Mantle flow models with a chemically distinct D′′ layer: Implications on the shape of plume conduits

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Radial Mantle Viscosity structure

Stress-strain relationship

$$\dot{\varepsilon} = C_1 \sigma^n exp\left(-\frac{H}{RT}\right)$$

Radial viscosity profile

$$\eta(z) = \eta_0 \exp\left(\frac{H(z)}{nR\bar{T}(z)}\right) \cdot \left(<\dot{\epsilon}^2>(z)\right)^{\frac{1-n}{2n}}$$

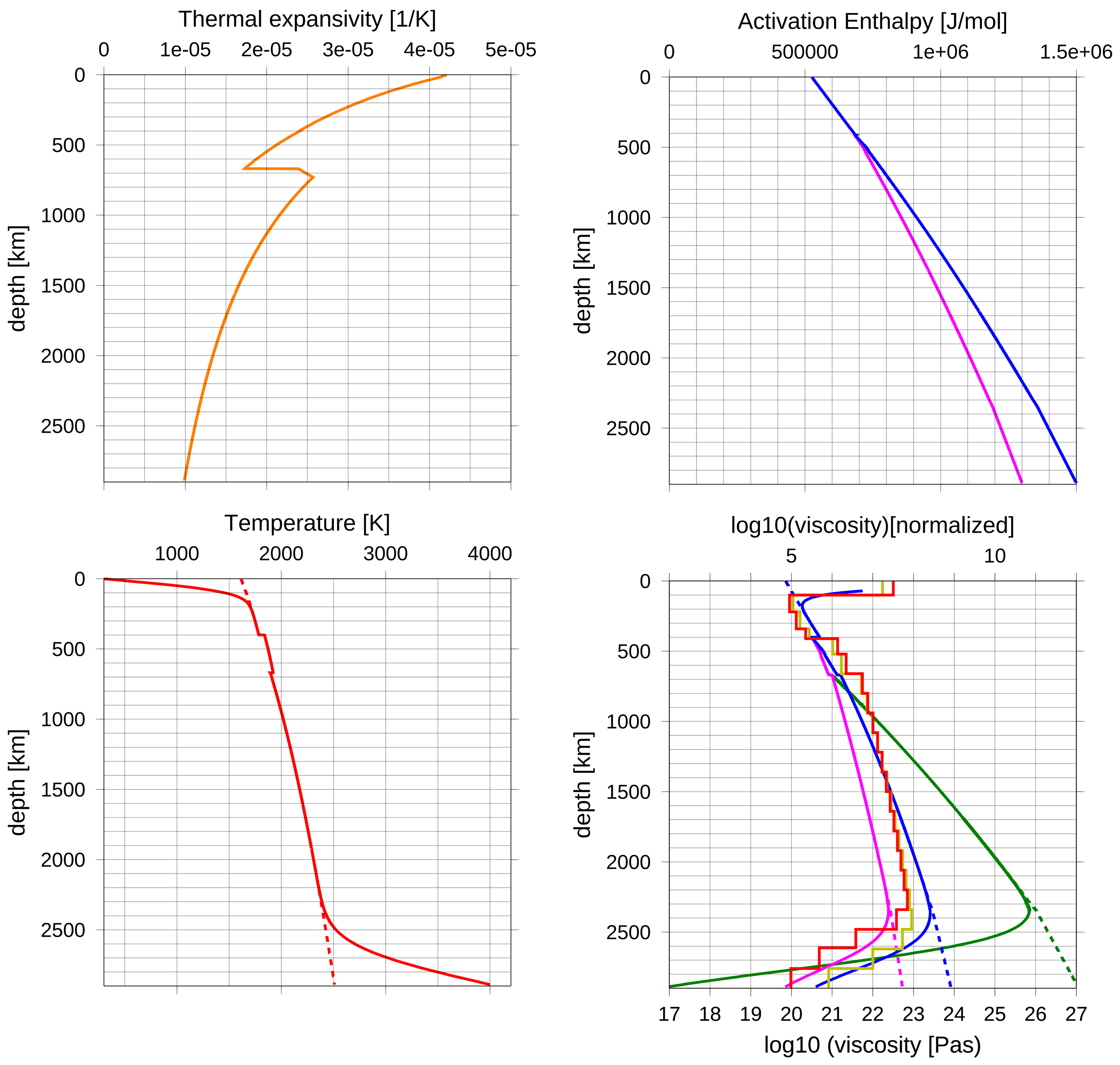
η_0 (may be different for upper mantle, transition zone, lower mantle) to be determined by optimizing fit to various observables (geoid, heat flux, CMB excess ellipticity ...)
Activation enthalpy $H(z) \approx gRT_m$: Reference case (purple line) $g \approx 35$. Uncertainties are very large. T_m is melting temperature.
Adiabatic temperature profile $T(z)$ obtained by integrating

