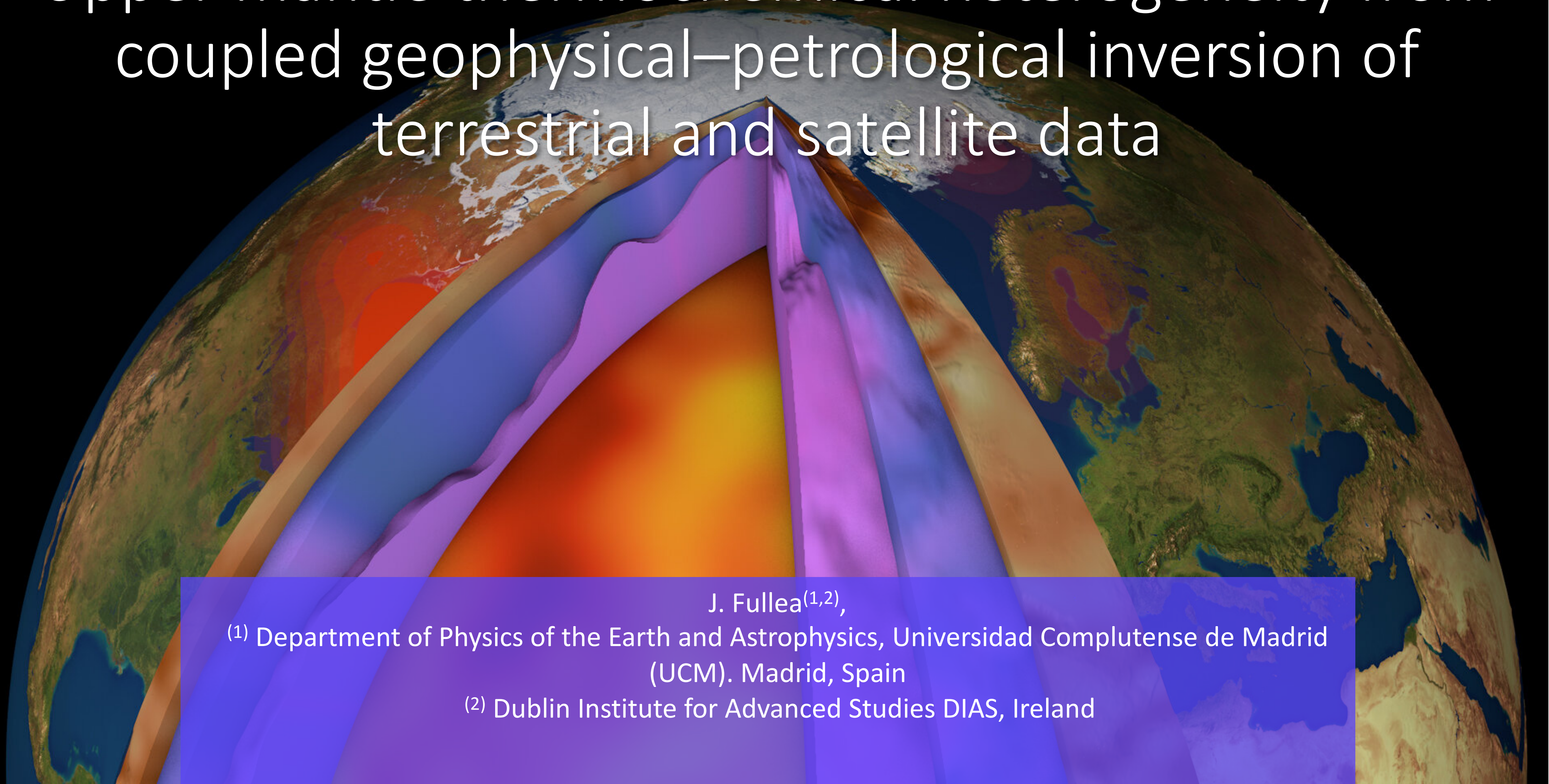
Upper mantle thermochemical heterogeneity from coupled geophysical–petrological inversion of terrestrial and satellite data



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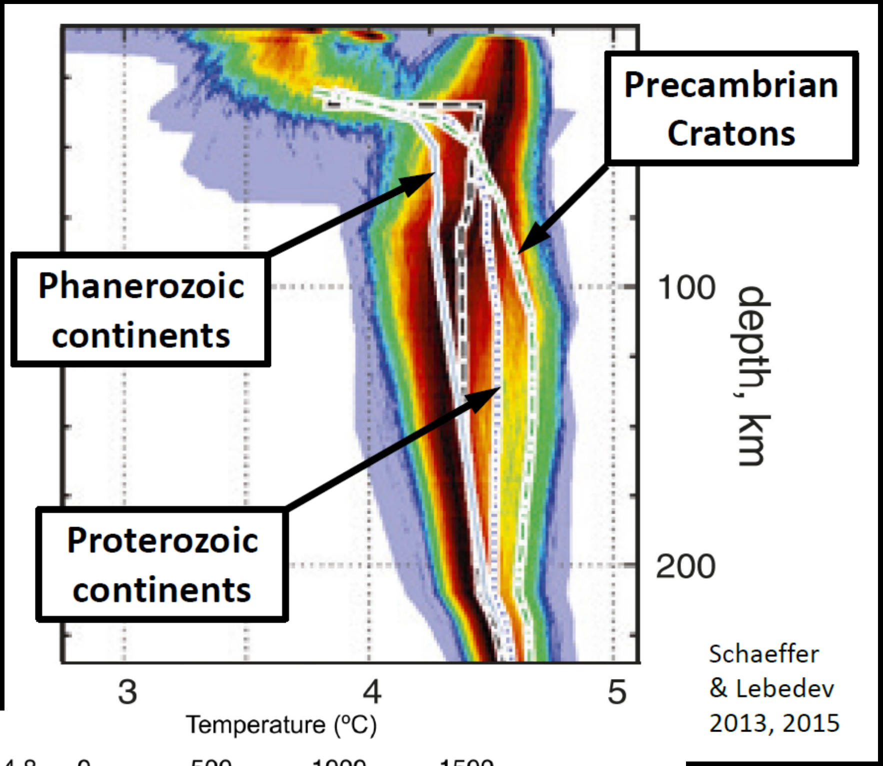
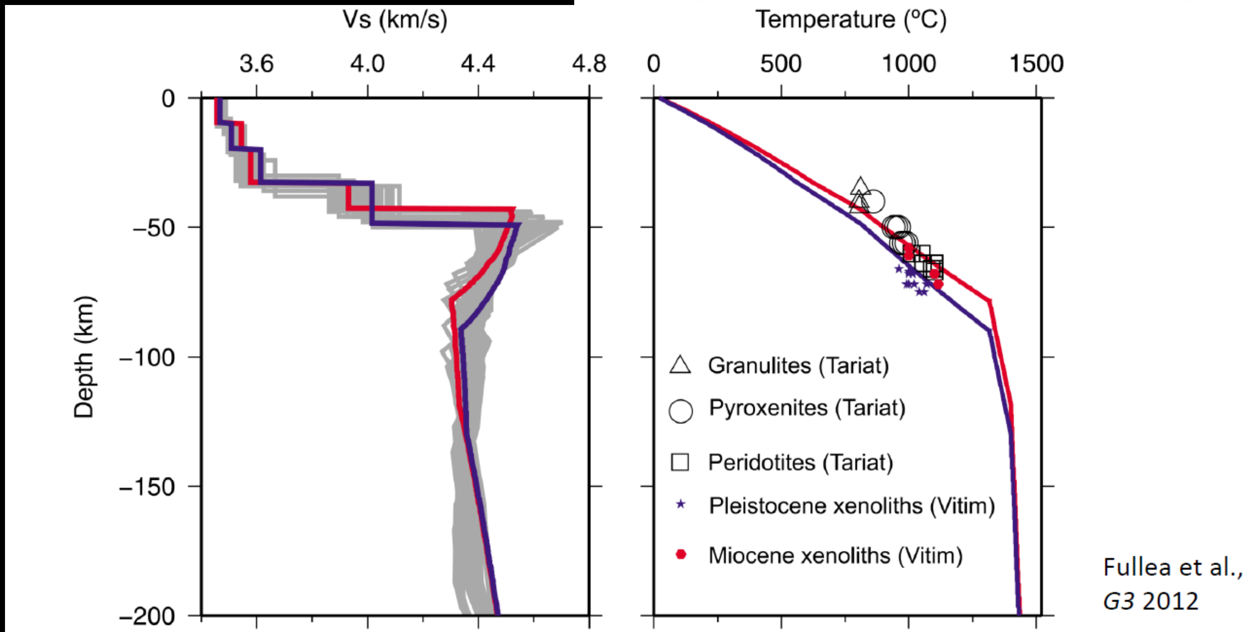
[2] Dublin Institute for Advanced Studies DIAS, Ireland

