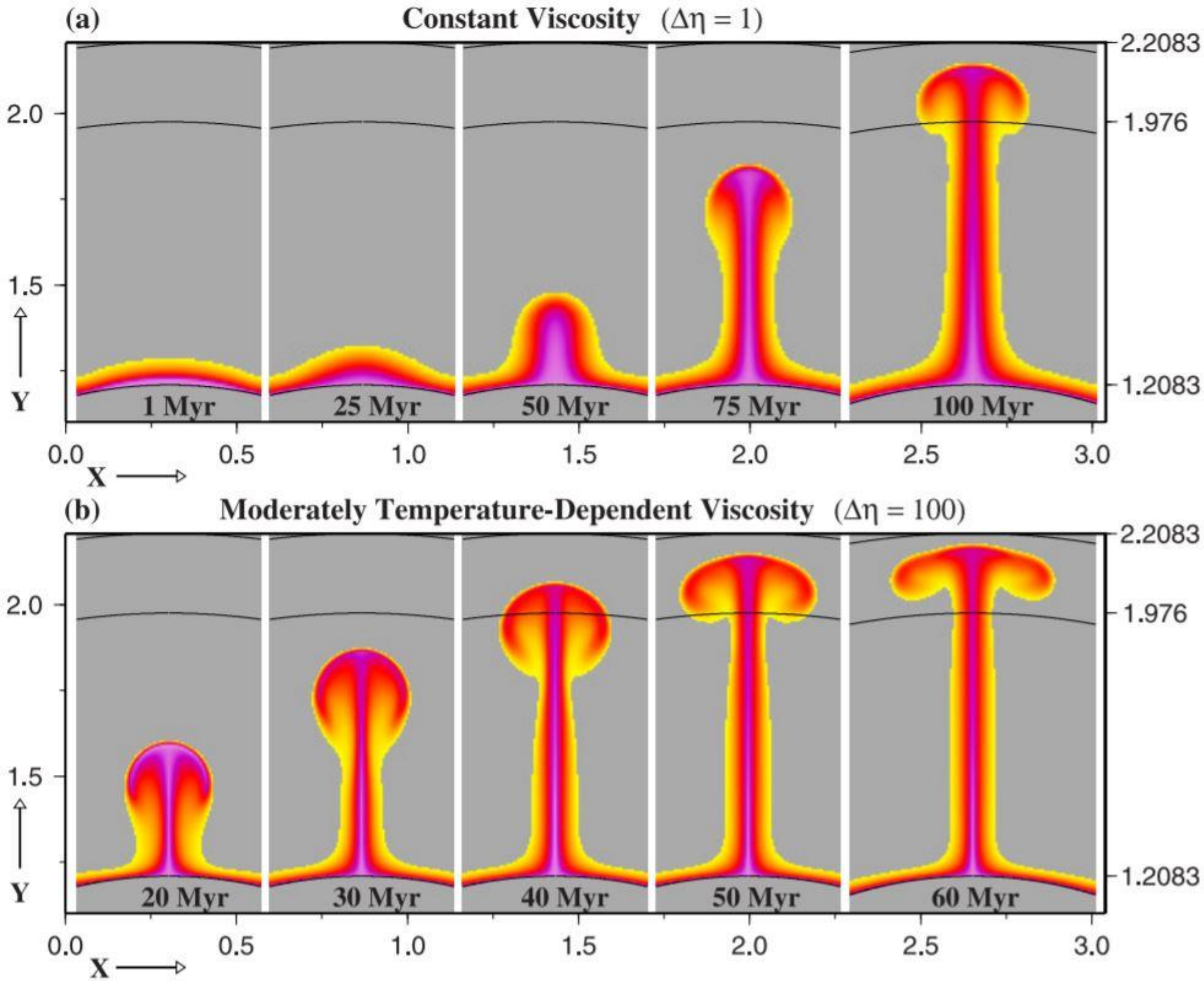
How long do plumes take to rise through the mantle?

Bernhard Steinberger (GFZ, CEED) **with contributions from Peter Nelson and Trond Torsvik**

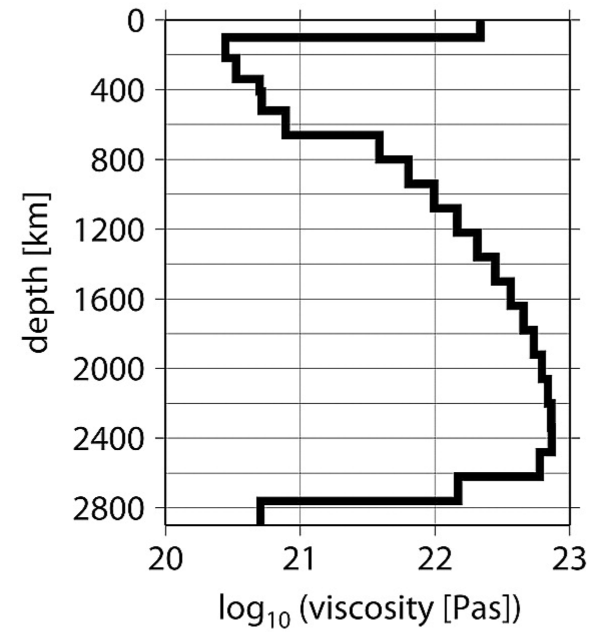
1) From Lin and van Keken (2006)

- Purely thermal plume
- Lower mantle viscosity 10^{22} Pas



2) Analytical estimate (Stokes formula)

- Viscosity from Steinberger & Calderwood (2006)



- Density contrast 30 kg/m^3
- Head diameter 1000 km (Campbell, 2007)

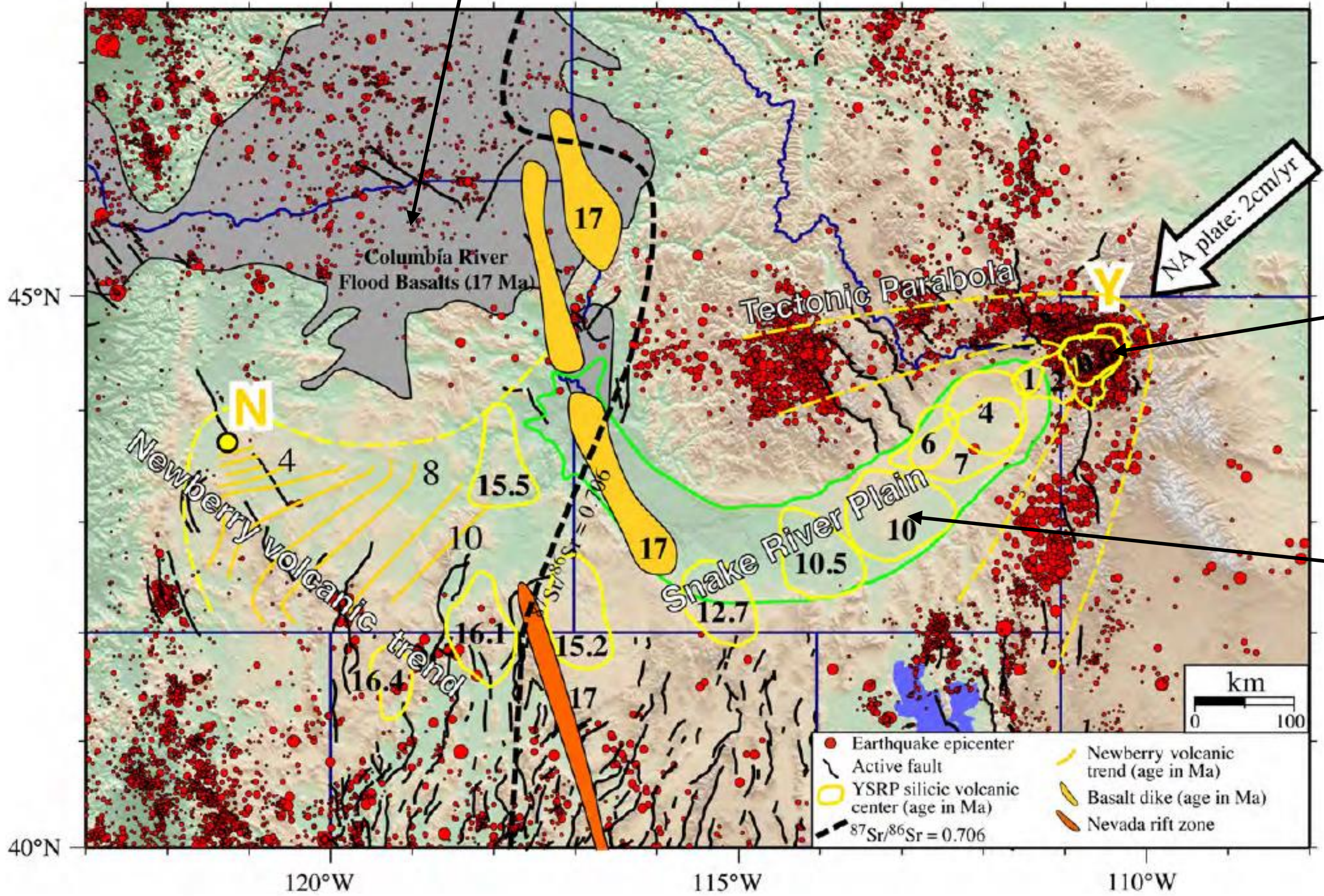
→ > 150 Myr

Uncertainties:

- Thermochemical?
- Mantle viscosity?
- Nonlinear viscosity?
- Large-scale flow?

Yellowstone – a classical hotspot?

associated with
Large Igneous
Province (LIP)

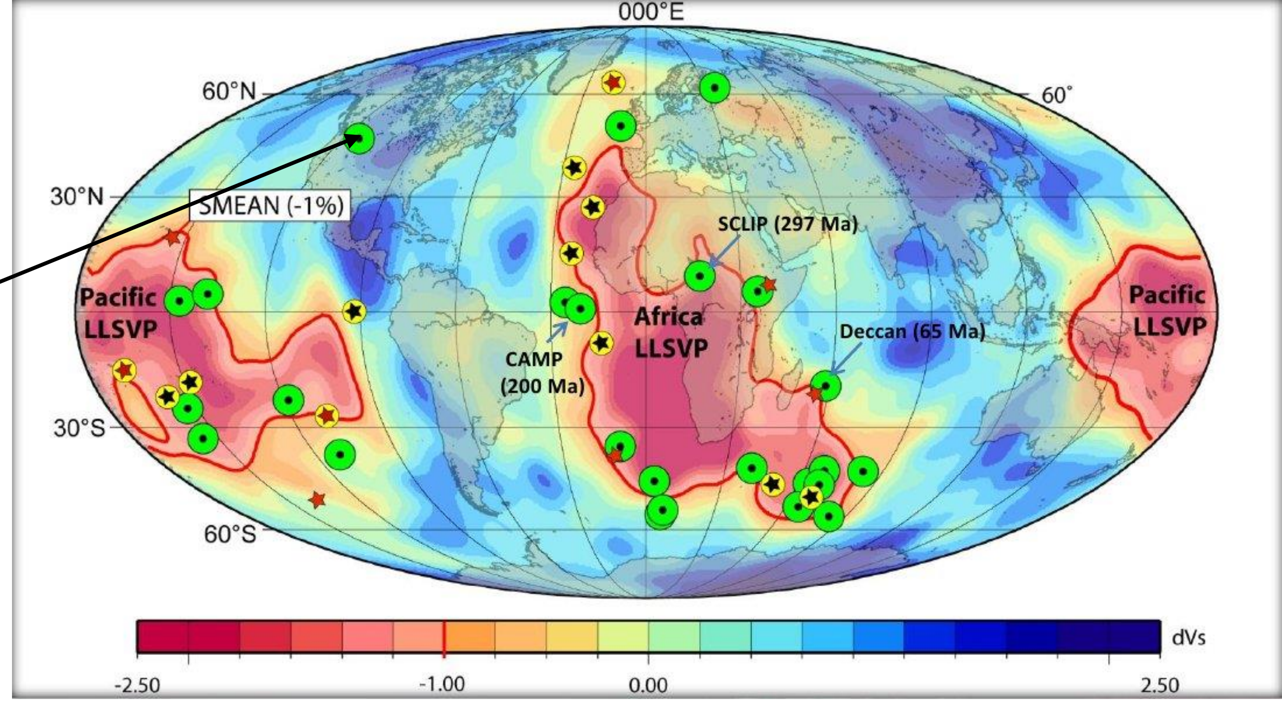


recent volcanism
on young end

age-progressive
volcanic chain

Figure from
Smith et al.
(JVGR, 2009)

… in a very untypical location !



reconstructed eruption site not along LLSVP margin

→ s-wavespeed anomalies in lowermost mantle,

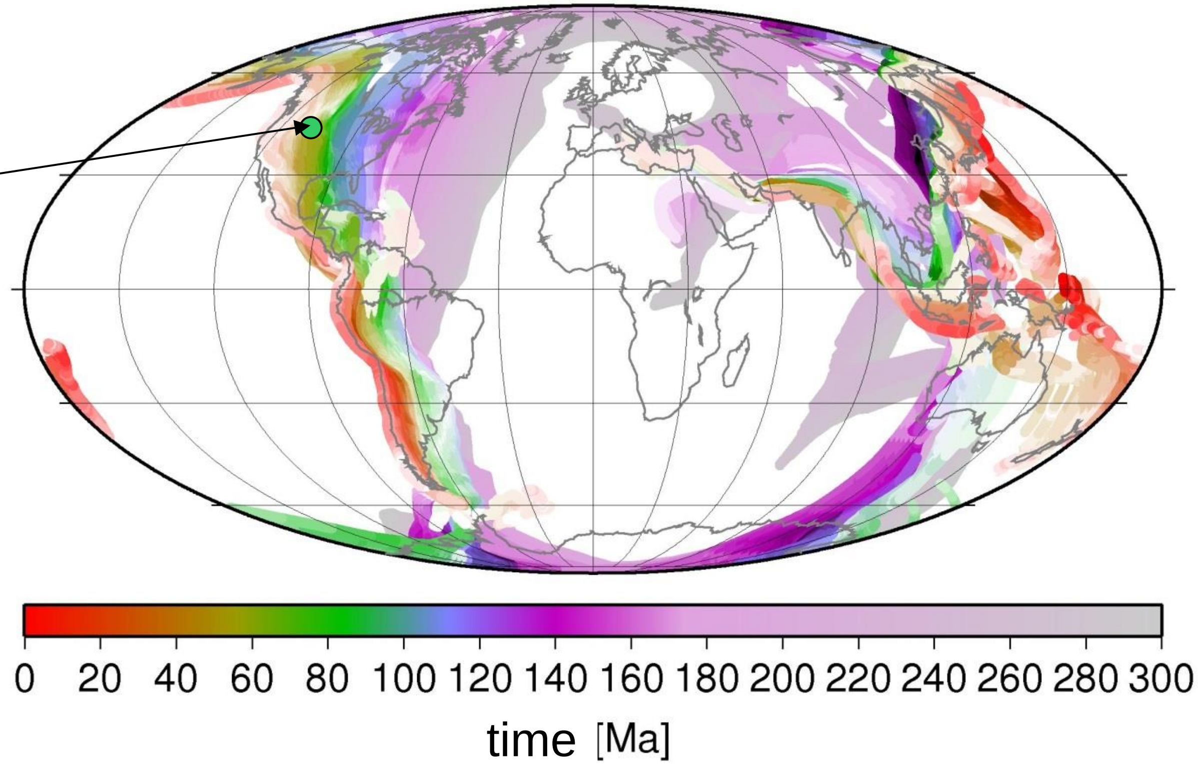
→ reconstructed LIPs (green)

→ likely deep hotspots (stars)

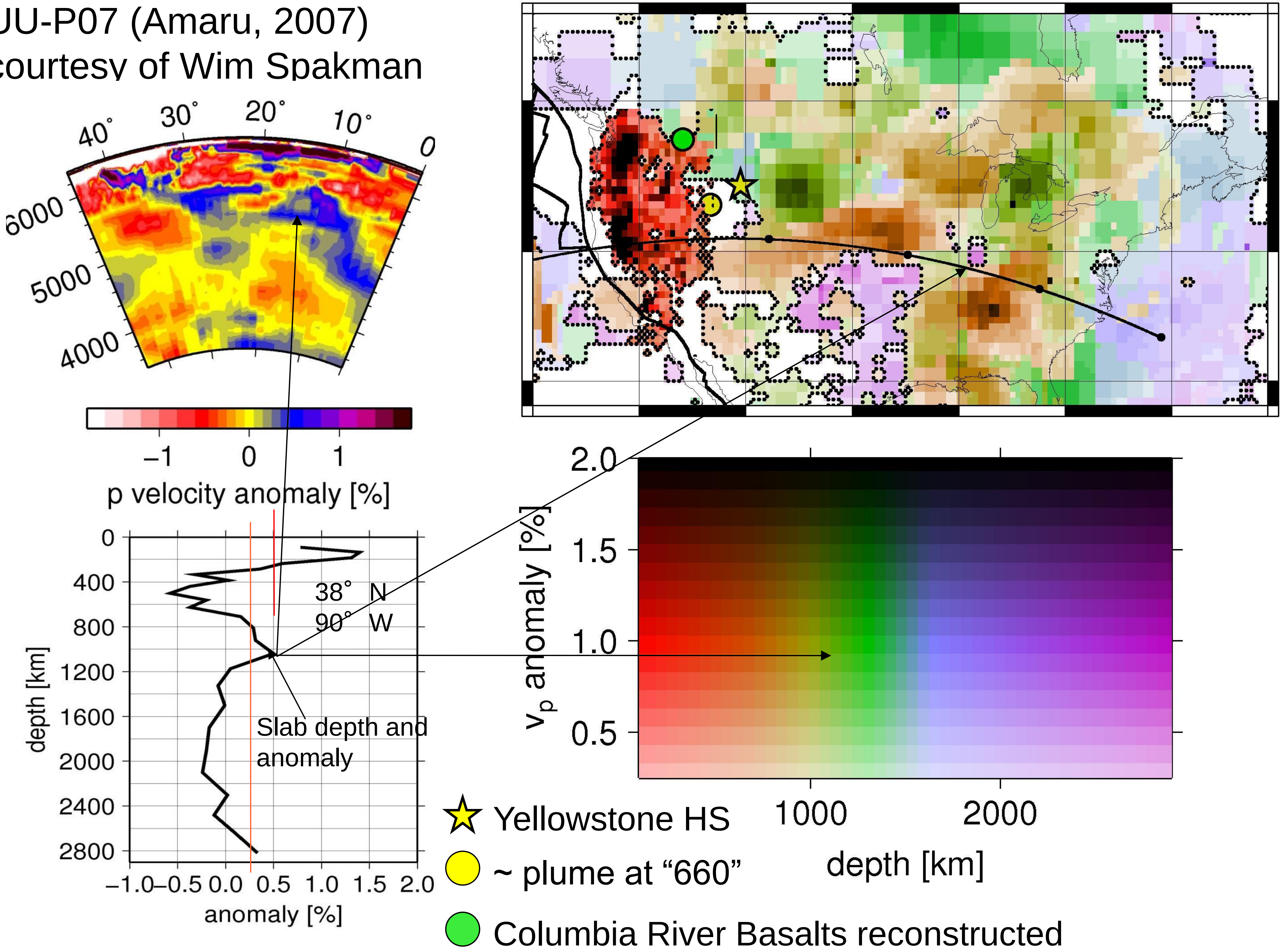
→ after Torsvik et al. (2006)

