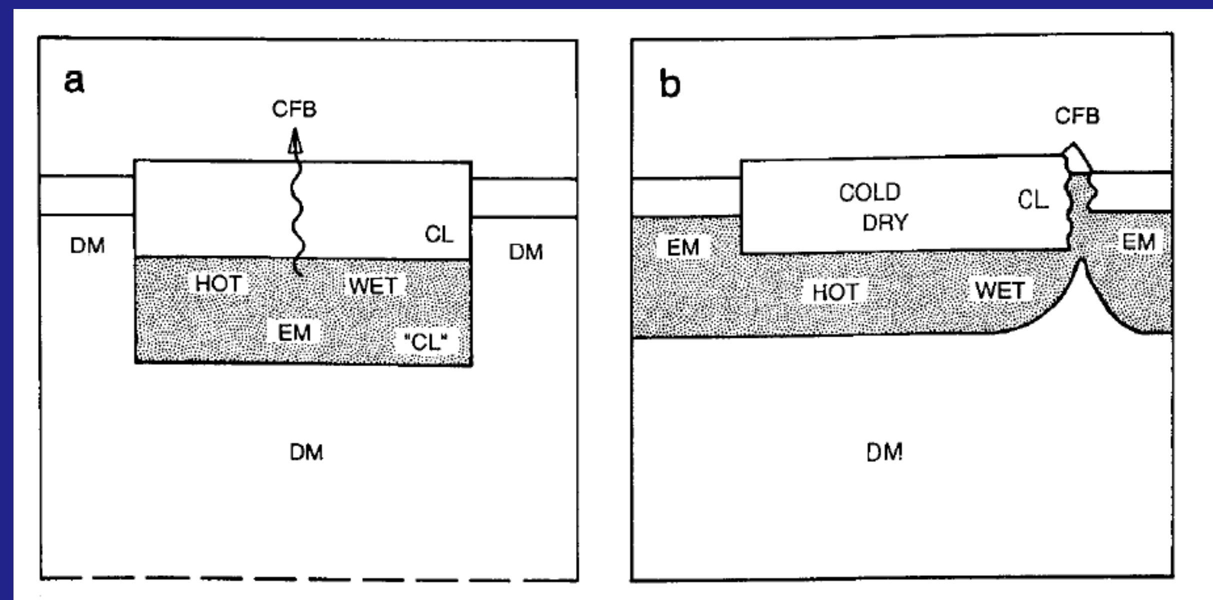
Foulger (2008)



