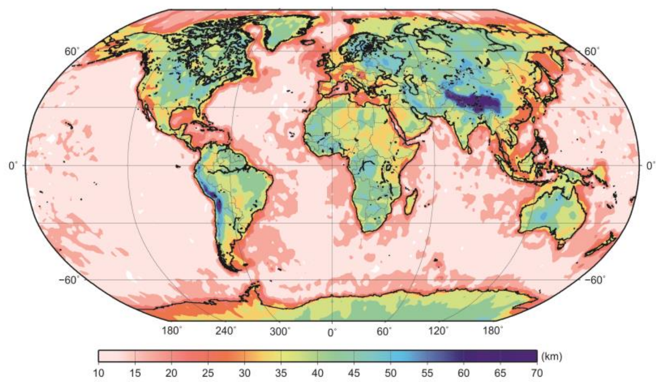
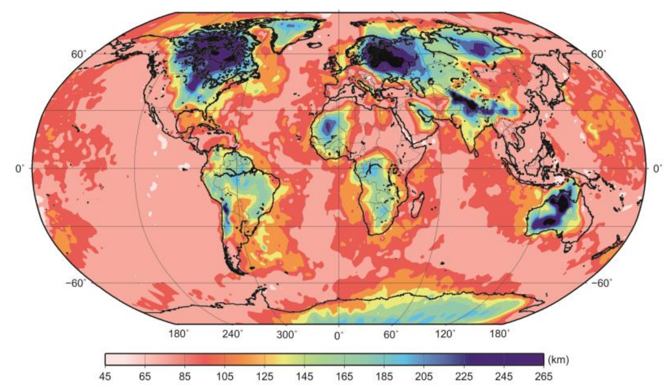
Unravelling the upper mantle heterogeneity from integrated multi-observable inversions

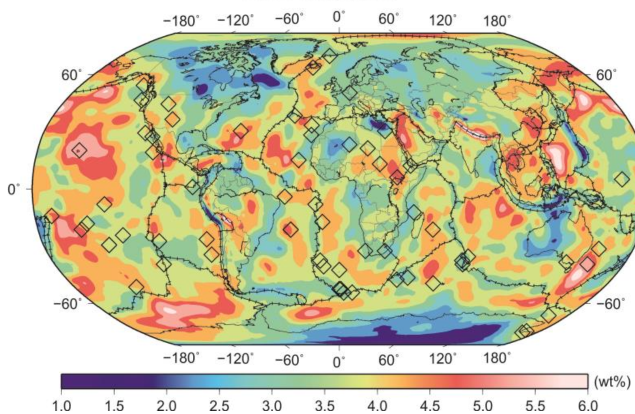
Moho depth



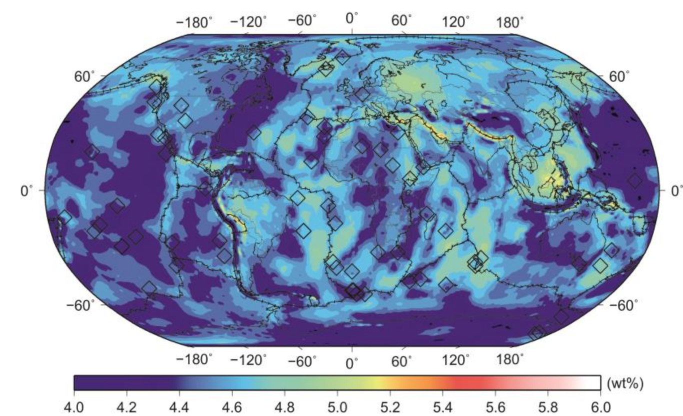
Lithospheric thickness



Al2O3 Lithosphere



Al2O3 sub-lithosphere



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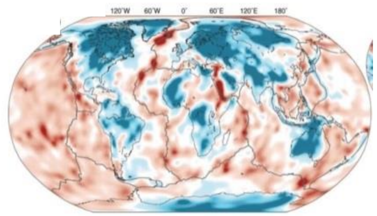
Lithosphere-upper mantle thermochemical structure: why bother?

- ✓ Mantle flow informing plate tectonics: density+ viscosity
- ✓ What supports the Earth's surface topography?
- ✓ Cooling of oceanic lithosphere: half-space vs plate model?
- ✓ Mid Oceanic Ridges: composition, temperature, spreading rate
- ✓ Mantle plumes: temperature and composition
- ✓ Stability of cratonic continental lithosphere

Many techniques/observations: just ONE Earth...

Seismic Velocity models



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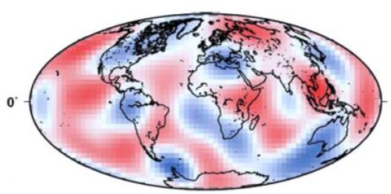
Electrical Conductivity models



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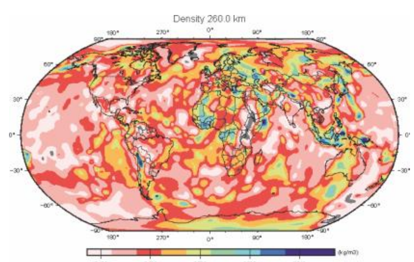
Density models



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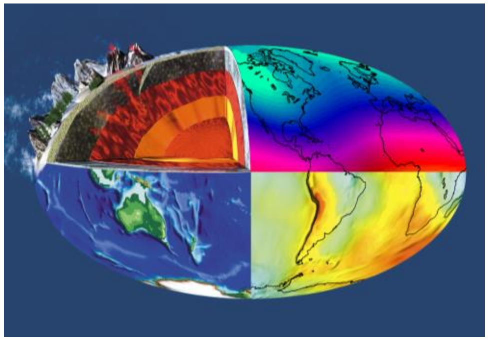
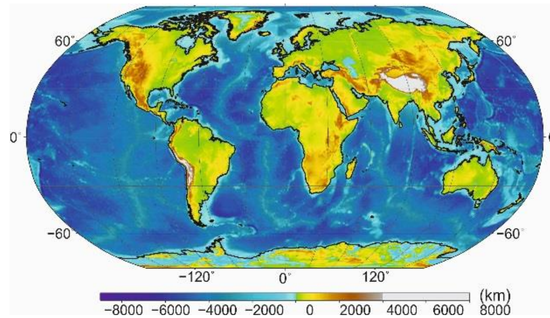
...

New WINTERC-grav global upper mantle thermochemical model

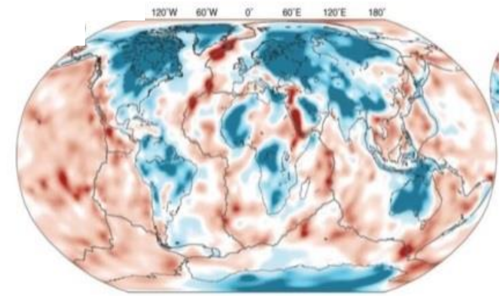
Satellite gravity

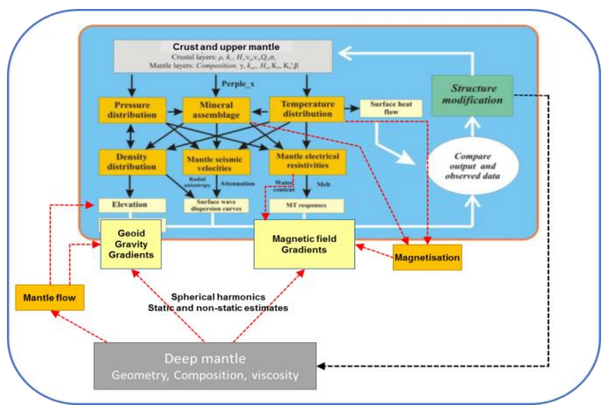


Topography



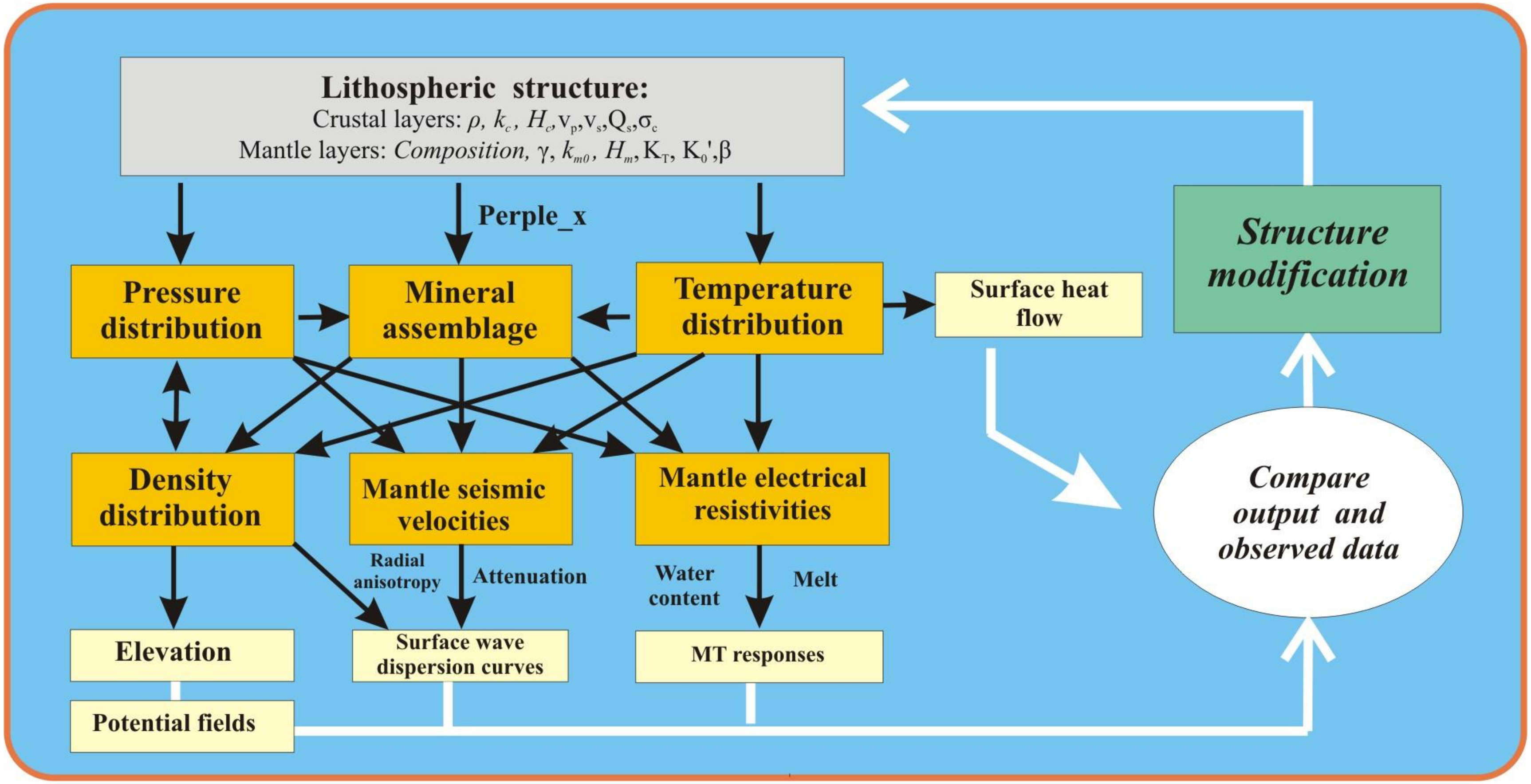
Seismic tomography





- ✓ Jointly modelling waveform tomography, elevation and satellite gravity data
- ✓ Sensitivity analysis of different data sets

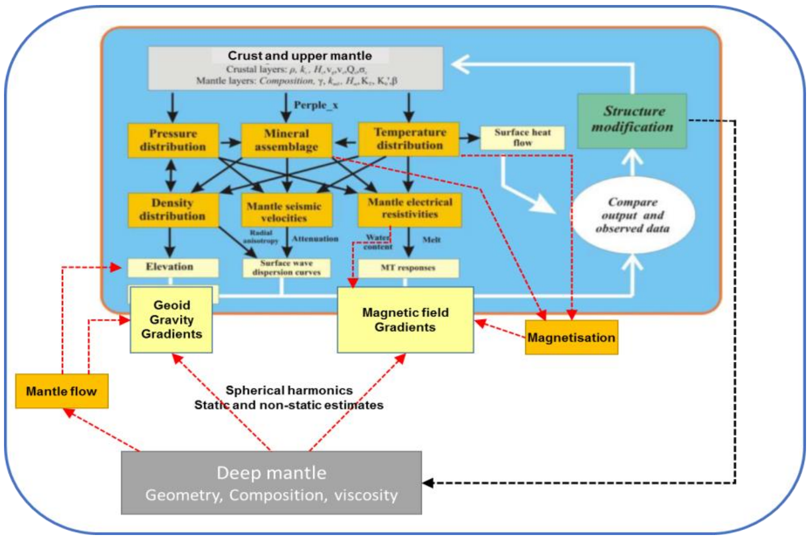
Connect mineral physics & petrology & thermodynamics with geophysics

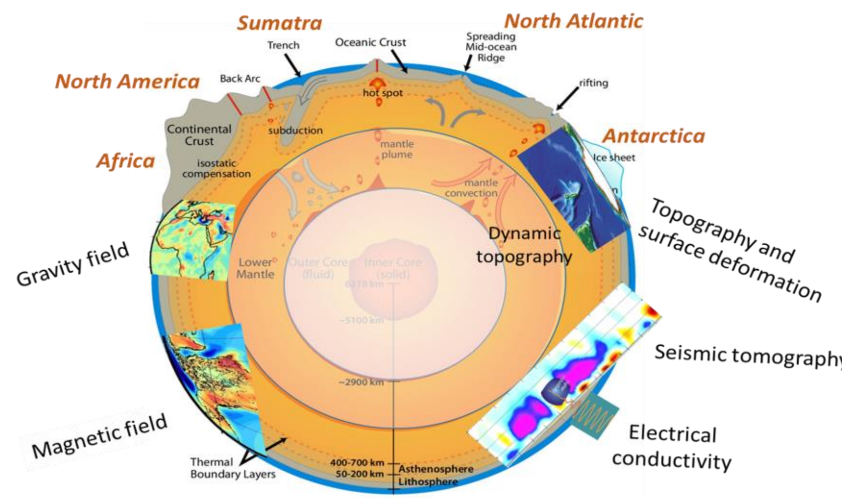


- *Integrated 1-,2- and 3-D forward and inversion regional modelling software: **LitMod** (Afonso et al., 2008, Fullea et al., 2009)*