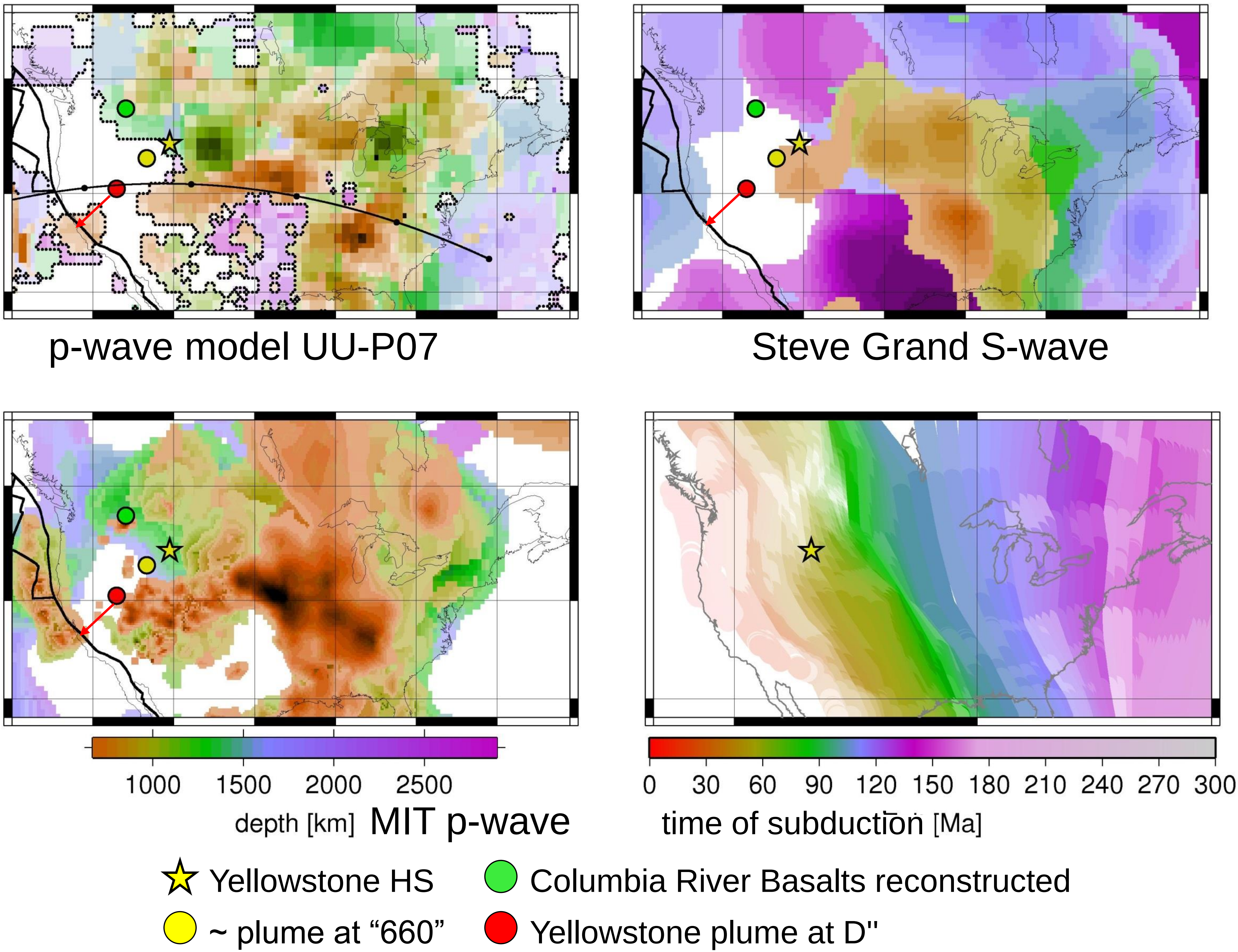
Only LIP since 300 Ma in area of recent subduction

Subduction locations and amounts (color intensity) from a global plate reconstruction (see Steinberger and Torsvik, 2012, for details)



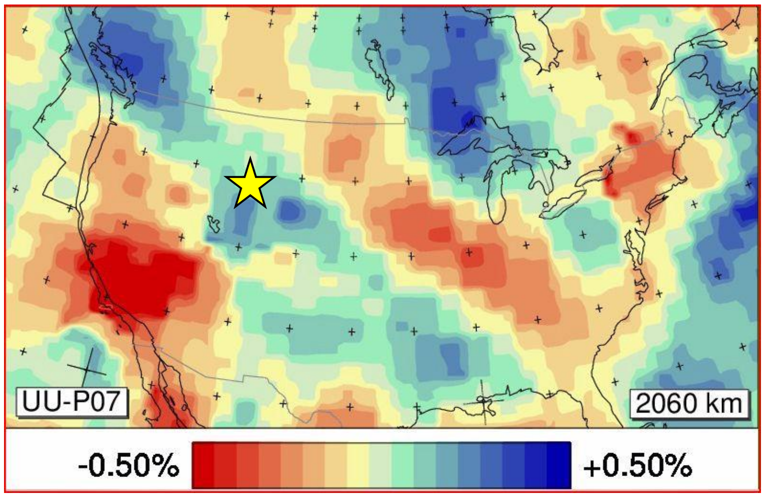
Slab depths from model UU-P07 (Amaru, 2007) courtesy of Wim Spakman

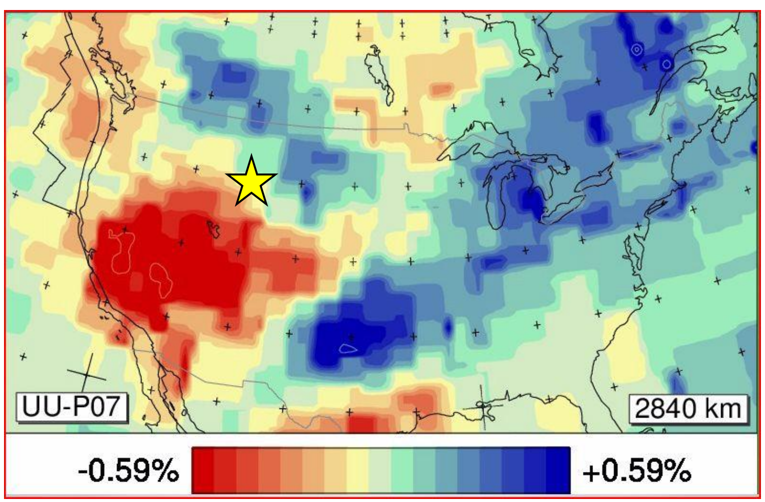



p-wave model UU-P07
Steve Grand S-wave
1000 1500 2000 2500
depth [km]
MIT p-wave
0 30 60 90 120 150 180 210 240 270 300
time of subduction [Ma]
Yellowstone HS
Columbia River Basalts reconstructed
~ plume at "660"
Yellowstone plume at D''

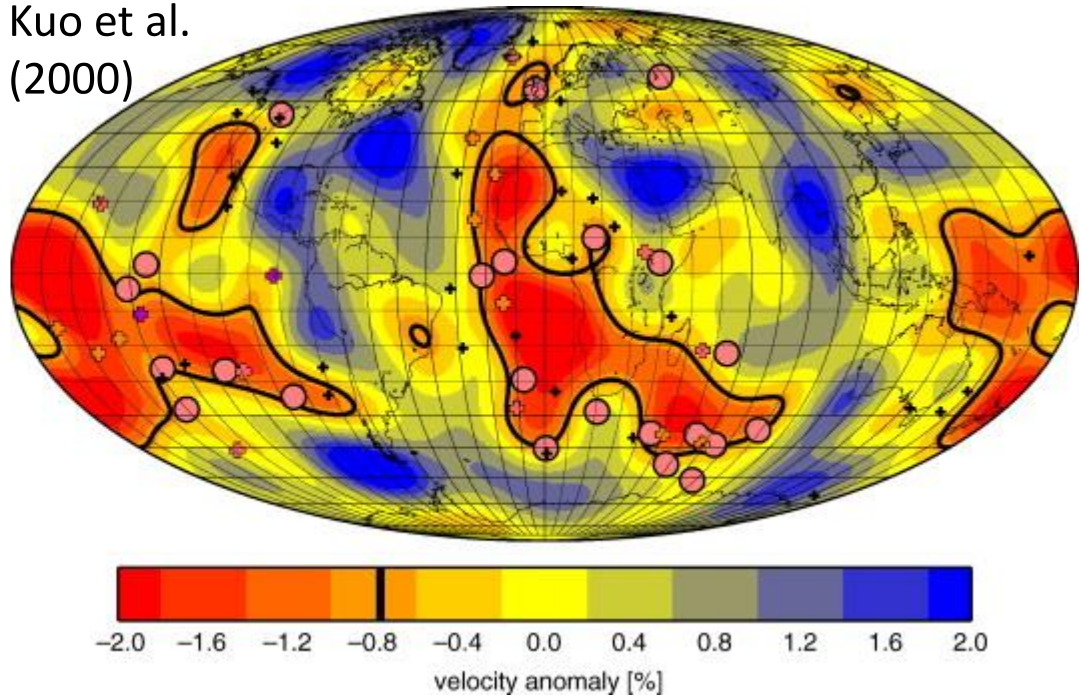
D'' models (Figures from Burke et al., 2008)

Utrecht tomography model
Figures from Wim Spakman

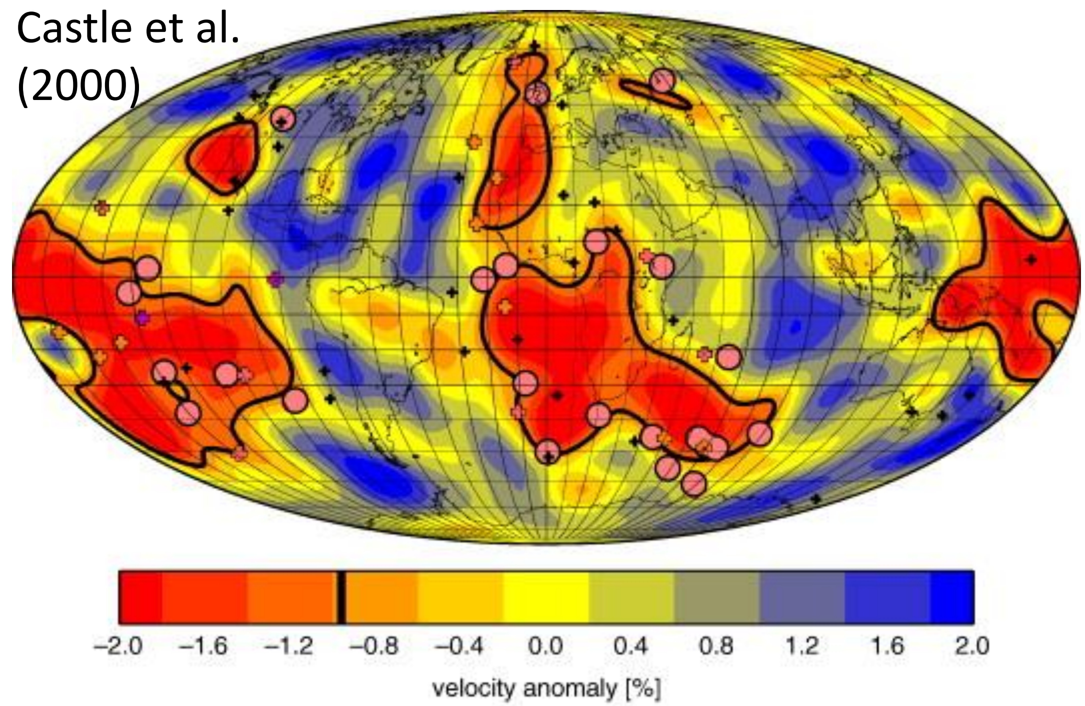




Kuo et al. (2000)



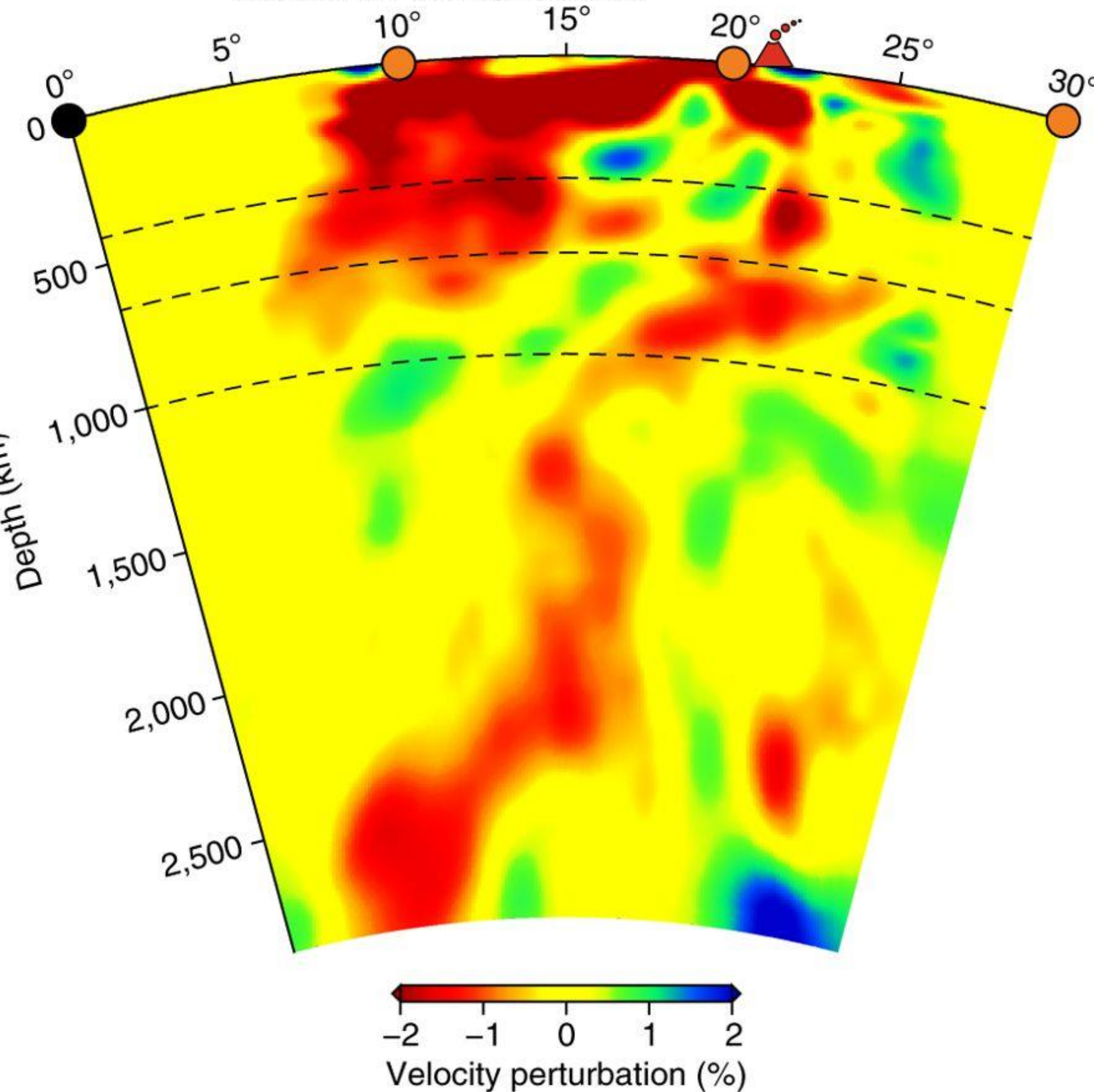
Castle et al. (2000)

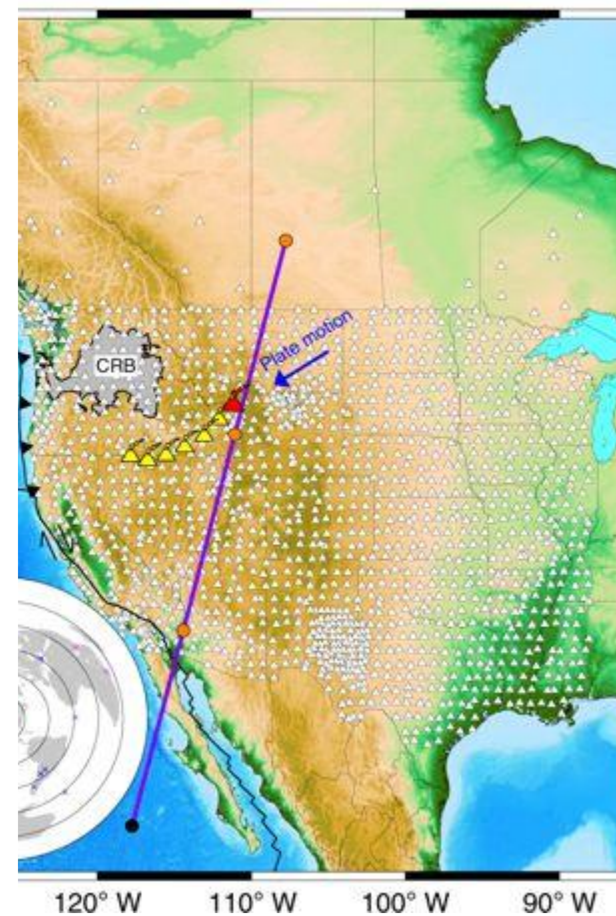


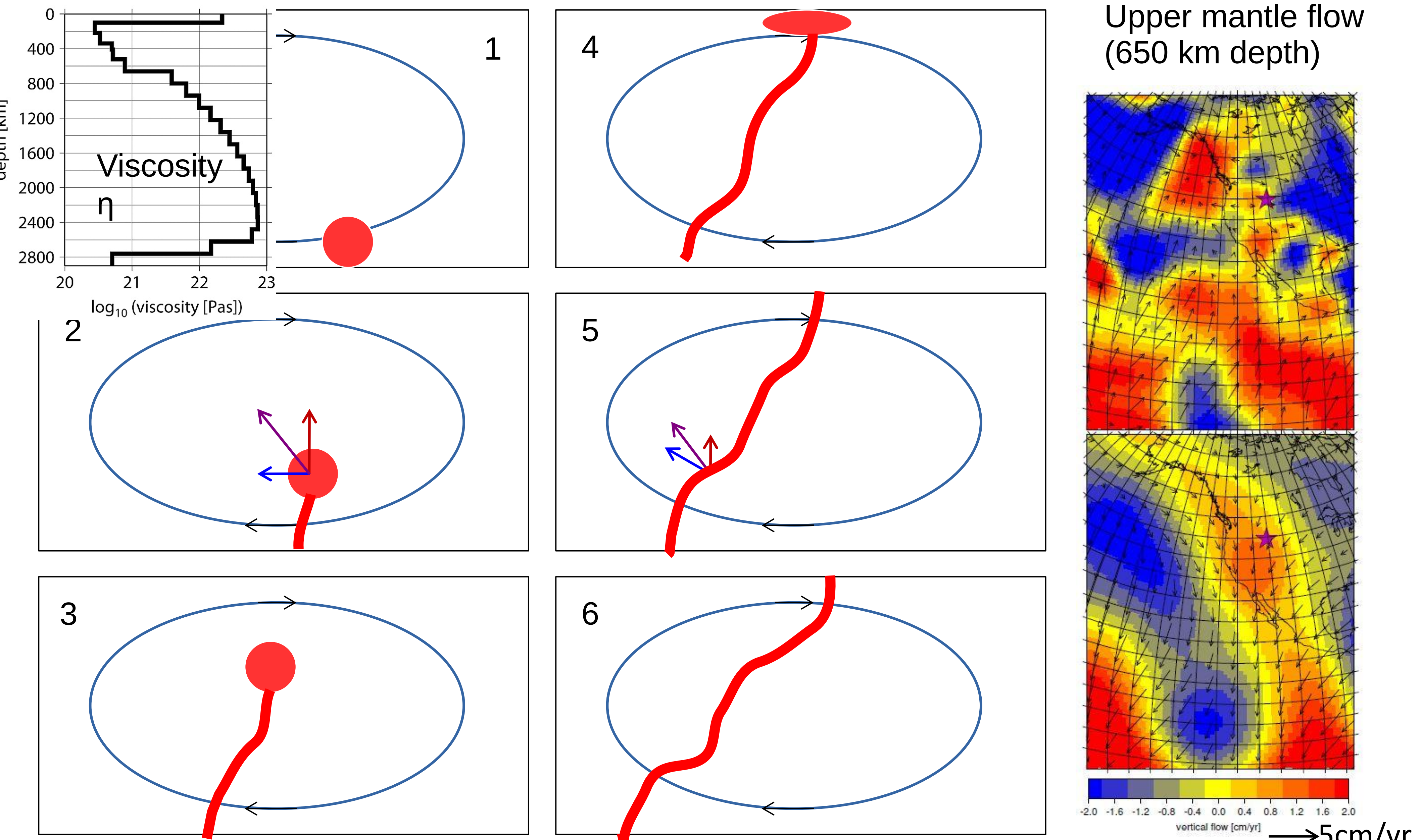
ARTICLES
https://doi.org/10.1038/s41561-018-0075-y
nature geoscience

