

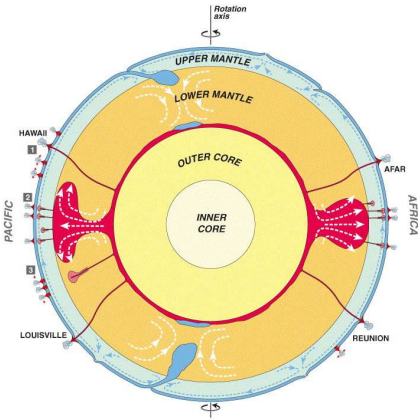
**Surface volcanism data since 400 Ma
as a constraint of mantle dynamics
and Principal Inertia Axes**

Marianne Greff and Jean Besse

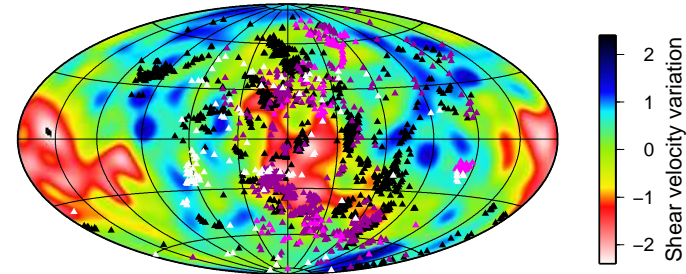
Institut de Physique du Globe de Paris

Geomagnetic and paleomagnetic teams

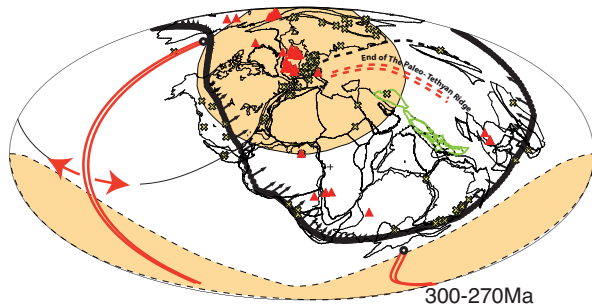
I-1) Large-scale pattern of mantle dynamics: contributions due to subducted lithosphere and to long wavelength upwellings.



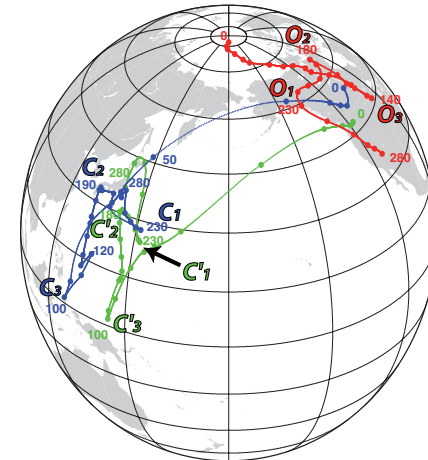
I-2) Position of two antipodal upwelling domes in the lower mantle estimated from the intra-plate alkaline volcanism



I-3) Amount of subduction since 400 Ma estimated from the study of the subduction volcanism in the past and plate motion history

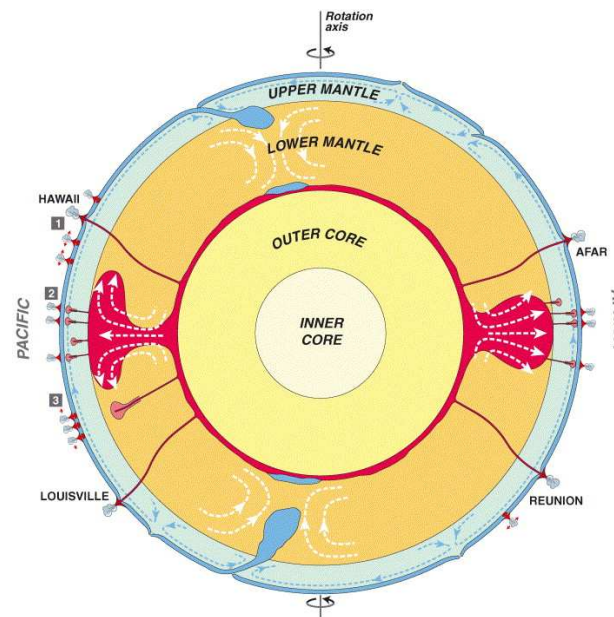


II) Principal Inertia Axis and Polar Wander



Surface volcanism data since 400 Ma as a constraint of mantle dynamics and Principal Inertia Axes

- Simple model for the large-scale pattern of mantle dynamics: contributions due to subducted lithosphere and to long wavelength upwellings.



from [Courtillot et al., 2003]

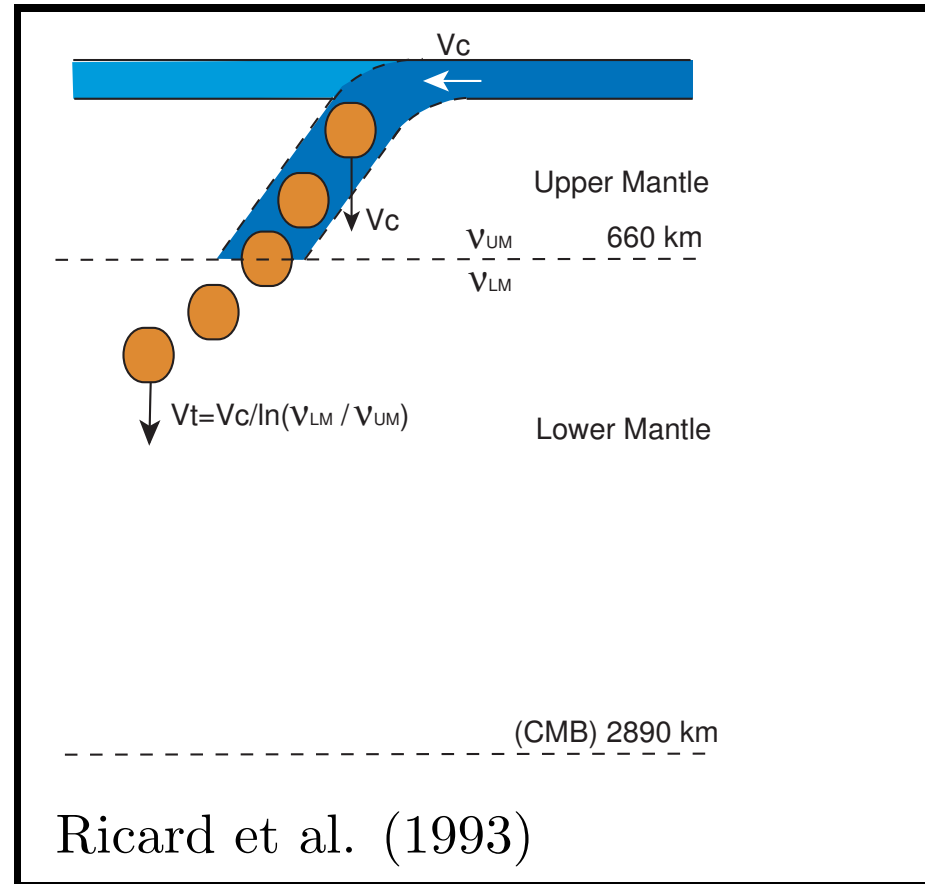
Mantle Downwellings [*Ricard et al., 1993*]

- Slabs sinking vertically into the mantle at the surface velocity
- At 660km depth, they are slowed and thickened by a factor 4

Ex: $V_c \simeq 8 \text{ cm/yr} \Rightarrow V_t = 2 \text{ cm/yr}$

\Rightarrow Characteristic time needed for a plate to sink through the whole mantle is 120 Myrs.

\Rightarrow Temporal evolution of the mantle density heterogeneities since 280 Myr is modeled assuming that plates sink down to the core-mantle boundary since 400 Myr.

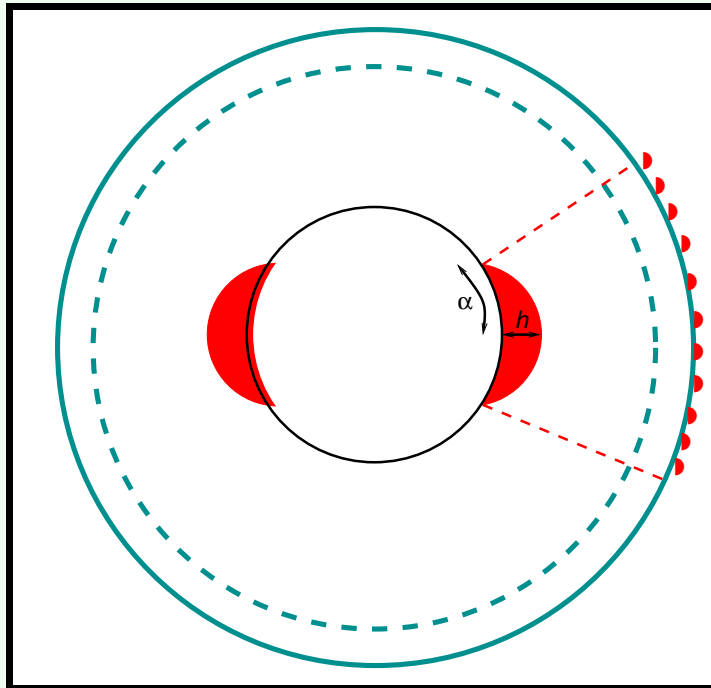


\Rightarrow We need the position of the subduction zones and surface velocities since 400 Myr.

Mantle Upwellings

Two large regions in which the material is thermally or compositionally less dense than the surrounding mantle

⇒ responsible for the superswells observed at the Earth's surface [*Davaille et al., 1999*].