$$\frac{dT}{dz} = T(z) \cdot \alpha(z) \cdot g(z)/C_p(z).$$

$g(z)$ is gravity, $C_p \approx 1250$J kg^{-1}K^{-1} is specific heat, $\frac{d \ln \alpha}{d \ln \rho} = -\delta_T$ along isotherms. In the upper mantle, use constant $\delta_T = 5.5$ and formalism by Schmeling et al. (2003).
In the lower mantle, use

$$\delta_T = \delta_{T0}\left(\frac{\rho_0}{\rho}\right)^b$$

with $\delta_{T0} = 5.5$ and $b = 1.4$ $\alpha_0(T) = (35 + 9T/1000\text{K}) \cdot 10^{-6}\text{K}^{-1}$ for zero pressure $\rho(z)$ from PREM, $rho_0(z)$ from evaluating PREM lower mantle parameters at z=0 and accounting for temperature difference. Thermal boundary layer at top; thickness 100 km, $1340°$C potential surface temperature. Thermal boundary layer at base; thickness 300 km, 4000 K CMB temperature. Phase boundary effect
Stress exponent n=3.5 (reference case; purple line); n=1 (green line)



Bottom right panel also shows scaled viscosity profiles for whole-manlte flow (golden line) and layered flow (red line).

Mantle density anomalies

Relate seismic velocity and density anomalies: $F_{s,th} := (\delta\rho/\rho)/(\delta v_s/v_s) = (\alpha/\rho)/(\partial \ln v_s/\partial T)_p$ Include anelastic and anharmonic effects:

$$-(\partial \ln v_s/\partial T)_p = -(\partial \ln v_{s,0}/\partial T)_p + (Q^{-1}/\pi) \cdot (H/RT^2)$$