Lower-mantle plume beneath the Yellowstone hotspot revealed by core waves

Peter L. Nelson* and Stephen P. Grand







Lower mantle flow
(2600 km depth)

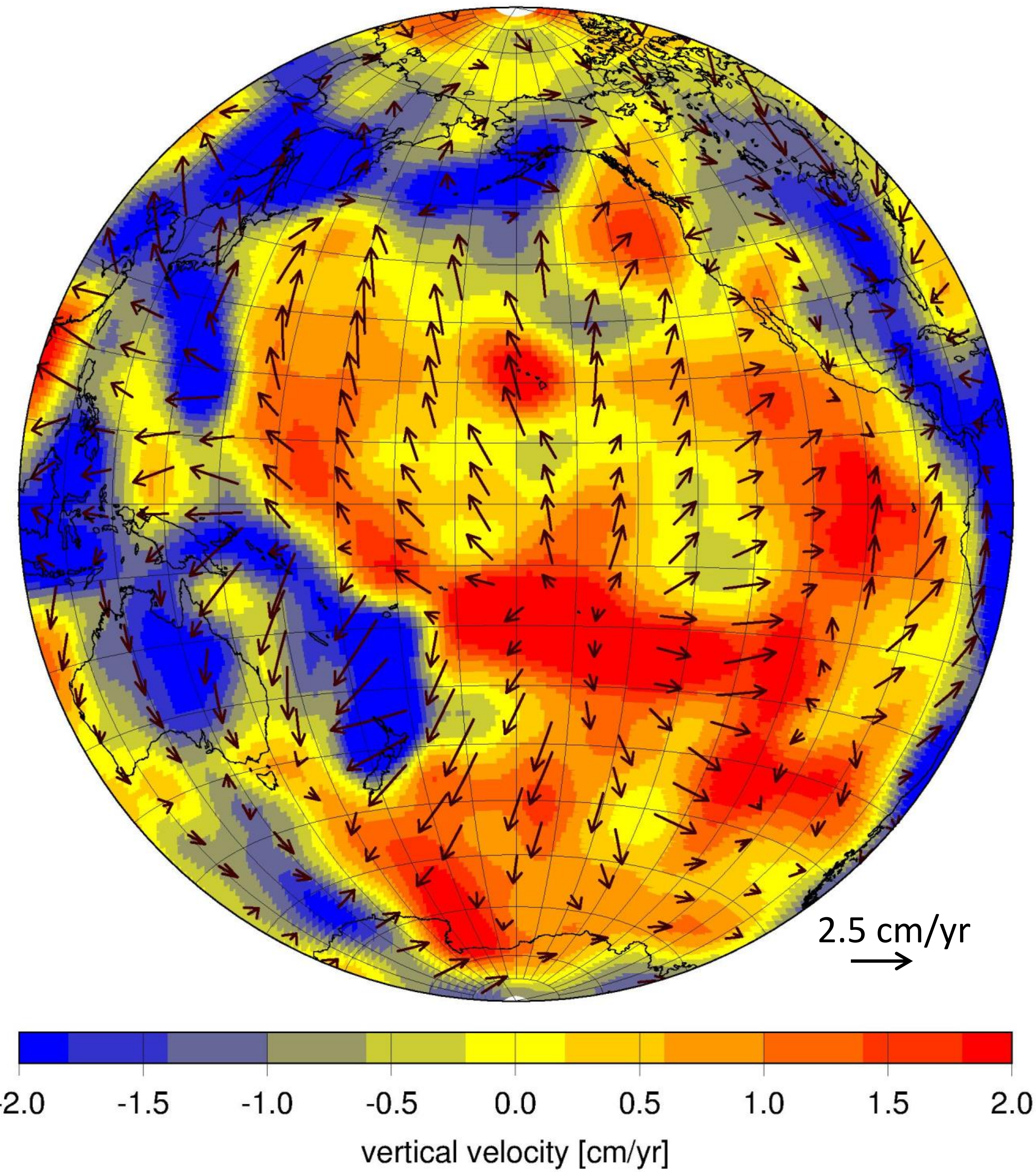
Plume head rises ($v_{rise} \sim 1/\eta$)
gets advected by large-scale flow
(density anomalies from tomography)
How fast?
→ vary total rise time (prescribed)

Plume conduit also rises
(but less fast) +
gets advected by large-scale flow

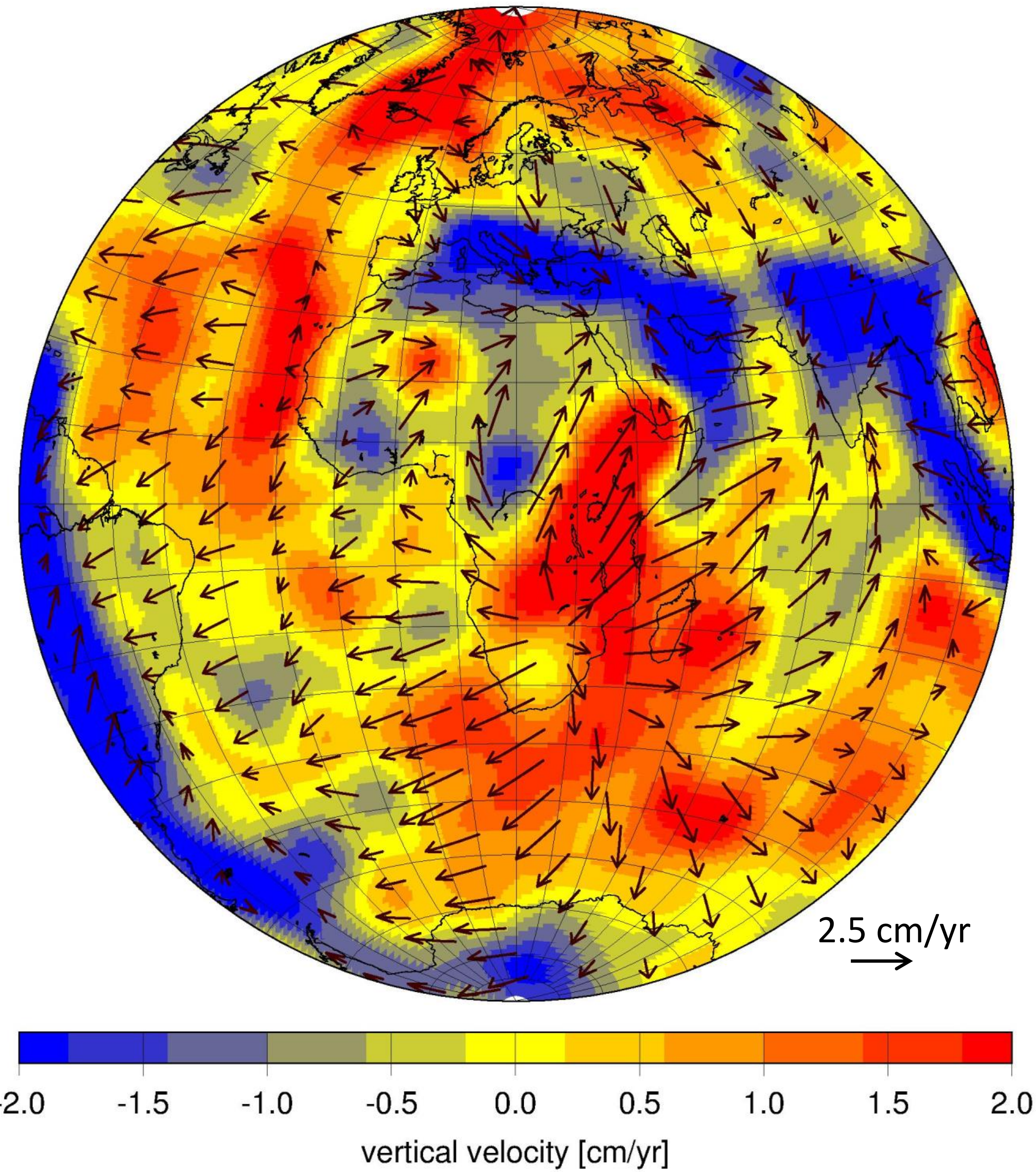
Computation of flow field

- Density field converted from tomography model $(d\rho/\rho)/(dv_s/v_s)$~0.25, reduced in uppermost 250 km
- Considered additional (chemical) density anomalies in LLSVPs
- Radial viscosity structure with strong increase with depth (~10^{20} Pas below lithosphere, to ~10^{23} Pas in lowermost mantle above D'')
- Plate velocities prescribed at surface
- Free-slip at CMB
- Time-dependence through time-dependent plate velocities and backward-advection of density heterogeneities

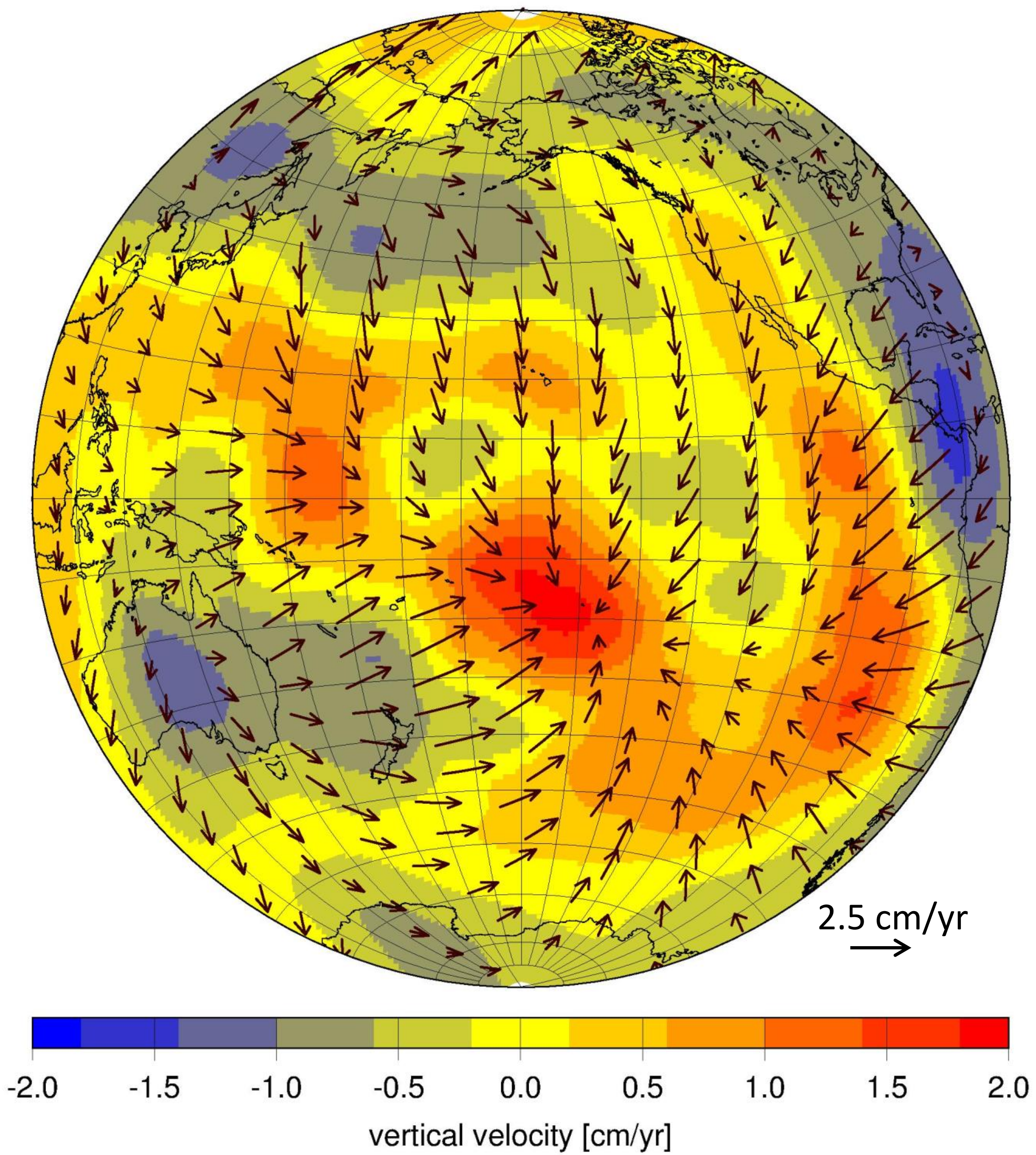
Pacific hemisphere flow depth 650 km; density from s10mean mean tomography



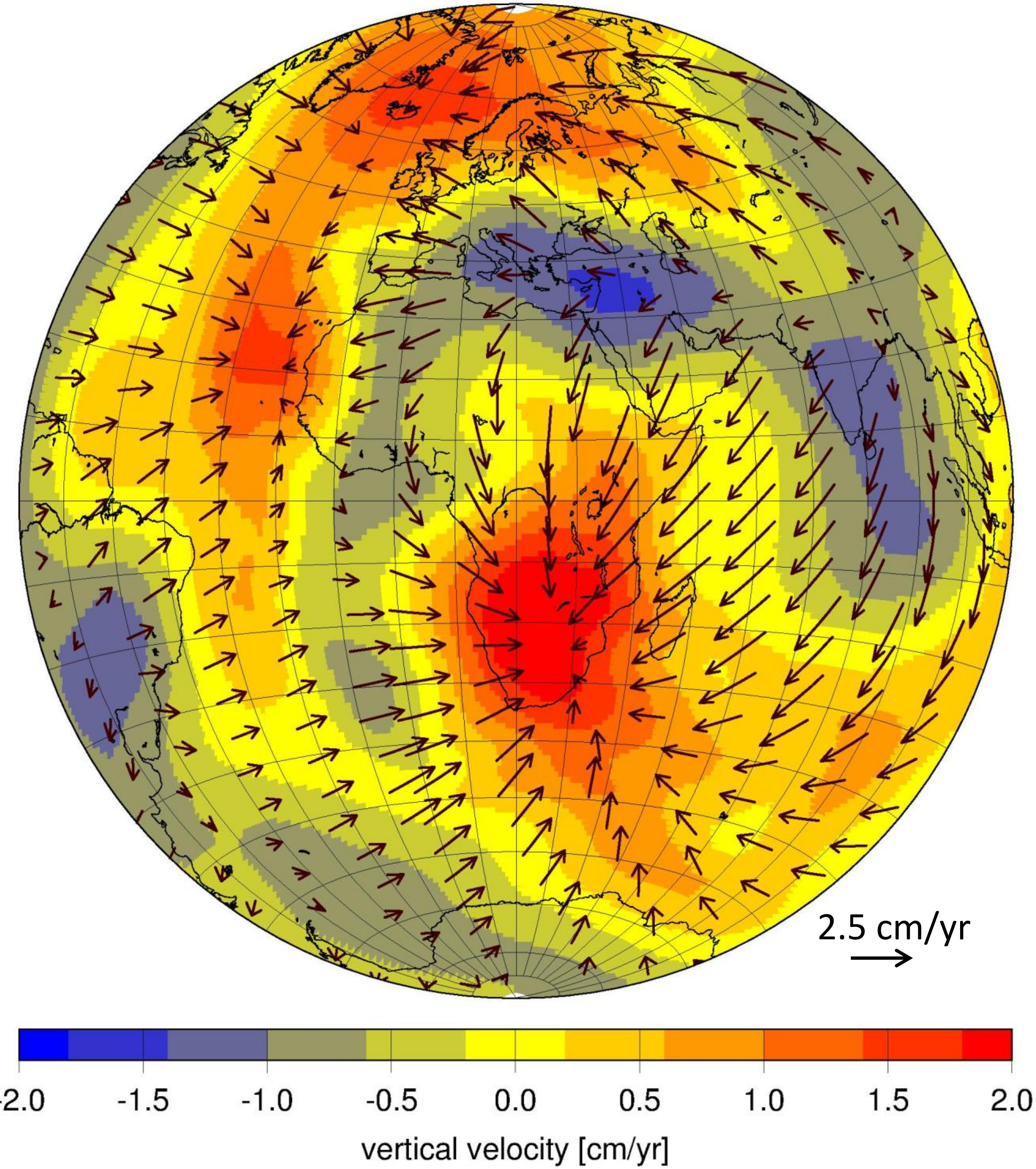
African hemisphere flow depth 650 km; density from s10mean mean tomography



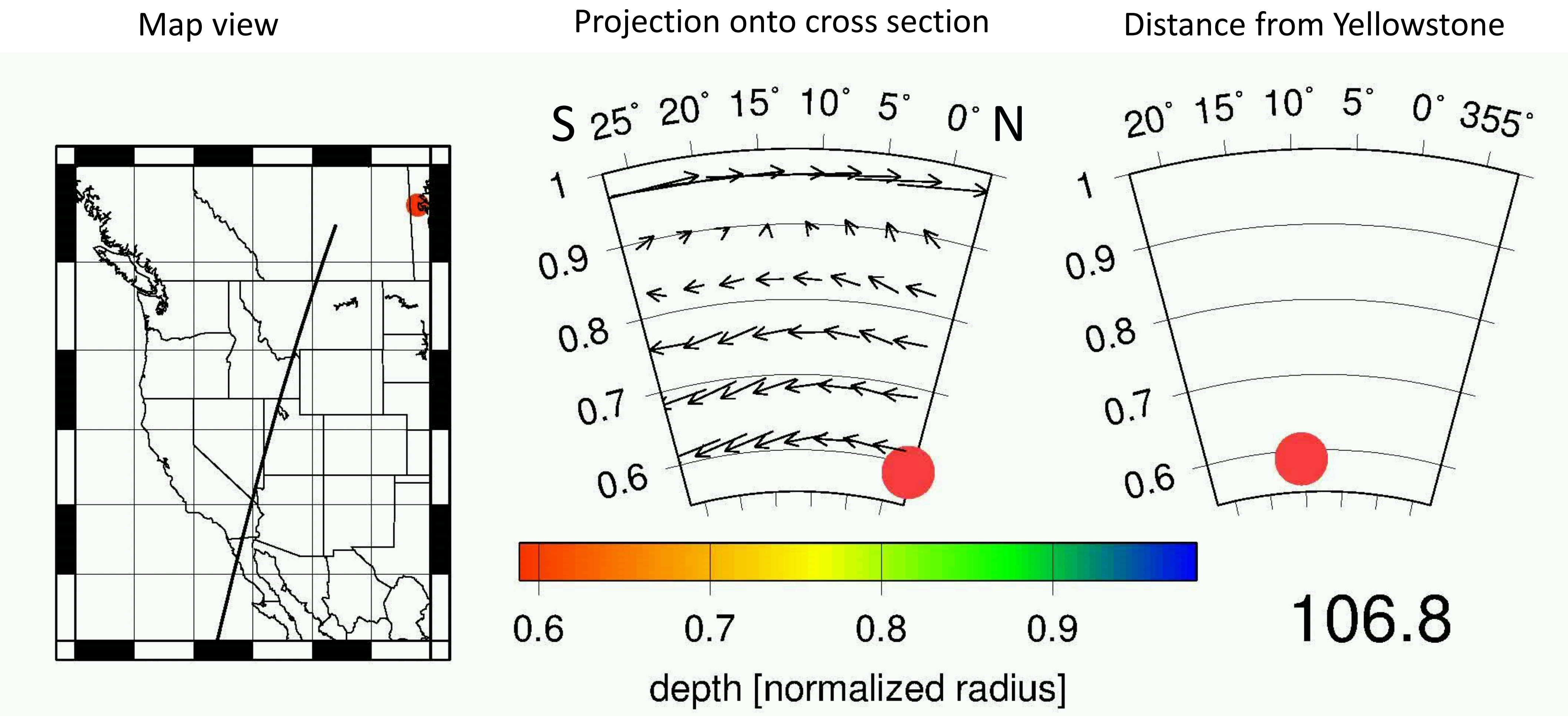
Pacific hemisphere flow depth 2650 km; density from s10mean mean tomography