Domes modeled as two hemispheres:

- Pacific dome assumed to be antipodal
- $h = 500$ km from present-day tomography
- Stable large zones ⇒ the time taken by the upwelling flow to cross the mantle is less than 20 Myr, because of pre-existing conduit between the dome and the surface.
- From the traces left at the surface by intra-plate volcanism, we assessed the geometrical parameters of the African dome

Surface volcanism data since 400 Ma

- **Extraction from three database** [Georoc, Usgs and the GP-MDB ver. 4.6 data base [McElhinny & Lock, 1996]] of the location and age of volcanic edifices

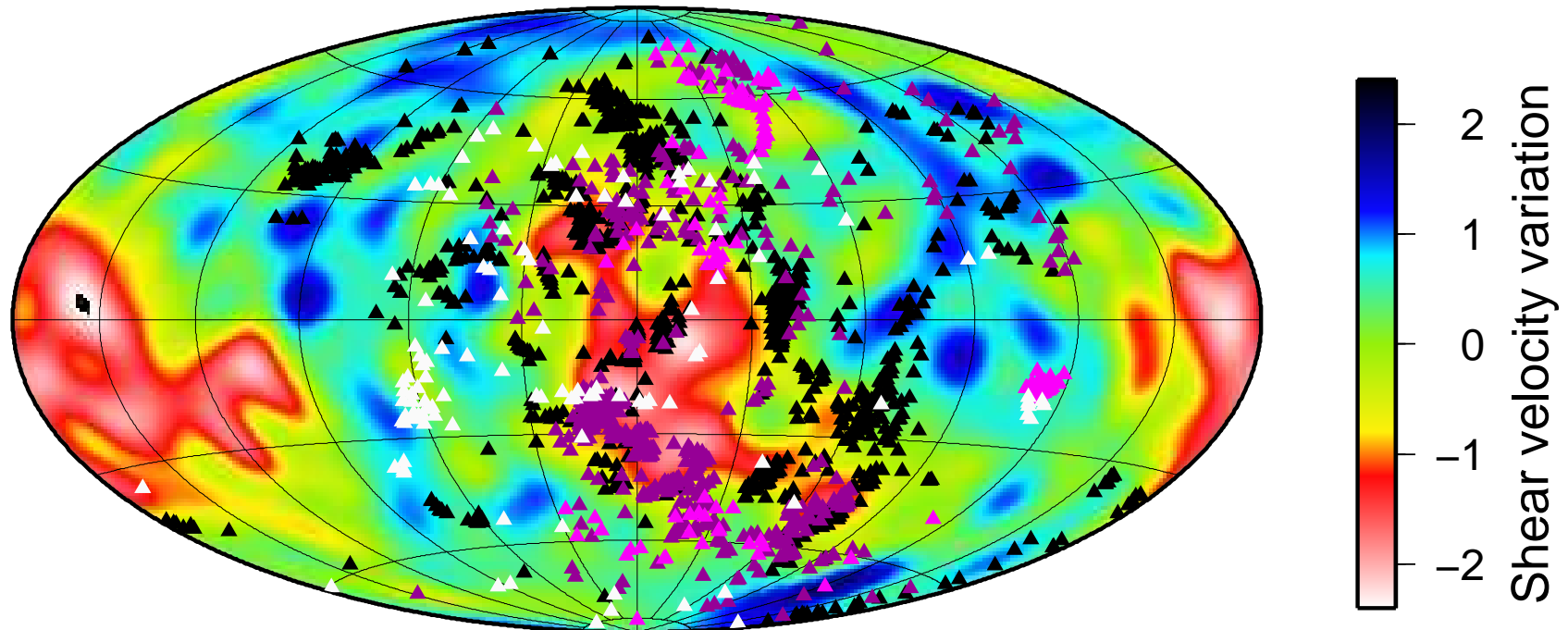
- **Sorting of volcanism into two types:**
intra-plate and subductions:

- **Reconstruction of their paleopositions** in a mantle reference frame where Africa is fixed or in the paleomagnetic frame from [McElhinny *et al.*, 2003] VPG.

- **Interpretations:**

- Position of the small circles above the Africa dome
- Position of the subduction zones

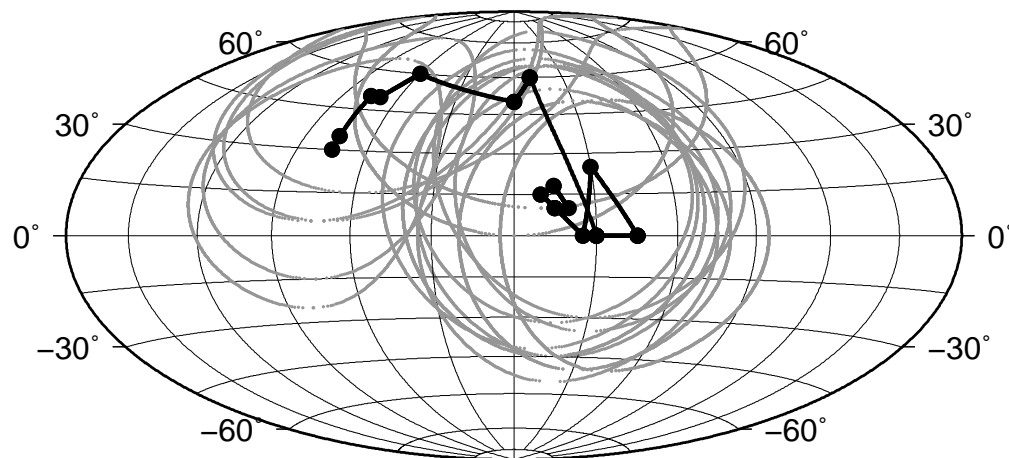
Paleopositions of intraplate volcanic edifices in the paleomagnetic frame since 400 Ma



Tomographic image of the deep mantle at the depth=2880 km (Ritsema et al. 1999)

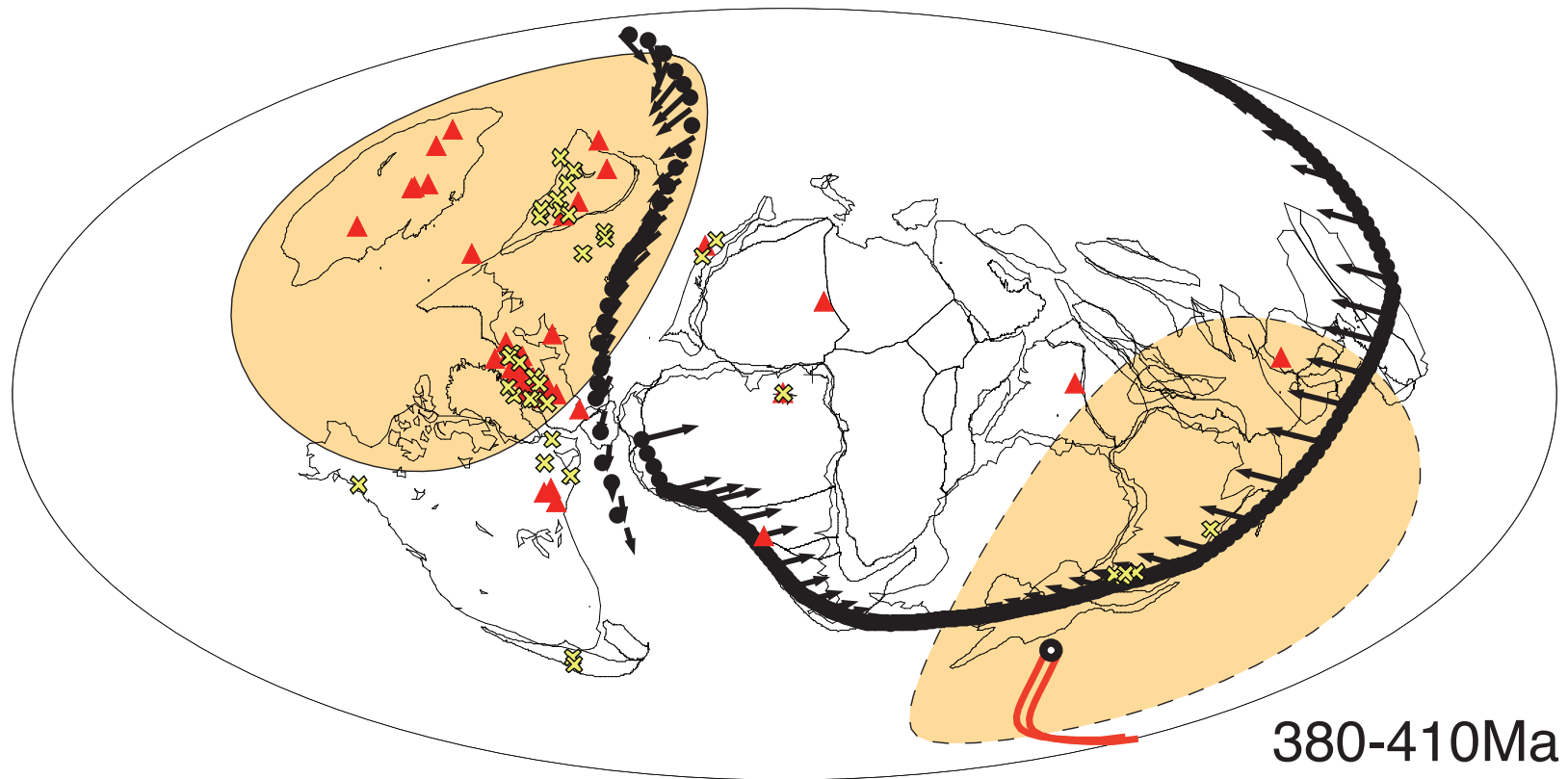
(black: recent time (< 100 Ma); purple: 100 < t < 200 Ma; pink: 200 < t < 300 Ma; white: 300 < t < 400 Ma)

Paleopositions of intraplate volcanic edifices in our fixed African reference frame since 400 Ma