Don Anderson has an alternative model for chemistry of hotspots

Continental rifting leads to upwelling which leads to continental flood basalts

Tap into shallow source of enriched mantle

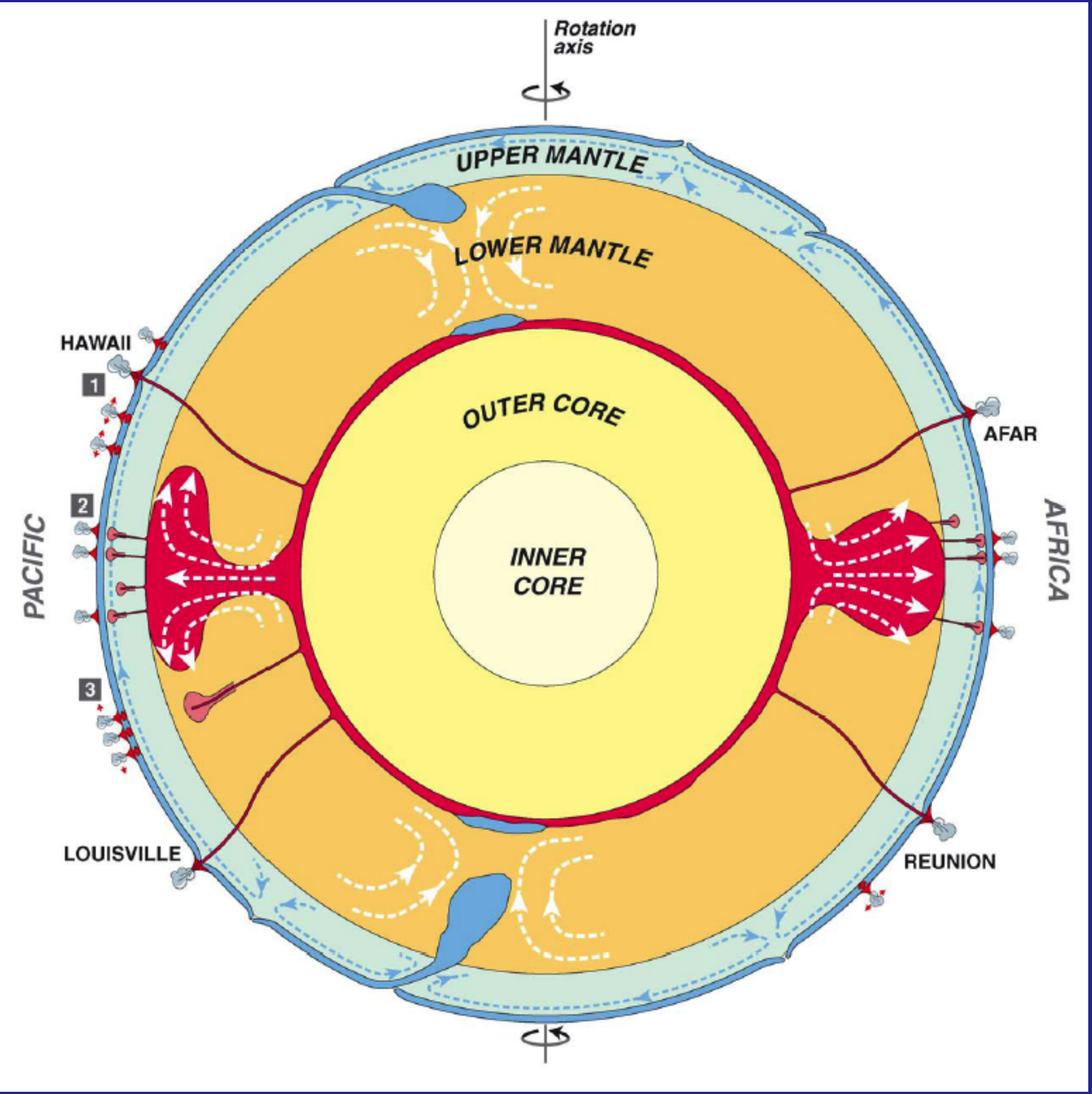


TBL = thermal boundary layer
CFB = continental flood basalts

Conventional model (left) has Depleted mantle (DM) beneath oceans and continents

Anderson model (right) has a shallow layer of enriched mantle (EM)

Anderson (1994)



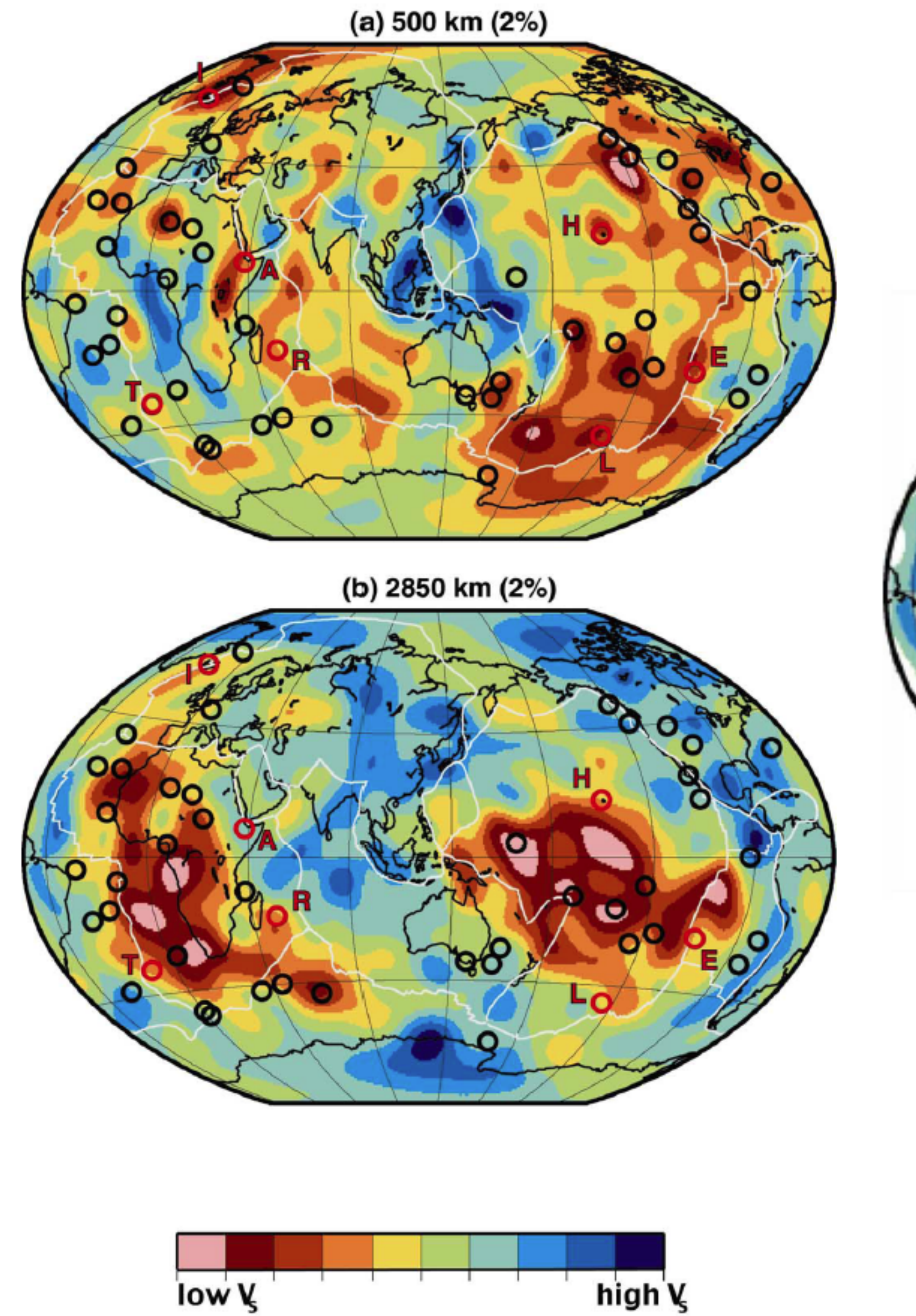
Middle ground?