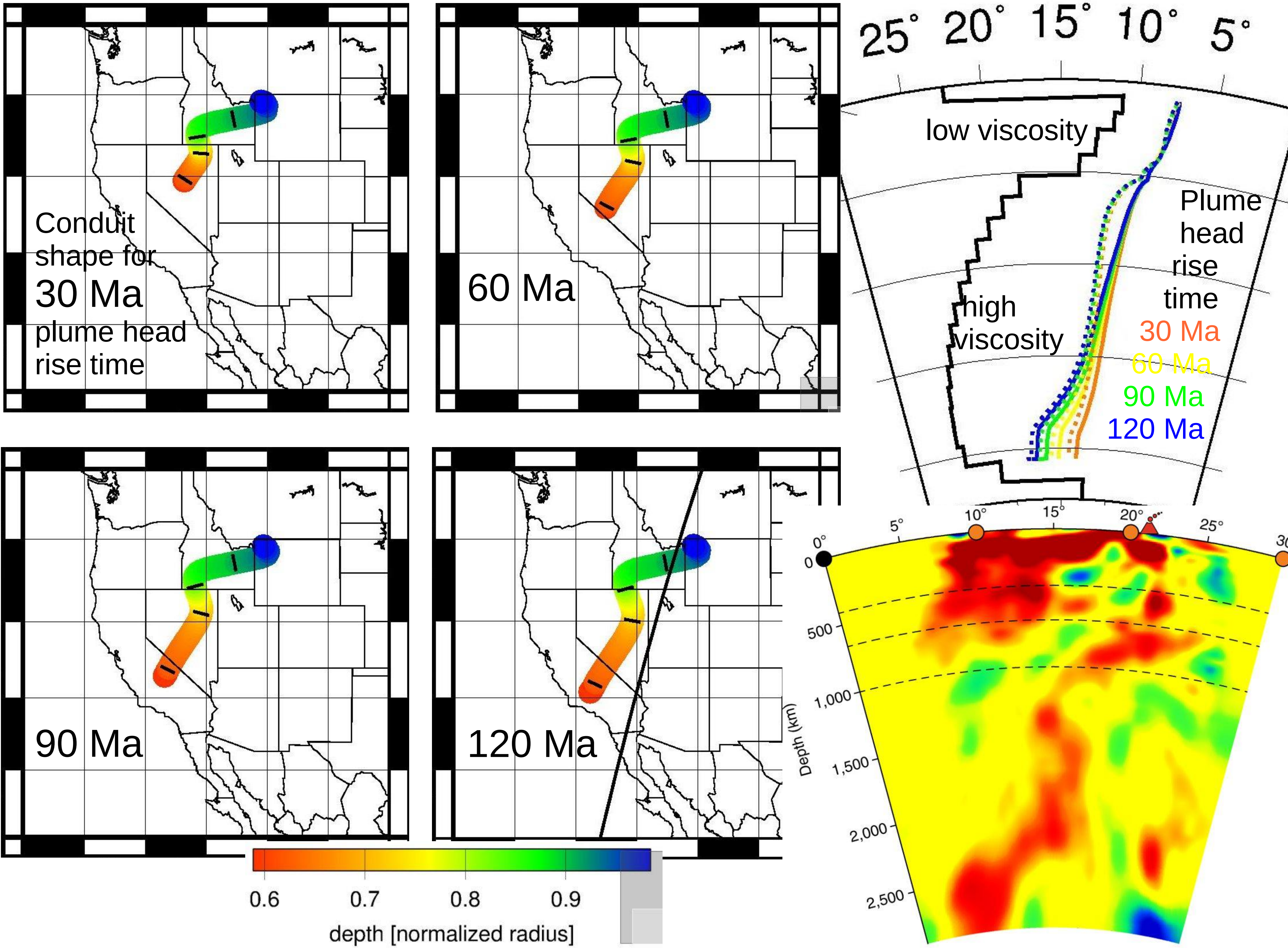


African hemisphere flow depth 2650 km; density from s10mean mean tomography

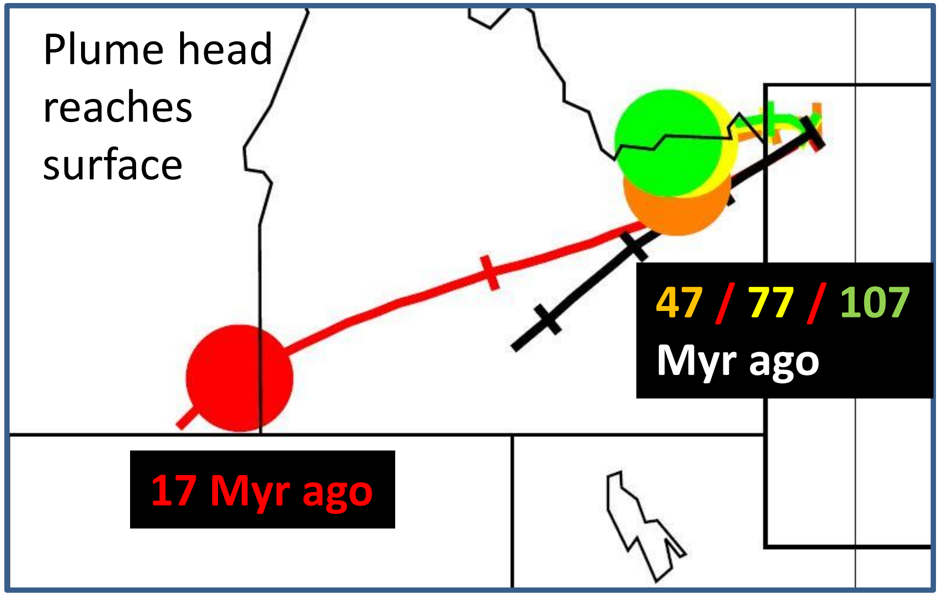


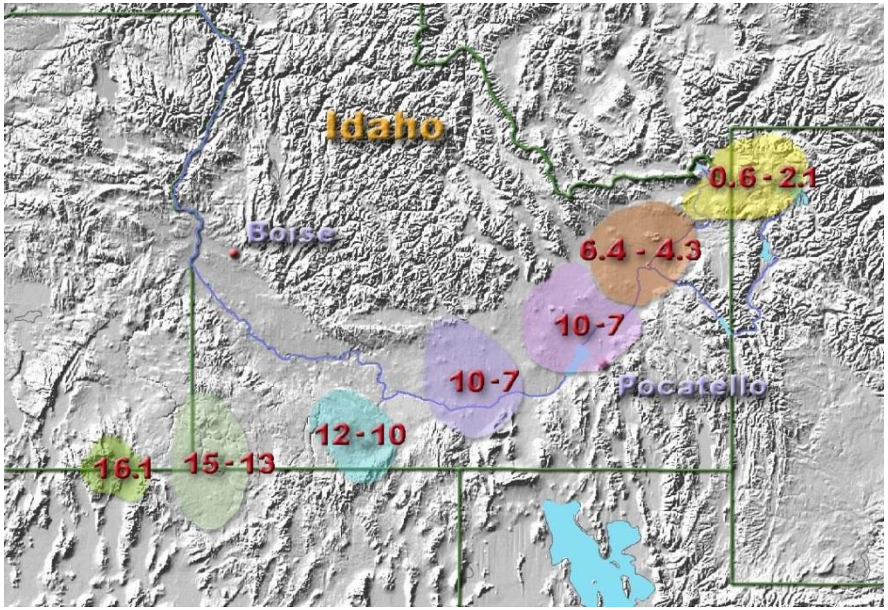
Yellowstone plume motion





Conduit shape for
30 Ma
plume head rise time
60 Ma
90 Ma
120 Ma
0.6
0.7
0.8
0.9
depth [normalized radius]
25°
20°
15°
10°
5°
low viscosity
high viscosity
Plume head rise time
30 Ma
60 Ma
90 Ma
120 Ma
0°
5°
10°
15°
20°
25°
0
500
1,000
1,500
2,000
2,500
Depth (km)





Many other things can also be varied

→ Seismic tomography model from which density model is derived (many models to choose from; relatively large influence)

→ Combination with high-resolution regional model (rather small change)

→ Whether or not LLSVPs are considered chemically distinct (also only small change)

→ Scaling from seismic velocity to density anomalies (to account for possible damping)
– essentially larger scaling gives faster flow and larger tilt

→ Mantle viscosity structure (overall lower viscosity gives larger tilt; apart from that, for those viscosity models, where results look "reasonable", they are also similar

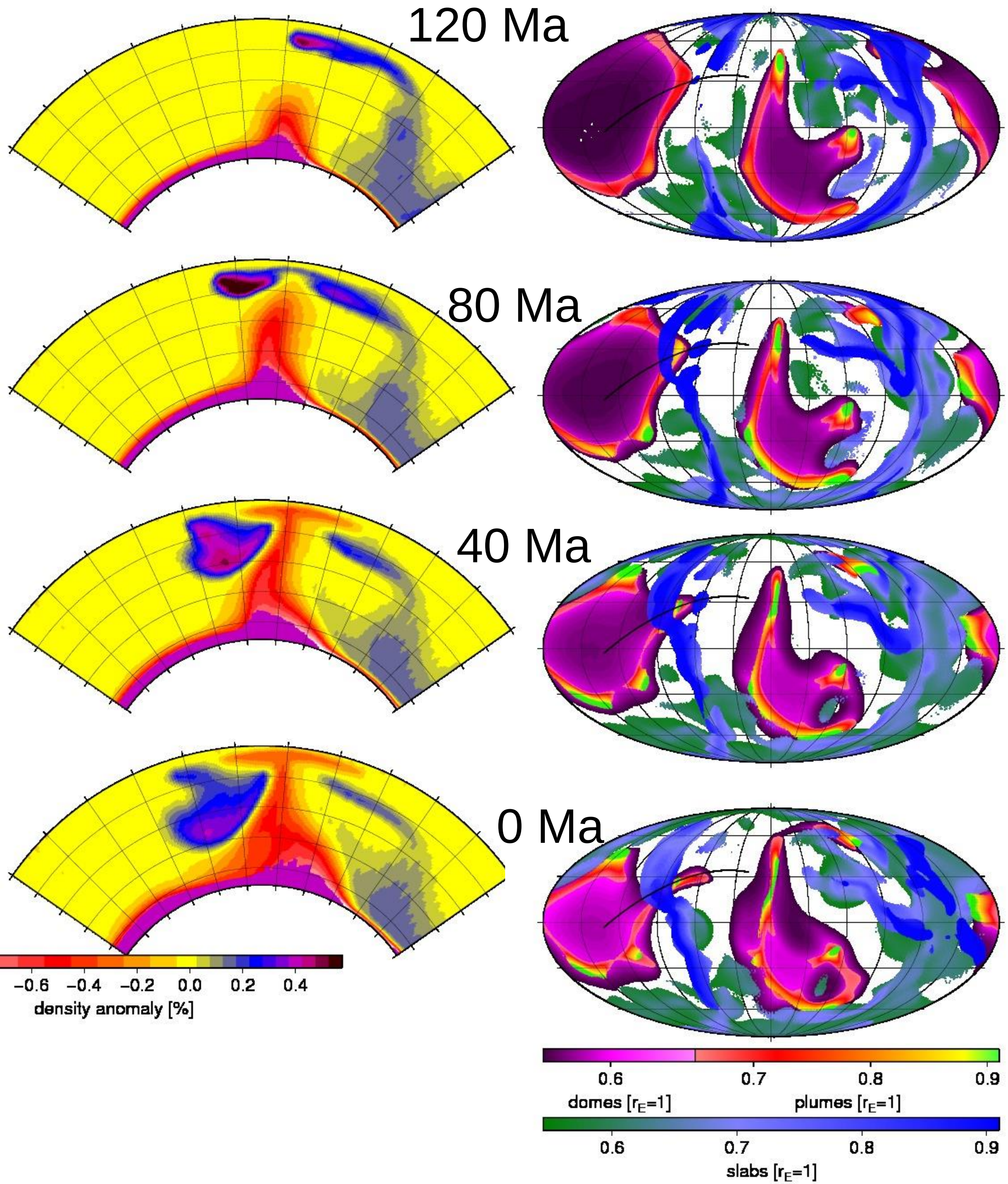
Dynamic model (Steinberger and Torsvik, G-Cubed, 2012):

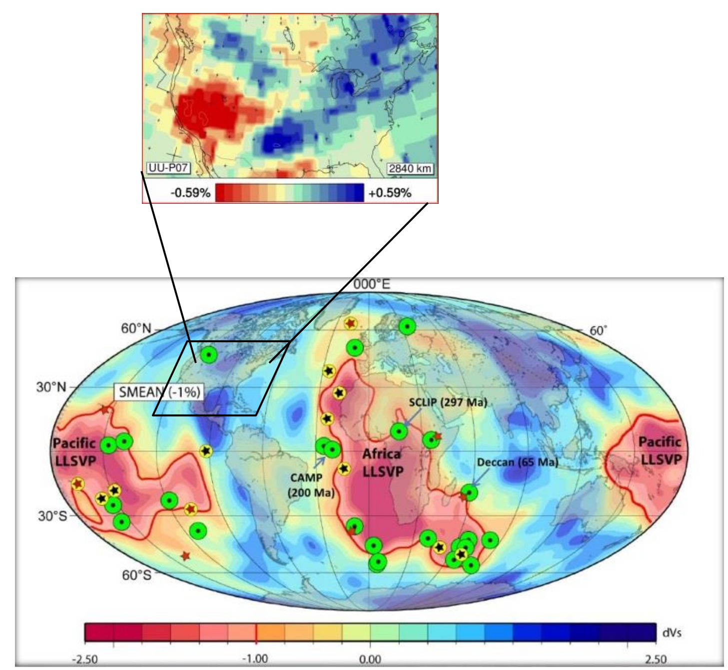
→ Subduction zone moving ~2 cm/yr

→ Typical hotspot motion <= 1 cm/yr

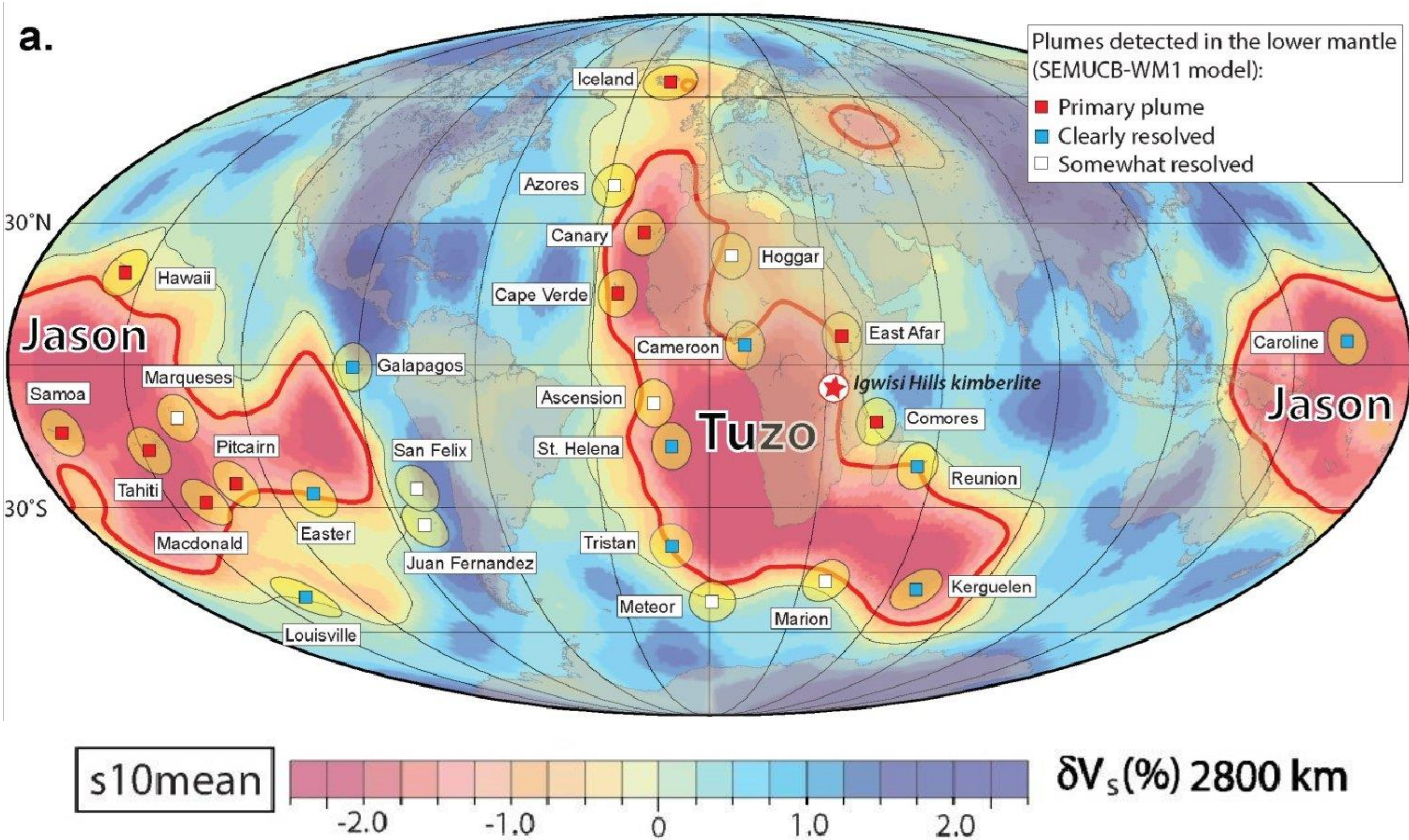
→ Plume overridden by subduction zone (Yellowstone at ~50 Ma)

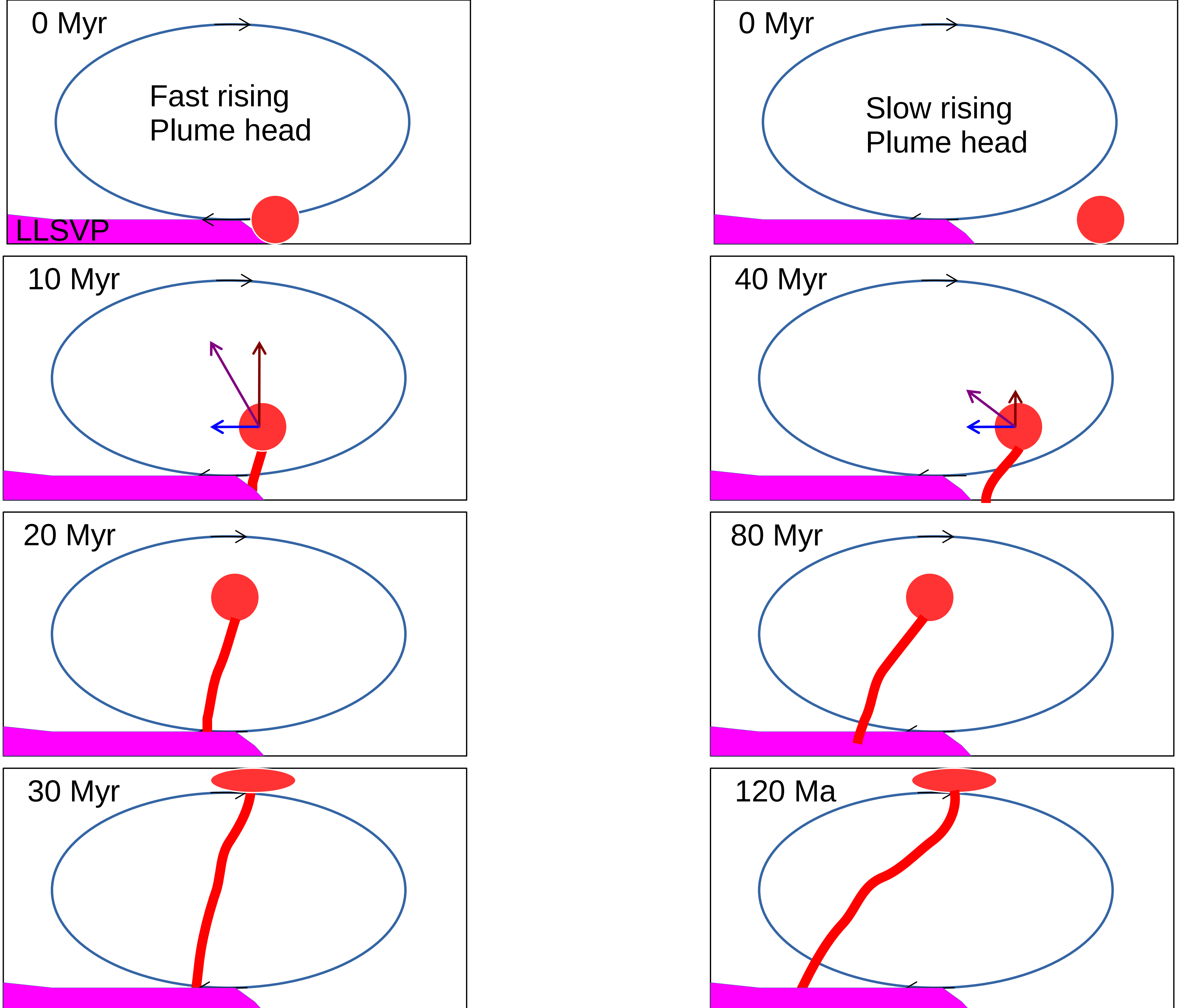
→ Plume reaches surface behind slab





Hotspots located near margins of Large Low Shear Velocity Provinces (LLSVPs) “Jason” and “Tuzo”