New WINTERC-grav global upper mantle thermochemical model

Fullea et al., in prep

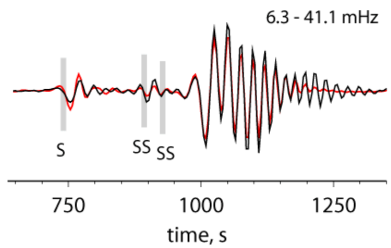




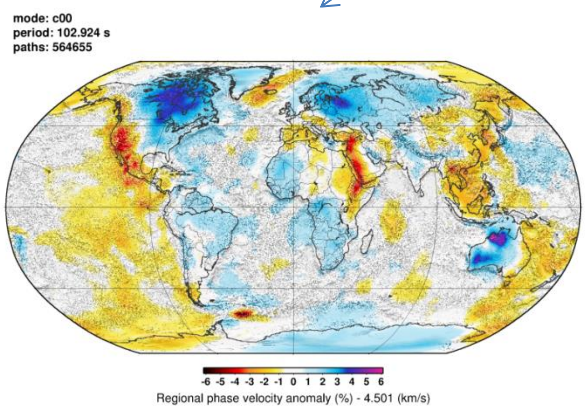
- ✓ **Two step global inversion:**
  - ❖ **Step 1 WINTERC: 1D- surface wave , surface elevation, heat flow**
  - ❖ **Step 2 WINTERC-grav 3D- gravity field data**
- ✓ **Thermodynamic parameterization of physical properties (rho, Vs, Vp): LitMod built in**
- ✓ **Focus on the lithosphere-uppermost mantle: temperature and composition**

WINTERC: seismic data

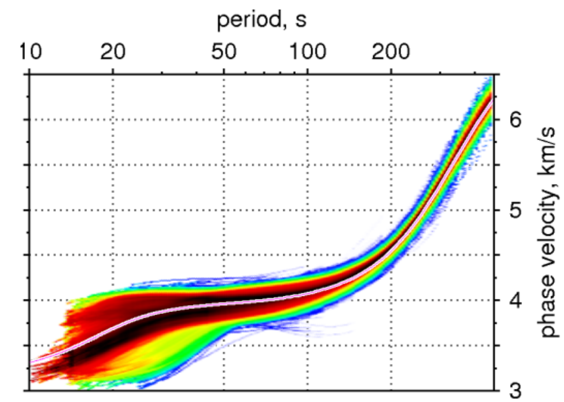
Waveform inversion



Seismogram reflecting Earth's structure along a path connecting earthquake and seismometer



2D Phase velocity maps

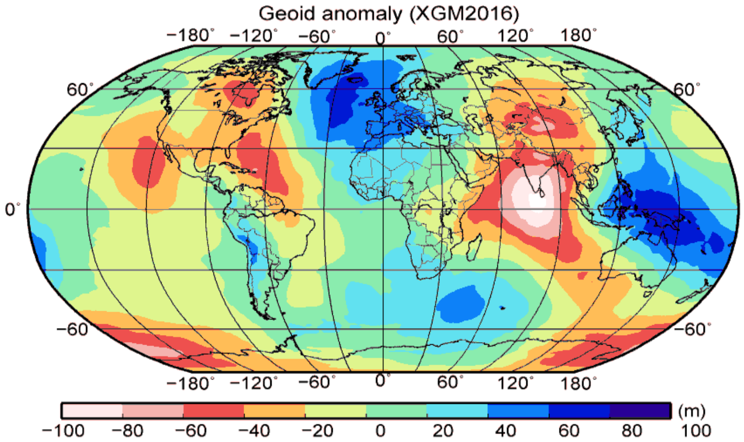


Phase velocity dispersion curves for each point (geographical coordinates grid).

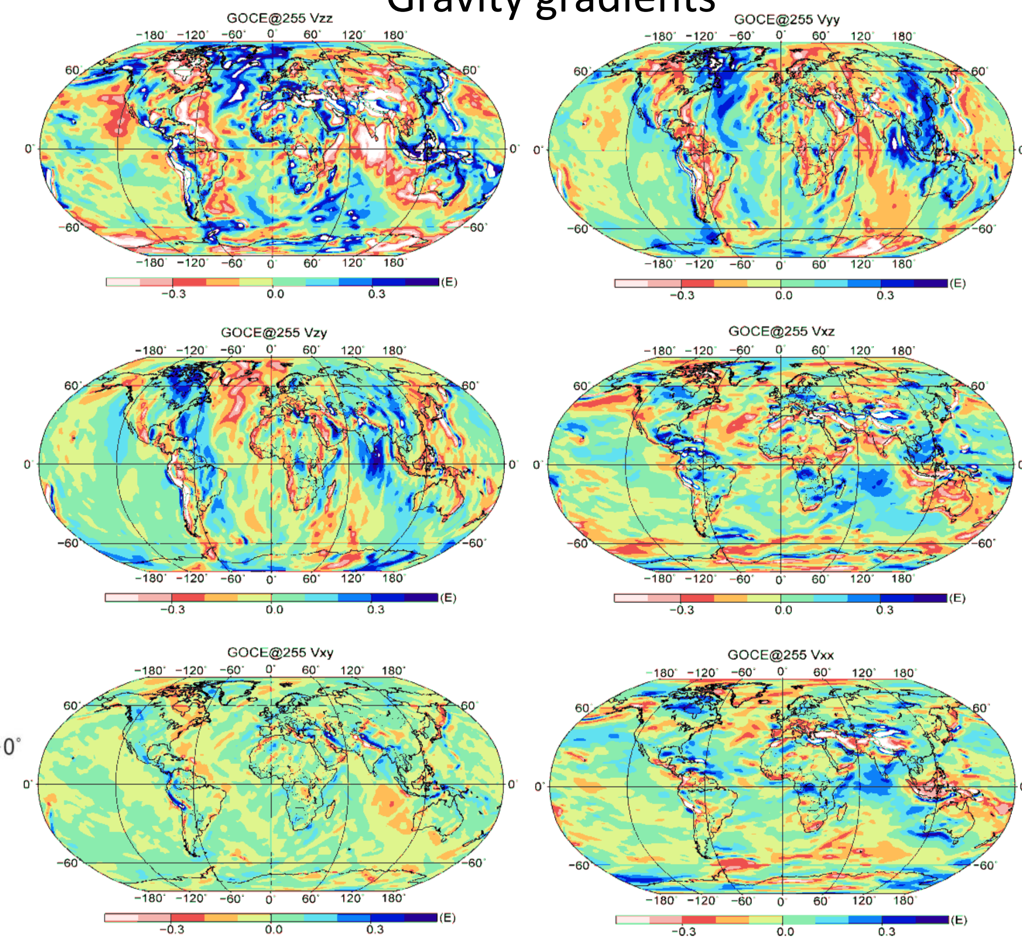
- ✓ 3D distribution of seismic velocities, currently using 6242 stations and 25496 events worldwide
- ✓ Sensitivity mostly to temperature and also composition
- ✓ 12,500 1D Columns (about 200 km inter knot spacing)

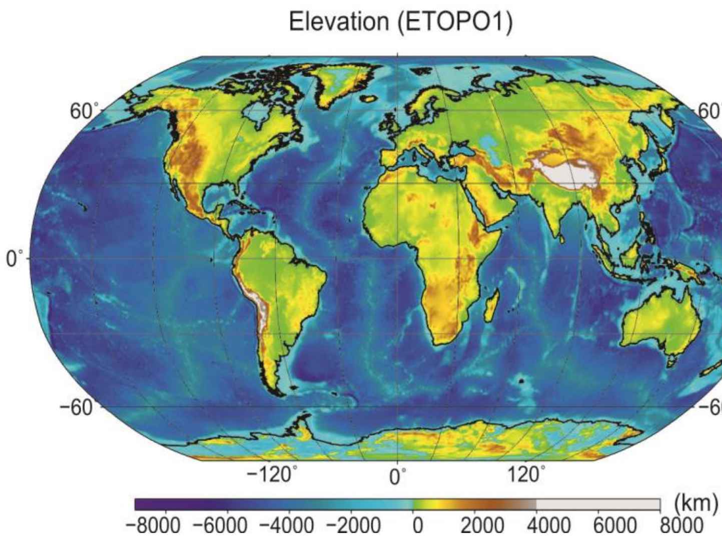
WINTERC-grav: gravity field & elevation data

3D Satellite gravity data (GOCE, XGM2016)



Gravity gradients

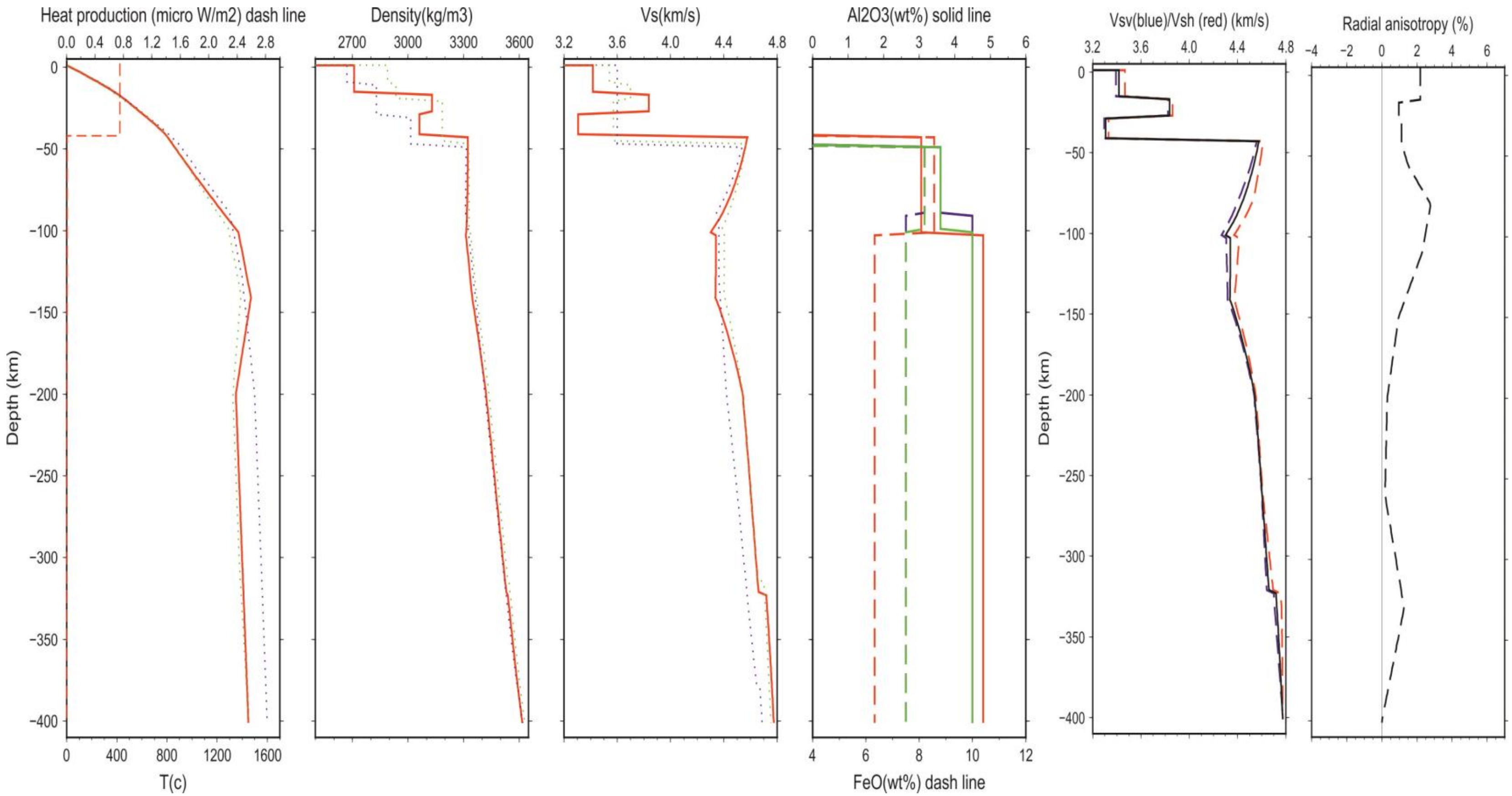




(Bouman et al., 2016.)

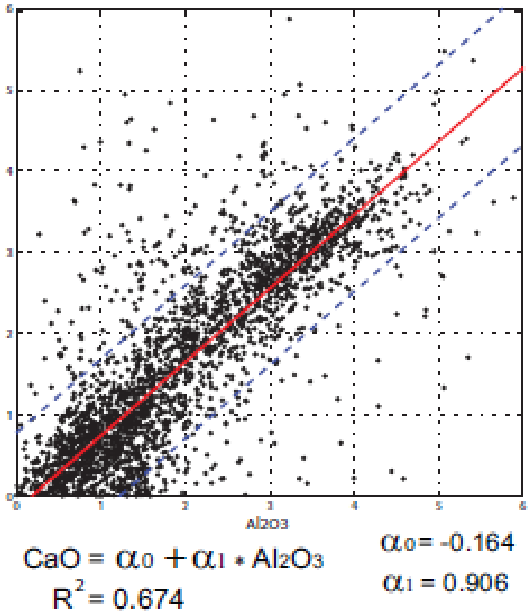
- ✓ Surface elevation is approximately in isostatic equilibrium (except dynamic topography)
- ✓ Sensitivity to density distribution
- ✓ Gravity data inversion: Intrinsically non-unique