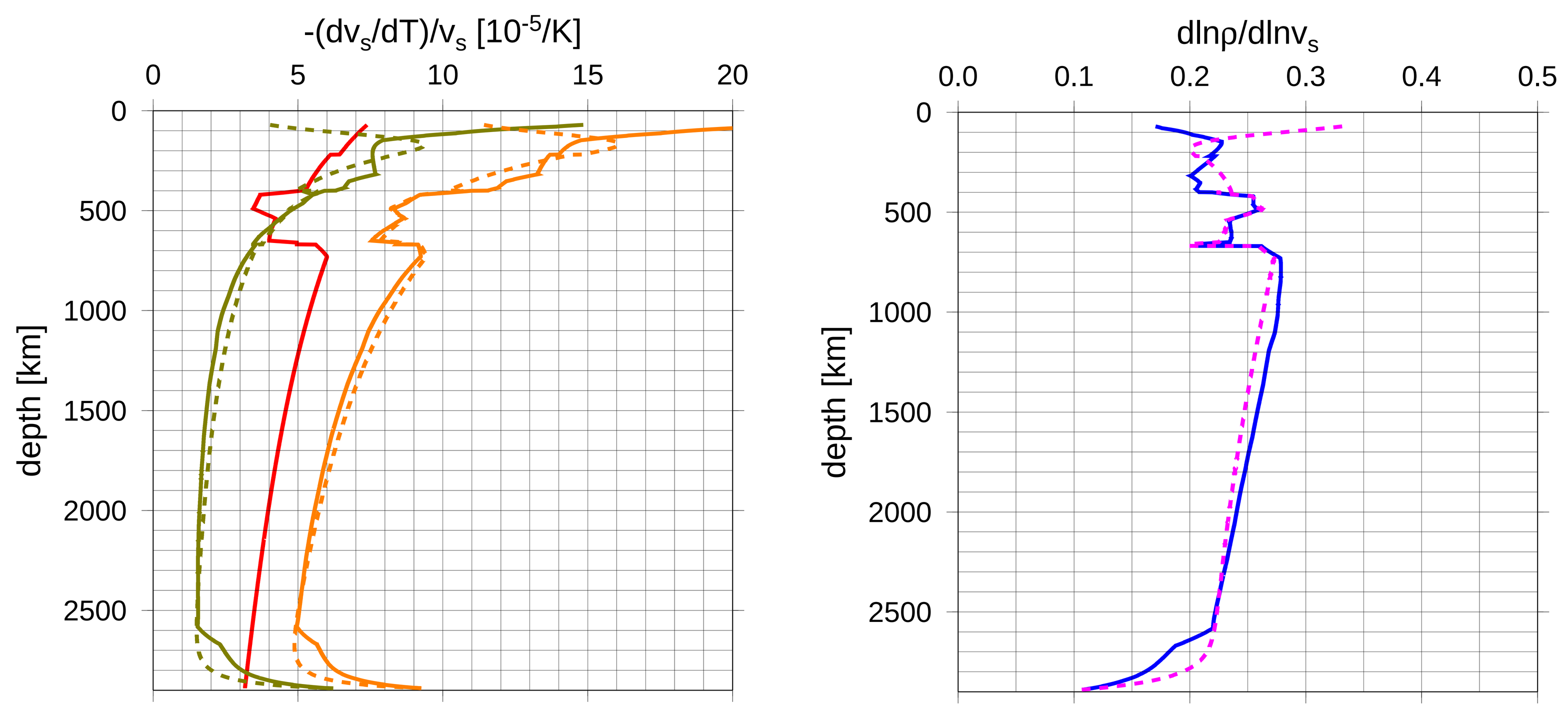
Red lines: In the upper mantle, anharmonic part after Goes et al. (2004); In the lower mantle, compute $\mu(T, z)$ by integrating

$$\frac{d\mu}{dz}(T_0(z) \pm \Delta T(z)) = \frac{d\mu}{dz}(T_0(z))(1 \pm \alpha(z)\Delta T(z)) \qquad (1)$$

(Duffy and Anderson, 1989). Starting point is

$$\mu(T_0(z_0) \pm \Delta T(z_0)) = \mu(T_0(z_0)) \pm \Delta T(z_0) \cdot \frac{d\mu_0}{dT}$$

$\frac{d\mu_0}{dT}$=27 MPa/K; $\frac{d\mu}{dz}(T_0(z))$ and $\mu(T_0(z_0))$ from PREM (Dziewonski and Anderson, 1981). Brown lines: Anelastic part. Continuous: Q model from Anderson and Hart (1978). Dashed: Shape from viscosity profile, magnitudes from Anderson and Hart. Orange/blue/purple: Total



A chemically distinct D′′ layer?

In the lowermost mantle, s-wave and bulk sound velocity anomalies are decorrelated, indicating that they are not merely of thermal origin. Interpretation of seismic velocity variations in terms of a chemical layer of variable thickness δh at the base of the mantle.

$$\frac{\delta v_s}{v_s} = \frac{1}{F_{s,th}}\frac{\delta\rho}{\rho}_{th} + k_s\delta h$$
$$\frac{\delta v_c}{v_c} = \frac{1}{F_{c,th}}\frac{\delta\rho}{\rho}_{th} + k_c\delta h$$