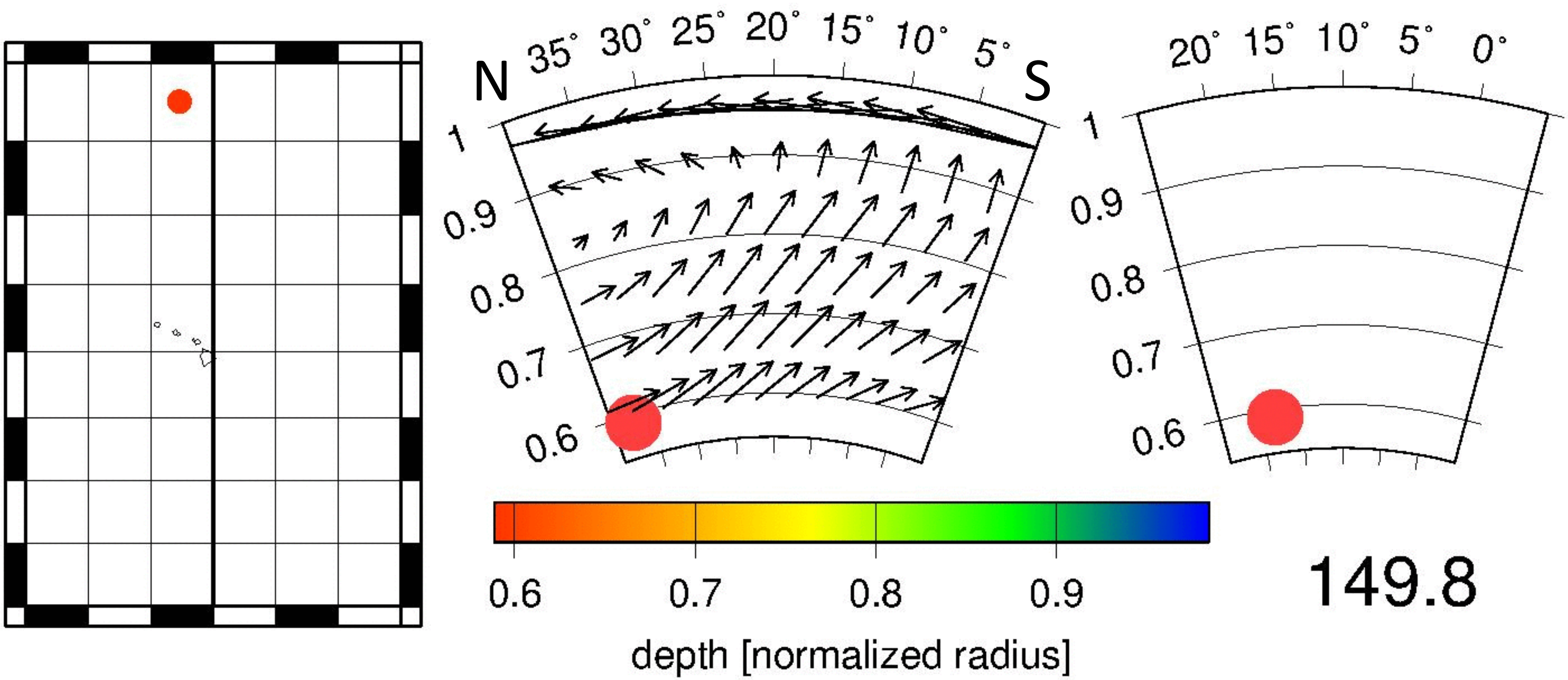

0 Myr
Fast rising
Plume head
LLSVP
10 Myr
20 Myr
30 Myr
0 Myr
Slow rising
Plume head
40 Myr
80 Myr
120 Ma

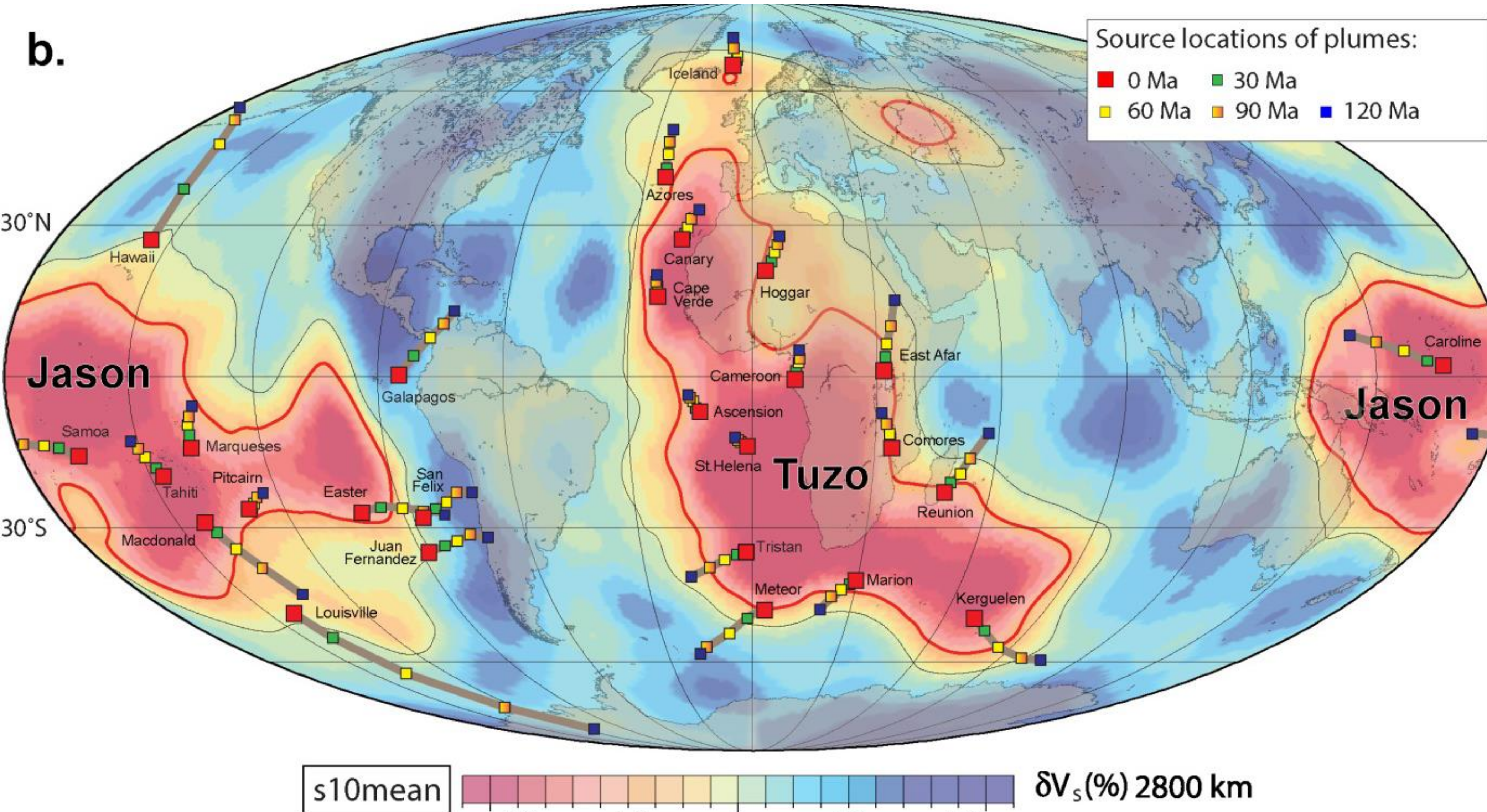
Hawaii plume motion

Map view

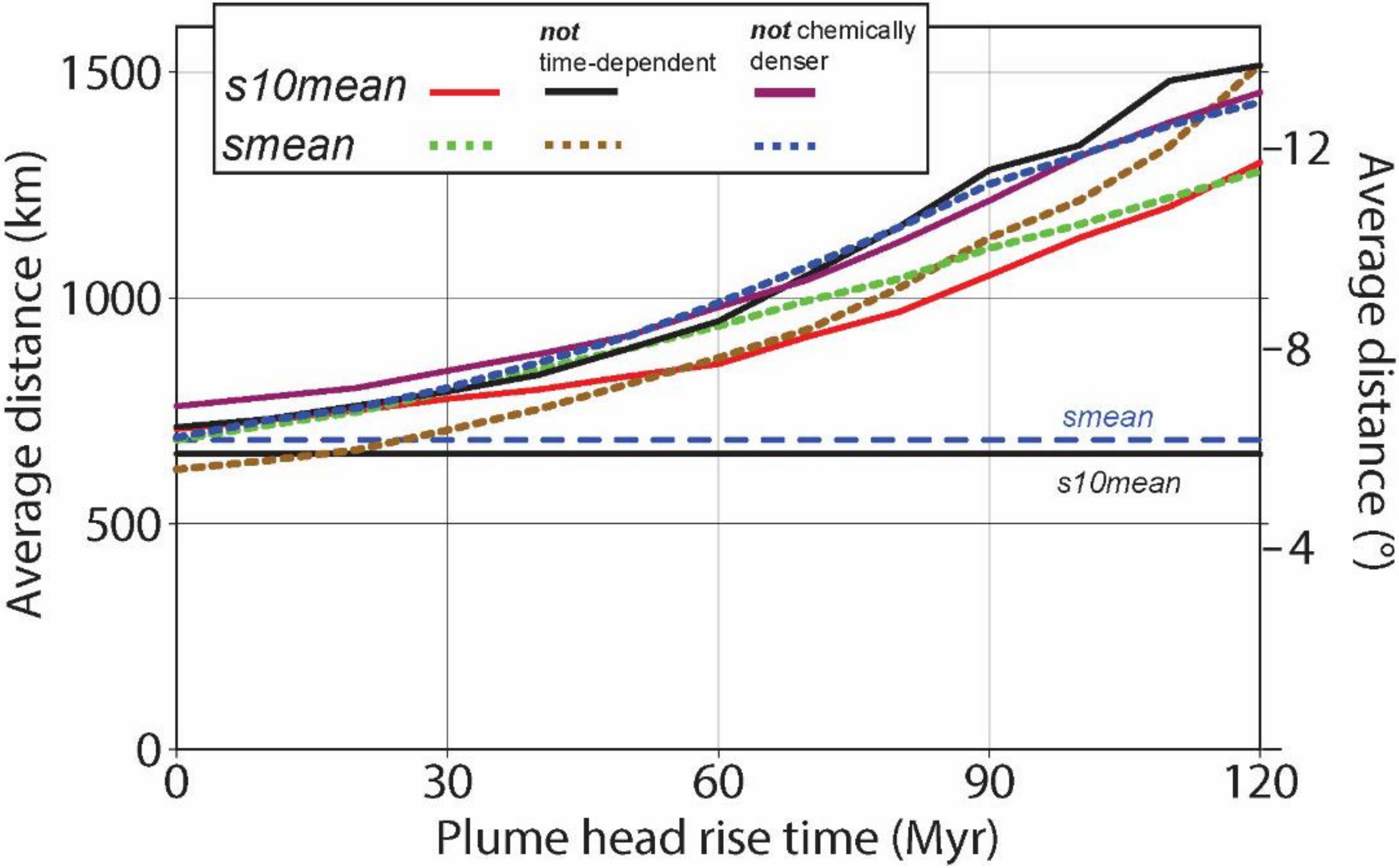
Projection onto N-S cross section

Distance from Hawaii

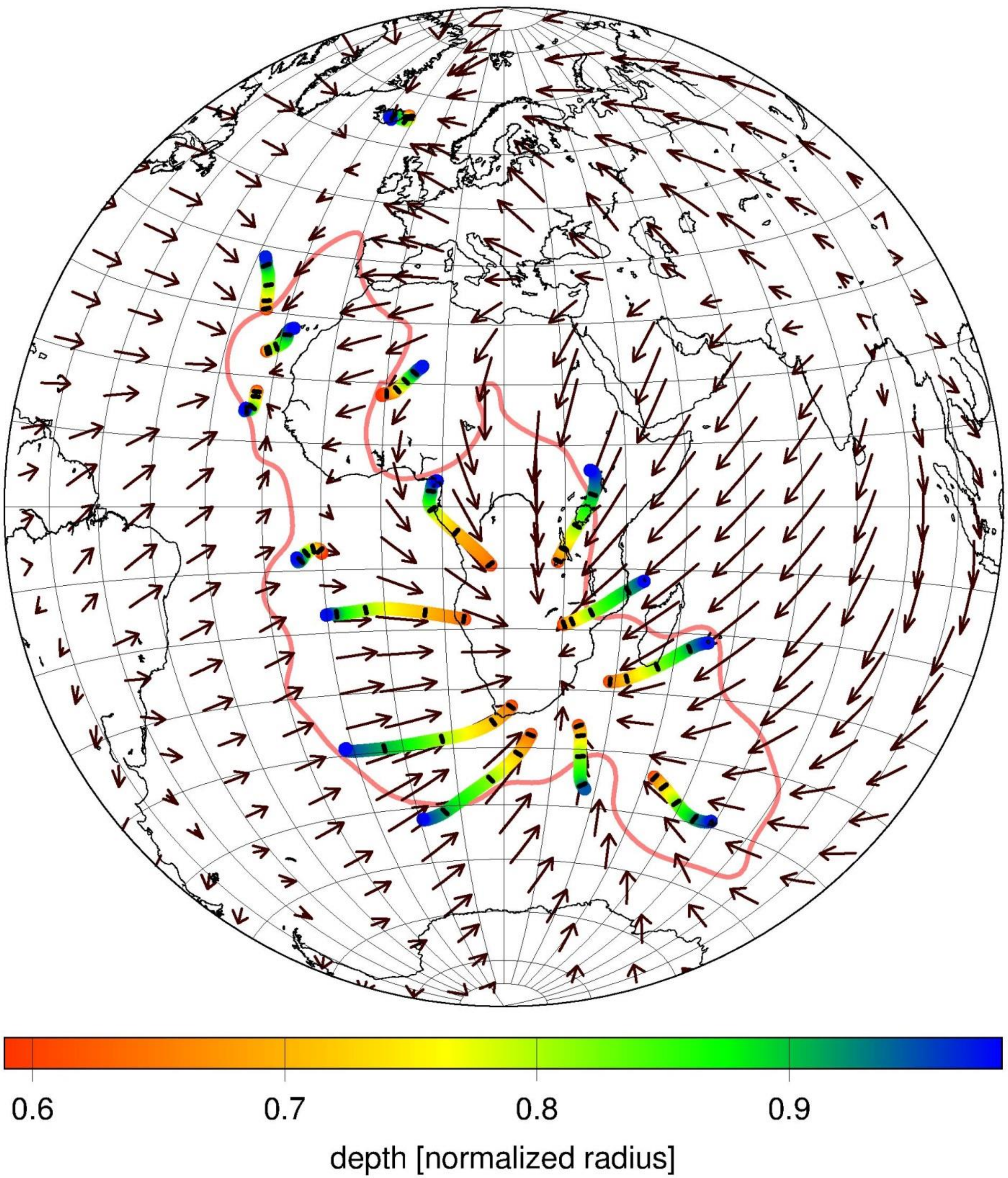


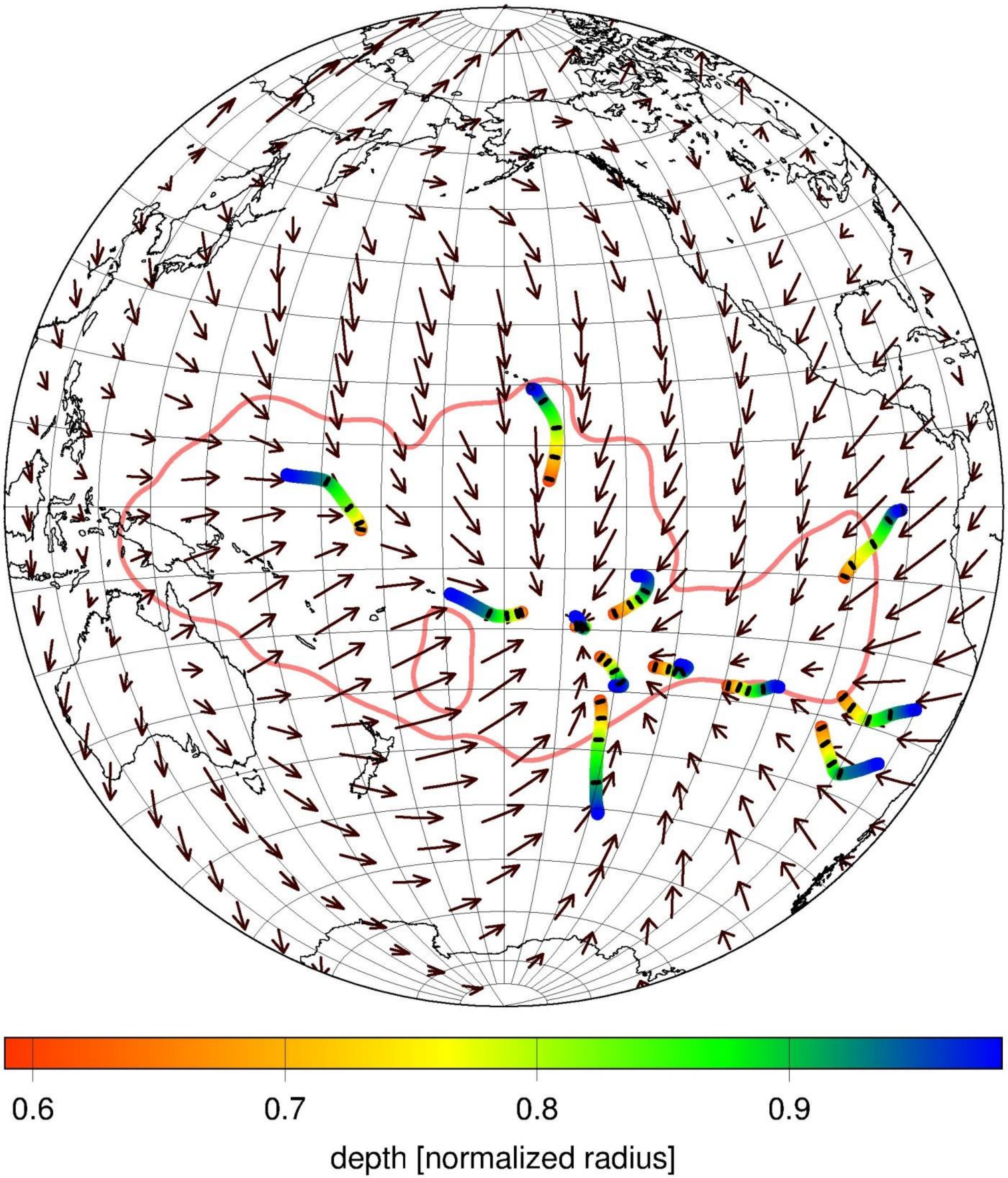


b.
Source locations of plumes:
0 Ma
30 Ma
60 Ma
90 Ma
120 Ma
30°N
30°S
Iceland
Azores
Canary
Cape Verde
Hoggar
Hawaii
Jason
Jason
Caroline
East Afar
Cameroon
Galapagos
Ascension
Comores
Samoa
Marqueses
St.Helena
Tuzo
Tahiti
Pitcairn
Easter
San Felix
Reunion
Macdonald
Juan Fernandez
Tristan
Marion
Meteor
Kerguelen
Louisville
s10mean
δV_S(%) 2800 km
-2.0
-1.0
0
1.0
2.0