Why Integrated geophysical-petrological thermochemical modelling?

*Vertical Vs profiles “converted” to temperature results in unrealistic geotherms

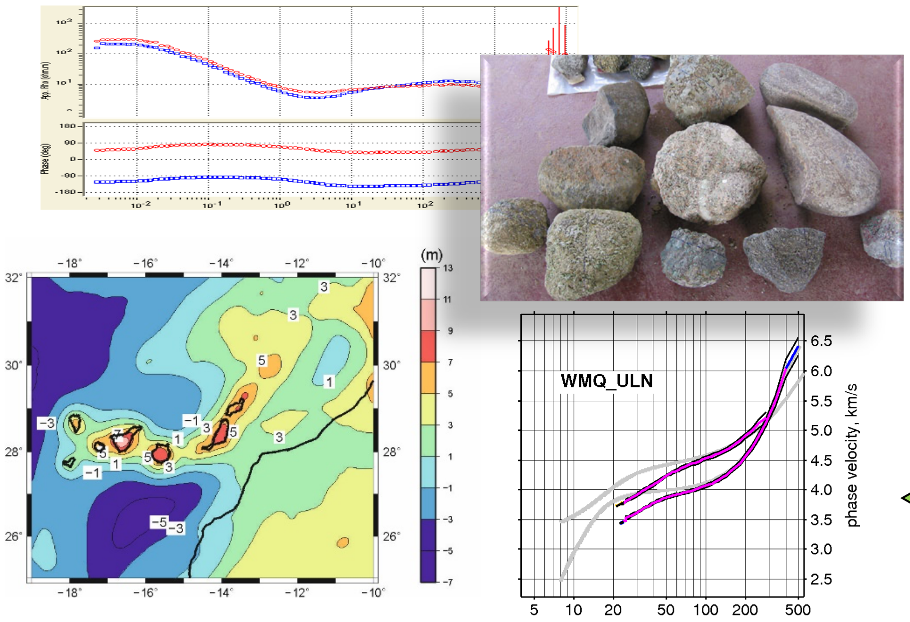
*Density anomalies from tomography models overpredict the observed gravity field





- **Integrating (self-consistently) geophysical and petrological data to image the lithosphere/uppermost mantle**

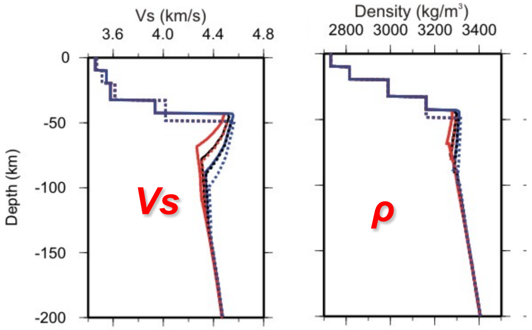
Geophysical & petrological data

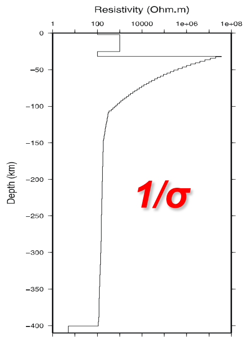


Inversion

Forward modeling

Geophysical parameters





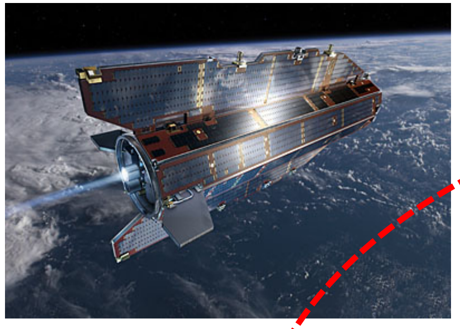
Integrated modelling

Temperature, Pressure, Composition

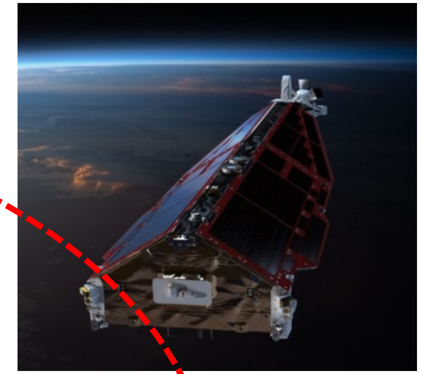
- **Forward approach**
- **Non-linear probabilistic inversion**