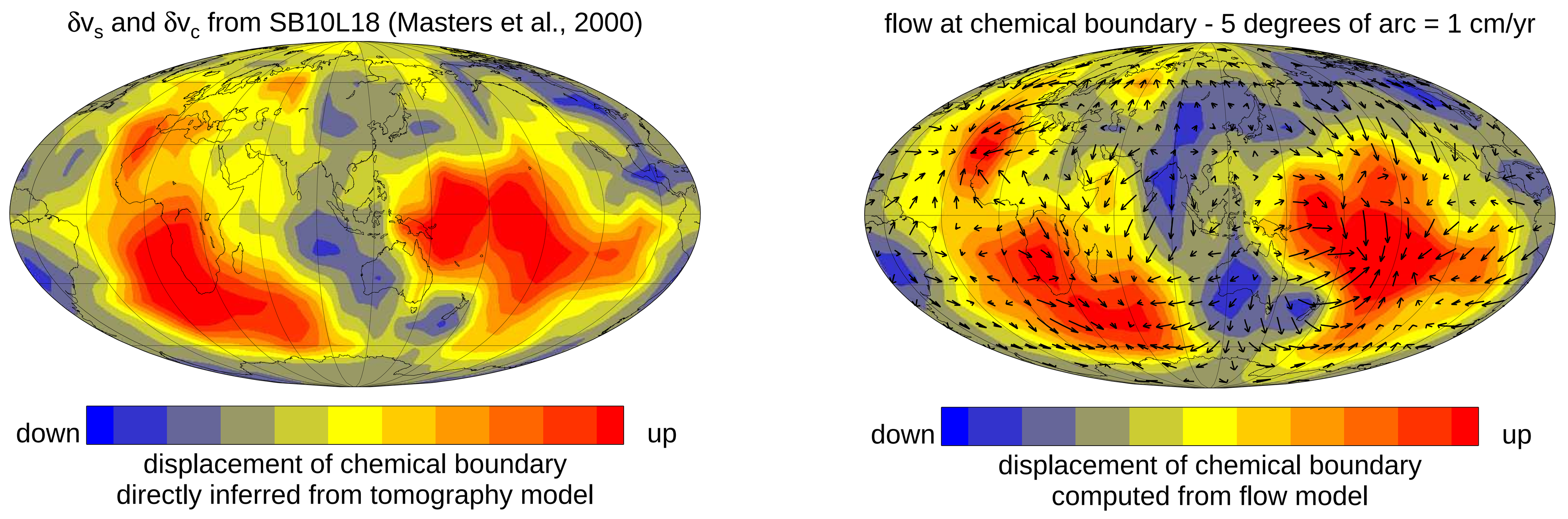
δv_s and δv_c are vertical averages below 2600 km (bottom two layers)

$$\delta h = \left(\frac{\delta v_c}{v_c} - \frac{F_{s,th}}{F_{c,th}}\frac{\delta v_s}{v_s}\right)\left(k_c - k_s\frac{F_{s,th}}{F_{c,th}}\right)^{-1}$$
$$\frac{\delta\rho}{\rho}_{th} = \frac{\delta v_s}{v_s} \cdot \alpha_{s,th} - k_1 \cdot F_{s,th} \cdot \left(\frac{\delta v_c}{v_c} - \frac{F_{s,th}}{F_{c,th}}\frac{\delta v_s}{v_s}\right)$$

$k_1 := k_s \cdot \left(k_c - k_s\frac{F_{s,th}}{F_{c,th}}\right)^{-1}$ is additional free parameter.