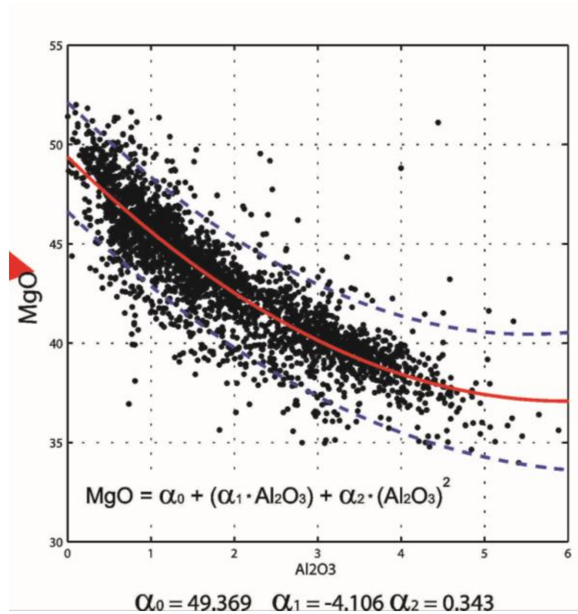
WINTERC, step 1: inversion setting

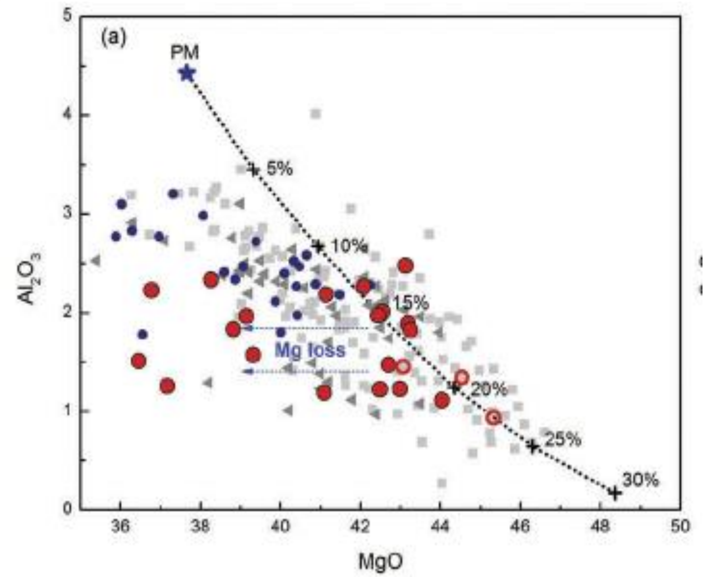


- ✓ 1D Inversion of surface wave tomography data, elevation and heat flow
- ✓ Crustal structure: density, seismic velocities, heat production and thickness
- ✓ Mantle structure: Thermal lithosphere (LAB) and sublithospheric temperature; mantle composition
- ✓ Radial anisotropy

WINTERC, step 1: inversion setting







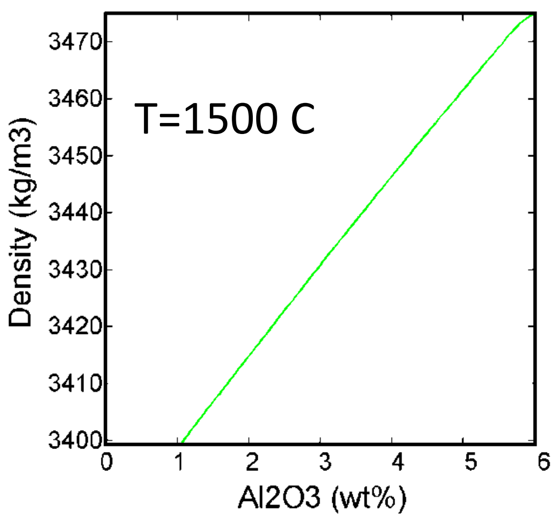
* Correlation between oxides regardless of tectonic age or facies from petrological data base (>2900 samples from xenoliths, perid. Massifs and ophiolites) (Afonso et al., 2013)

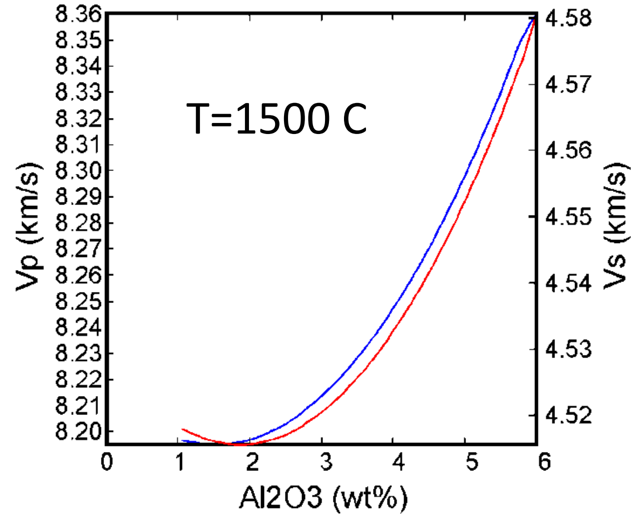
Melting trend

- ✓ Mantle composition described by **Al2O3** and FeO independent variables (CaO and MgO=F(Al2O3))
- ✓ Chemical parameterization following melting trend, analogous to pyrolite (Harz+basalt)

WINTERC-grav, step 2: inversion setting

Physical properties-derivatives @ P=7.6 Gpa and FeO=7.9 wt% (Perple_X)

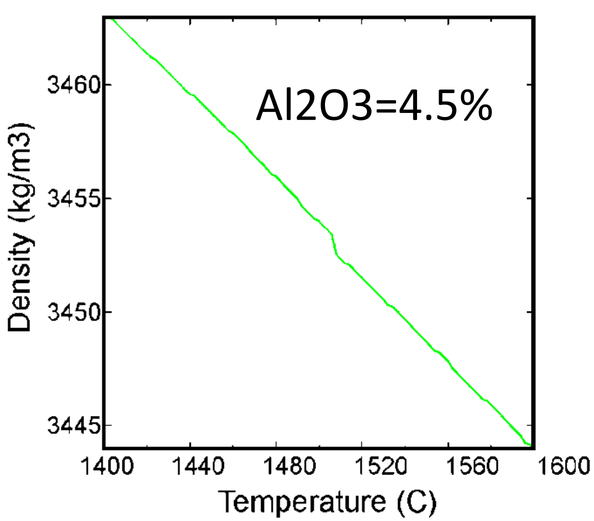


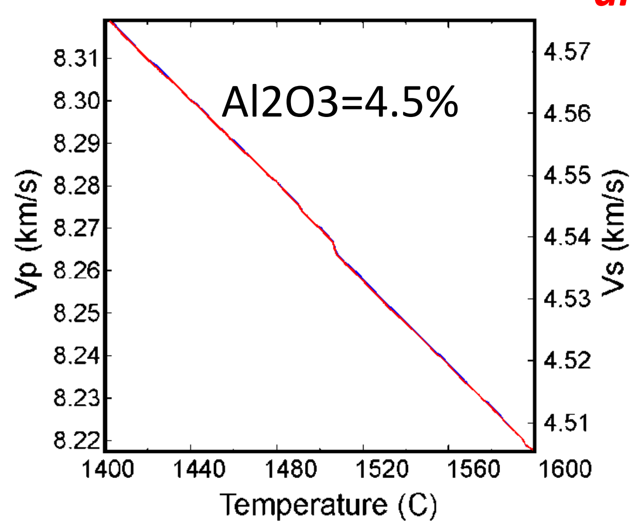


Chemical derivative

For drho=15 kg/m3→
dAl2O3=1wt%
(dVs=0.2%)

drho/dAl2O3=150* drho/dT





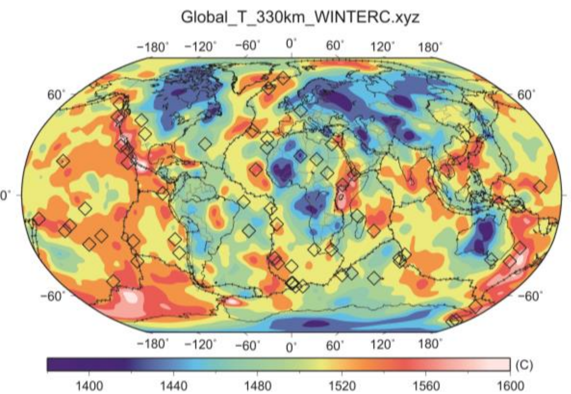
Temperature derivative

For drho=15 kg/m3→
dT=200 C(dVs=1.8%)

- Temperature affects density and Vp, Vs similarly
- Composition affects mostly density

WINTERC-grav, step 2: gravity field

- ✓ 3D Gravity data inversion regularized by temperature & composition from WINTERC (step1: surface wave, elevation and SHF data)
- ✓ Variables for the gravity inversion are the composition (Al2O3) of lithosphere and sublithosphere and crustal density
- ✓ Geoid anomaly constrains upper mantle density, gravity grads@255 km constrain crustal density



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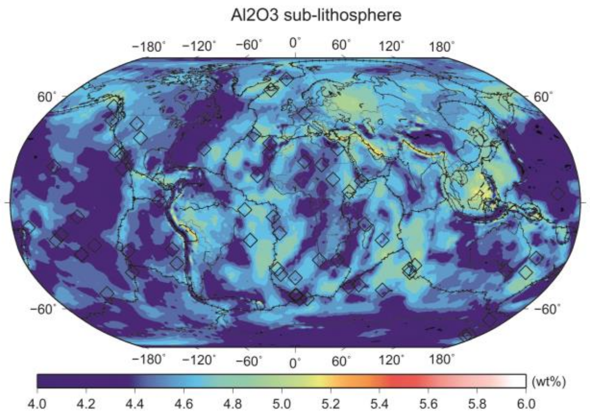

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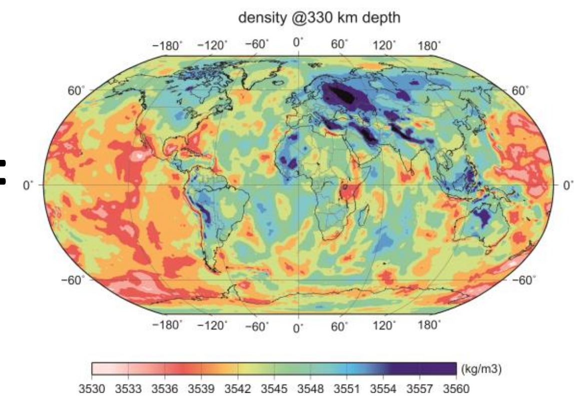
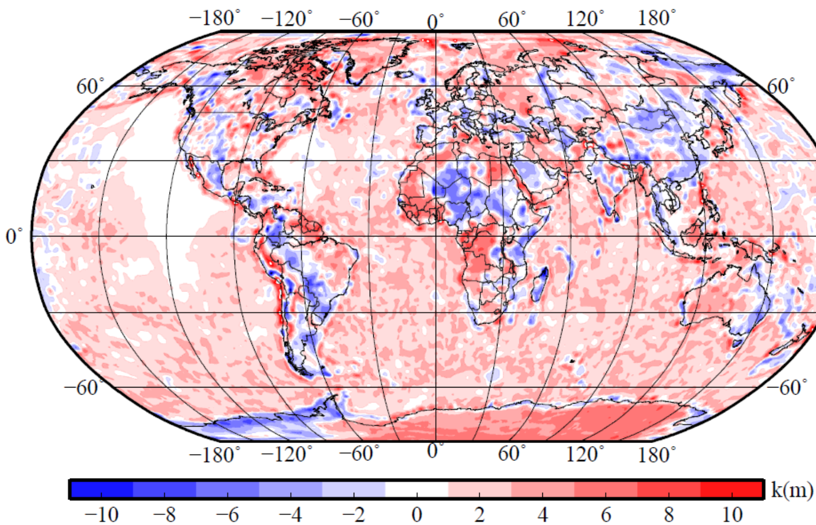
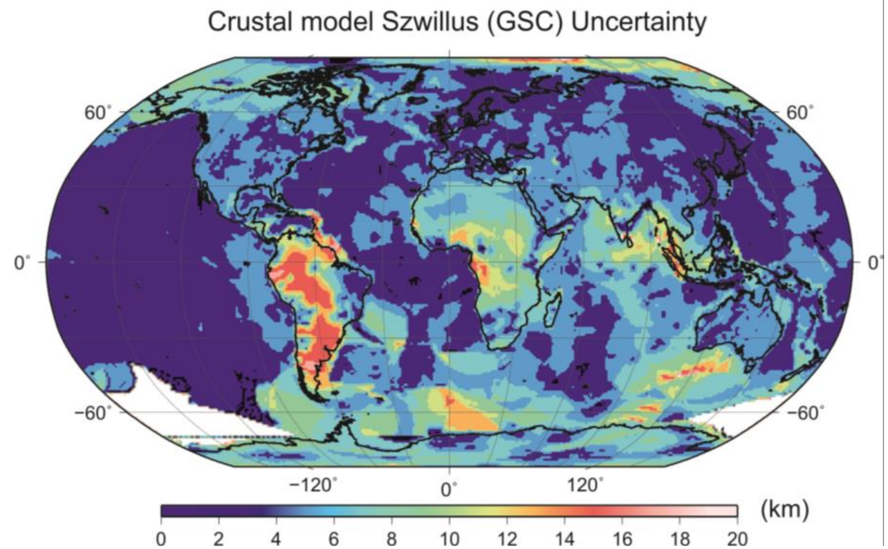
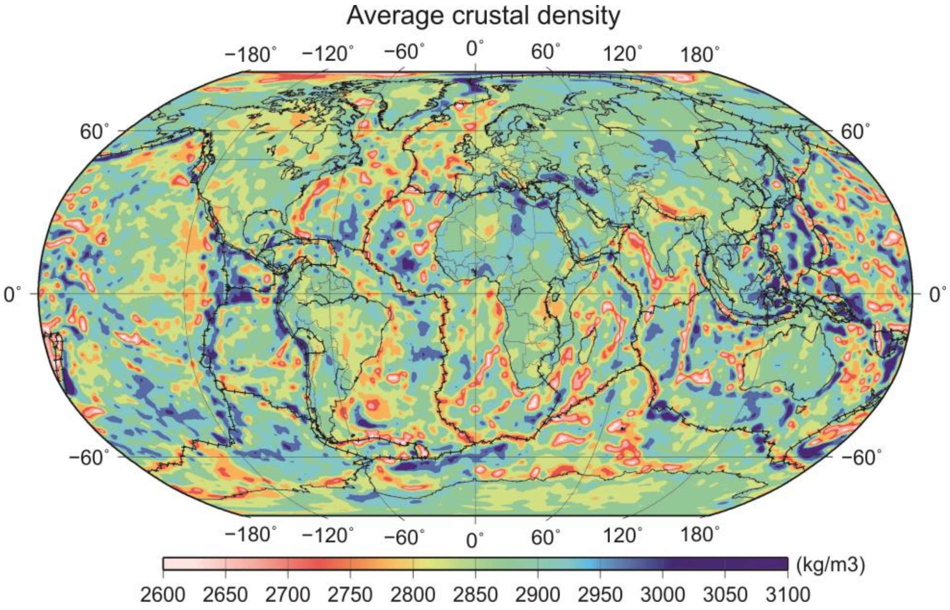


WINTERC-grav: new crustal model

Differences in crustal thickness for WINTERC_grav with respect to CRUST1.0 (within the uncertainties statistically estimated from Szwillus et al., 2019)