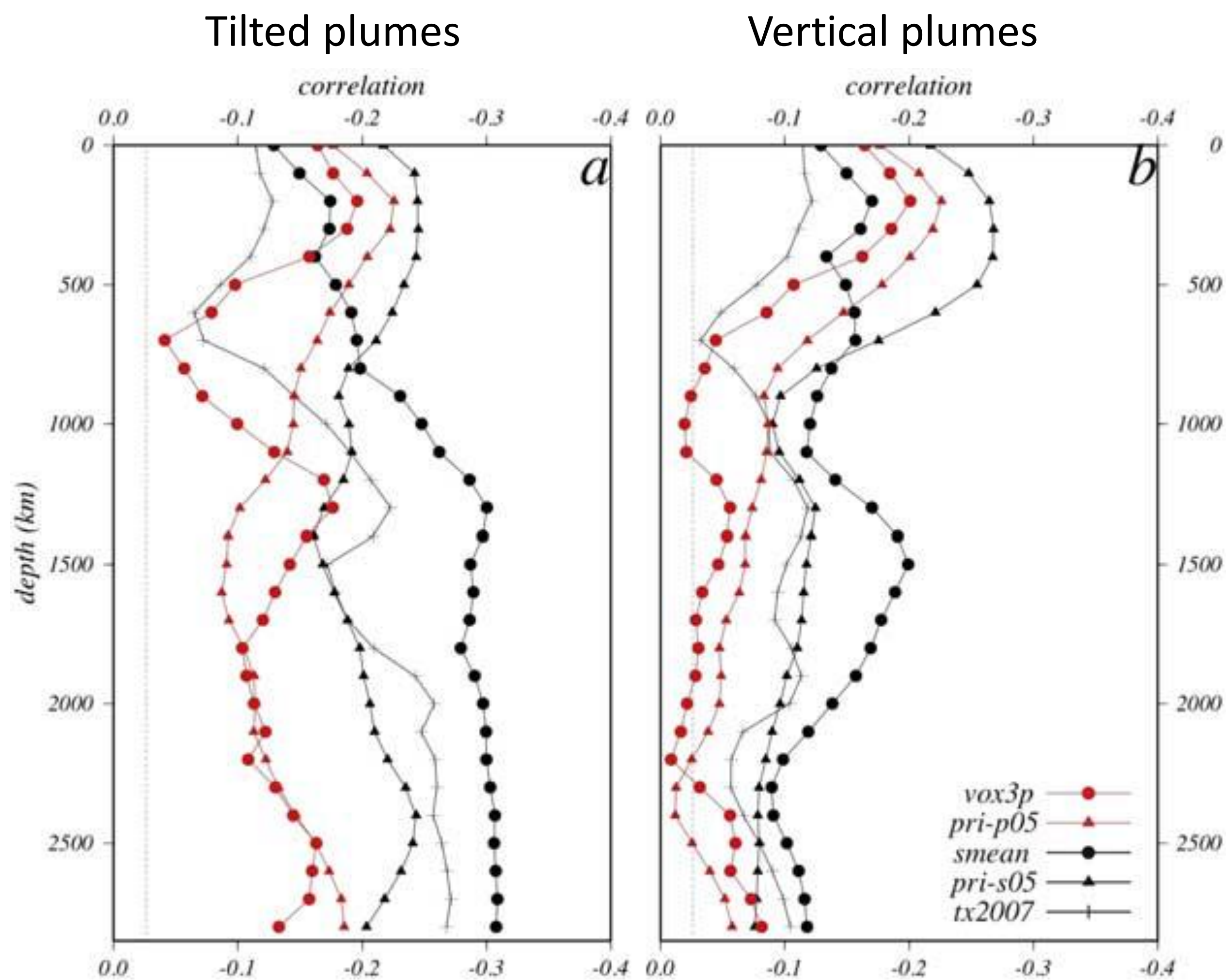


s10mean
smean
not
time-dependent
not chemically
denser
1500
1000
500
0
0
30
60
90
120
Plume head rise time (Myr)
Average distance (km)
Average distance (°)
12
8
4
smean
s10mean

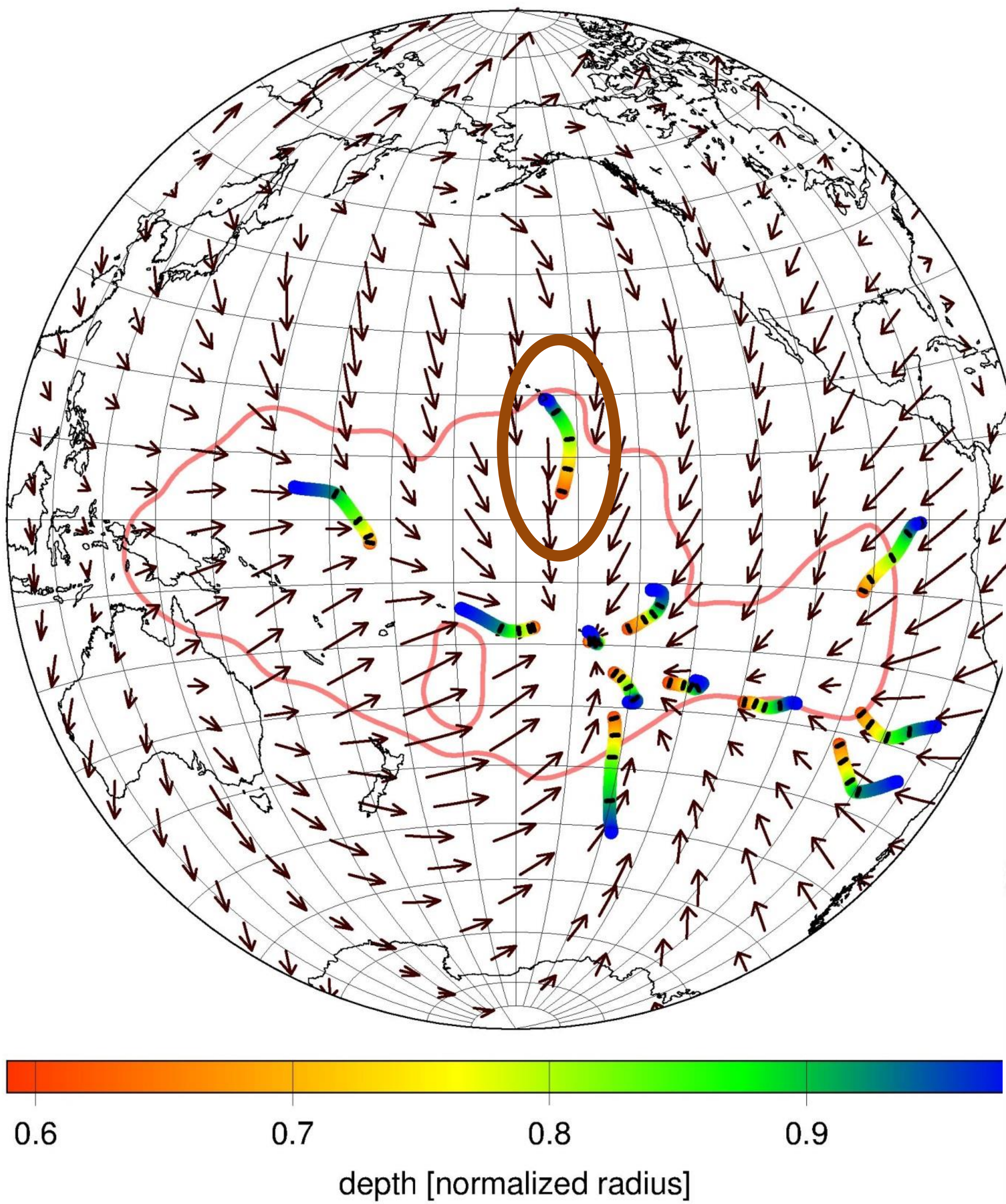

0.6
0.7
0.8
0.9
depth [normalized radius]

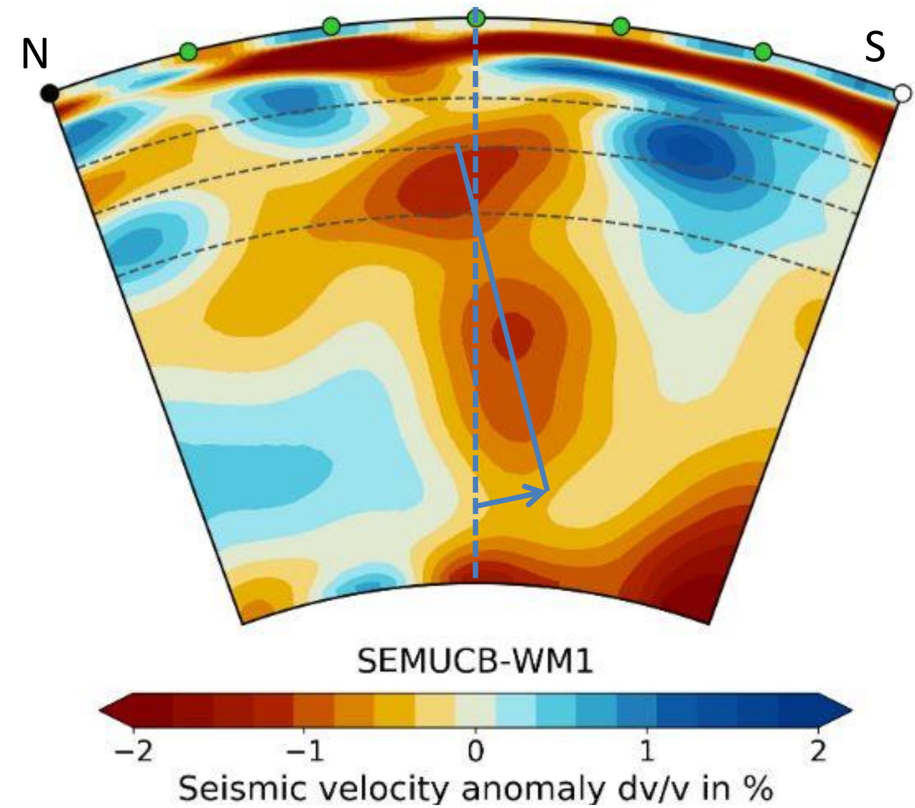

0.6
0.7
0.8
0.9
depth [normalized radius]

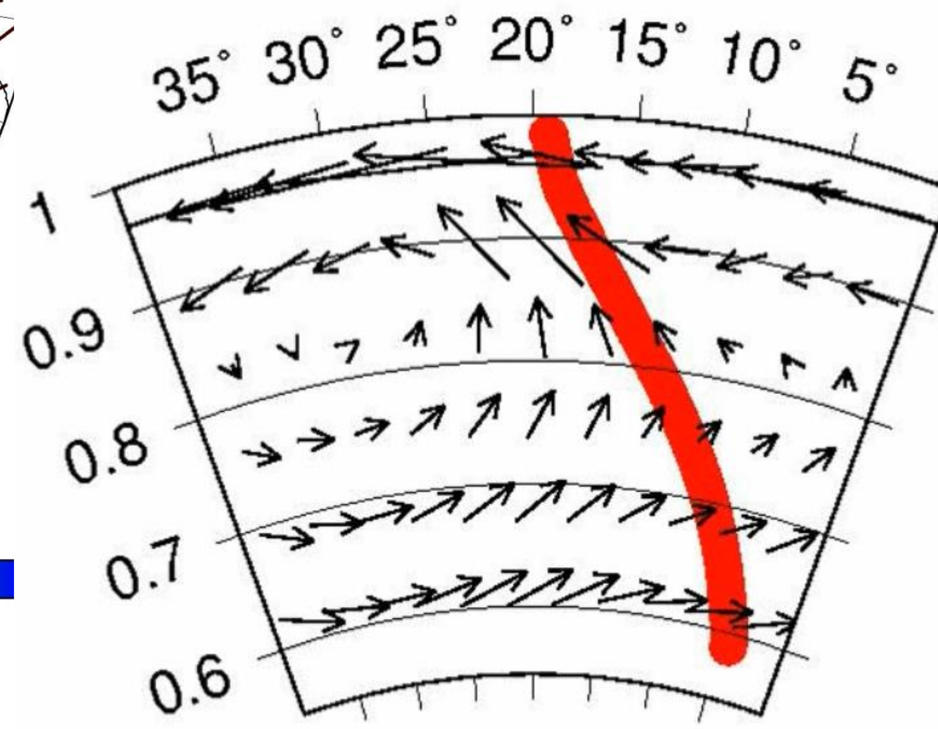
From Boschi, Becker and Steinberger (G-Cubed, 2007)



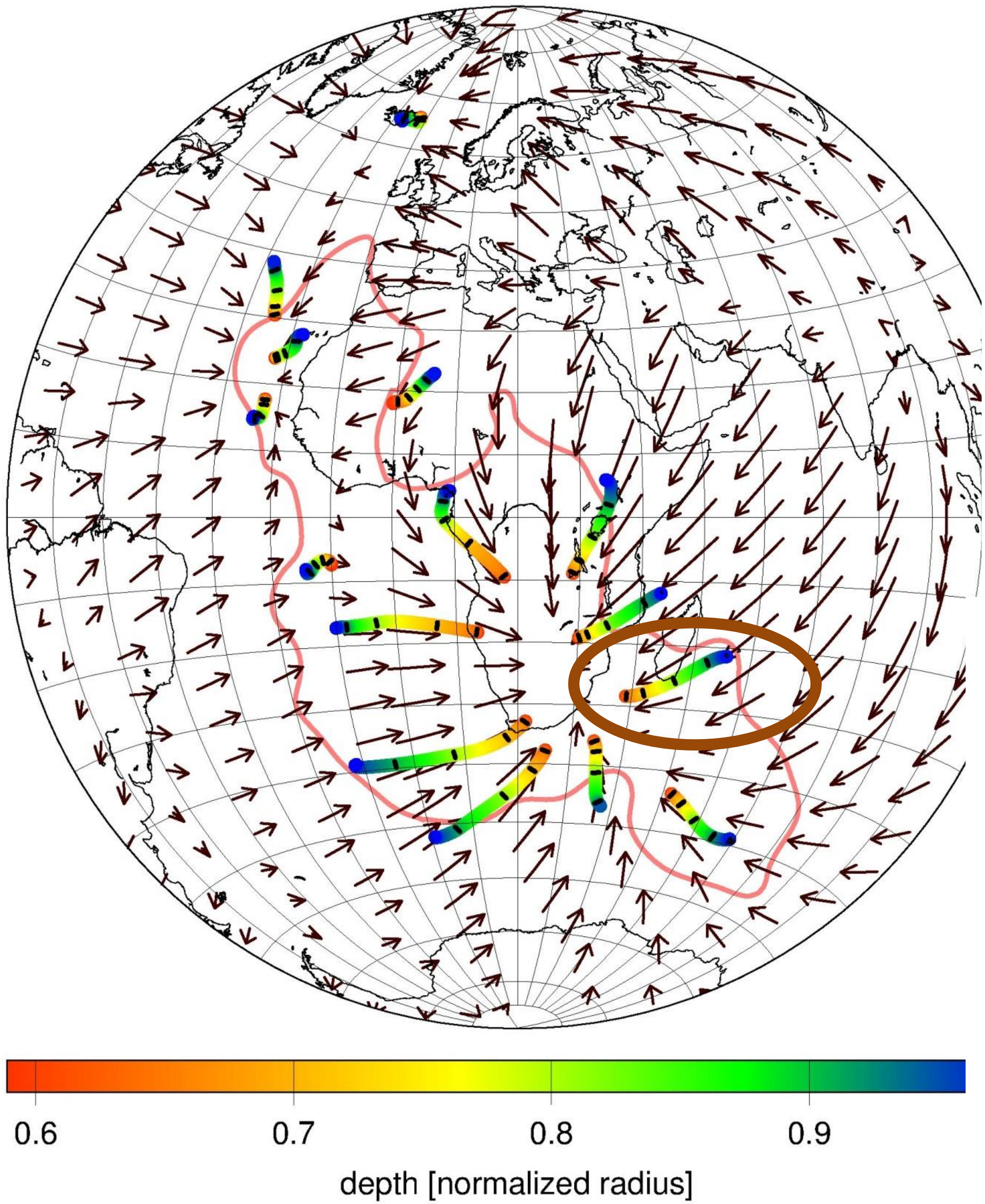
Hawaii


0.6
0.7
0.8
0.9
depth [normalized radius]

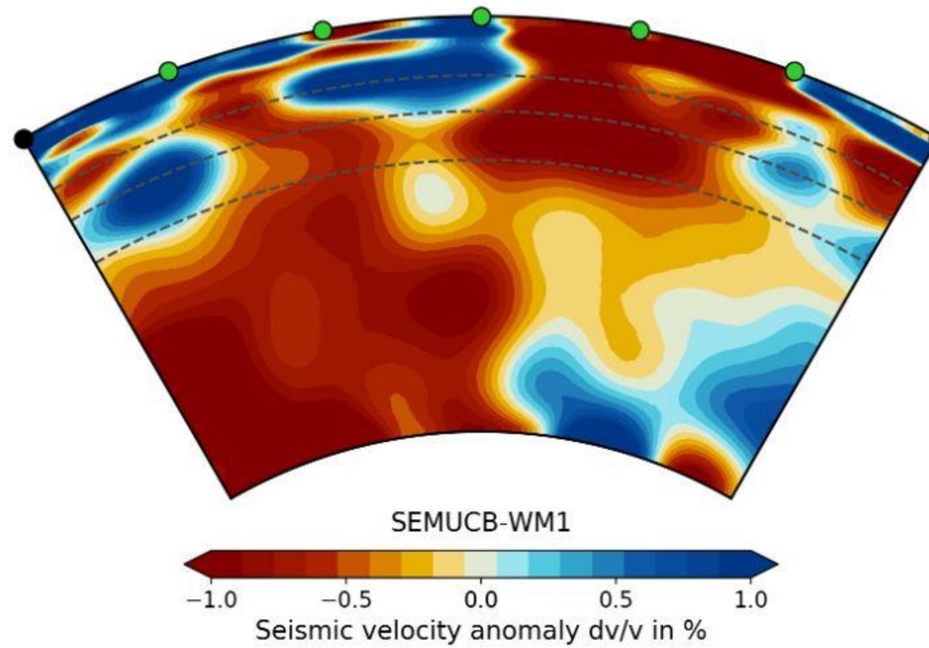

N
S
SEMUCB-WM1
−2
−1
0
1
2
Seismic velocity anomaly dv/v in %


35°
30°
25°
20°
15°
10°
5°
1
0.9
0.8
0.7
0.6

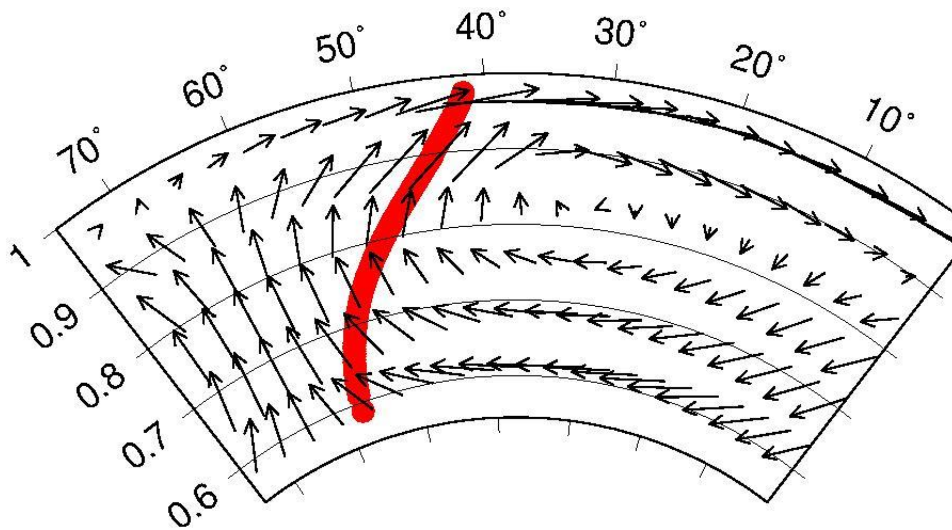
La Reunion



0.6
0.7
0.8
0.9
depth [normalized radius]