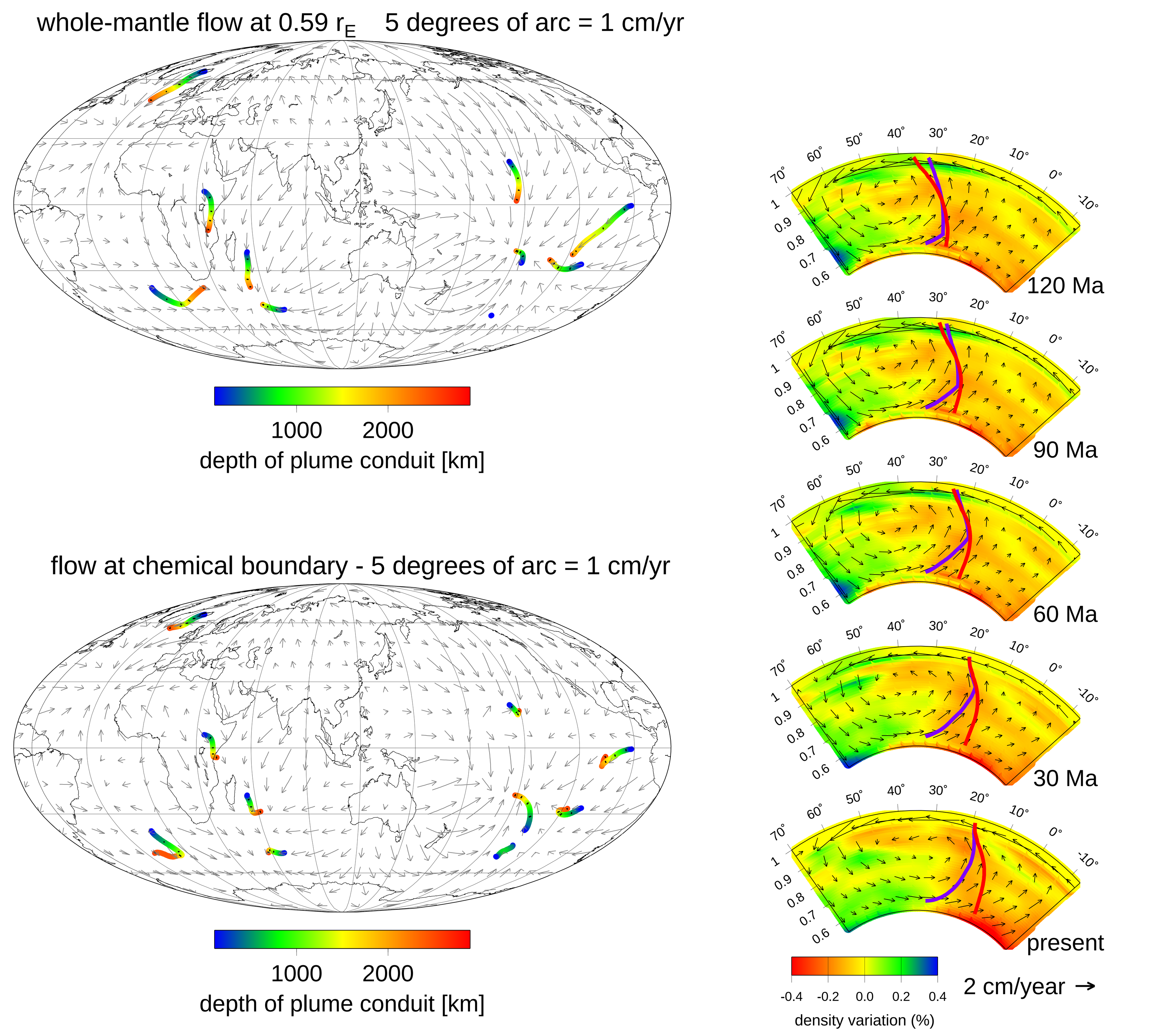
Mantle flow

Flow with no chemical boundary is dominated by flow towards the large-scale upwellings beneath Africa and the Pacific; predicted CMB excess ellipticity too large. Flow at chemical boundary at 0.59 r_E represents a balance between driving forces from upwellings in a layer above and restoring forces due to thickness variations in the layer below. The flow structure is thus more complicated than for a chemically homogeneous mantle; topography at chemical boundary reduces CMB topography and yield appropriate CMB excess ellipticity.



Plume conduits

It is assumed that the base of plume conduits, at the top of D′′, moves with the horizontal flow component at that depth: Flow and plume conduits with no chemical boundary (top) and with chemical boundary at 0.59 r_E (bottom). Right panels show cross-section through a similar whole-mantle flow field at $150°$ W and Hawaiian conduit for moving source (red) and fixed source (purple) at different times.



Comparison of predicted shapes of plume conduits with seismic observations can give important insights regarding flow in the lowermost mantle and the nature of the D′′ layer.

Acknowledgement

Figures were prepared using GMT graphics (Wessel and Smith, 1995).

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