Not all hotspots come from deep mantle plumes

Some may come from the top of domes near the transition zone

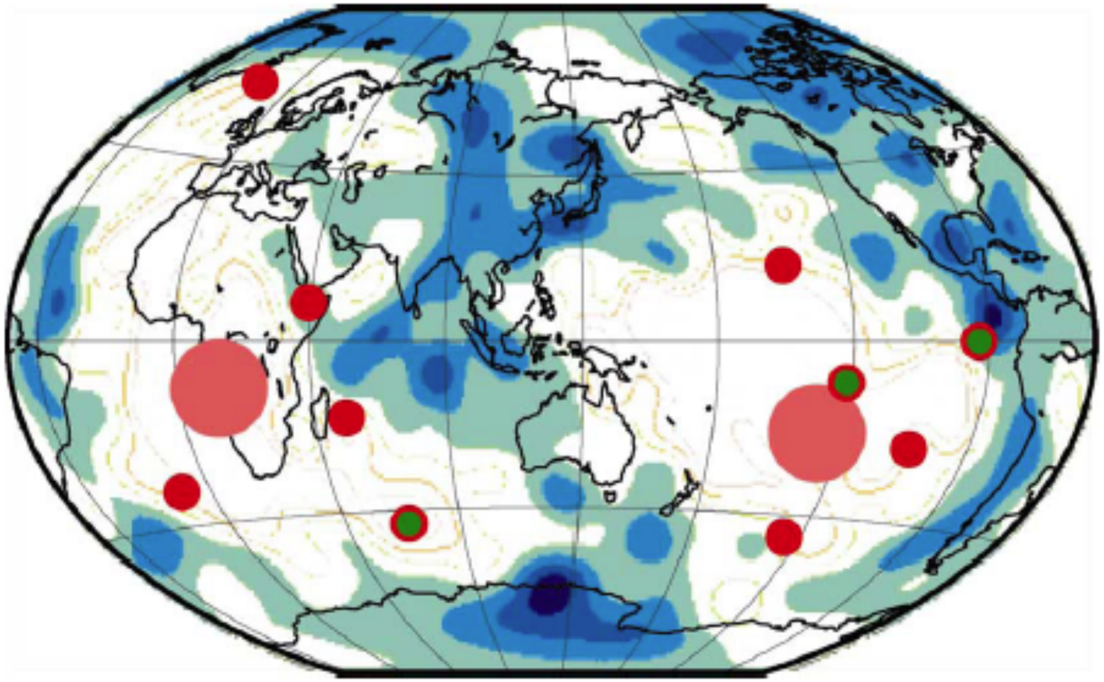
Still others may have a shallow origin due to cracks in lithosphere