Integrated geophysical-petrological modelling

Gravity field (GOCE)



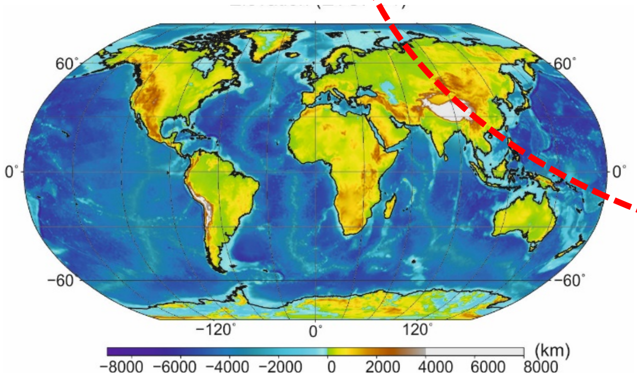
Magnetic field (Swarm)



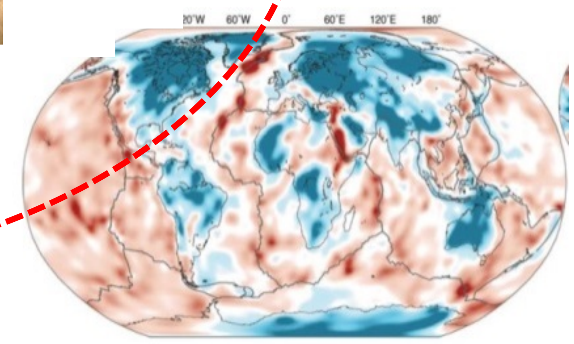
- ✓ ***Temperature***
- ✓ ***Composition***

$$dG = V\,dP - S\,dT + \Sigma_i\, \mu_i\, dX_i$$

Petrology & Mineral physics



Surface elevation



Seismology

Earth and Planetary Science Letters 409 (2015) 71–88

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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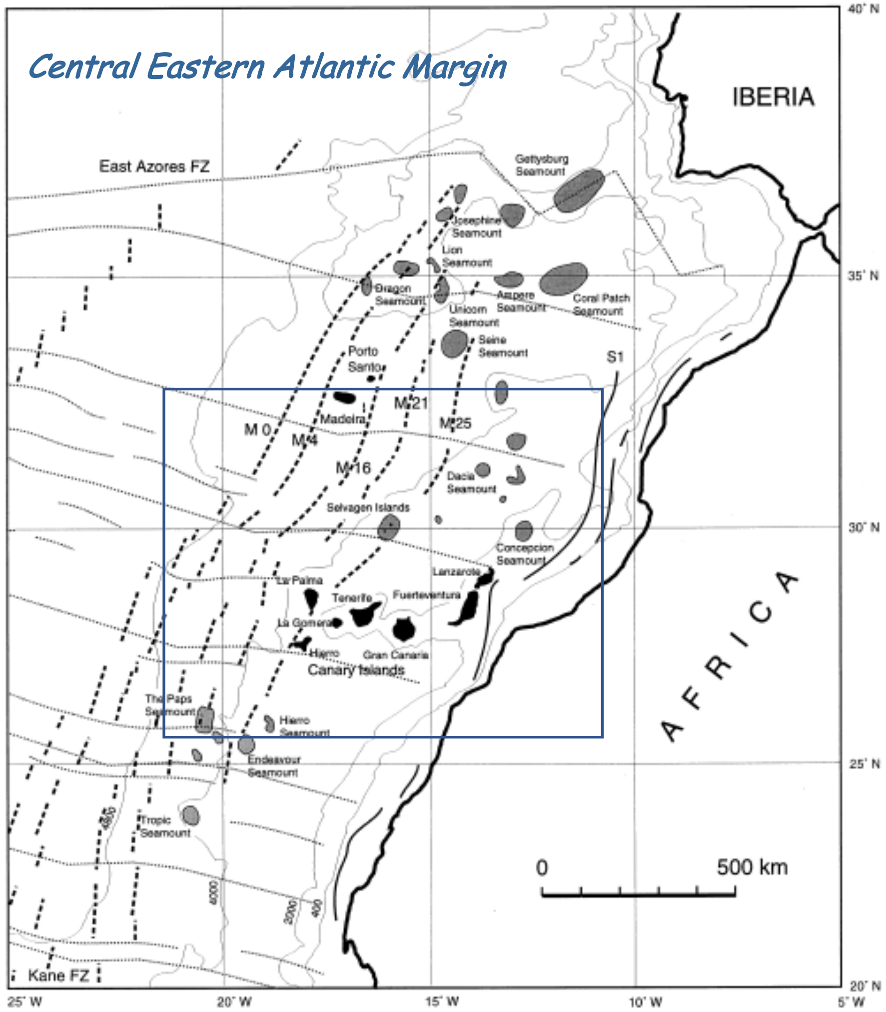
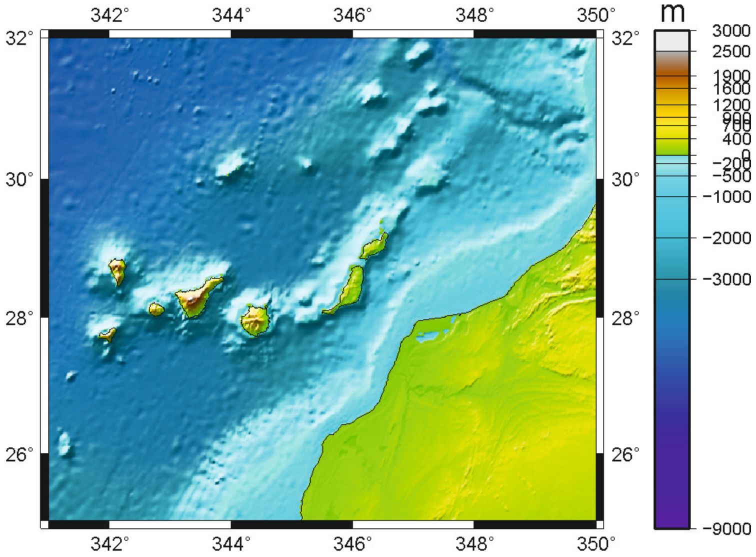
The Canary Islands hot spot: New insights from 3D coupled geophysical–petrological modelling of the lithosphere and uppermost mantle