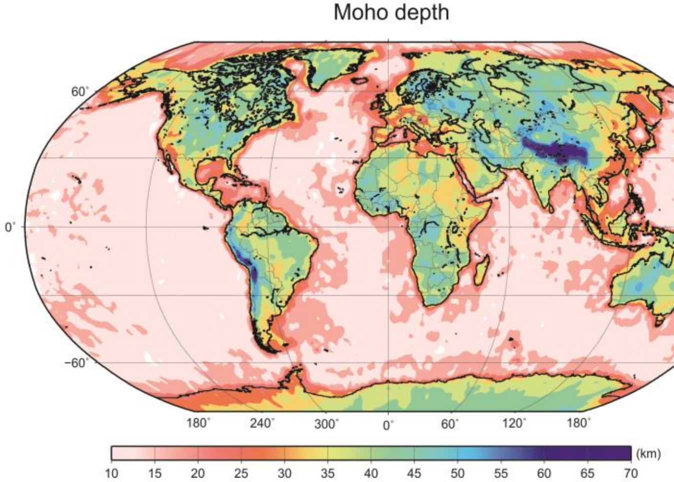


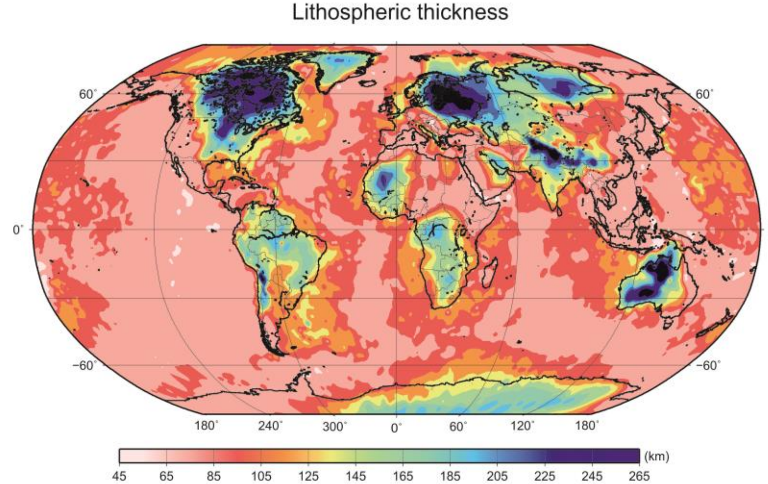


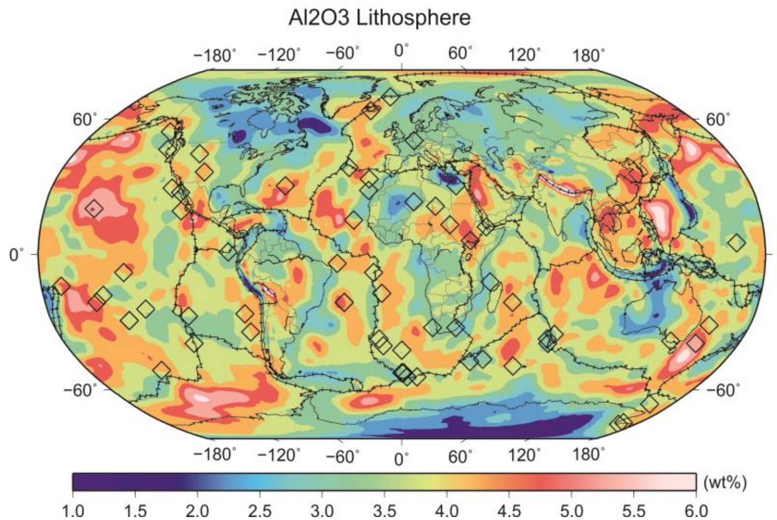


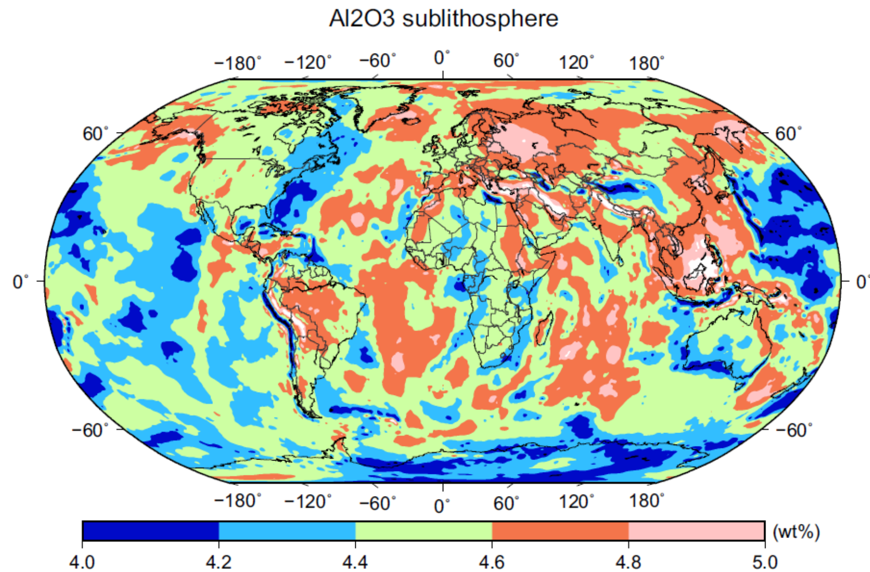
- ✓ Geometry (Moho depth, upper-mid/lower crust)variations
- ✓ Vs, Vp upper-mid/lower crust
- ✓ Average density

WINTERC-grav: Lithosphere & mantle composition



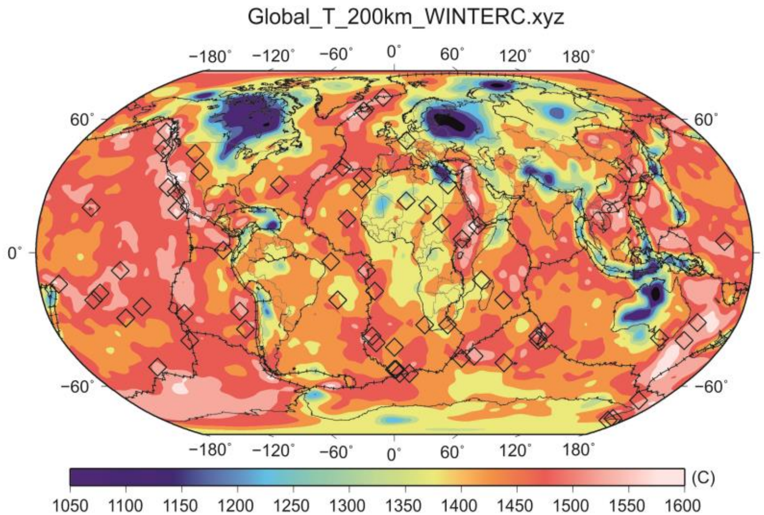


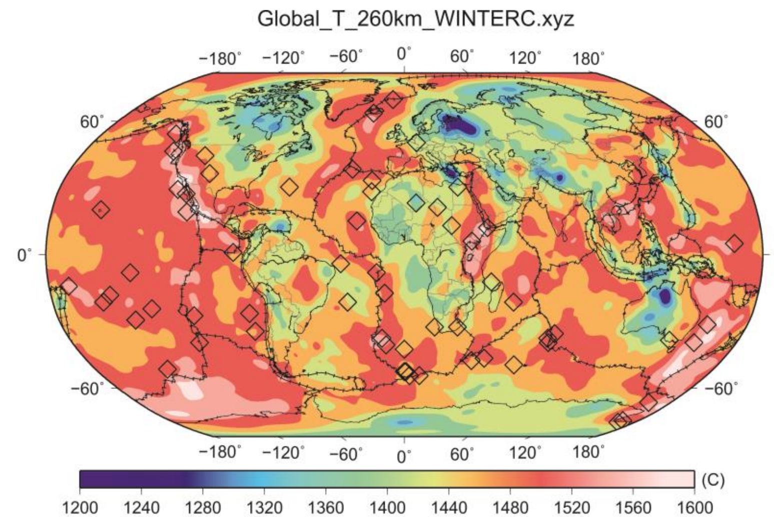


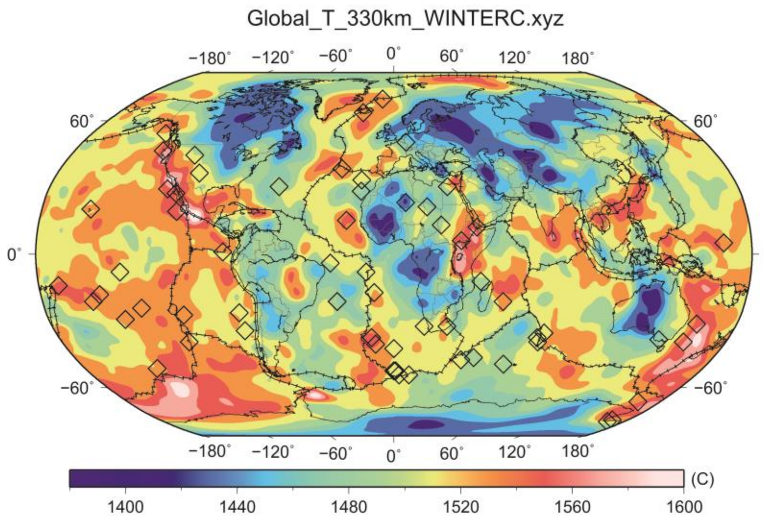


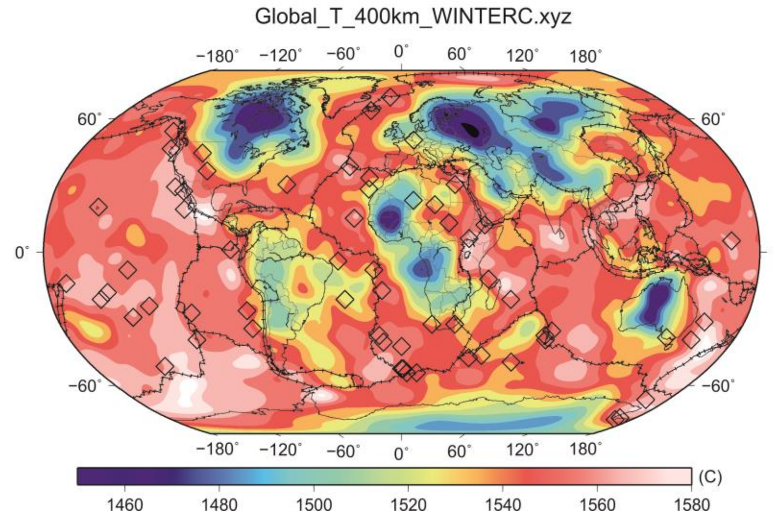
- ✓ High Al_2O_3→fertile, low Mg#, Low Al_2O_3→refractory, high Mg#
- ✓ Mantle plumes: fertile and hot; Cratons: refractory and cold
- ✓ Sublithosphere is more refractory in Pacific than Atlantic and Indian oceans