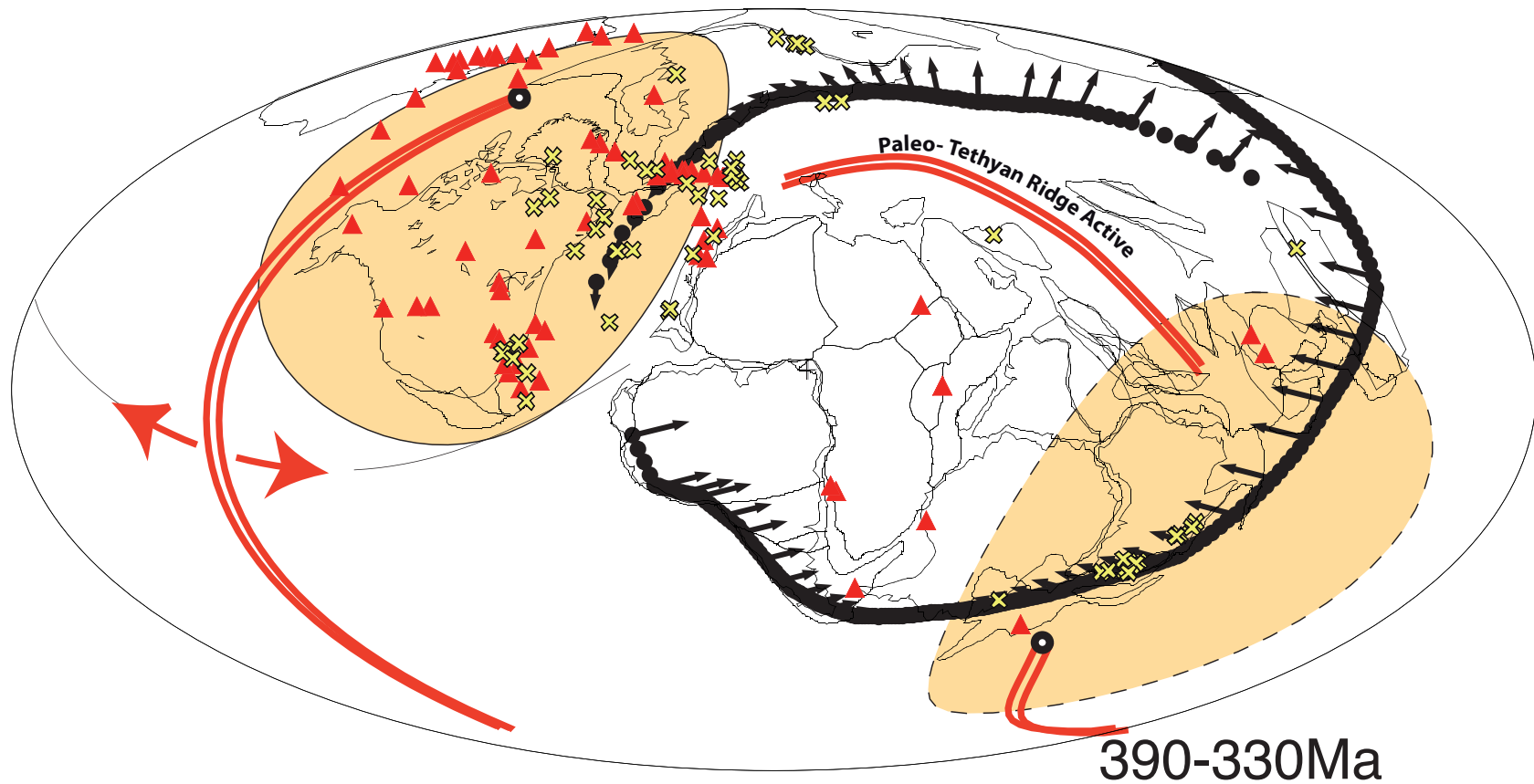


- Small circle modelling the trace left at the surface by intra-plate volcanism above the dome for each 20 Myrs interval from -400 Ma to present.
- Temporal evolution of the center of small circle related to the motion of Africa in the paleomagnetic frame.
- The width of the small circle above the 'African' dome is around $45 - 50^\circ$

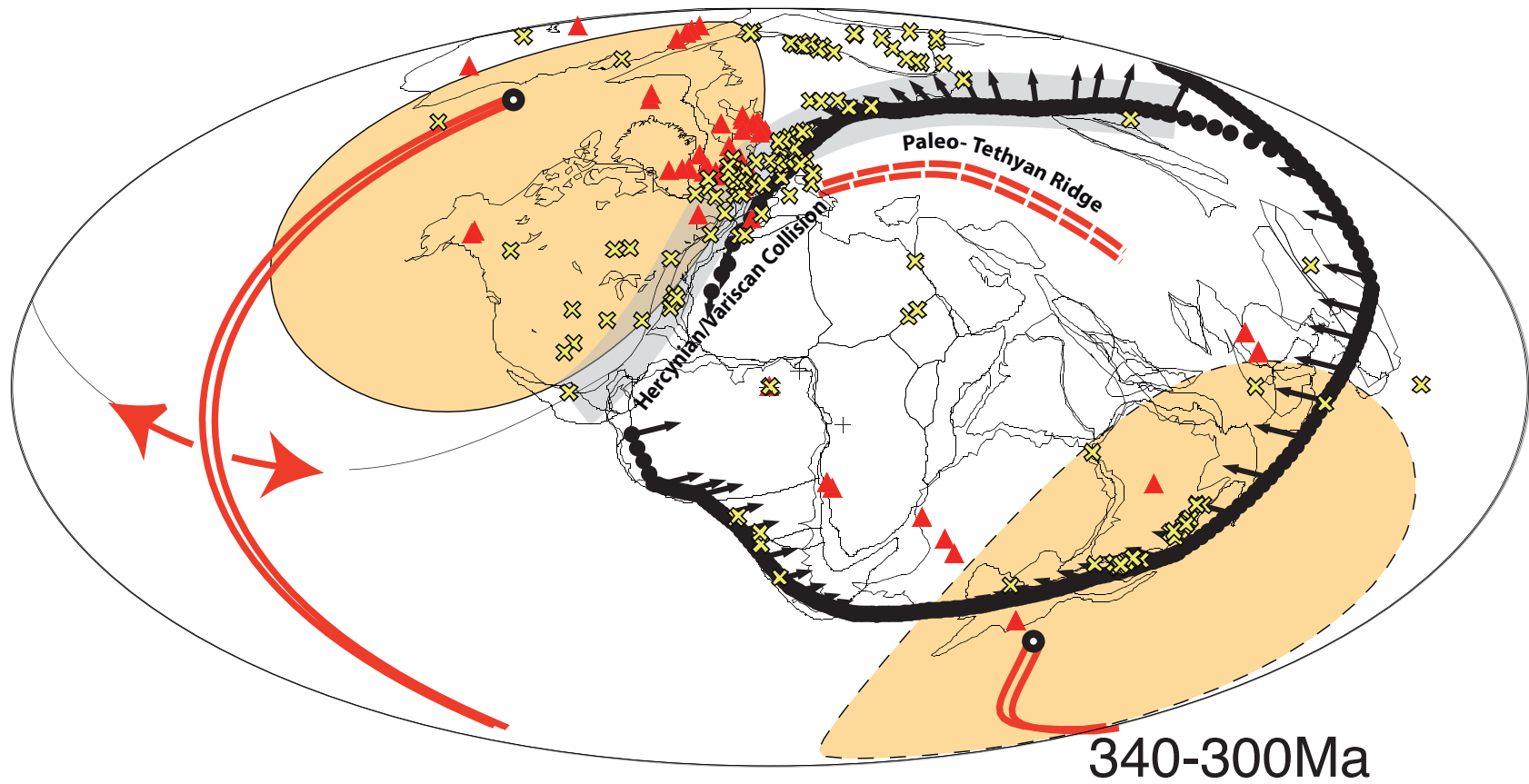
Paleopositions of subduction zones in the Africa fixed reference frame since 400 Ma



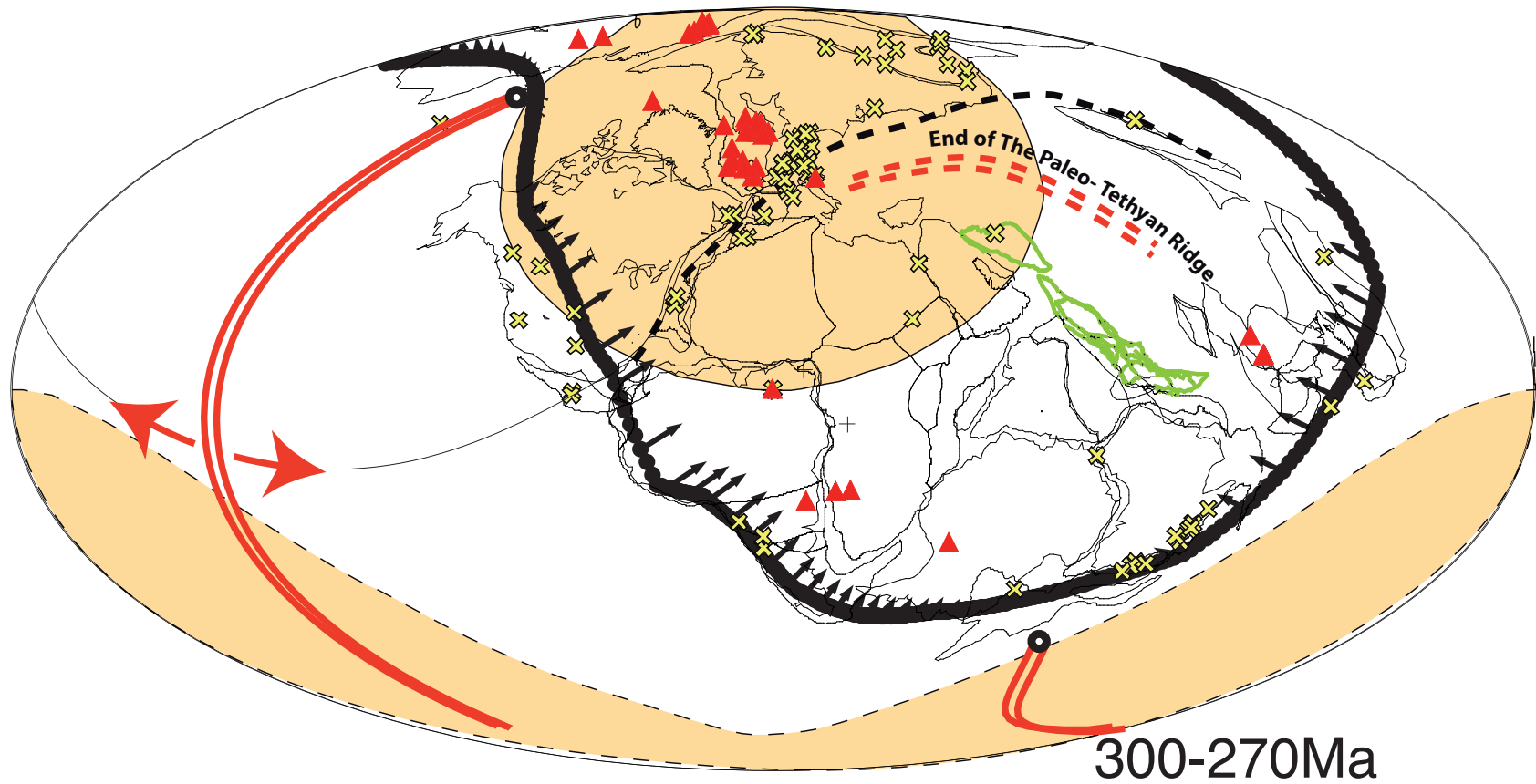
Paleopositions of subduction zones in the Africa fixed reference frame,
390-330 Ma