Javier Fullea [a,*], Antonio G. Camacho [a], Ana M. Negredo [a,b], José Fernández [a]

[a] Institute of Geosciences (CSIC, UCM), Plaza de Ciencias, 3, ES-28040 Madrid, Spain
[b] Dept. of Geophysics, Facultad CC Físicas, Universidad Complutense de Madrid, Plaza de Ciencias, 1, ES-28040 Madrid, Spain



A regional example: the Canary Islands

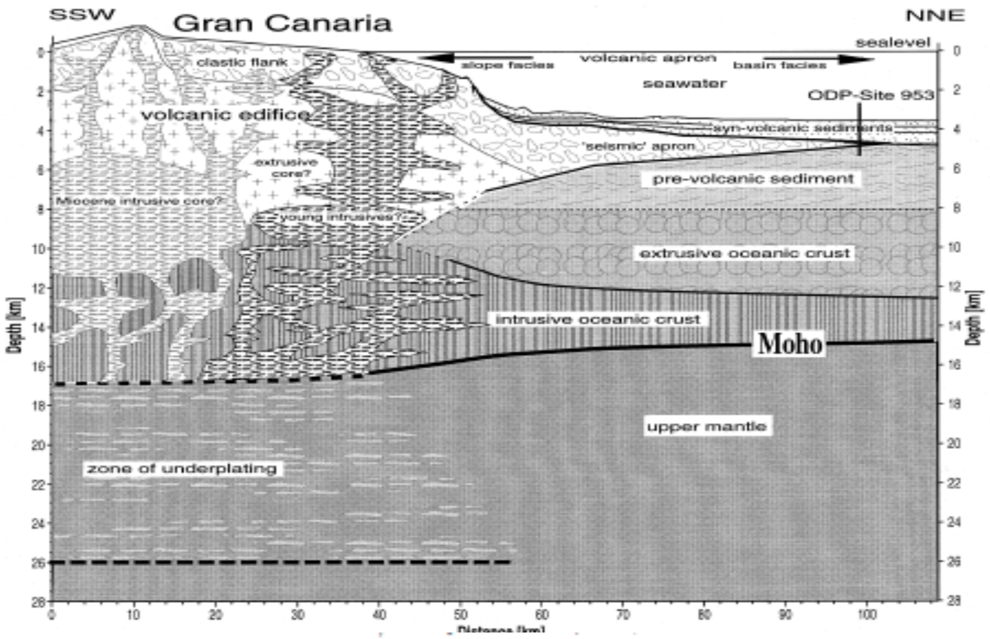


*Old oceanic lithosphere (150-170 Ma) adjacent to the NW African margin.

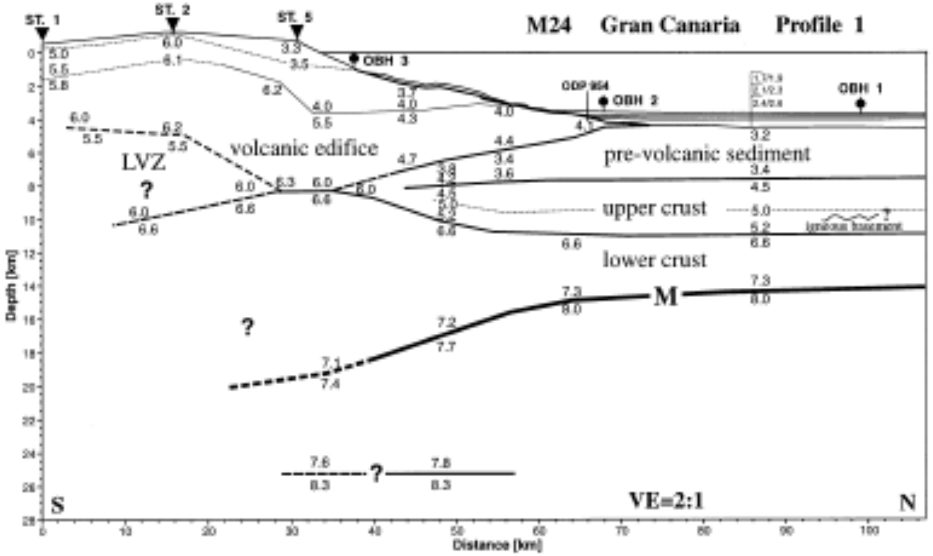
*3000-km-long volcanic belt that includes a considerable number of seamounts and volcanic islands.

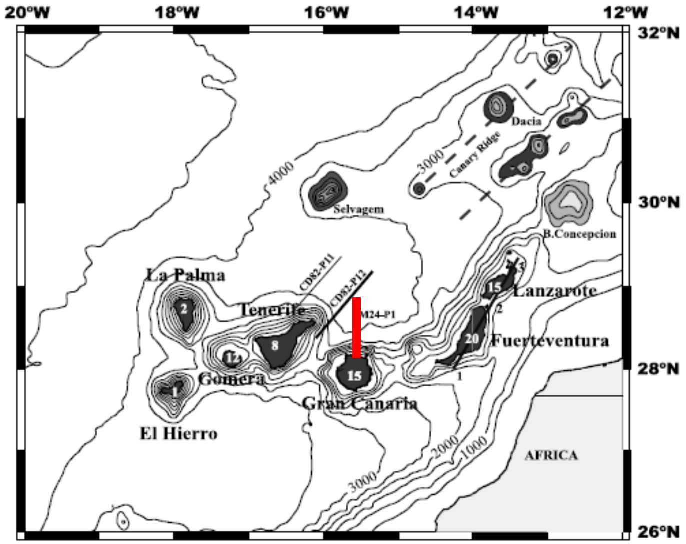
*East-west age progression with the oldest exposed volcanic rocks in Fuerteventura (20 Ma) and the youngest (<4 Ma) in the western islands (La Palma and El Hierro).