WINTERC-grav: temperature



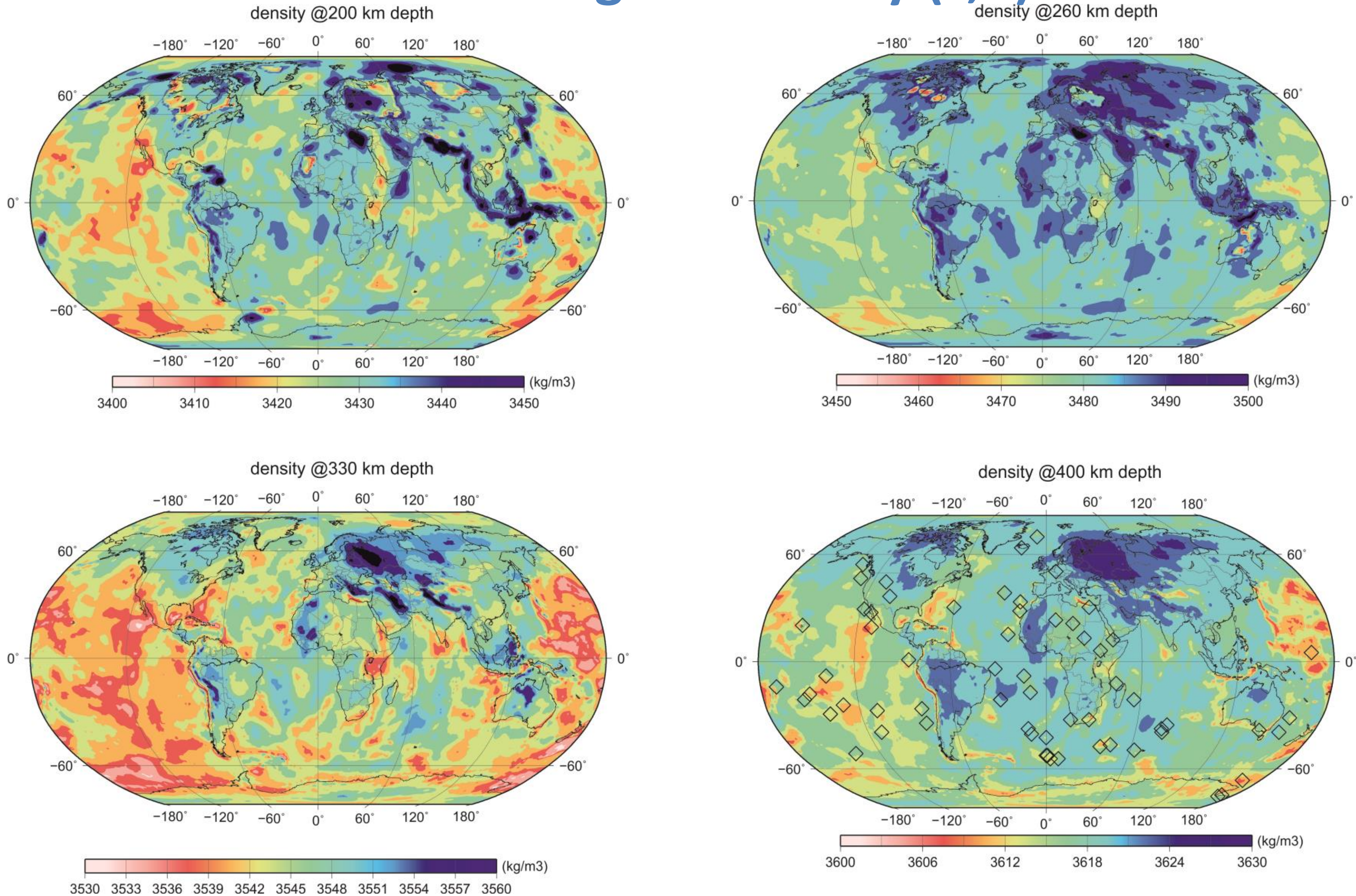






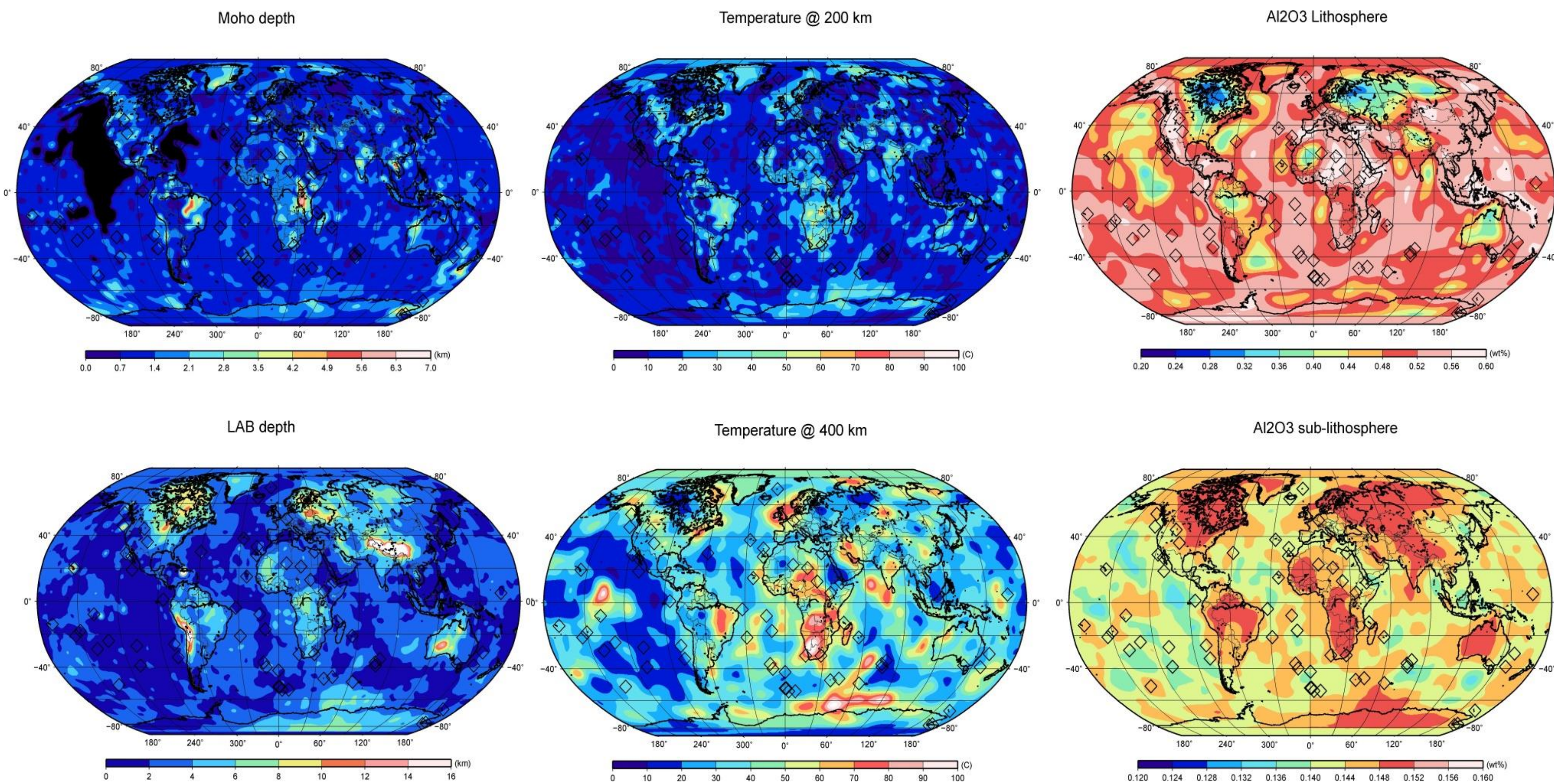
- ✓ Mantle plumes are warmer than the ambient mantle
- ✓ Continental cratonic cores remain cold down to the transition zone (Specially N America, E Europe and W Australia)

WINTERC-grav: density (T,C)



- ✓ Density=F(temperature, Composition)
- ✓ Densest sublithospheric mantle in Eastern Europe

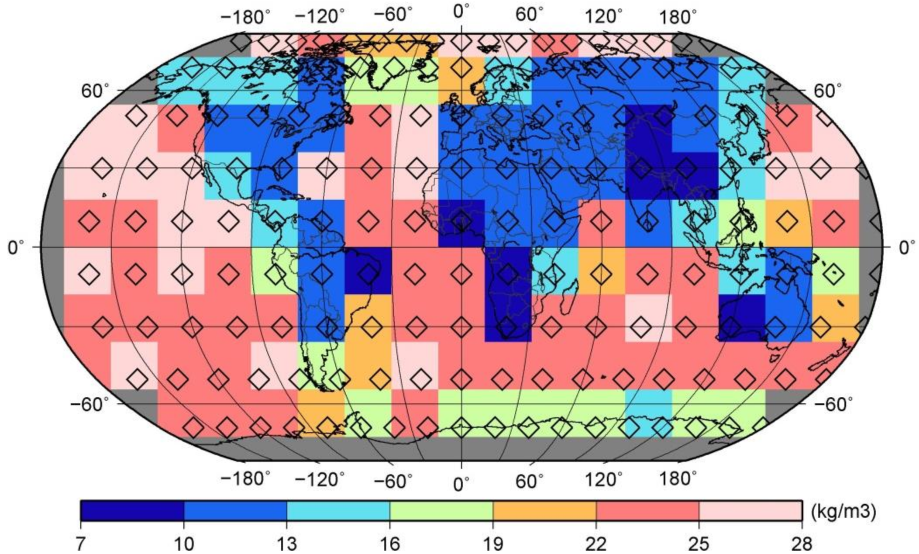
WINTERC-grav uncertainties: Posterior covariances step 1
Waveform tomography+elevation+SHF



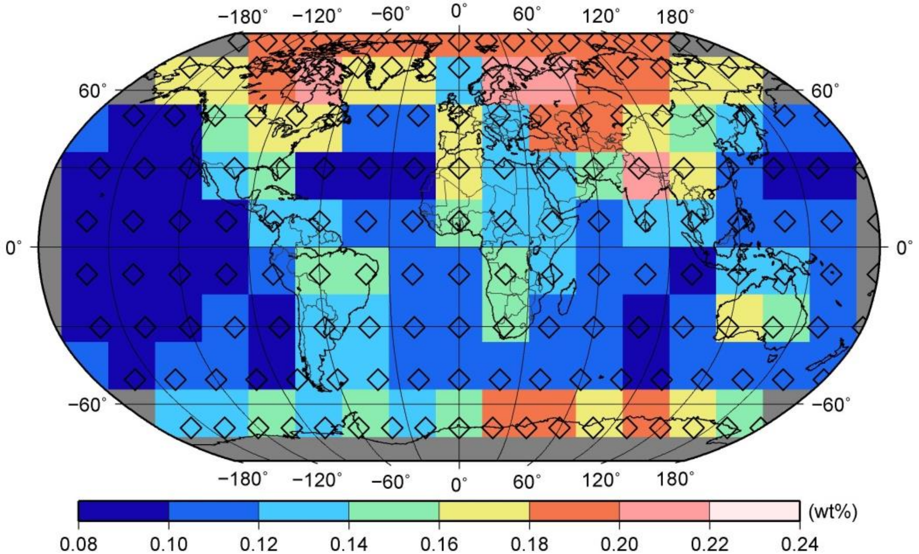
- ✓ Each model column: full covariance matrix
- ✓ Thermal lithospheric thickness is the best resolved parameter
- ✓ Uncertainty increases with depth (temperature, composition)

WINTERC-grav uncertainties: Posterior covariances step 2
Gravity field

Average crustal density

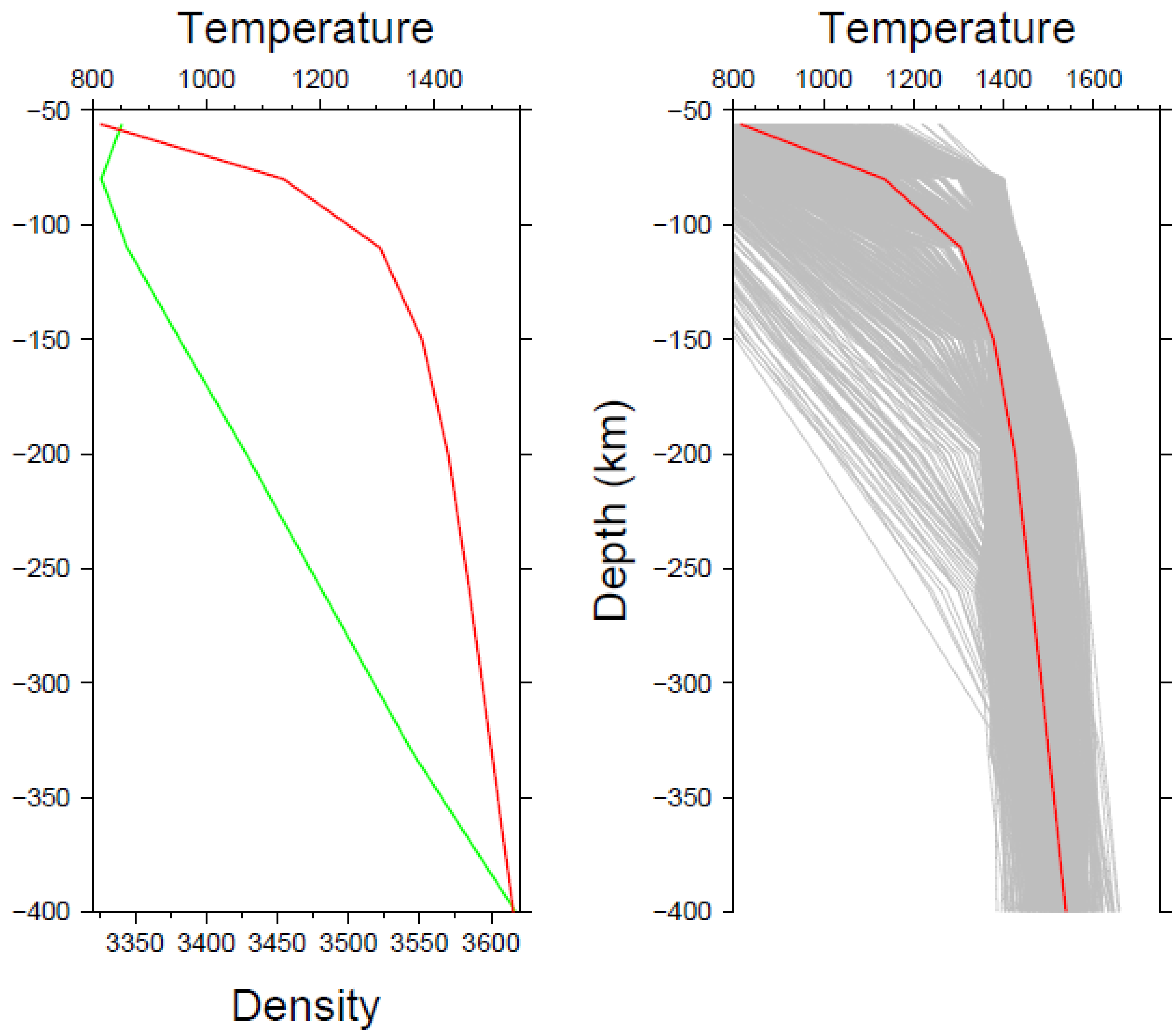


Average mantle composition



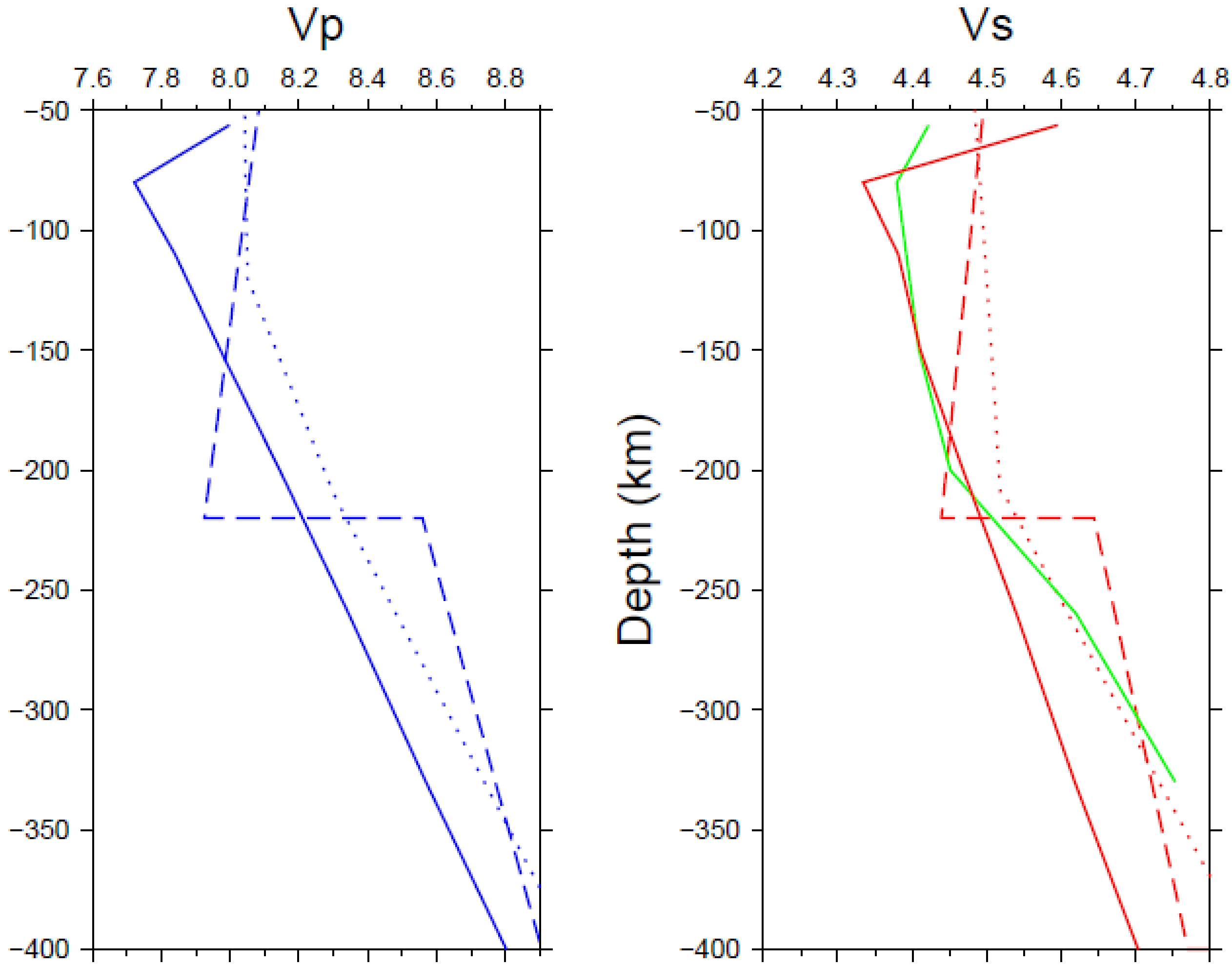
- ✓ Covariance matrix computed at coarser model resolution (20 deg) but full resolution at observations $G_{ij} = \left(\frac{\partial g_{\mathbf{3D}}(m_{post})_i}{\partial m_j}\right)$
- ✓ Crust density better resolved in continents than in oceans
- ✓ Mantle composition better resolved in oceans than in continents