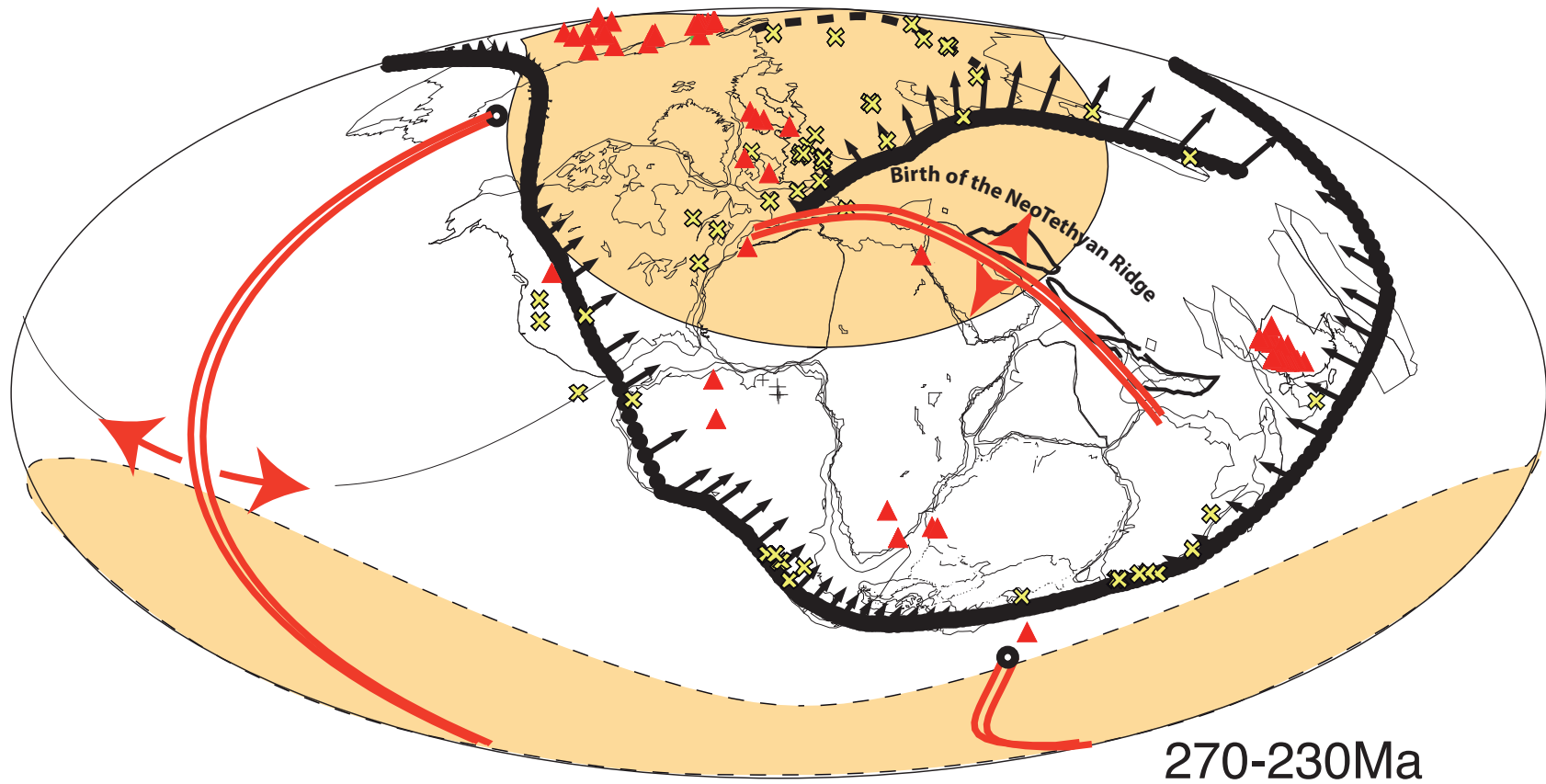
Paleopositions of subduction zones in the Africa fixed reference frame,
340-300 Ma



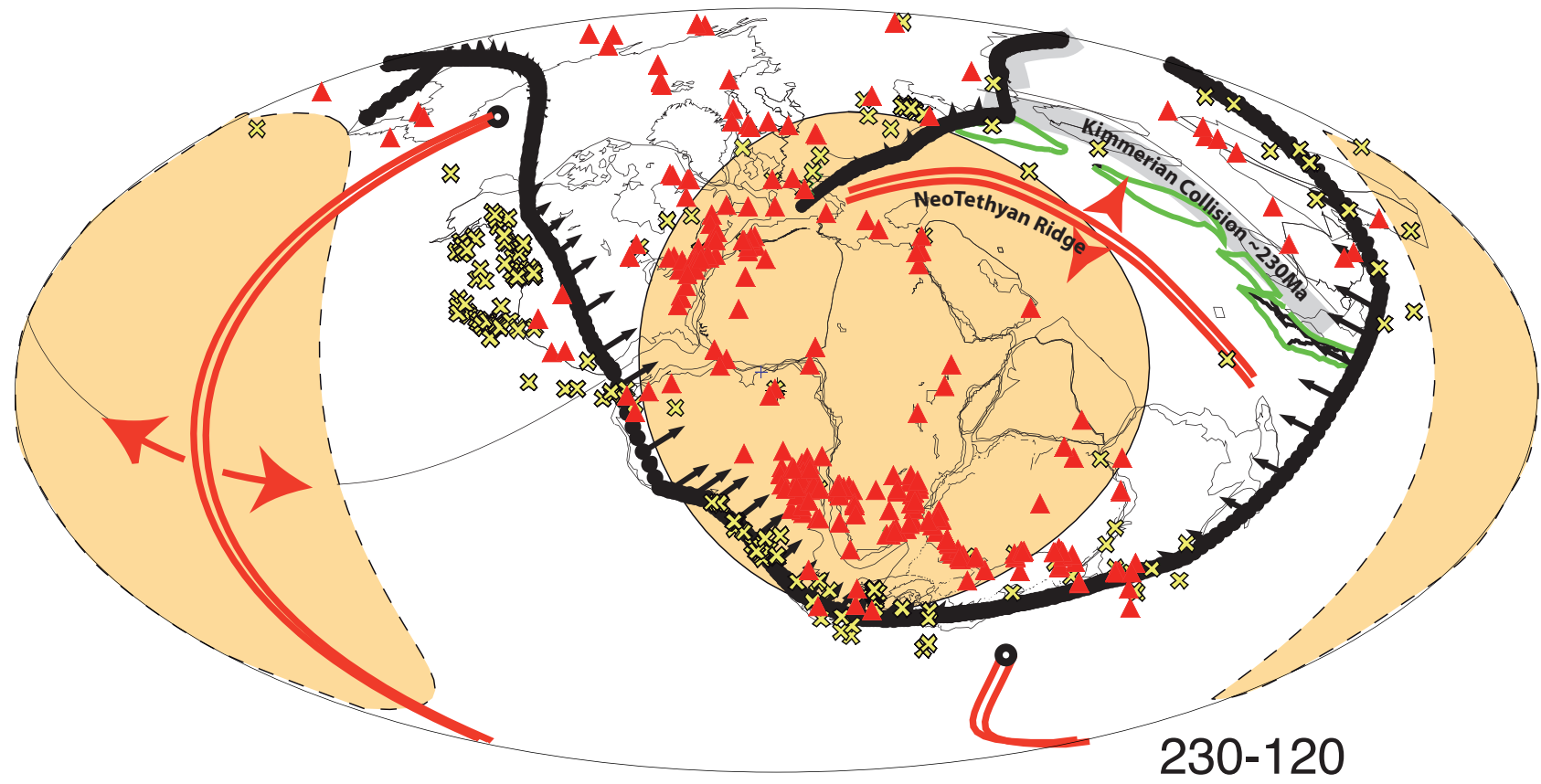
Paleopositions of subduction zones in the Africa fixed reference frame,
300-120 Ma



Paleopositions of subduction zones in the Africa fixed reference frame,
270-230 Ma



Paleopositions of subduction zones in the Africa fixed reference frame,
230-120 Ma



Paleopositions of subduction zones in the Africa fixed reference frame, since 120 Ma

- For the past 120 Myr, we use a compilation of plates motions by [*Lithgow-Bertelloni et al., 1993*] in the hotspot reference frame which we convert into our fixed Africa frame.