Crustal structure: seismic refraction profiles: Gran Canaria



From Ye et al. 99

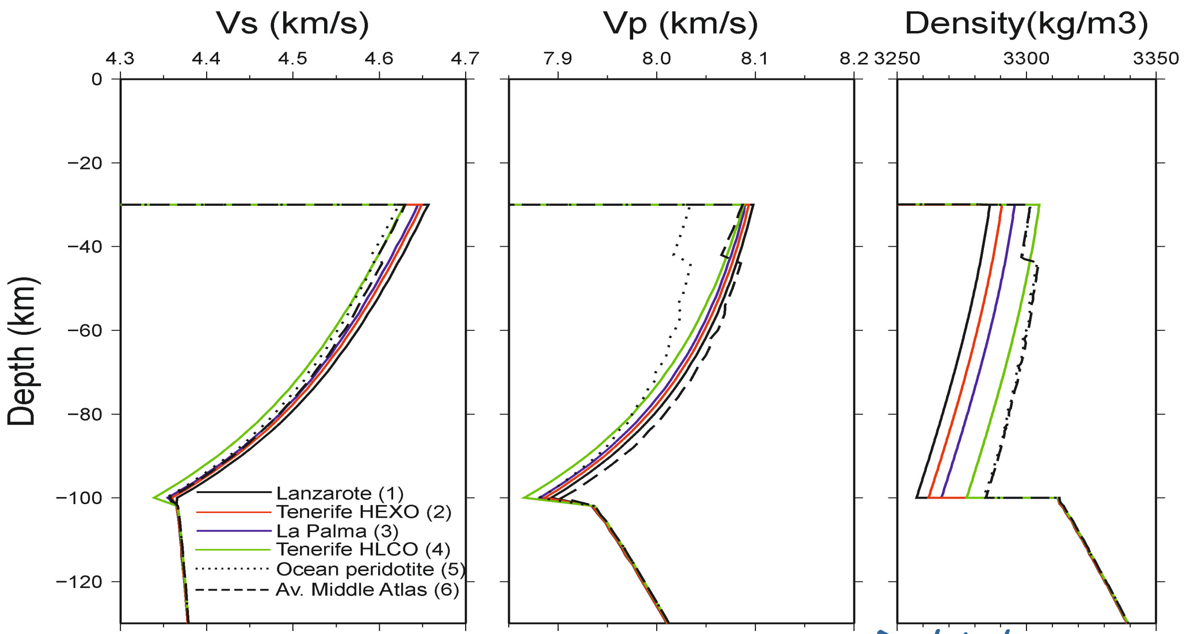


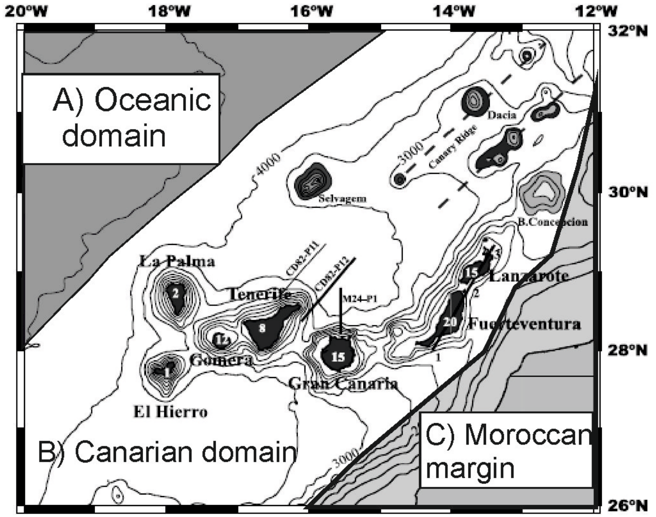


Indication of 10-km-thick zone of underplating below the Moho (16-18 km depth)

Low velocity zone (Vp<6 km/s) in the lower part of the volcanic edifice (Miocene feldspar-rich core)

Mantle composition: mantle xenoliths and compositional domains





Depleted

Depleted +metasomatised

Canarian xenoliths exhibit high degree of **depletion** (200 MA widespread tholeiitic event)+ **metasomatism** (e.g. wherlites, dunites)

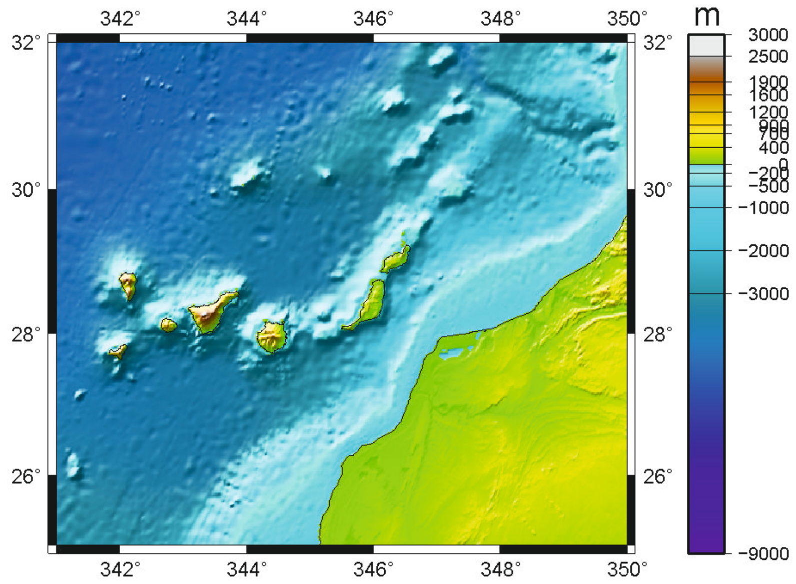
	1) Av. Harz. Lanzarote (wt%)[a]	2) Av. HEXO Tenerife (wt%)[b]	3) Av. Harz. La Palma av. (wt%)[c]	4) Av. HLCO Tenerife (wt%)[b]	5) Av. Ocean floor peridot. (wt%)[d]	6) Av. Middle Atlas (wt%)[e]
SiO_2	43.78	43.32	43.07	42.14	45.09	43.48
Al_2O_3	0.7	0.61	0.53	0.73	2.33	2.38
FeO	7.79	8.04	8.43	8.8	8.4	8
MgO	46.1	45.31	45.19	44.14	41.23	42.6
CaO	0.6	0.81	0.68	1.68	1.32	2.83
Na_2O	0.1	0.14	0.17	0.18	0.23	0.24
Mg#	91.34	90.96	90.53	89.94	89.7	90.47

Table values after Neumann et al. and Wittig et al.