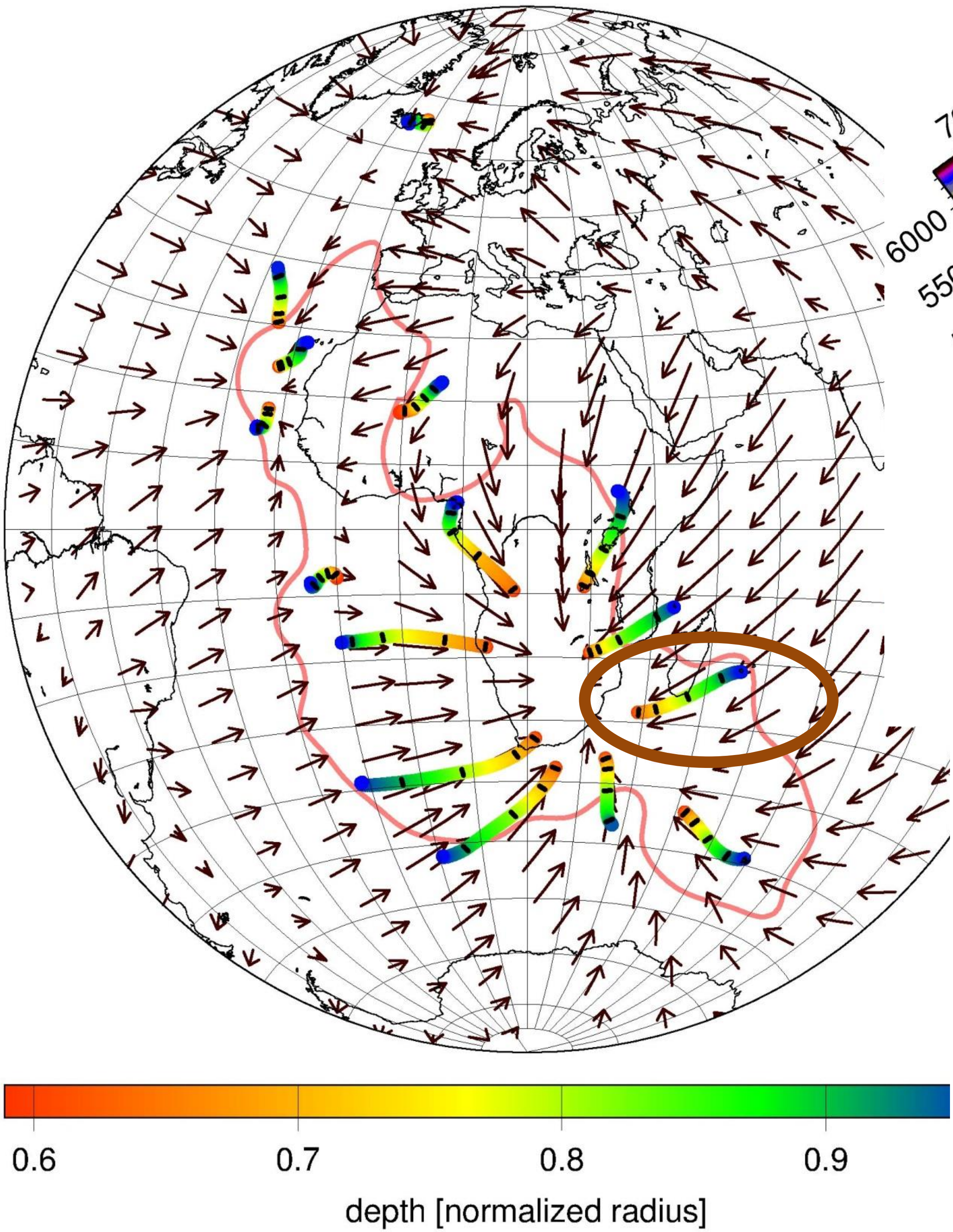


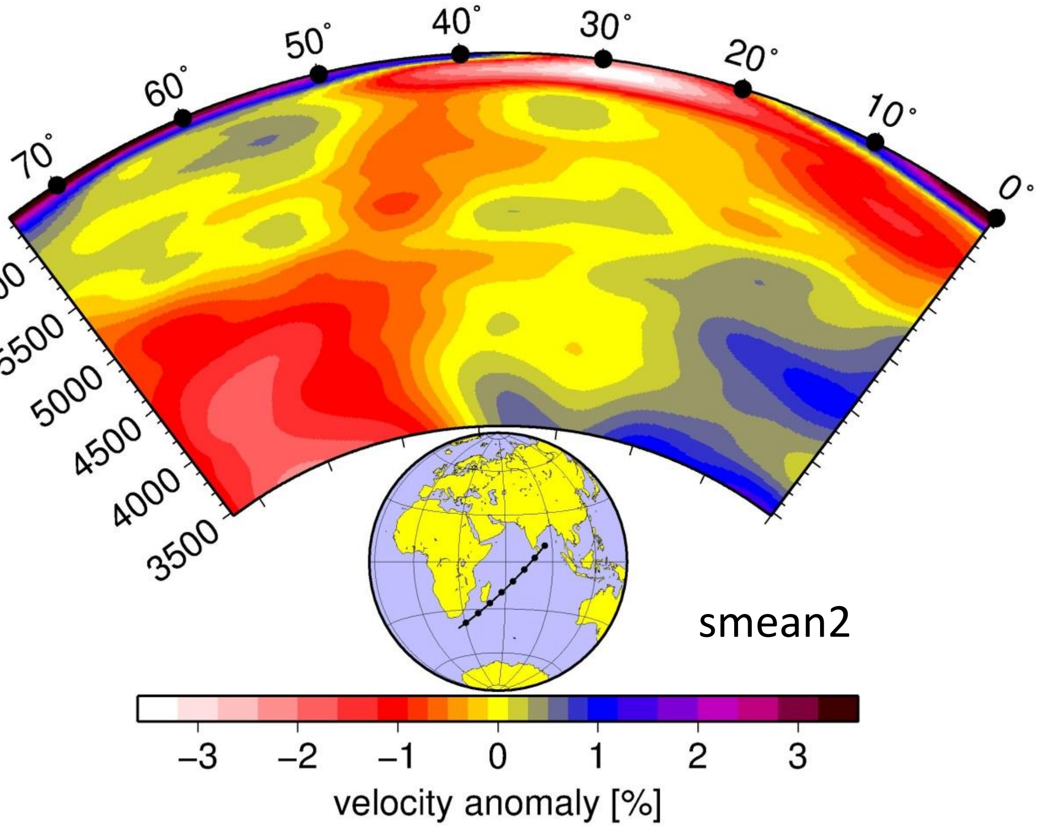
SEMUCB-WM1
−1.0
−0.5
0.0
0.5
1.0
Seismic velocity anomaly dv/v in %

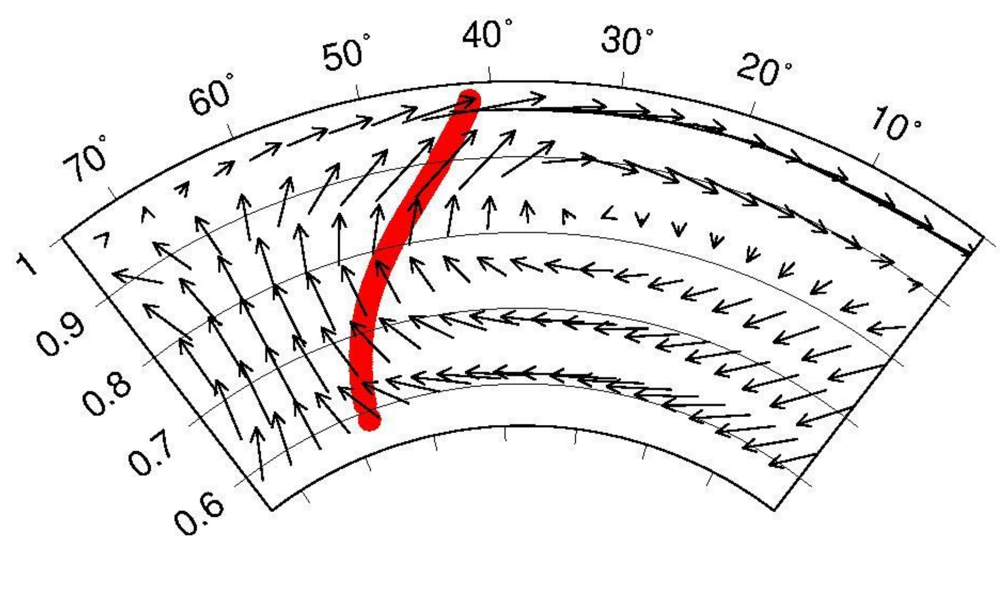


70°
60°
50°
40°
30°
20°
10°
1
0.9
0.8
0.7
0.6

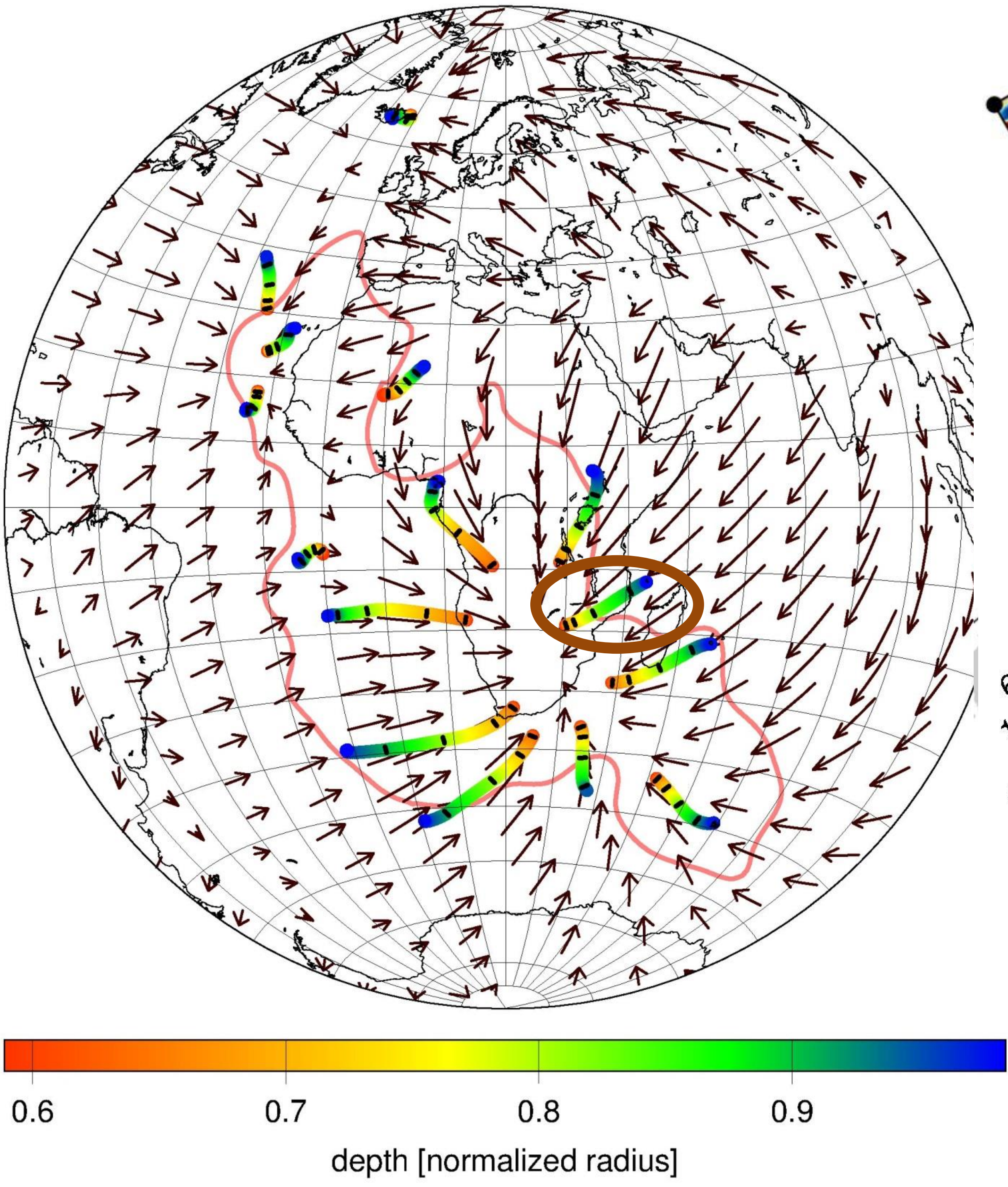
La Reunion

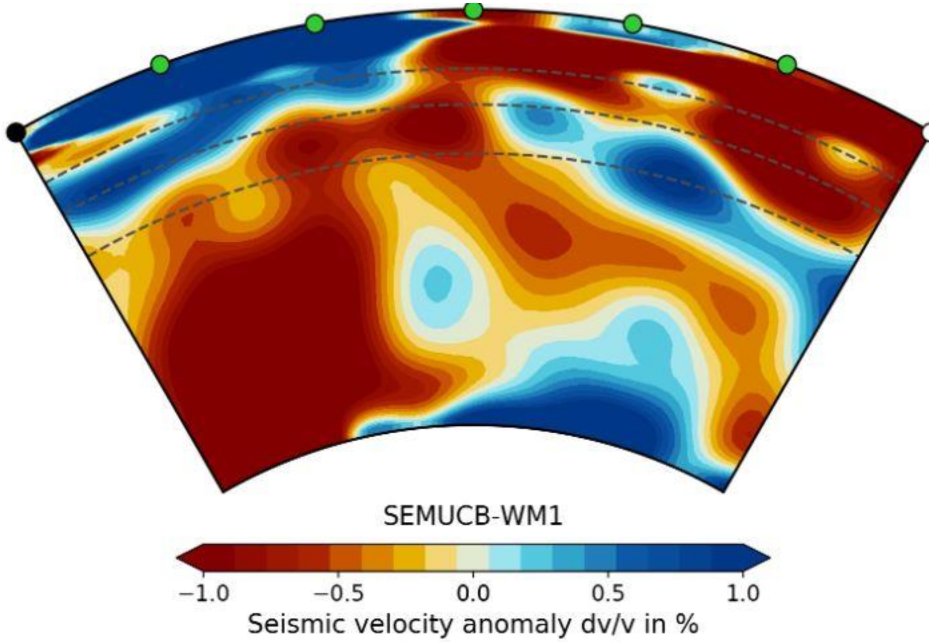

0.6
0.7
0.8
0.9
depth [normalized radius]

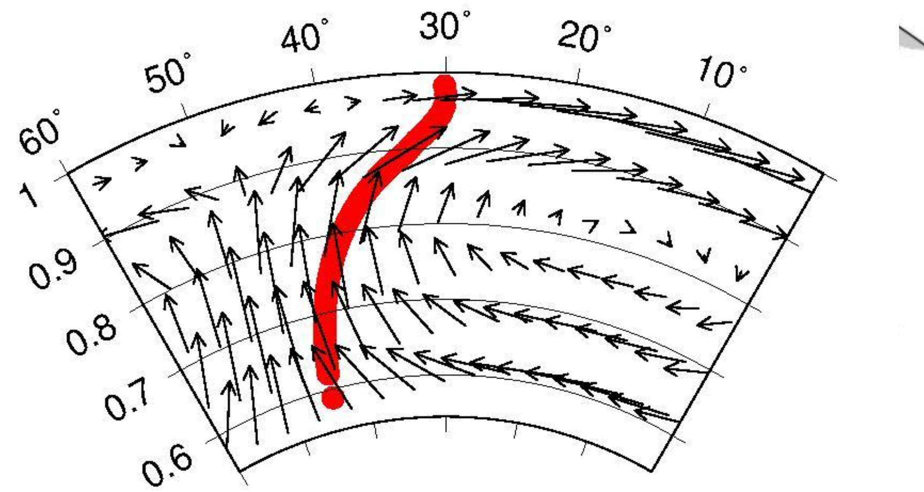

70°
60°
50°
40°
30°
20°
10°
0°
6000
5500
5000
4500
4000
3500
smean2
−3
−2
−1
0
1
2
3
velocity anomaly [%]