Perturbation of the Earth's inertia tensor

Simple model for the large-scale pattern of mantle dynamics combining contributions due to subducted lithosphere and to long wavelength upwellings

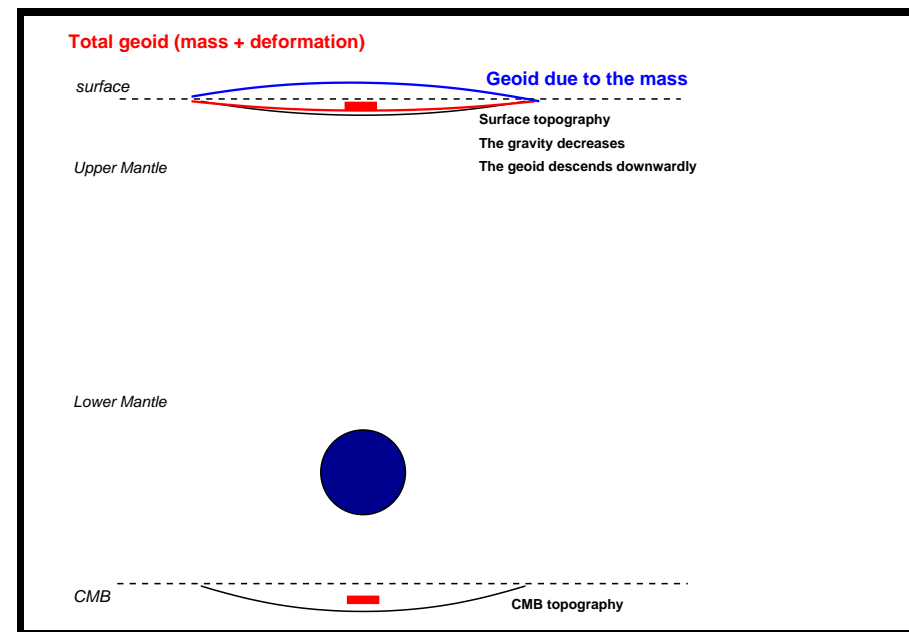
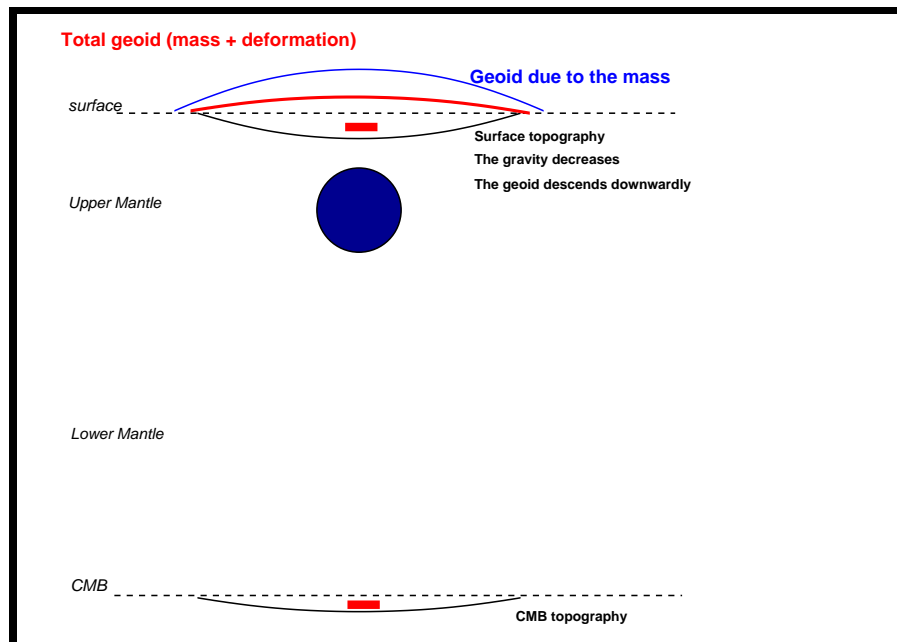
$$Geoid(\theta, \varphi) = a \sum_{n=2}^{nmax} \sum_{m=0}^n \left(c_{nm} \cos m\varphi + s_{nm} \sin m\varphi \right) P_n^m(\cos \theta)$$

Inertia tensor of the Earth:

$$I_{ij} = Ma^2 \begin{pmatrix} \frac{c_{20}}{3} - 2c_{22} & -2s_{22} & -c_{21} \\ -2s_{22} & \frac{c_{20}}{3} + 2c_{22} & -s_{21} \\ -c_{21} & -s_{21} & -2\frac{c_{20}}{3} \end{pmatrix}$$

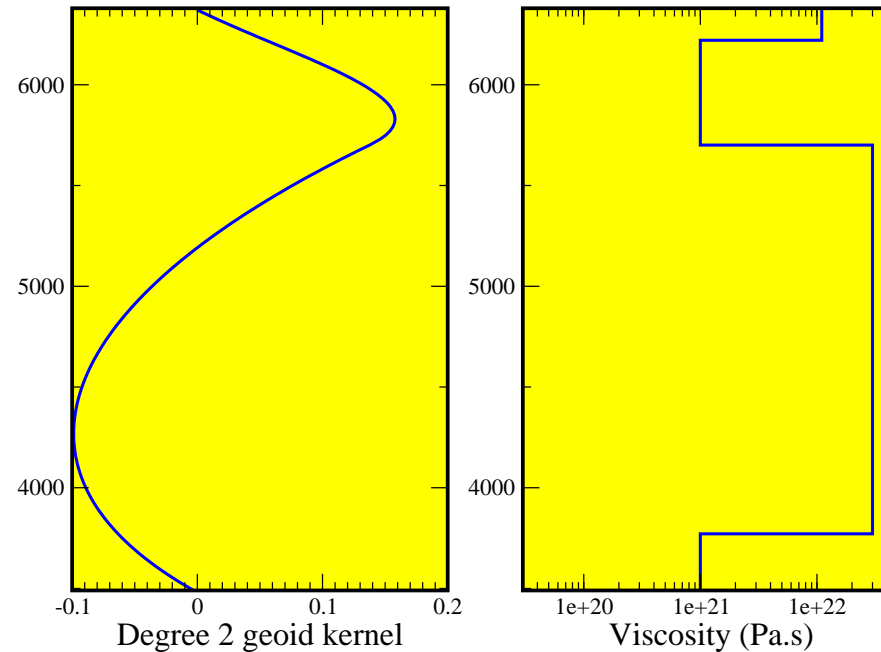
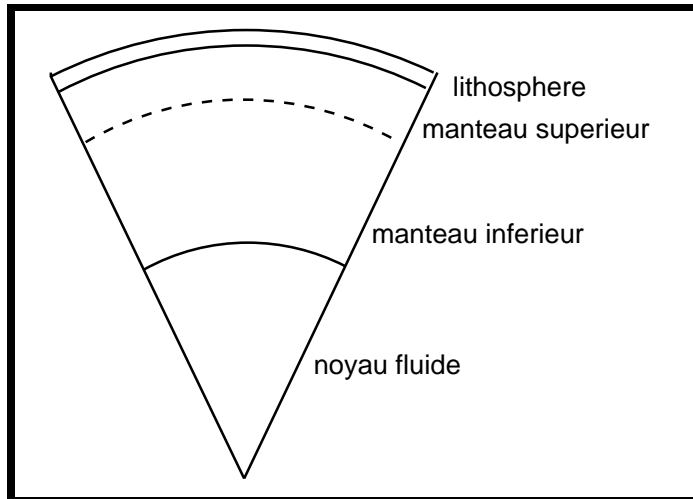
⇒ Diagonalization ⇒ Eigenvalues and Principal Inertia Axes (PIA)

Mantle mass anomalies and geoid



⇒ The geoid depends on the depth and the size of the mass anomaly.

Earth's model and degree 2 geoid kernel



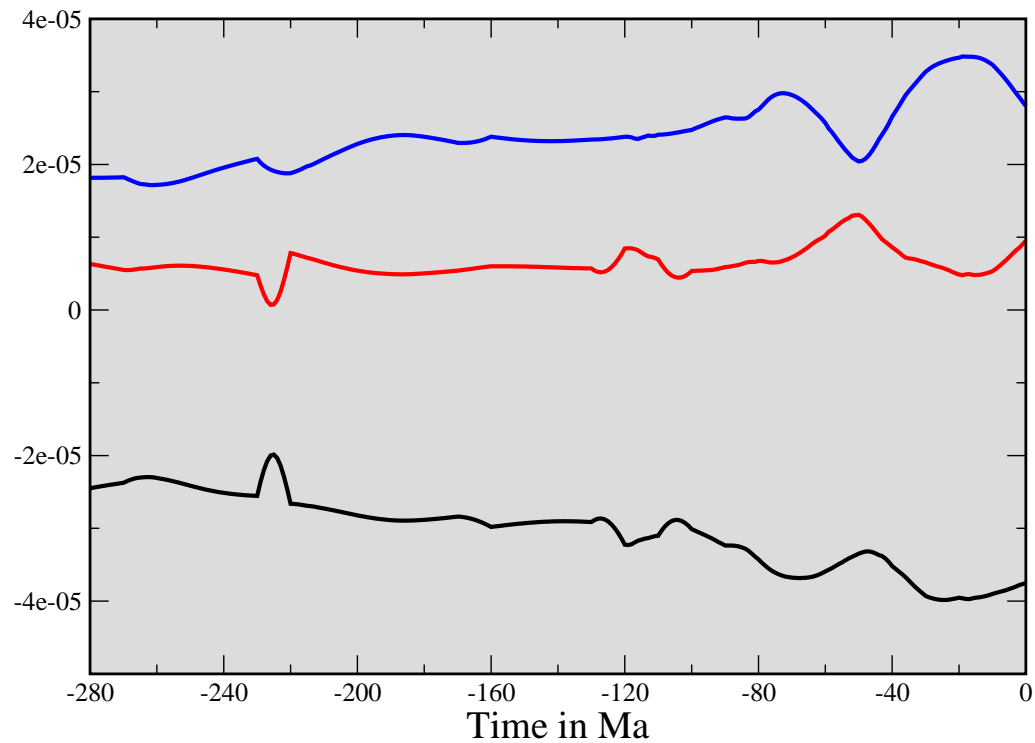
A positive degree 2 mass anomaly located in the upper part of the mantle will involve a positive geoid whereas a positive mass anomaly in the lower mantle will involve a negative geoid.