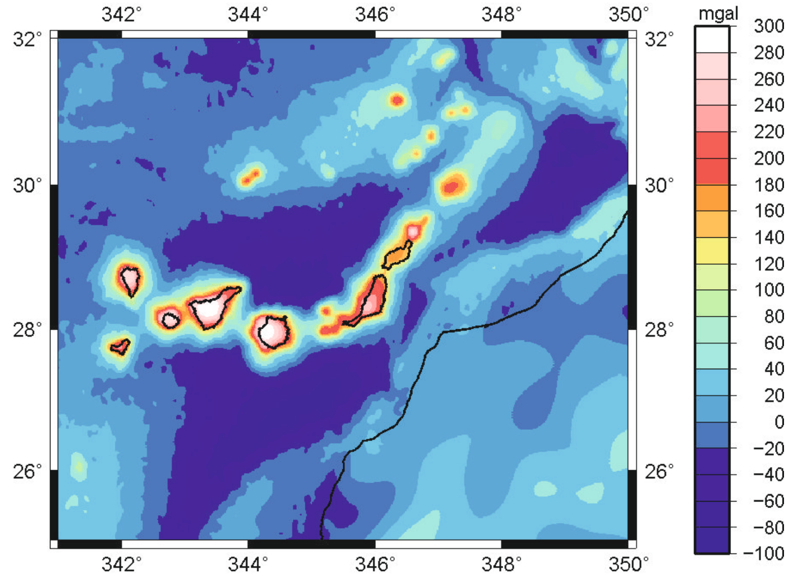
Mantle Depletion (partial melting) ← → *Mantle metasomatism (refertilization)*

Lithospheric models: geophysical data sets

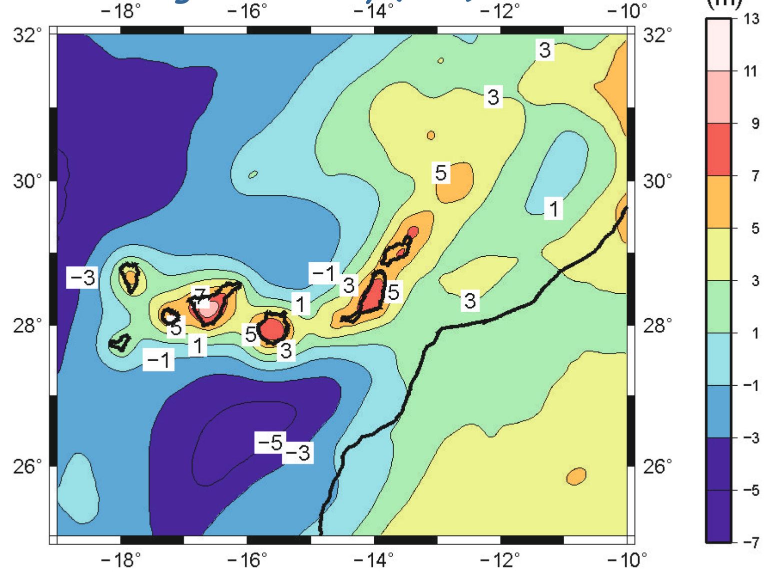
Elevation (ETOPO2)



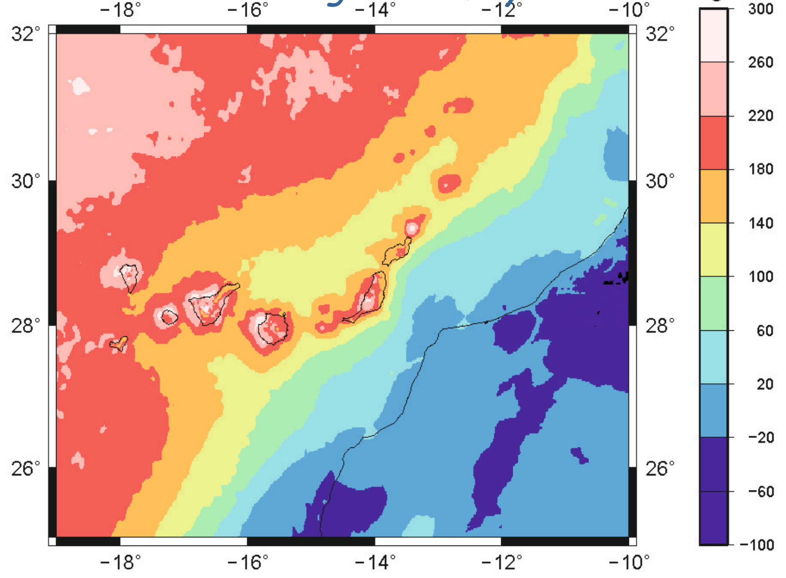
Free air anomaly (Sandwell & Smith 97)