Courtillot et al. 2003



Courtillot et al. 2003

Map of 49 hotspots relative to velocity anomalies at 500 km and 2850 km

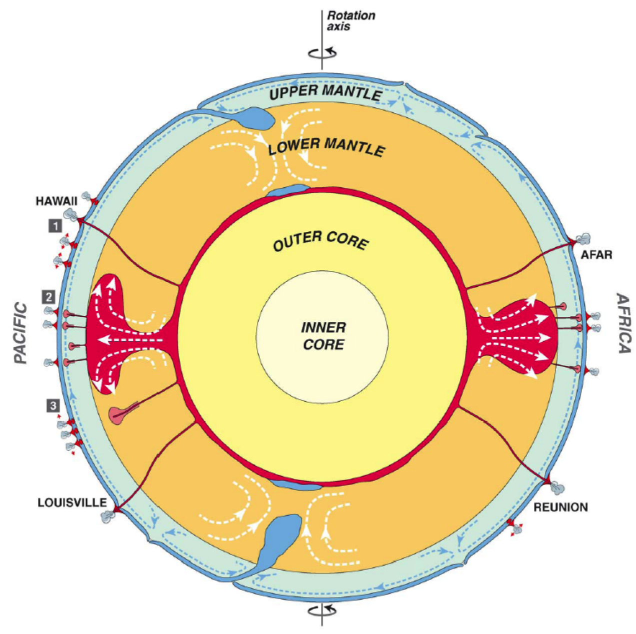


Above, only show fast (blue) anomalies at 2850 km

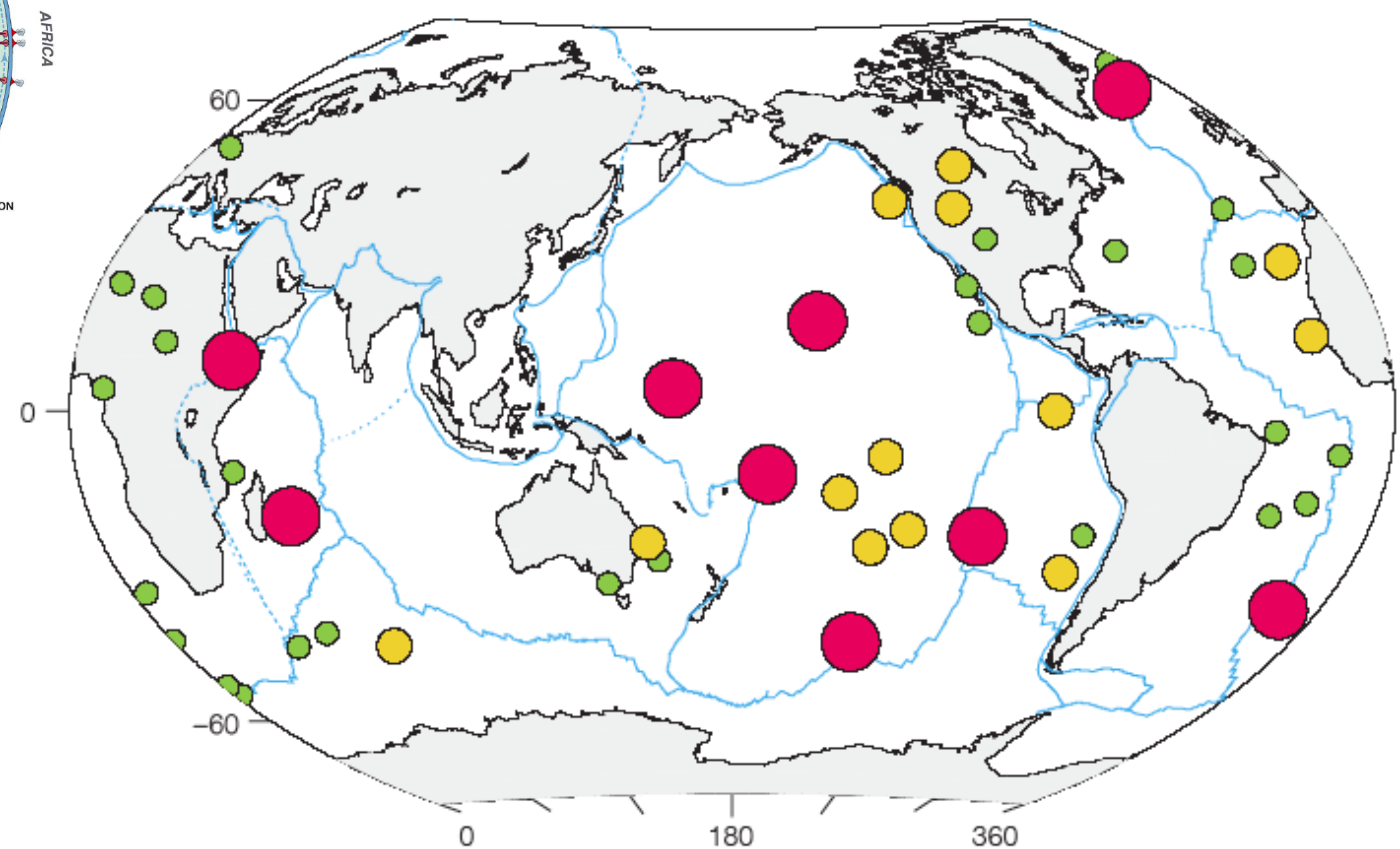
Lower mantle superswells are large pink dots

Seven primary hotspots in red; 3 others are green with red margins

Primary hotspots form above edges of superswells



Source of plumes:
Red = core mantle boundary
Yellow = base of upper mantle
Green = in the lithosphere



DePaolo and Foulger (2003)