Inertia product perturbations:

$$I_{13}(t) = -\frac{4\pi}{5} \int r^4 \ker_2(r) \sigma_2^{c1}(r, t) dr$$

Inertia Eigenvalues

PIA eigenvalues

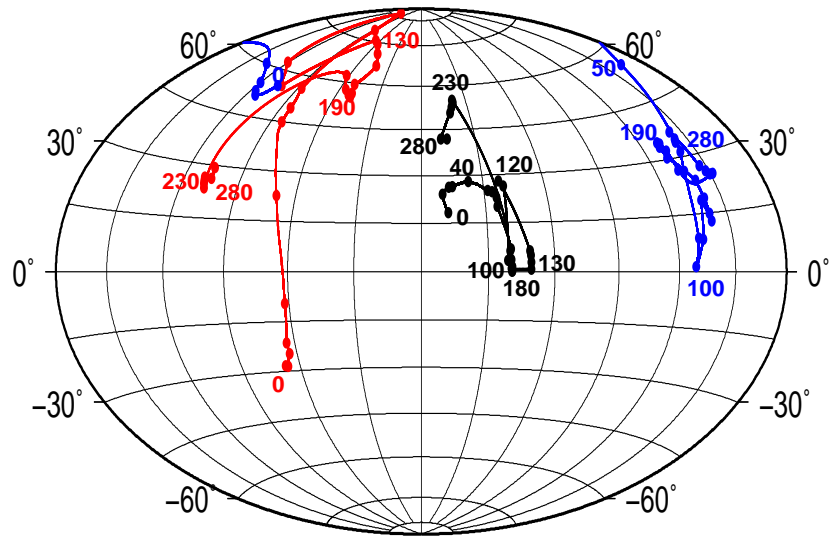


Three eigenvalues clearly distinct:



since 280 Ma, there is no inertial interchange.

Principal Inertia Axes

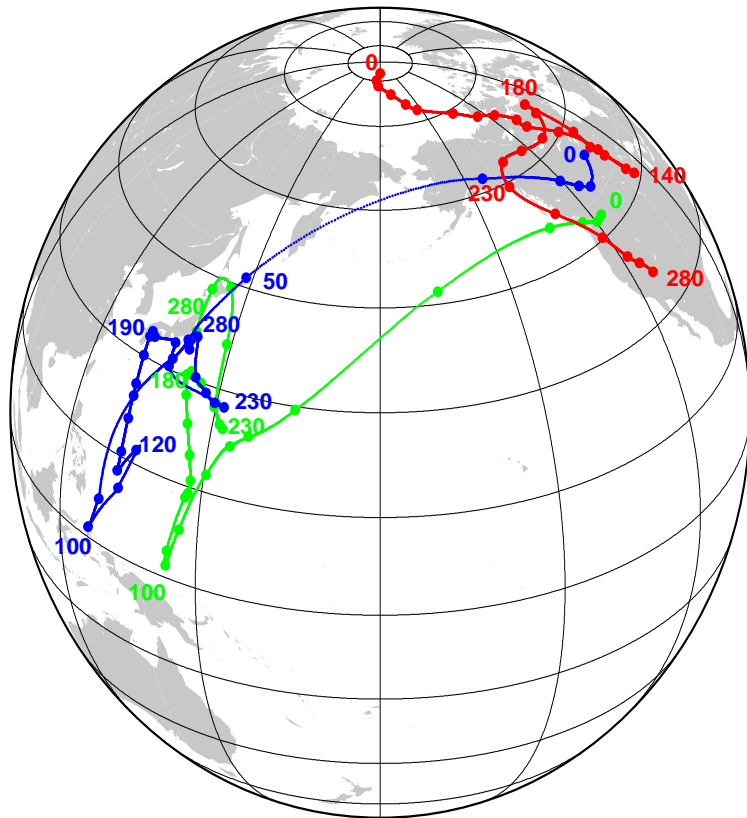


Minimum PIA: relatively stable

Maximum PIA has driven in a plane perpendicular to Africa along a quasi-meridian.

This meridian seems to be stable with time, similarly to large-scale pattern of the subduction around the Pacific.

Polar wander

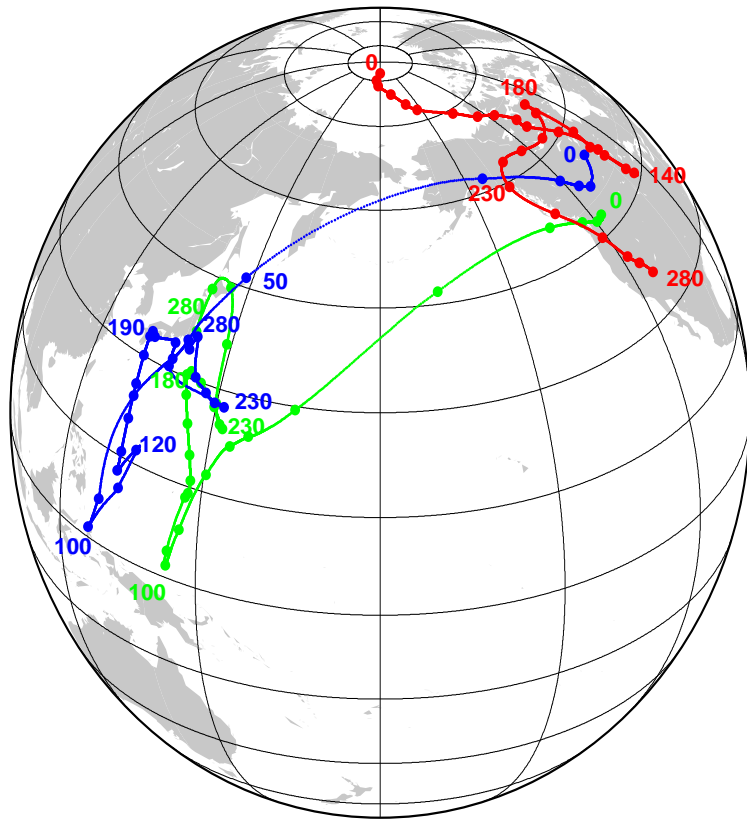


Conservation of the angular momentum
⇒ at geological time-scale, the rotational axis coincides with the maximum PIA.

Polar motion since 280 Ma for two cases:
plates alone and both **domes and plates**.
⇒ **the effect of domes does not change significantly the shape of the curve.**

In red: **Observed Apparent Polar Wander Path (APWP) of Africa**: motion of the magnetic dipolar axis with respect to Africa

Polar wander

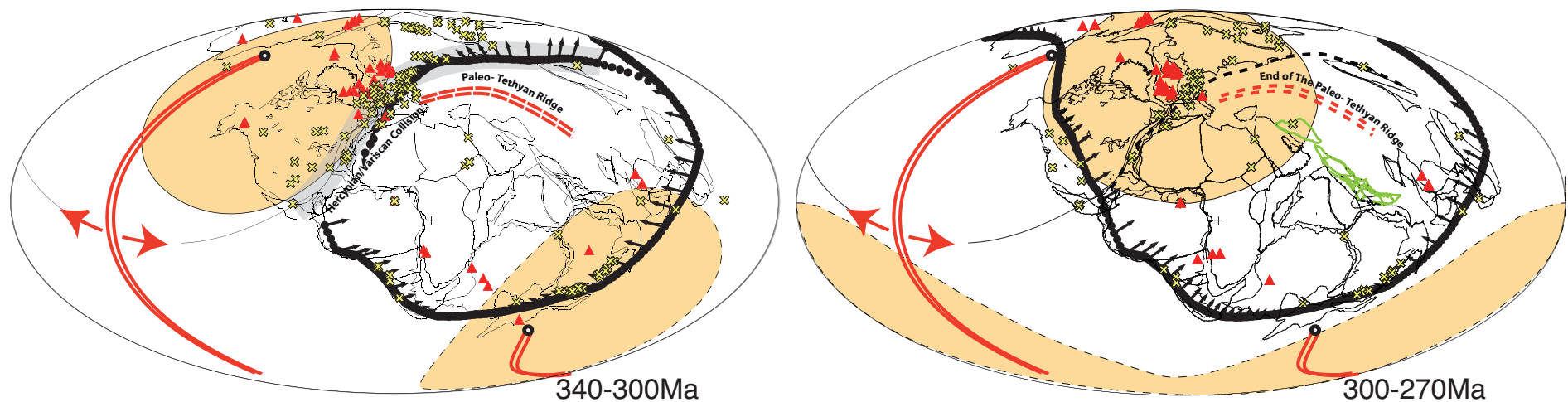


- Differences in the amplitudes and directions of rotation vs paleomagnetic poles
⇒ Possible motion of our mantle reference frame upon which Africa plate is fixed with respect to the paleomagnetic reference frame

- **Common features:**

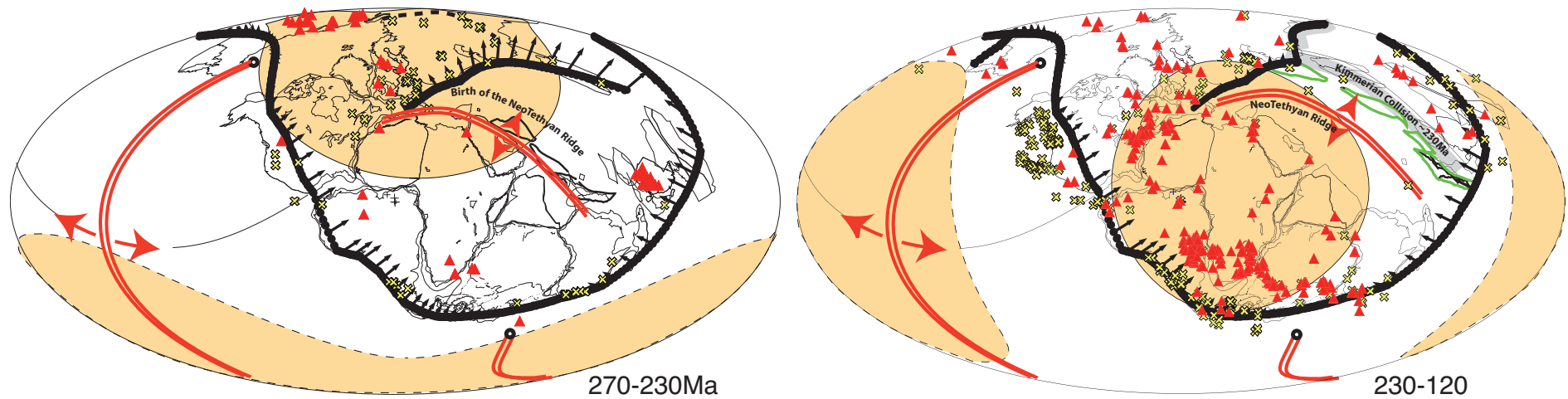
Cusps around 230 Ma and 180 Ma appear in apparent polar wander paths of different plates, as well as in our computed pole.