Filtered geoid anomaly (n>10) EGM2008

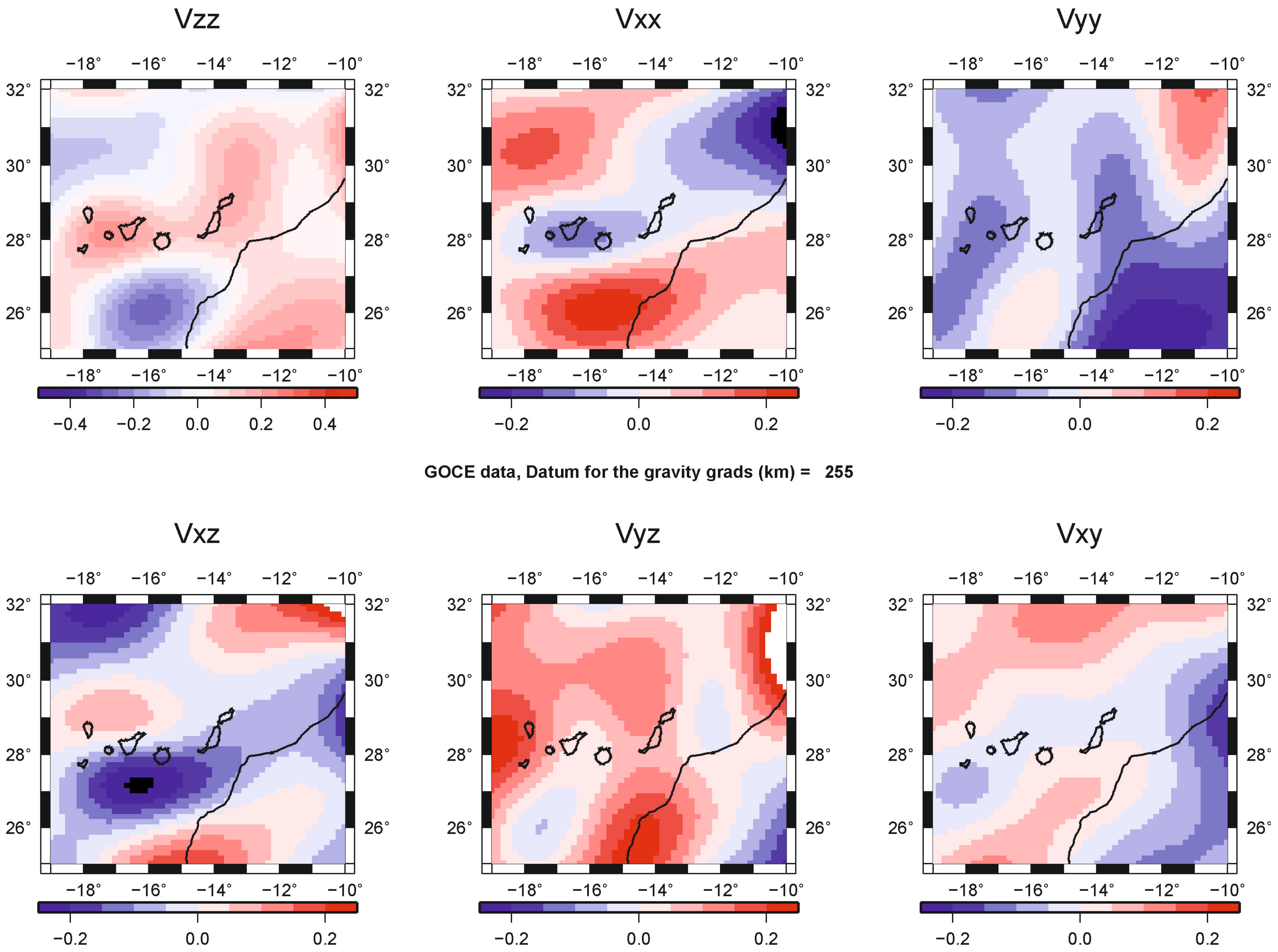


Bouguer anomaly



Lithospheric models: geophysical data sets

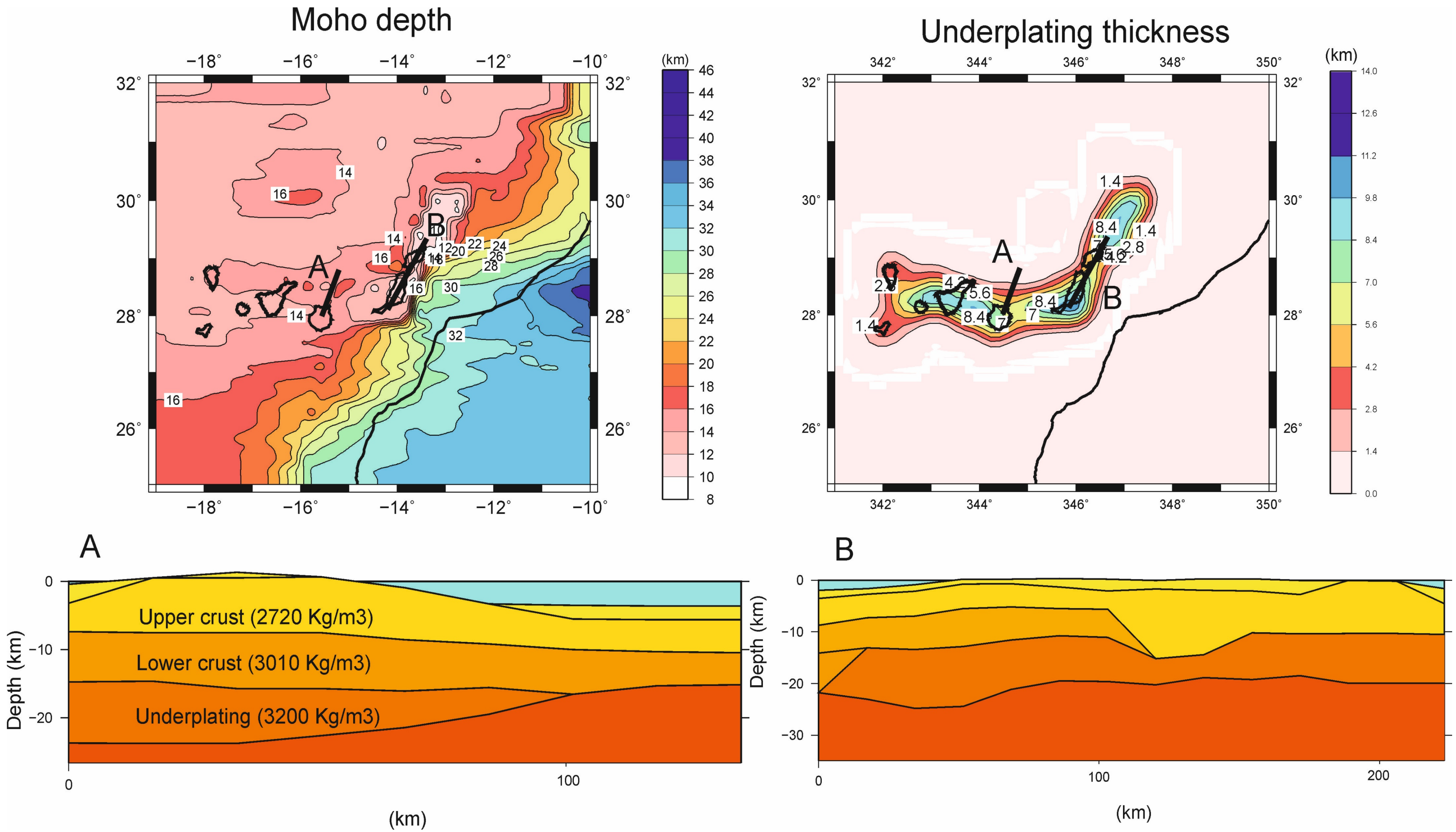
GOCE Gravity gradients @ 255 km (GOCO03S) LNORF (x→N, y→W)