70°
60°
50°
40°
30°
20°
10°
1
0.9
0.8
0.7
0.6

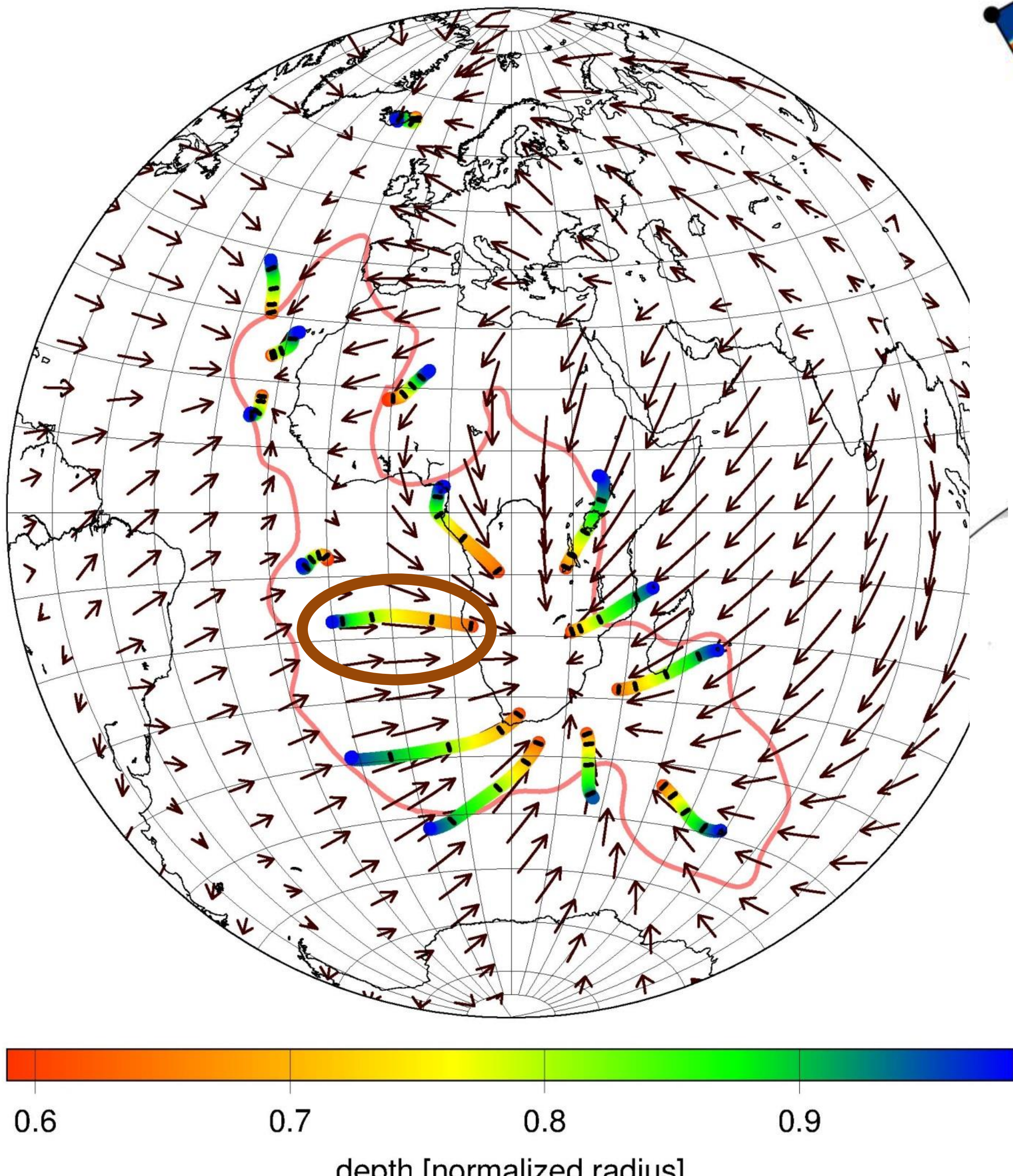
Comores

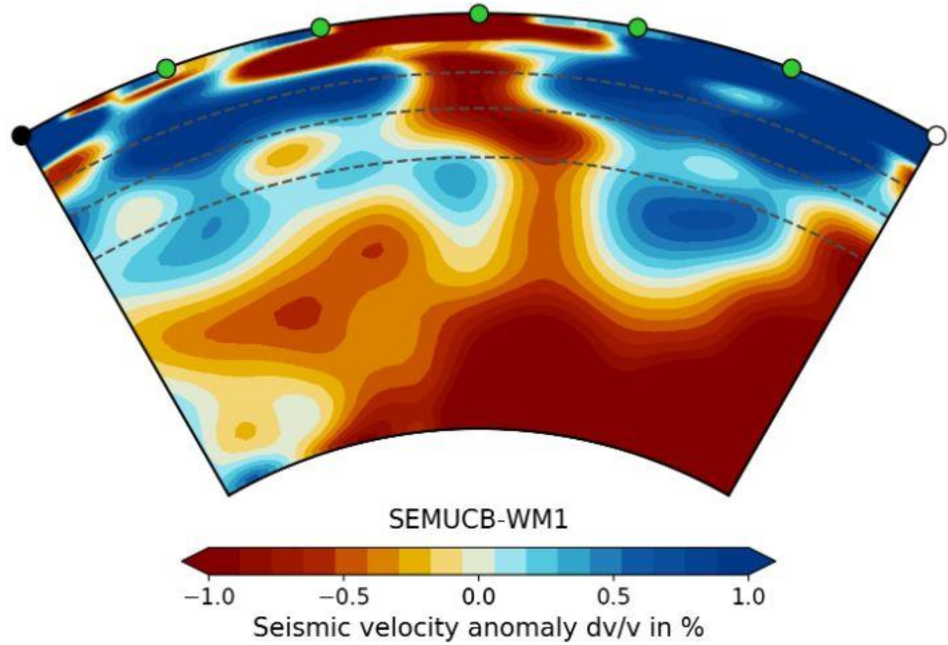

0.6
0.7
0.8
0.9
depth [normalized radius]

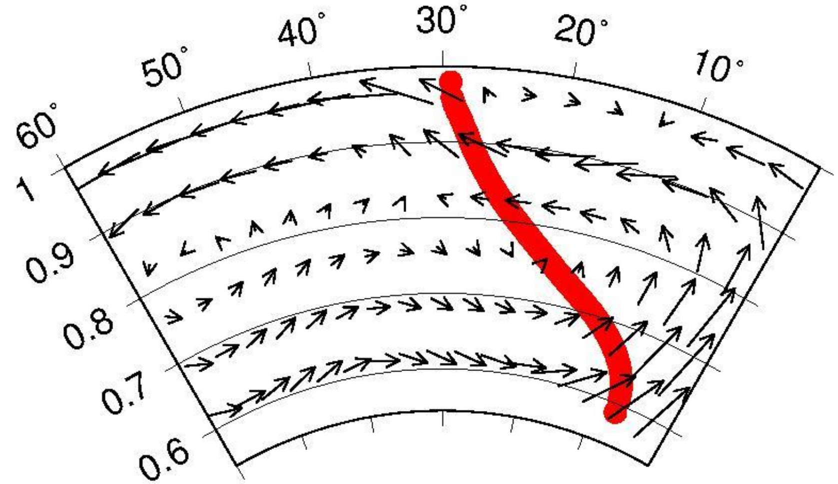

SEMUCB-WM1
−1.0
−0.5
0.0
0.5
1.0
Seismic velocity anomaly dv/v in %


60°
50°
40°
30°
20°
10°
1
0.9
0.8
0.7
0.6

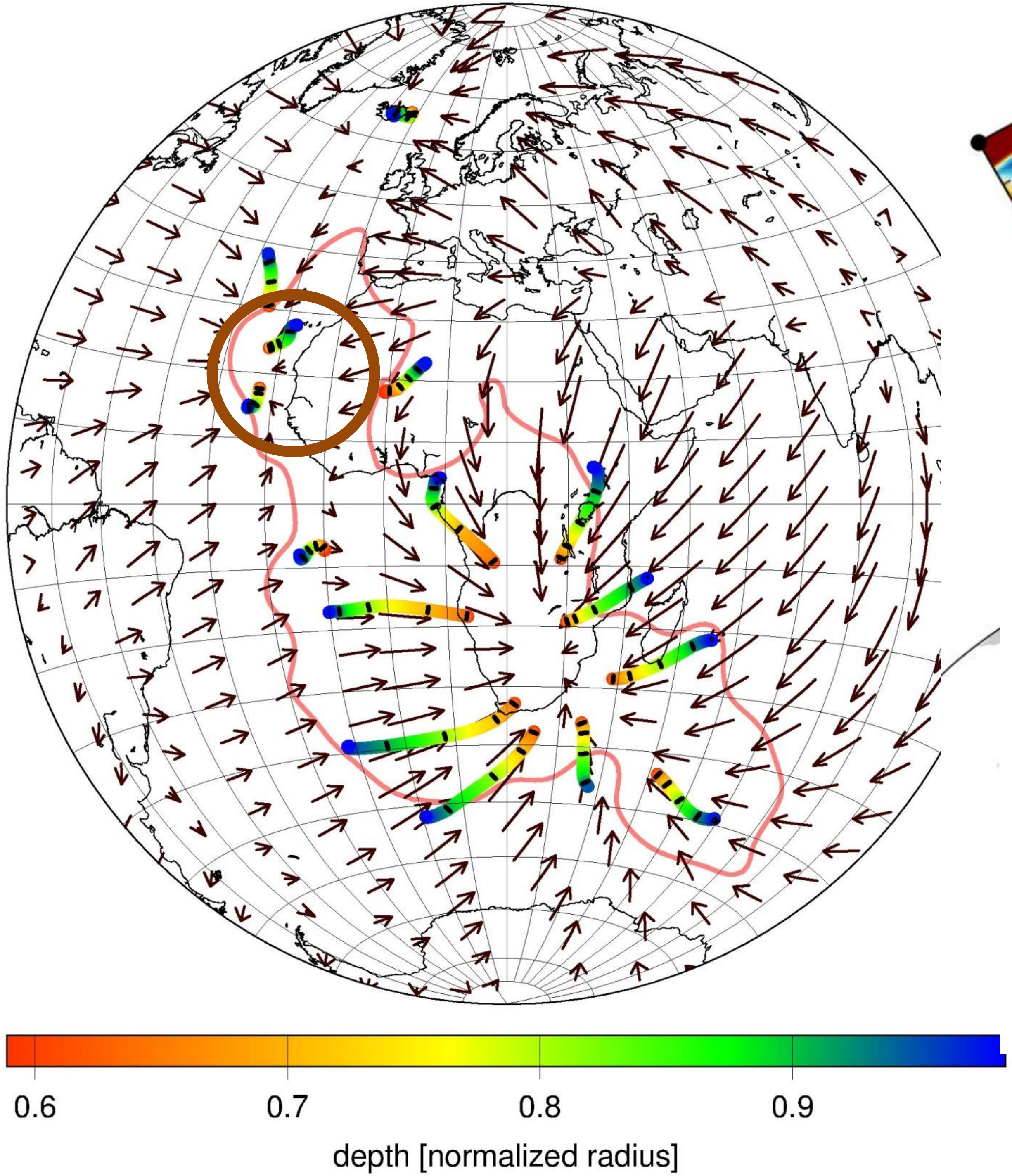
St Helena

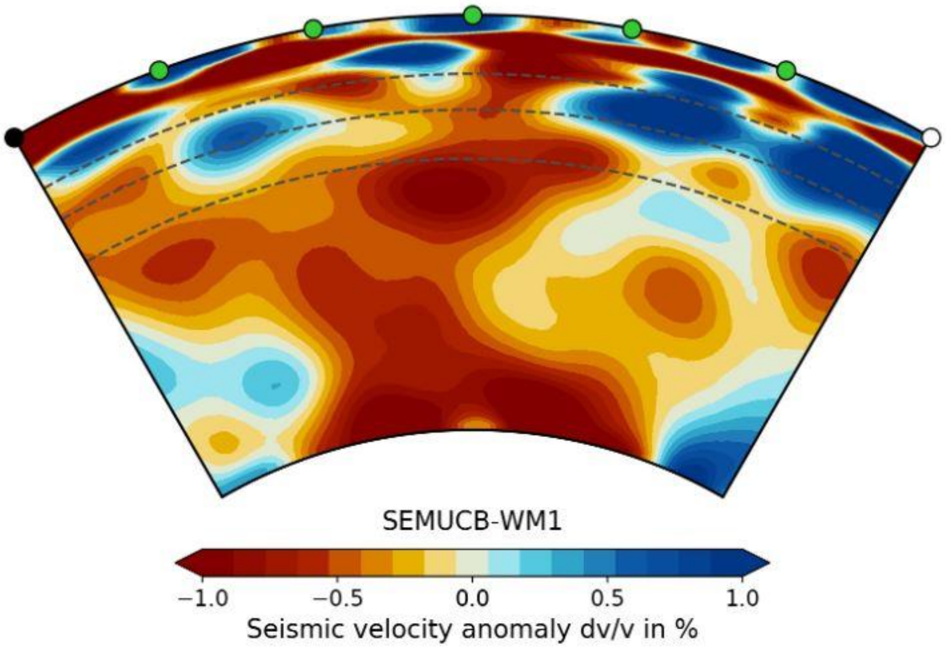

0.6
0.7
0.8
0.9
depth [normalized radius]

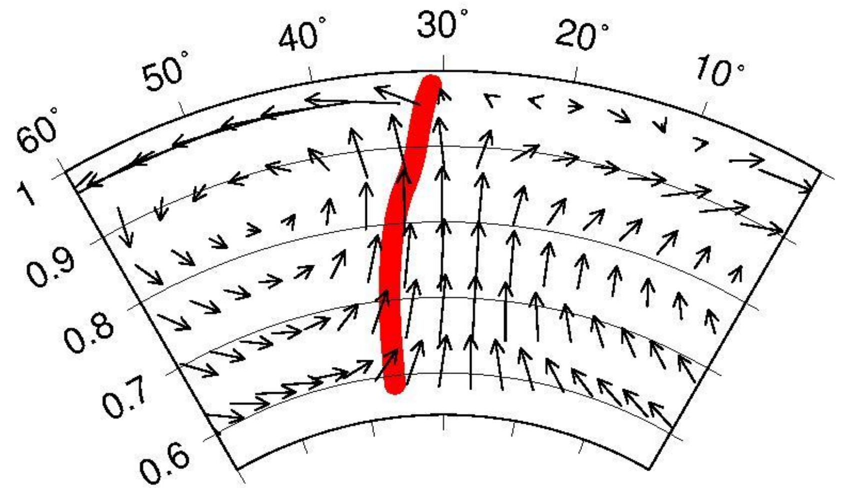

SEMUCB-WM1
−1.0
−0.5
0.0
0.5
1.0
Seismic velocity anomaly dv/v in %


60°
50°
40°
30°
20°
10°
1
0.9
0.8
0.7
0.6

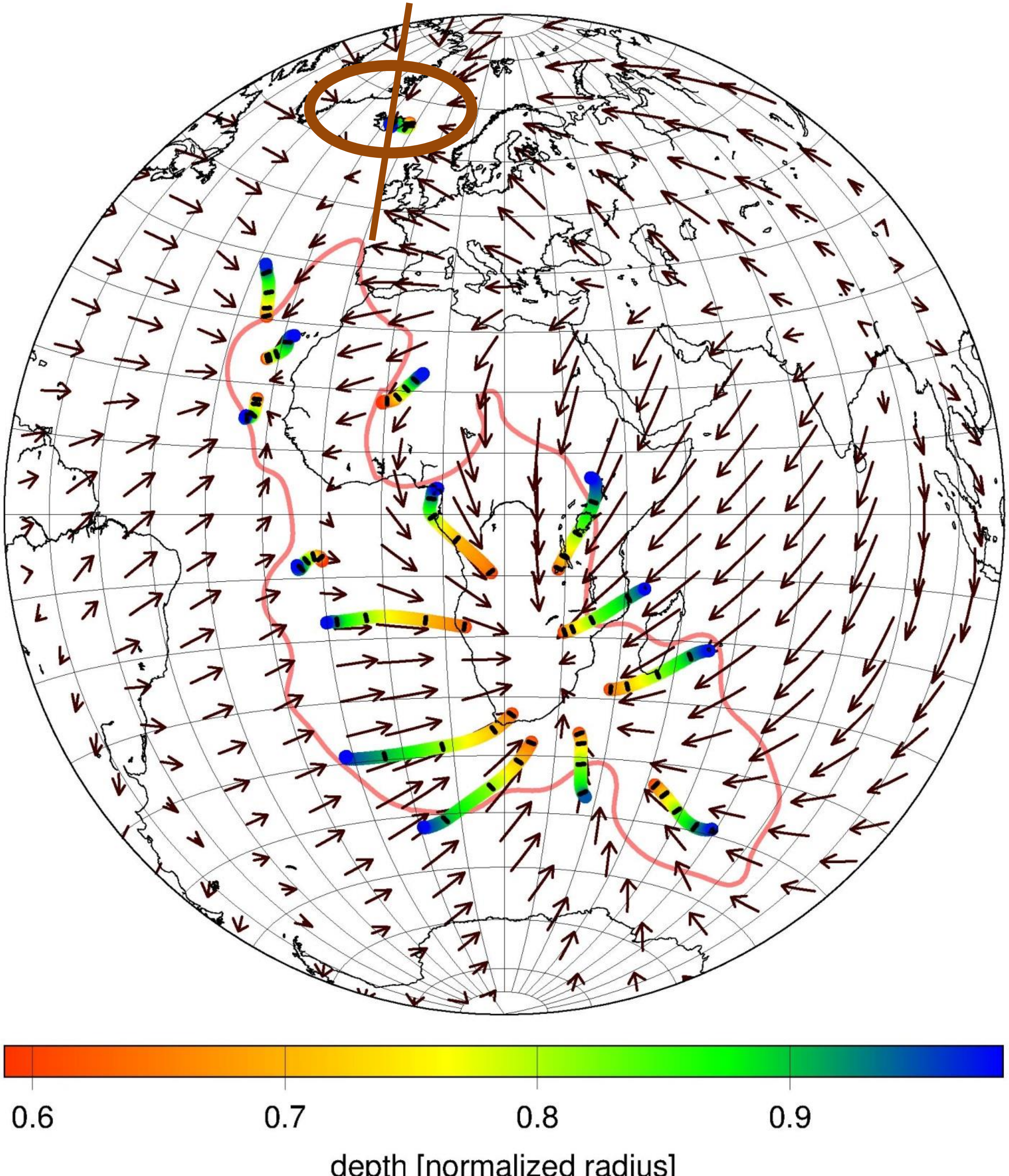
Canary (/ Cape Verde)

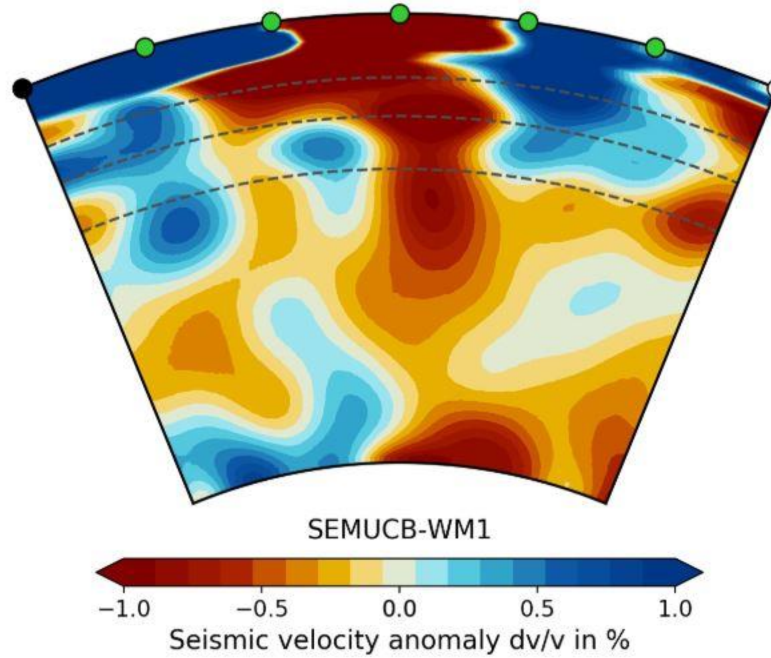




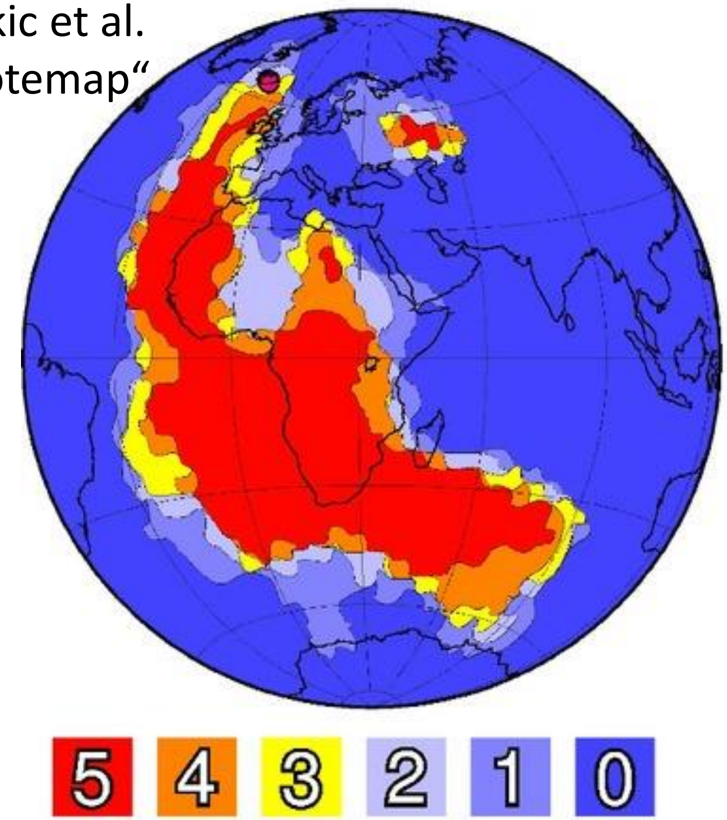


Iceland





Lekic et al. „votemap“



Eifel

Projection
on E-W cross section