⇒ These cusps are essentially due to the Hercynian (340-300 Ma) and Kimmerian (270-230 Ma) continental collisions.



- The stop of the subduction of the Paleo-Tethys plate 300 Ma ago and the creation of a perpendicular new convergence zone during the stage 300-270 Ma will create a cusp in the pole curve 230 Ma ago.

Without taking into account the subduction of the Tethys plate (during 270-230 Ma), this cusp will occur around 200 Ma ago. But the start of the Tethysian subduction moves the point of inflection C_1 toward 230Ma.



- The cusp around 180 Ma is essentially due to the stop of the subduction of the Tethys plate 230 Ma ago.

This plate has an averaged velocity about 10 cm/year and it needs less than 30 Myrs to reach the depth about 1200 km where the kernel of the degree 2 geoid changes its sign and 95 Myrs to reach the CMB where it is isostatically compensated: the change in the PIA directions will occur consequently between 30 and 95 Myrs after the collision.

The new convergence zone appearing after 230 Ma has too small velocity to perturb the PIA at this time-scale.

Polar wander

- Cusps around 230 Ma and 180 Ma appearing in apparent polar wander paths of different plates, as well as in our computed pole are essentially due to the Hercynian (340-300 Ma) and Kimmerian (270-230 Ma) continental collisions.

- The drift direction in the observed African APWP and in the computed path is quite different.

⇒ Possible motion of our mantle Africa fixed reference frame with respect to the paleomagnetic reference frame

⇒ Mantle mass anomalies associated with plates do not systematically reach the core mantle boundary ?

The depth down to which the subducted plates present a significant density contrast with respect to the surrounding mantle is unknown.

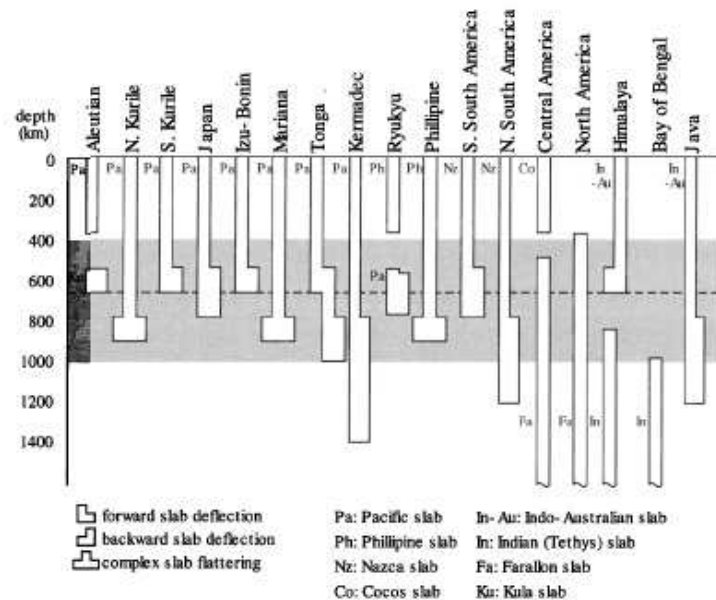


Figure 11. Schematic illustration of slab configurations. This cartoon summarizes the tomographic images of stagnant slabs and deeply sinking slabs but involves many simplifications and assumptions as cautioned in the text. The slab images under North America, Himalaya, and Bay of Bengal are based on the figures presented by van der Hilst et al. [1997], Grand et al. [1997], and Bijwaard et al. [1998] (see text for details).

Fukao et al., 2001

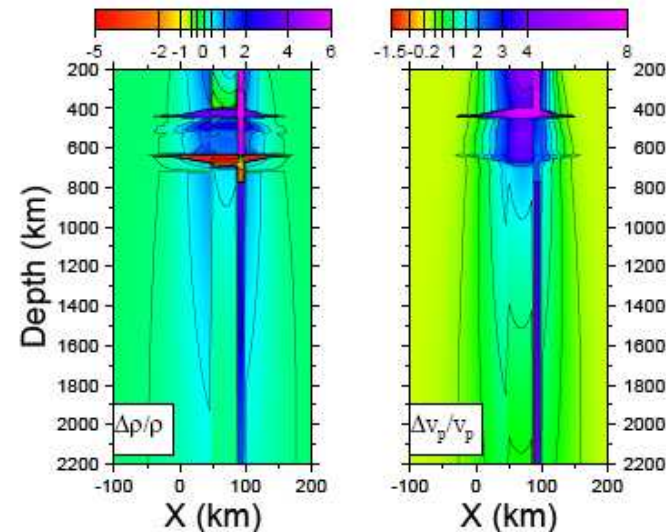
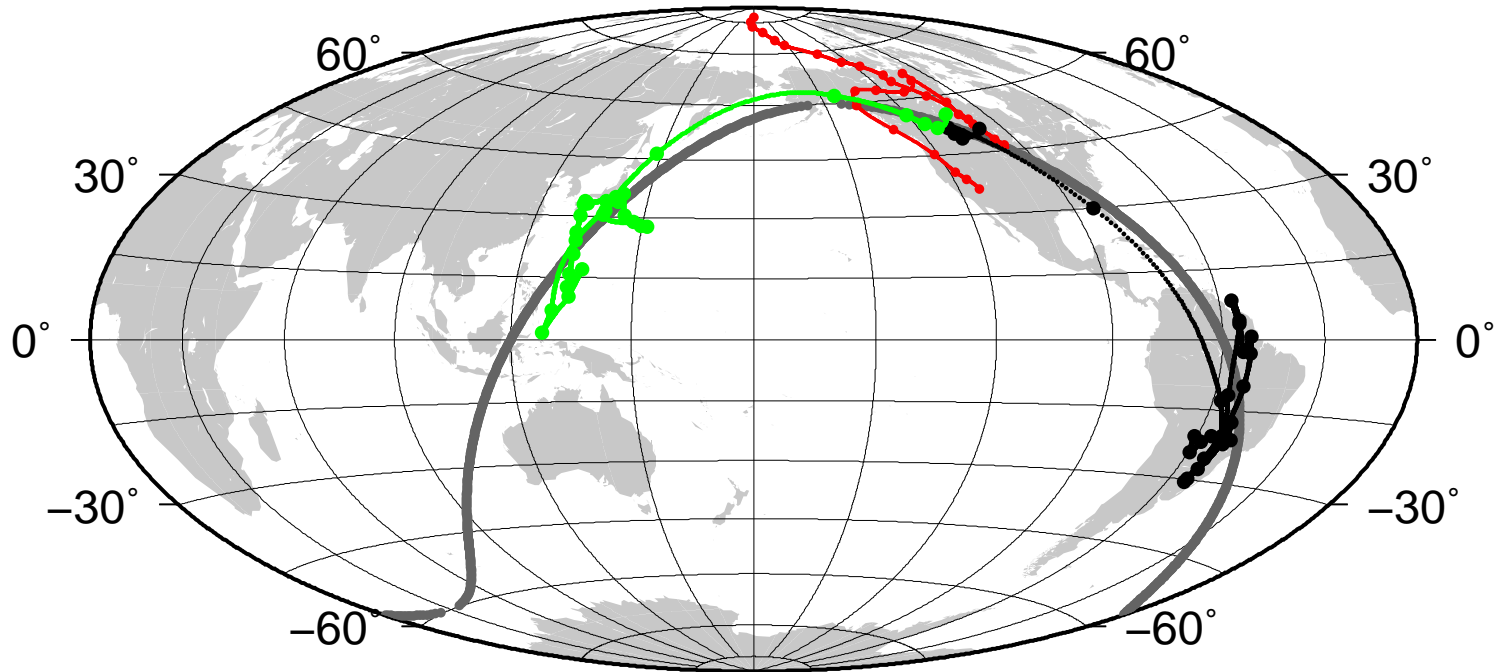


Figure 6. Lateral density and P-velocity variations associated with a slab sinking vertically in the mantle. Compare to Figure 5, the slab now includes a 10 km thick oceanic crust (MORB composition) overlying a 40 km thick depleted lithosphere (harzburgitic composition).