WINTERC-grav: 1D average temperature and density



- ✓ Average adiabatic gradient 0.55-0.6 K/km (depth >200 km)
- ✓ Average mantle potential temperature 1300-1320 C (depth >200 km)

WINTERC-grav: 1D average seismic velocity



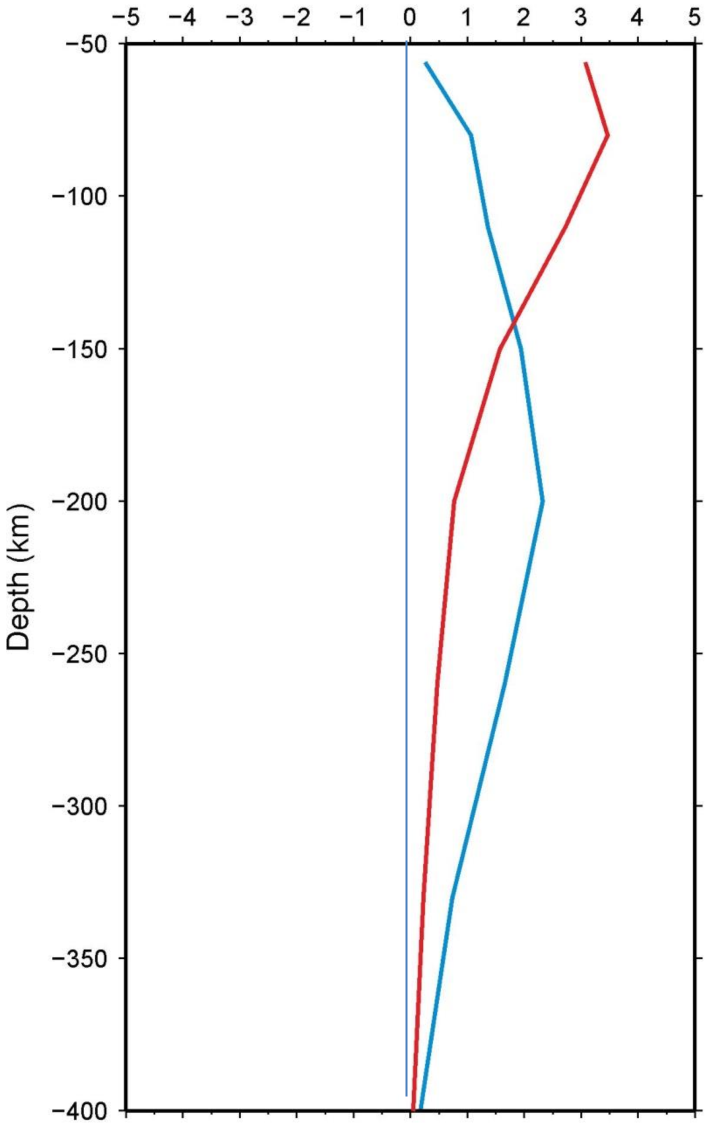
- ✓ Solid line WINTERC-grav, dashed line: AK135, dotted line PREM, solid green Vs: Schaeffer&Lebedev 2013
- ✓ Uniform Vs gradien throughout the upper mantle (no need for 200 km discontinuity or gradient increase)

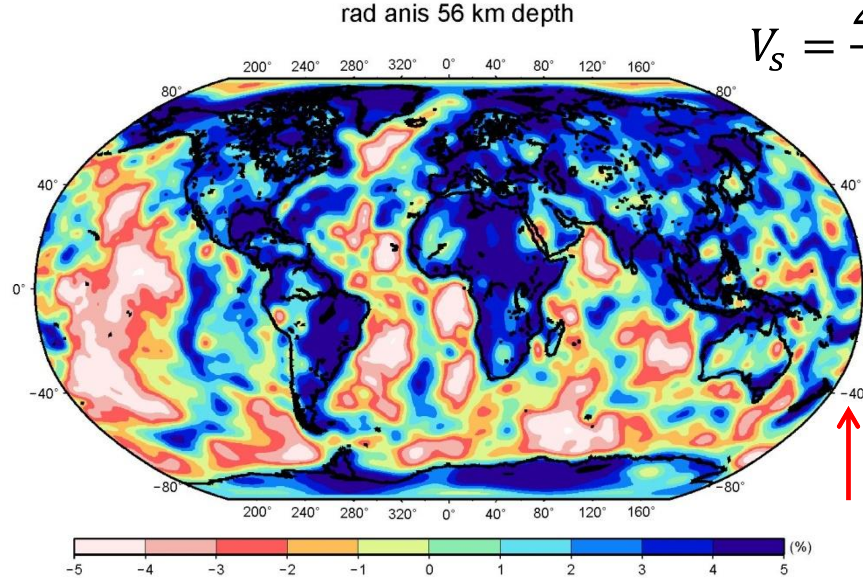
WINTERC-grav: Average radial anisotropy

$$R_{anis} = \frac{V_{SH} - V_{SV}}{V_s}$$

$$V_s = \frac{2V_{SV} + V_{SH}}{3}$$

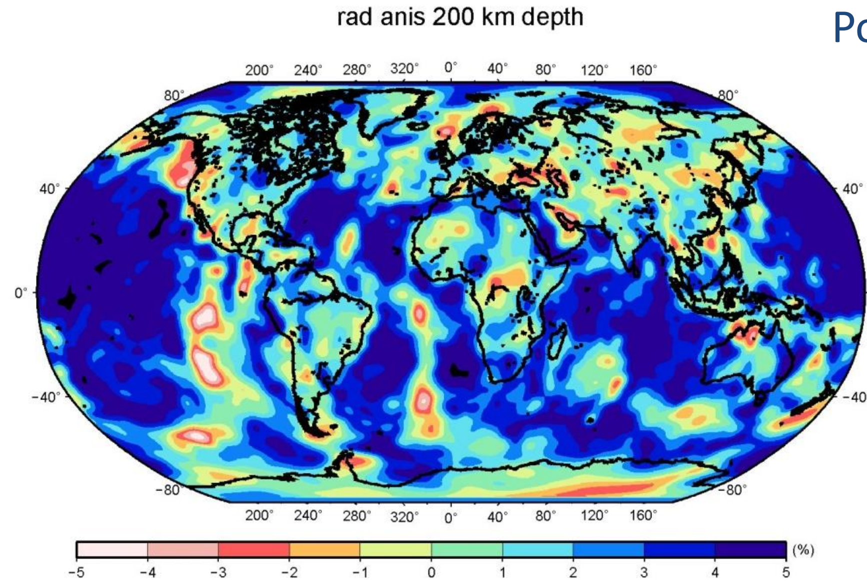
Red Continents Blue Oceans





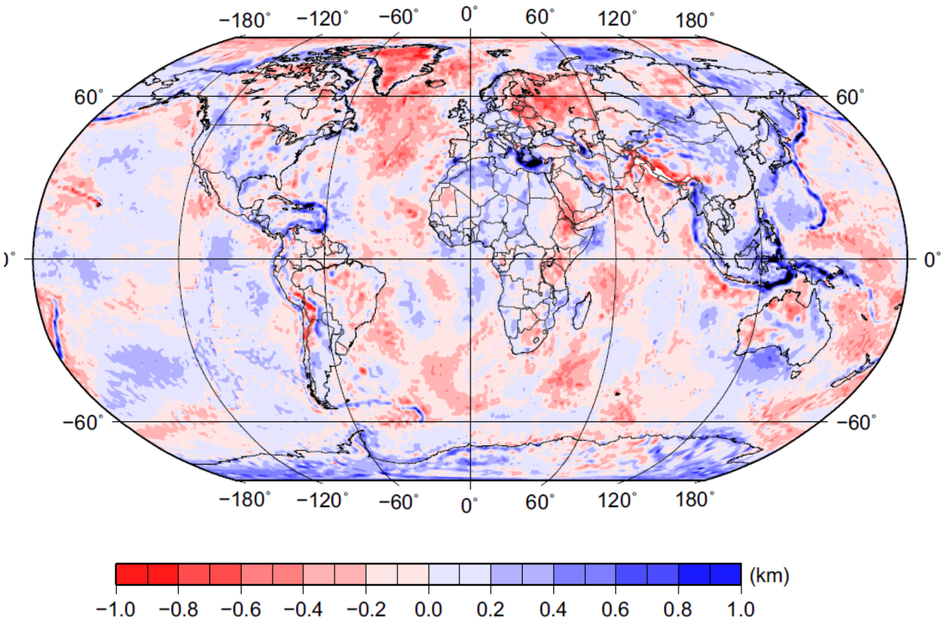
Negative anis

Positive anis



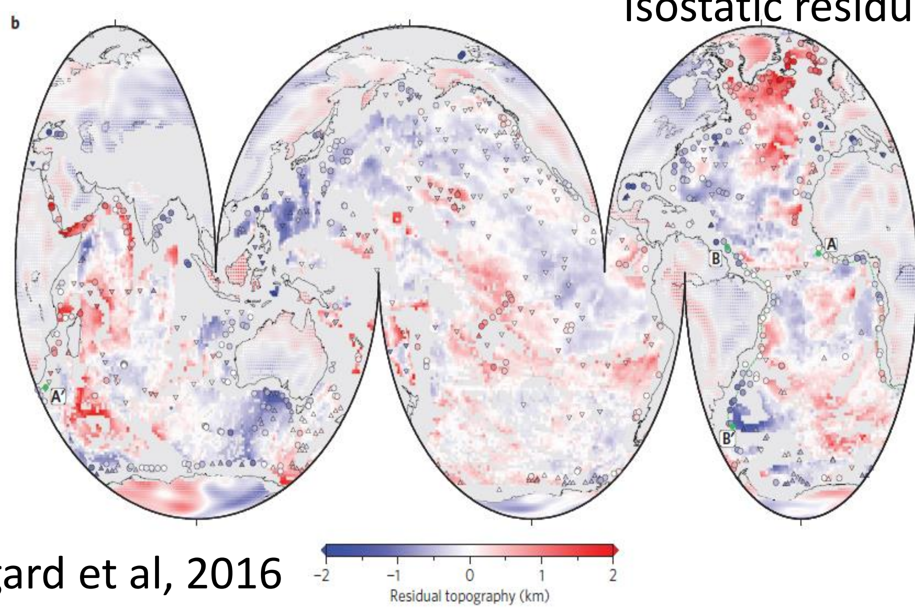
WINTERC-grav: Isostatic/dynamic elevation

Isostatic residual elevation-WINTERC-grav

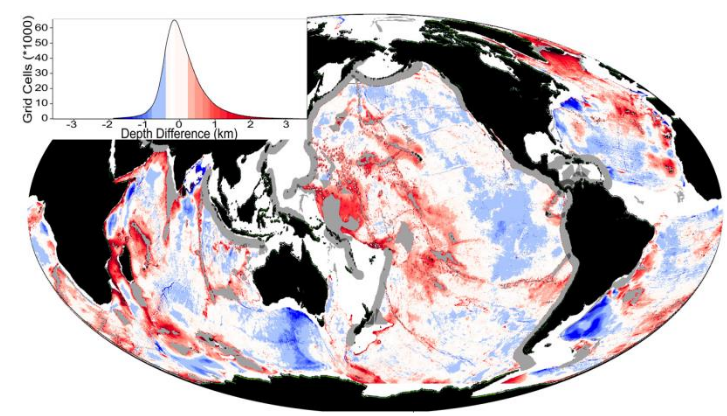


- ✓ Good agreement in oceans with independently derived residual maps
- ✓ In continents residual/dynamic published models show more dispersion

