Unravelling the upper mantle heterogeneity from integrated multi-observable inversions

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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

Electrical Conductivity models

Density models

...
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)

- Geoid anomaly (XGM2016)
- Gravity gradients
- Surface elevation is approximately in isostatic equilibrium (except dynamic topography)
- Sensitivity to density distribution
- Gravity data inversion: Intrinsically non-unique

(Bouman et al., 2016.)
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)

✅ Mantle composition described by Al$_2$O$_3$ and FeO independent variables (CaO and MgO=F(Al$_2$O$_3$))

✅ Chemical parameterization following melting trend, analogous to pyrolite (Harz+basalt)
Physical properties—derivatives @ P=7.6 Gpa and FeO=7.9 wt% (Perple_X)

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

Chemical derivative
For $\Delta \rho=15$ kg/m$^3$ $\rightarrow$
$\Delta Al_2O_3=1$ wt% 
($\Delta Vs=0.2\%$)

Temperature derivative
For $\Delta \rho=15$ kg/m$^3$ $\rightarrow$
$\Delta T=200$ C ($\Delta Vs=1.8\%$)

$d\rho/dAl_2O_3=150^{\ast} d\rho/dT$
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
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 Al₂O₃ → fertile, low Mg#, Low Al₂O₃ → refractory, high Mg#
- Mantle plumes: fertile and hot; Cratons: refractory and cold
- Sublithosphere is more refractory in Pacific than Atlantic and Indian oceans
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
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 $G_{ij} = \left( \frac{\partial g_{3D}(m_{post})_i}{\partial m_j} \right)$

✓ 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)
Solid line WINTERC-grav, dashed line: AK135, dotted line PREM, solid green Vs: Schaeffer&Lebedev 2013

Uniform Vs gradient throughout the upper mantle (no need for 200 km discontinuity or gradient increase)
WINTERC-grav: Average radial anisotropy

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

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

- 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

- 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

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

Niu and O’Hara, 2008
Mantle fertility and density decrease and temperature increase with spreading rate (up to 50-60 mm/yr).

Muller et al. (2008).

Sublithospheric mantle composition from WINTERC-grav vs spread rate

Oceanic lithosphere < 20 Ma old at 10 mm/yr bins
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?)