Ricard et al., 2005

- **Test:** If the density contrast beneath South America for depth larger than 1400 km is zero:



Temporal evolution of the rotational axis in our Africa fixed reference frame: in green line, all the plates reach the CMB; in black line, the test

- ⇒ the pole drift in the same great circle but in opposite direction
- ⇒ the intermediate PIA and the maximum PIA have been exchanged

Conclusion

1) The peri-pacific subduction is a quite permanent feature of the earth's history at least since 400 Ma

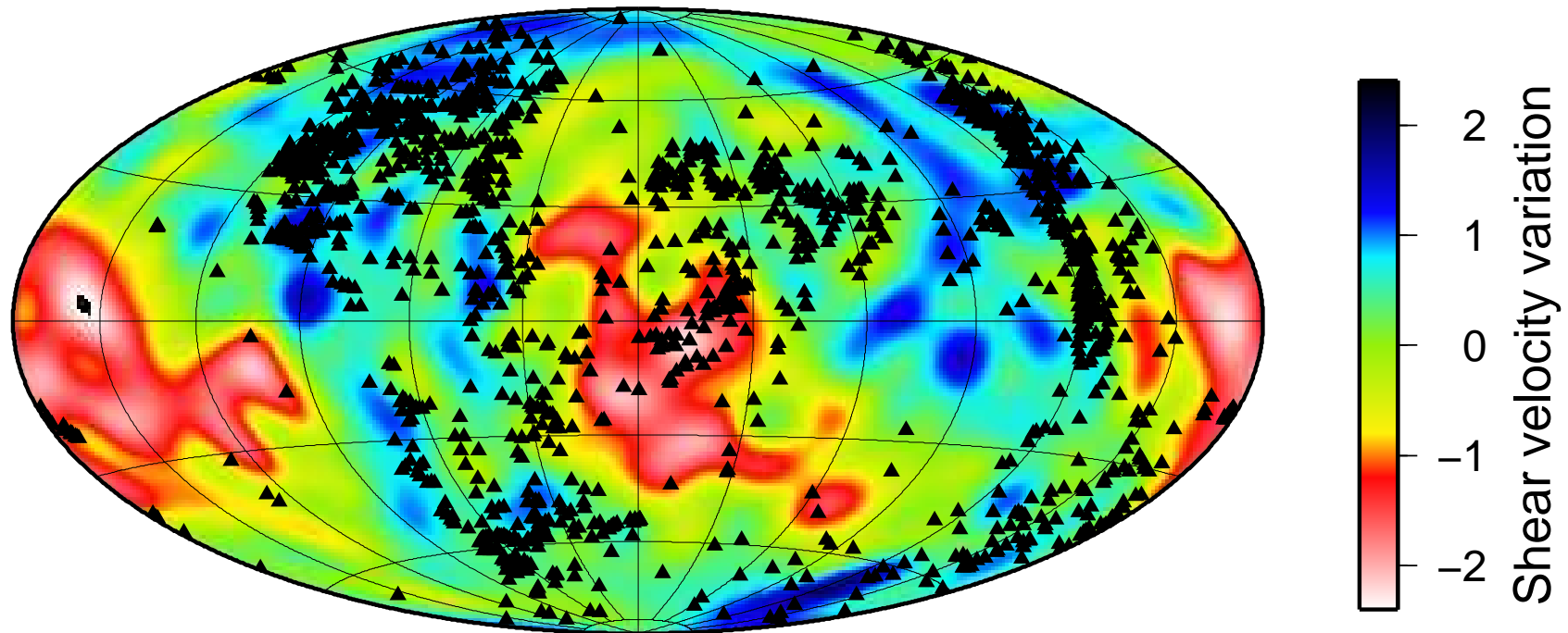


- The minimum PIA is relatively stable and close to the axis passing through the central Pacific and its antipodal position.
- Because of this stable structure, the rotation axis (Maximum PIA) is in a plane perpendicular to this axis.

2) The "Tethyan" subductions having a complex history with successive continental collisions and episodically rebirth of E-W subduction zones, they involve cusps (around 230 Ma and 180 Ma) in the polar motion.

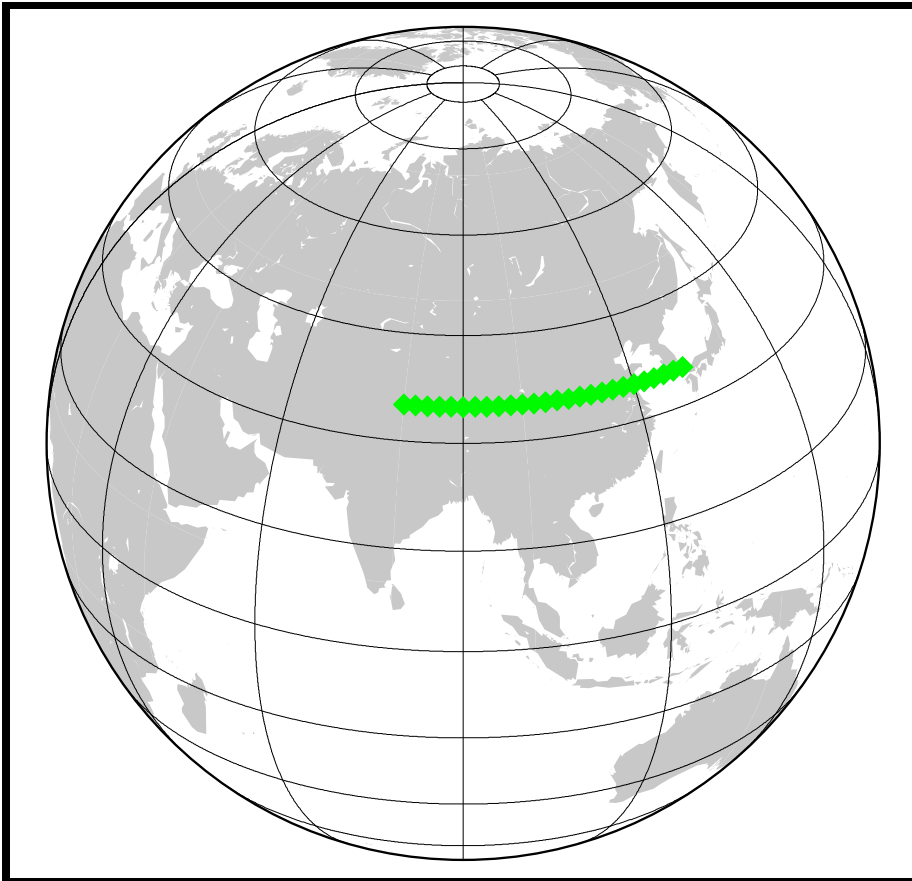
Next step: Do the mantle mass anomalies associated with plates systematically reach the core mantle boundary ?

Paleopositions of subduction volcanic edifices in the paleomagnetic frame since 400 Ma



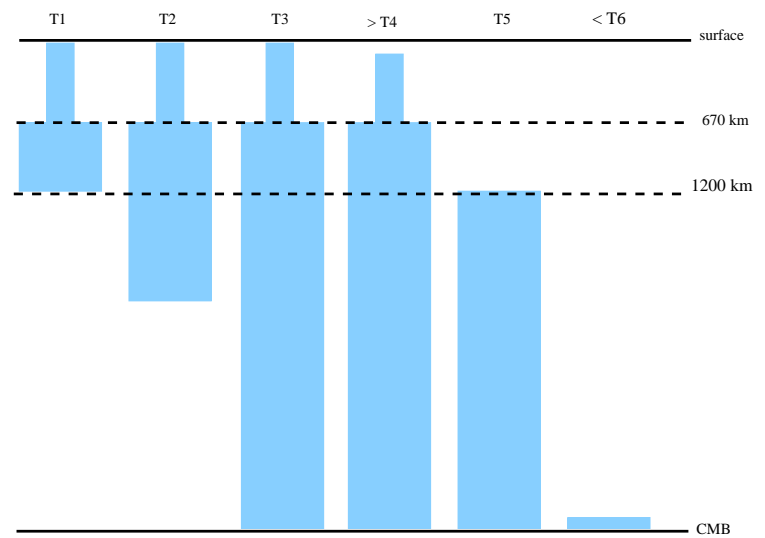
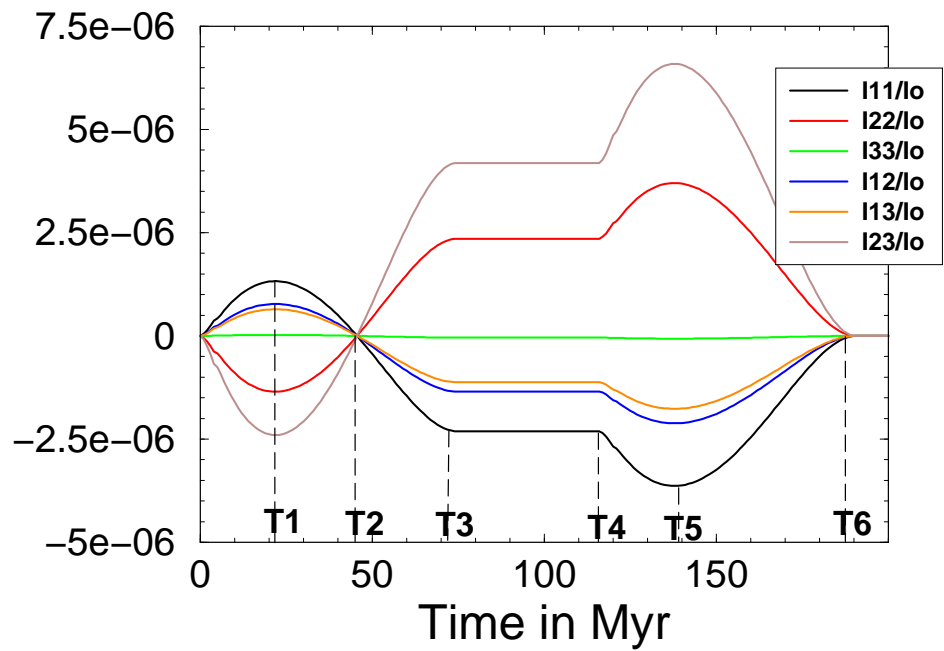
Reconstructed subduction volcanism for the last 400 Myr in the paleomagnetic reference frame
Tomographic image of the deep mantle (model S20RTS of *Ritsema et al.* [1999] at the depth=2880 km).

Example: one slab sinking vertically within the mantle



- At $t = 0$, the plate starts to sink within the mantle at the surface velocity of 12 cm/yr
- At $t = 115$ Myr, it stops to sink.

Associated inertia tensor perturbations



Associated PIA