Isostatic residual elevation- Oceans



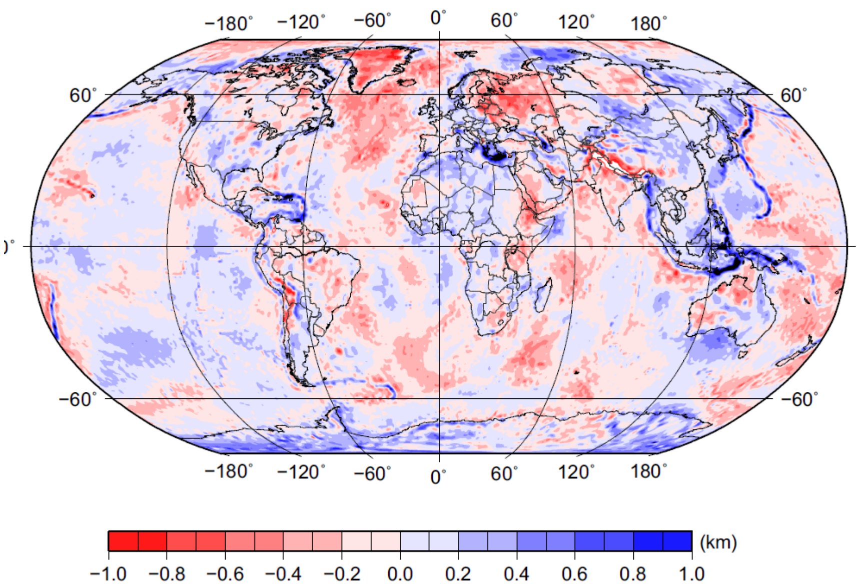
Hoggard et al, 2016

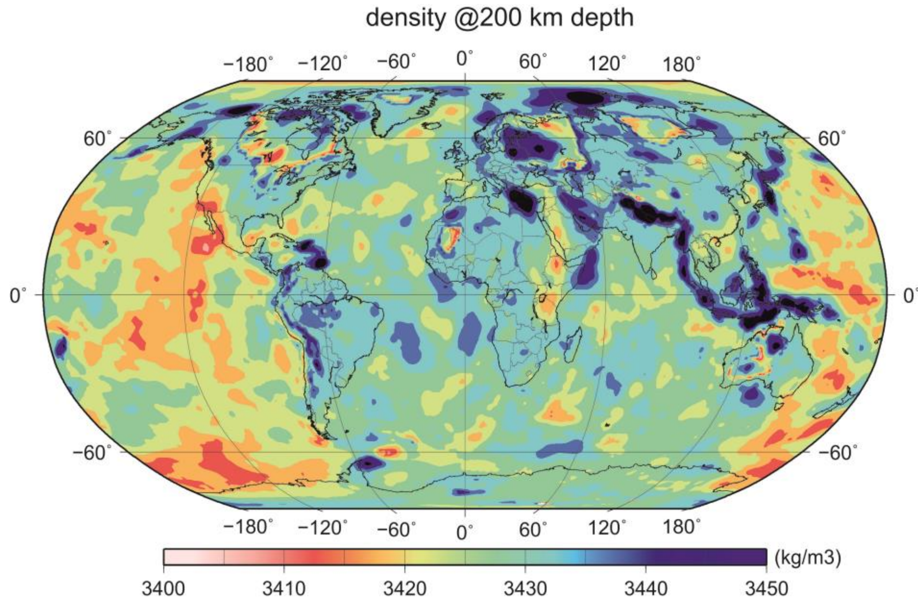


Rowley, 2018

WINTERC-grav: Isostatic/dynamic elevation

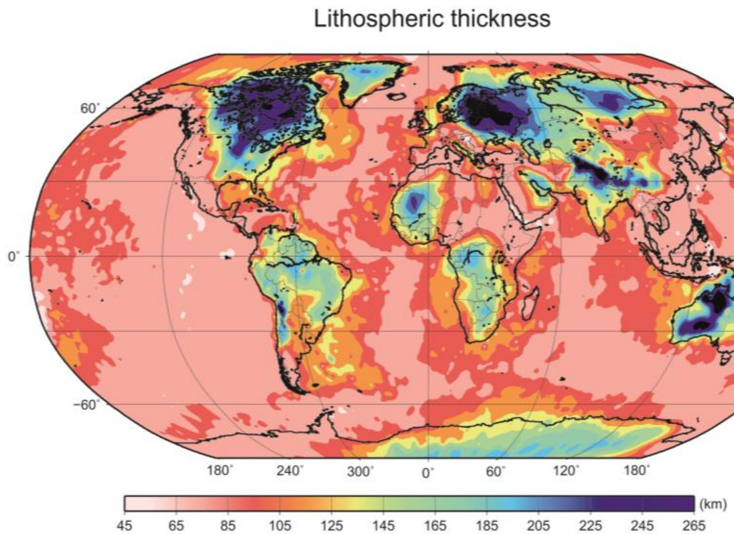
Isostatic residual elevation-WINTERC-grav

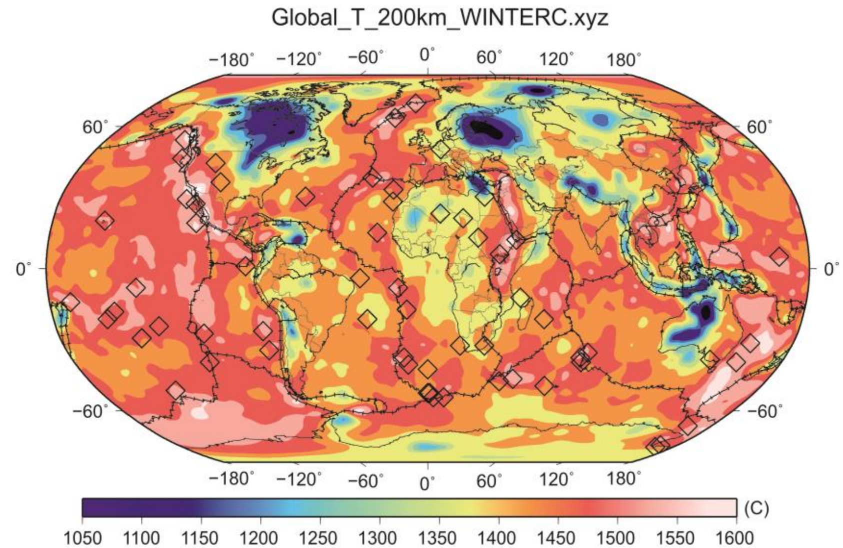


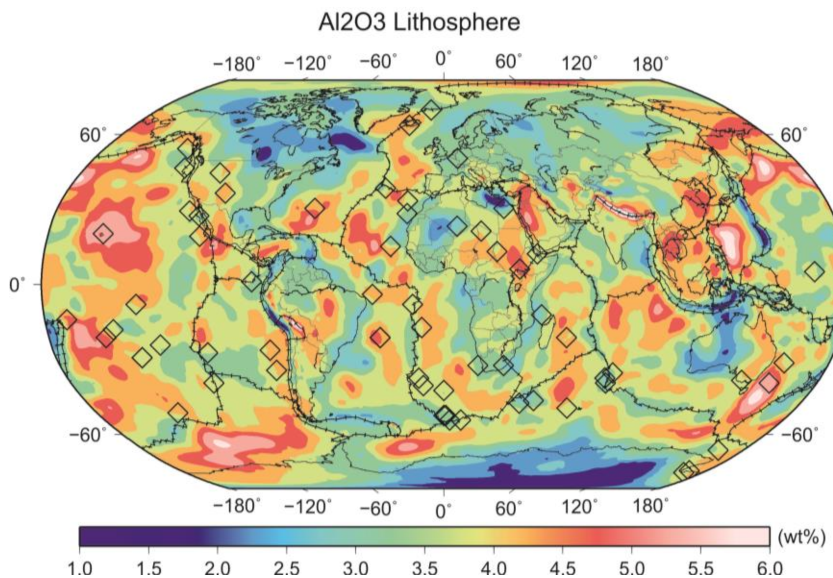


- ✓ Only partial correlation between upper mantle density anomalies (positive/negative) and residual isostatic elevation (positive/negative)
- ✓ Discrepancies are worse over continents (e.g., E. Europe, Greenland)
- ✓ Possible contribution from lower mantle and CMB (?)

Lithospheric composition

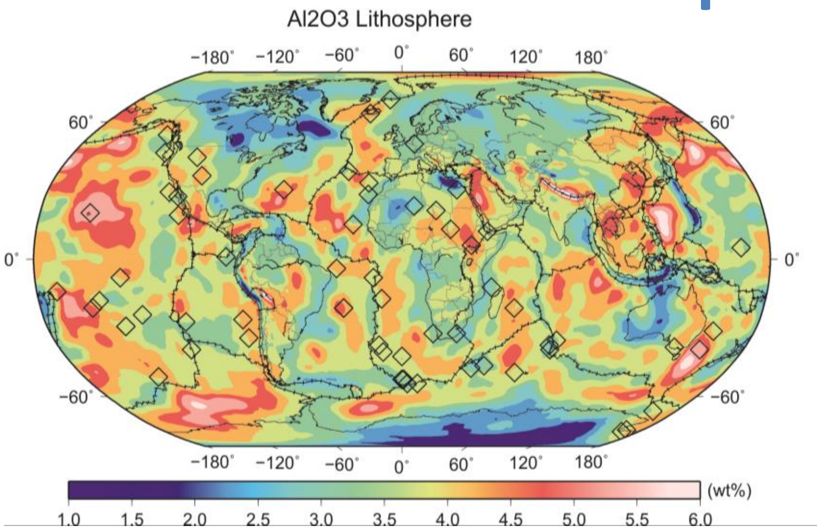






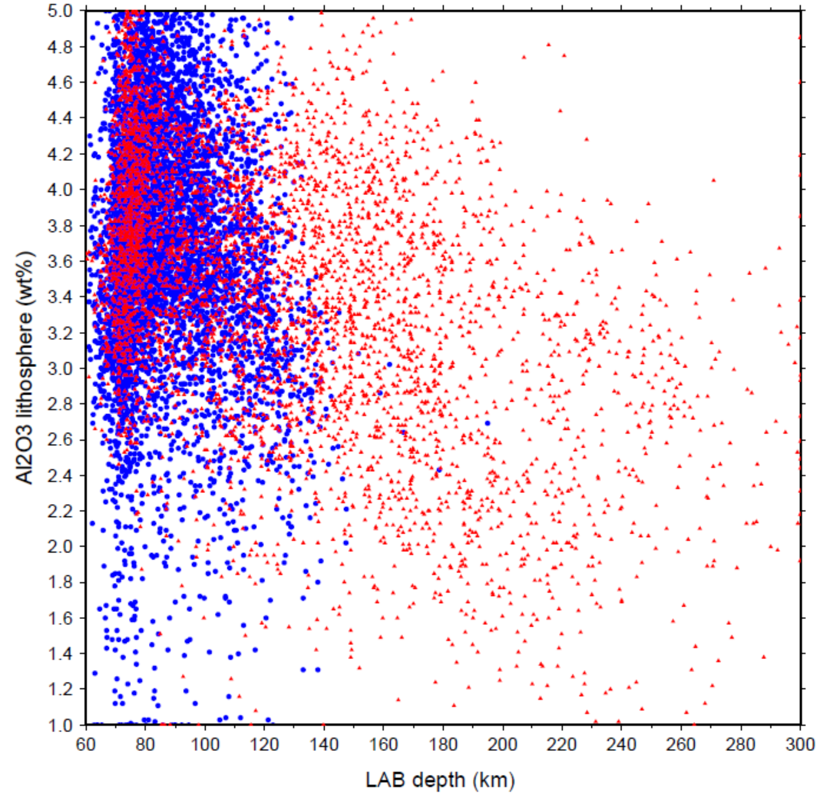
- ✓ Most cratons are refractory
- ✓ Plumes are hot in the sublithosphere and fertile in the lithosphere

Lithospheric composition

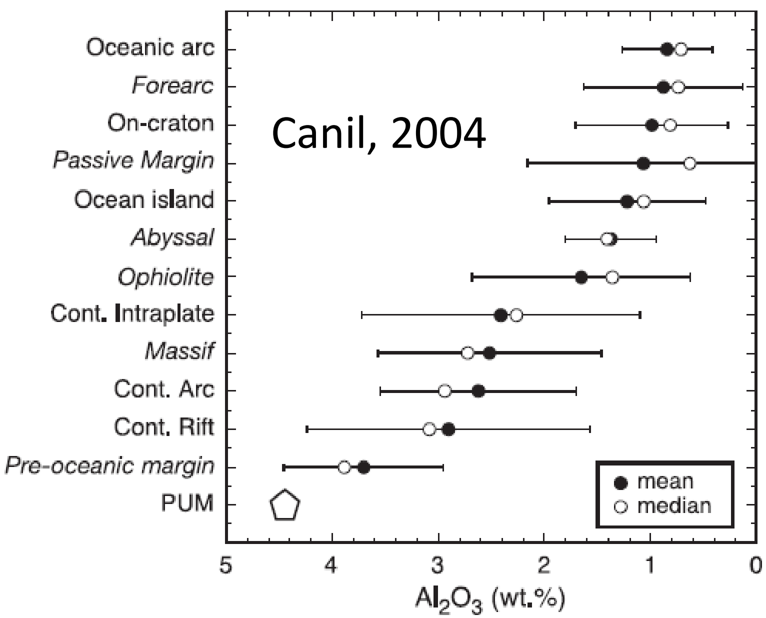


Red Continents

Blue Oceans



Global petrological data base

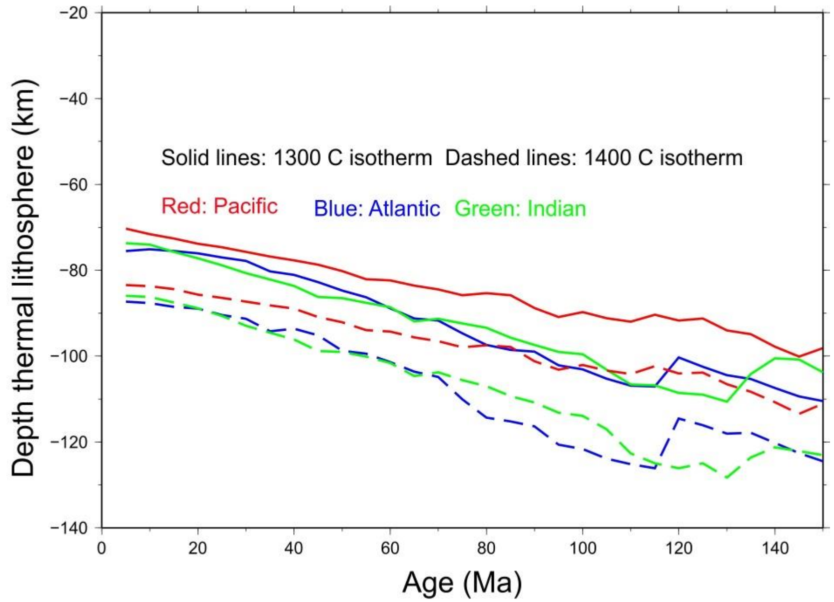


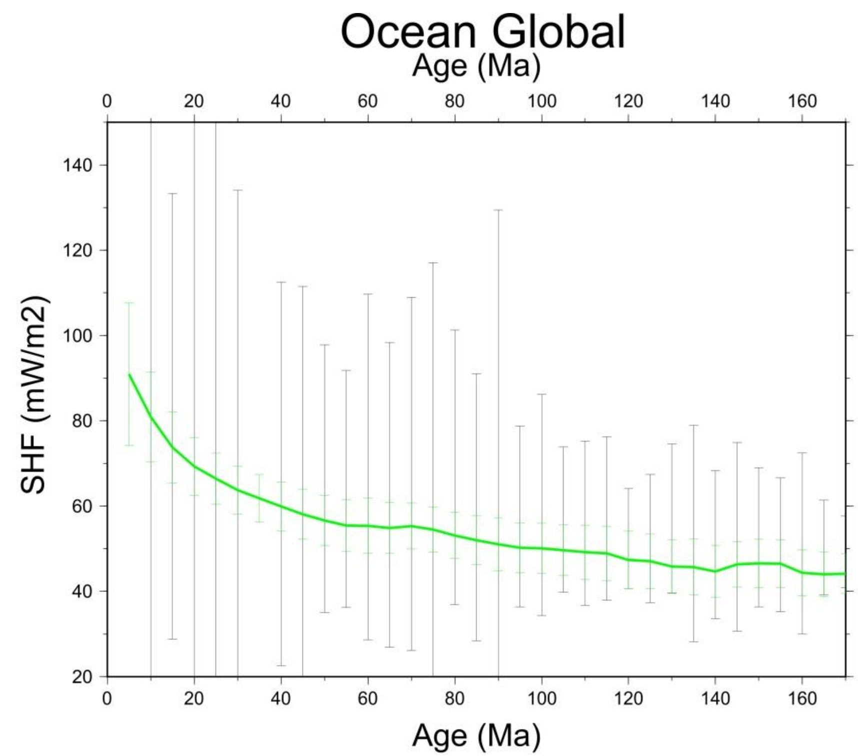
Canil, 2004

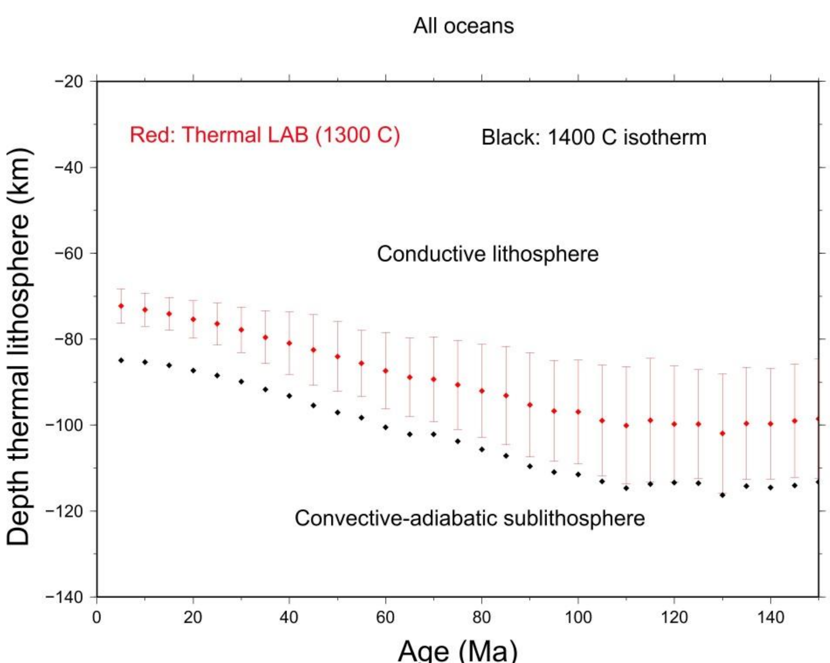
- ✓ General trend continents: lithospheric thickening (age increasing) fertility decrease
- ✓ Oceans: MOR's are depleted, fertility peaks at intermediate age

Thermal oceanic lithosphere: cooling model

Lithospheric thickness and heat flow vs age (5 Ma bins)



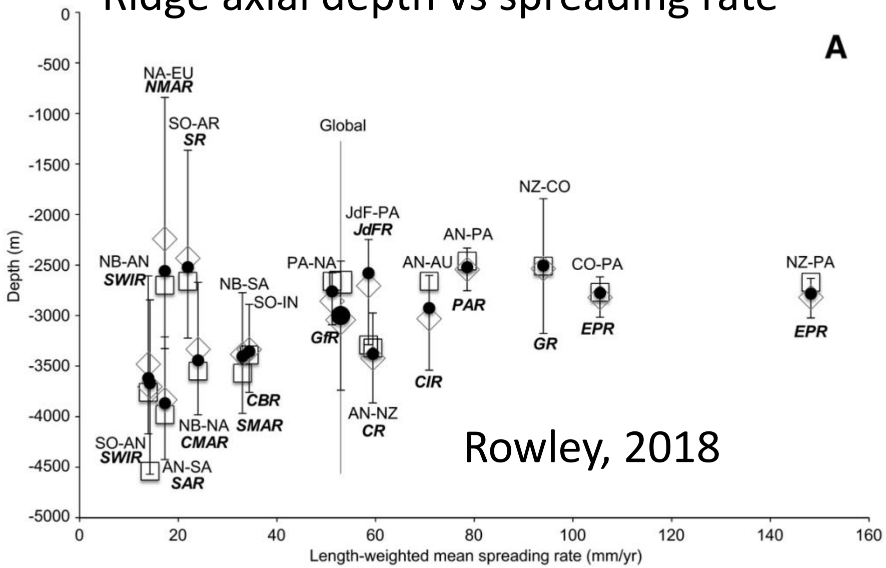




- ✓ Ocean SHF predictions match data except for lithospheric age<15 Ma approx.
- ✓ Oceans cool differently at intermediate rate between half-space and plate models

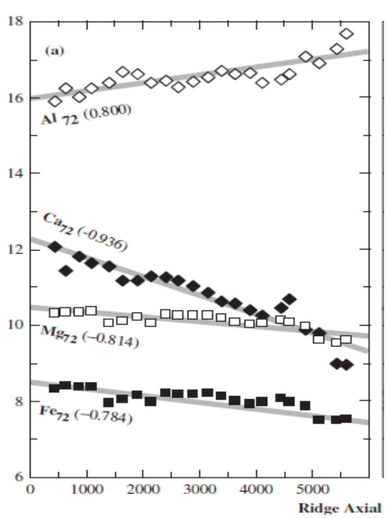
Mid Oceanic Ridges

Ridge axial depth vs spreading rate

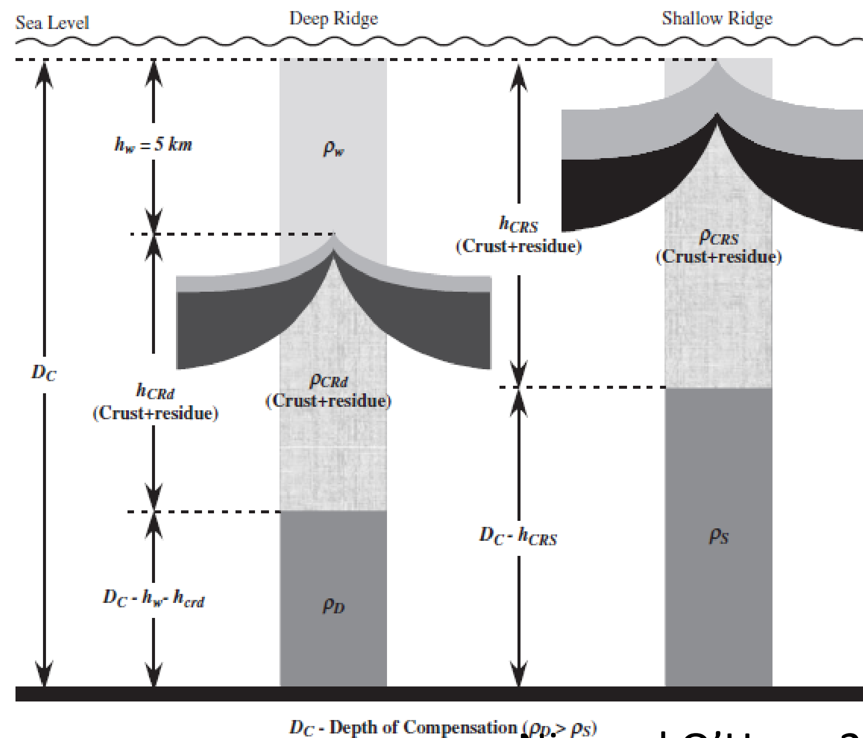


Rowley, 2018

Bulk composition MORB vs ridge depth



Niu and O'Hara, 2008

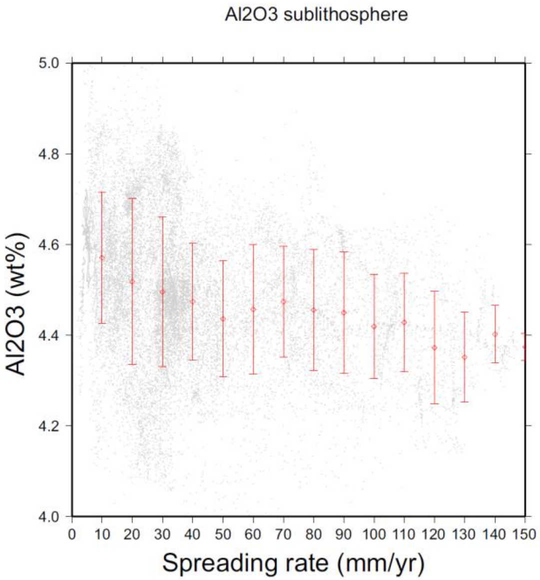


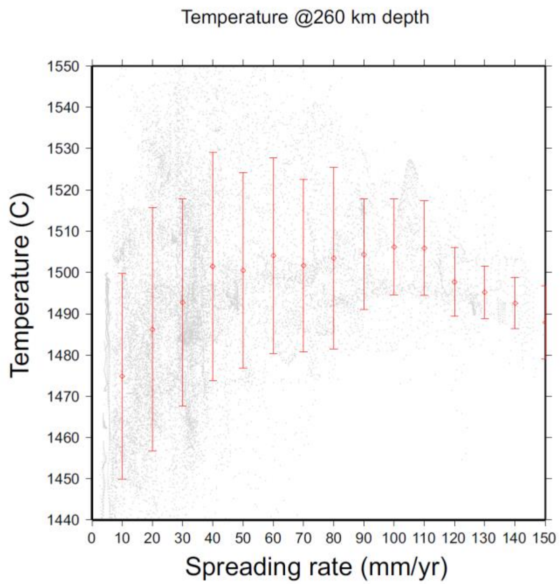
Niu and O'Hara, 2008

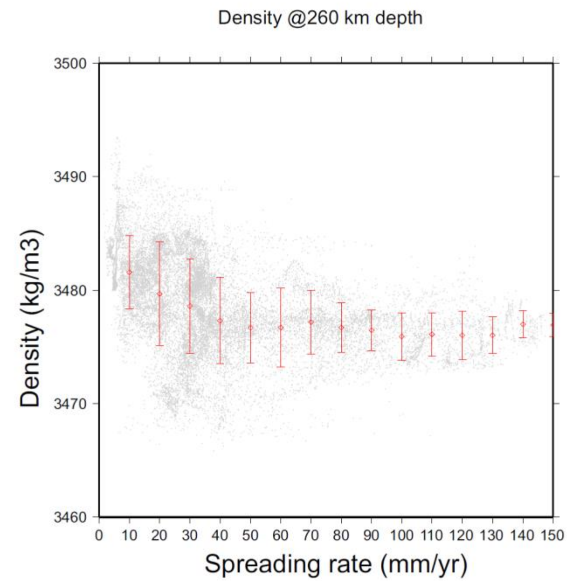
- ✓ Shallow ridges spread faster than deep ones
- ✓ Slab pull vs ridge push
- ✓ Fertility of mantle melt source increases with ridge depth

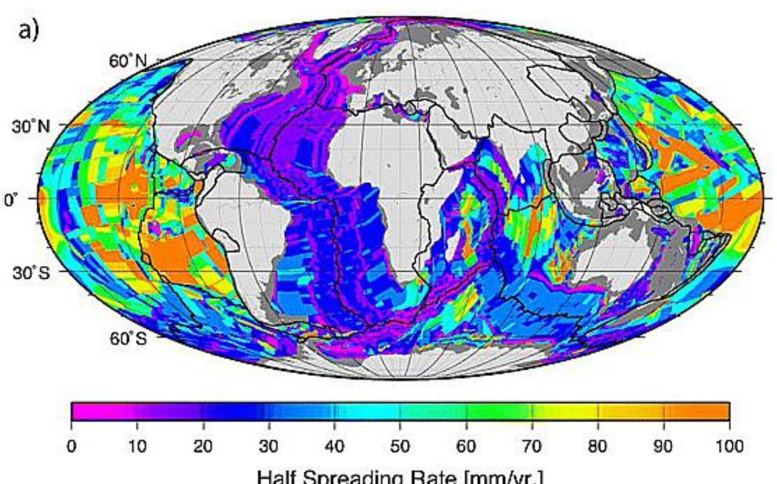
WINTERC-grav vs spread rate

oceanic lithosphere < 20Ma old at 10 mm/yr bins

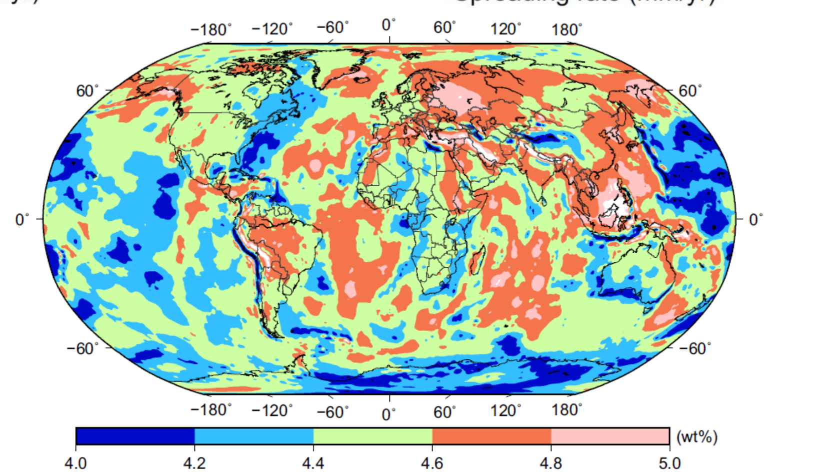








Muller et al. (2008).



Sublithospheric mantle composition from WINTERC-grav

- ✓ Mantle fertility and density decrease and temperature increase with spreading rate (up to 50-60 mm/yr).

Conclusions (so far…)

- ✓ WINTERC-grav: new global lithospheric/upper mantle thermochemical model integrating waveform tomography, SHF, isostasy, satellite gravity and petrology
- ✓ New crustal mode revisiting Crust1.0: geometry, density
- ✓ Mantle plumes: fertile and hot; Cratons: refractory and cold
- ✓ Pacific ocean upper mantle is more refractory and warmer (=less dense) than Indian and Atlantic oceans
- ✓ Mapping dynamic topography
- ✓ Revisiting the half-space vs plate oceanic lithosphere cooling models
- ✓ Mid Oceanic Ridges: mantle fertility-spreading rate (revisiting ridge push for slow spreading MOR's?)