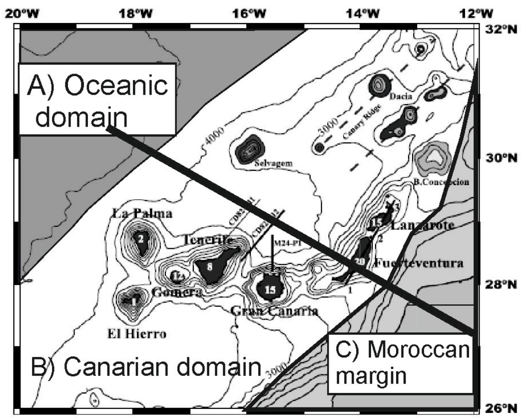
Lithospheric models: crustal structure

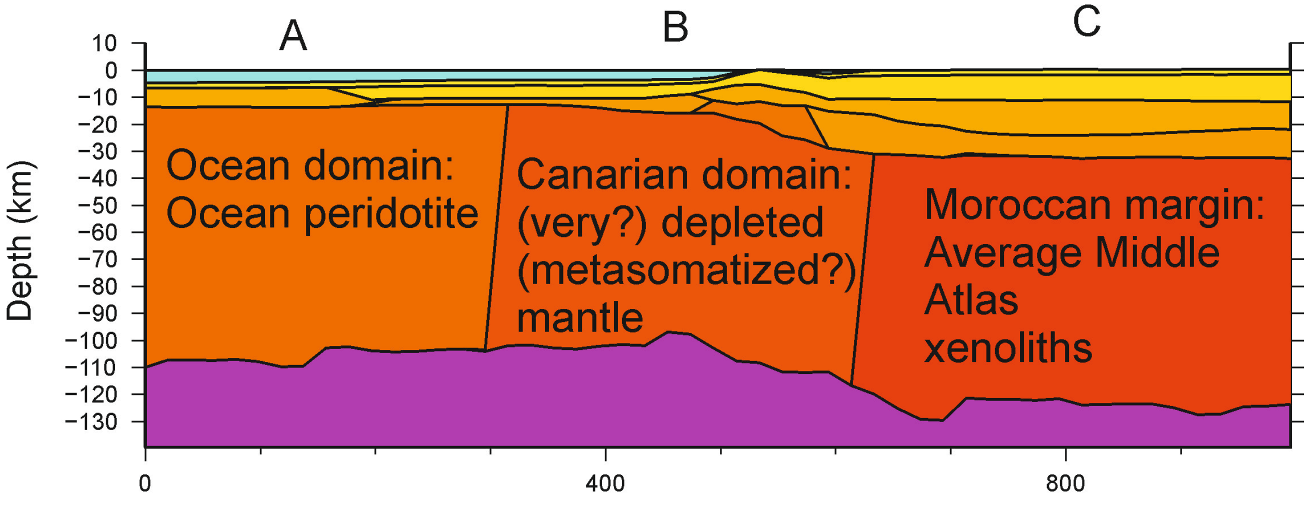
Crustal model:

- ***1D geoid + elevation inversion (background)***
- ***Seismic refraction constraints (where available)***
- ***5 layers: sediments, upper crust, middle/oceanic crust, lower crust and magmatic underplating***



Mantle compositional domains





Depleted *Depleted +metasomatised*

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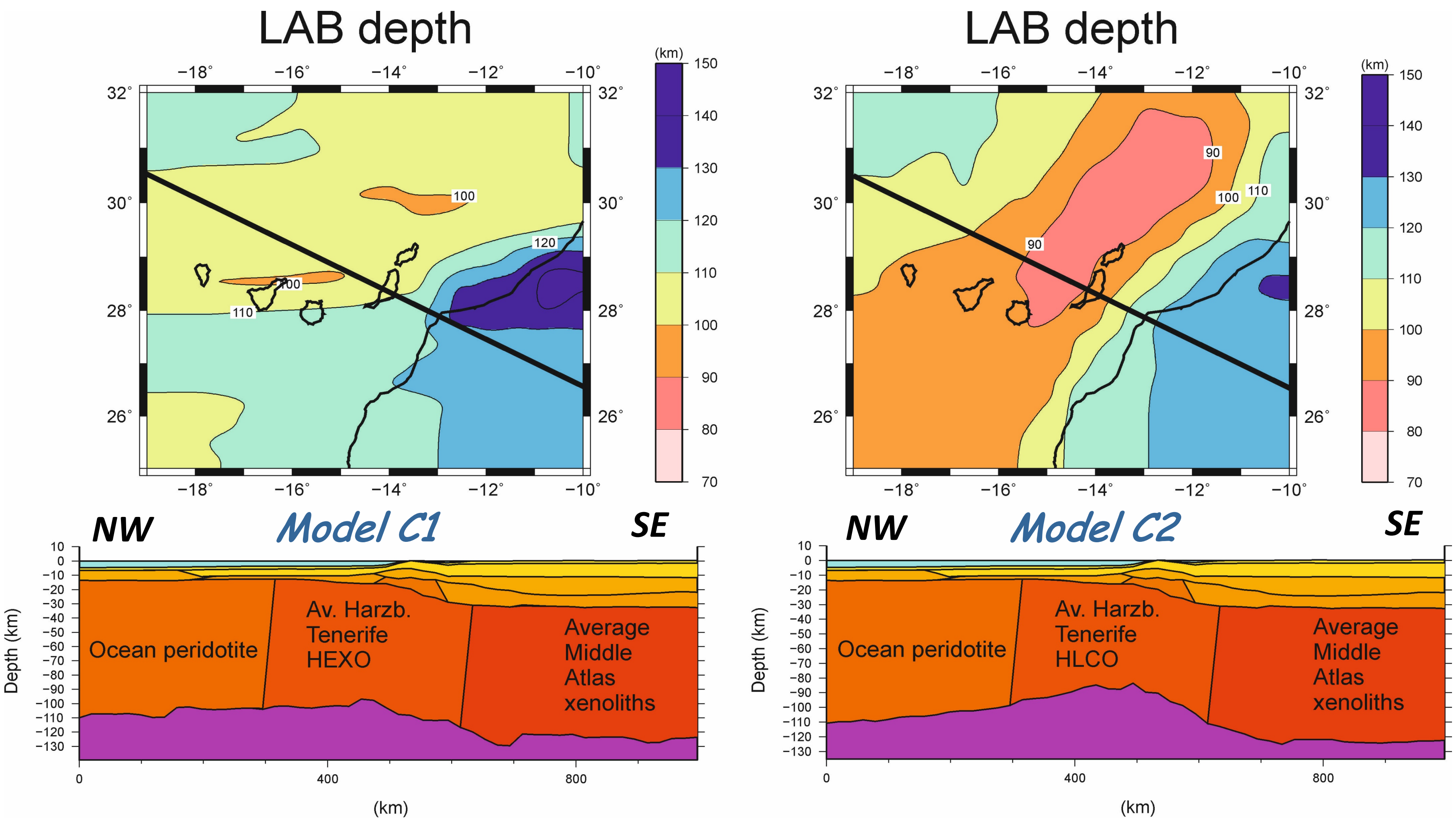
Na_2O	0.1	0.14	0.17	0.18	0.23	0.24
Mg#	91.34	90.96	90.53	89.94	89.7	90.47

← *Mantle Depletion (partial melting)*   *Mantle metasomatism (refertilization)* →

Lithospheric models

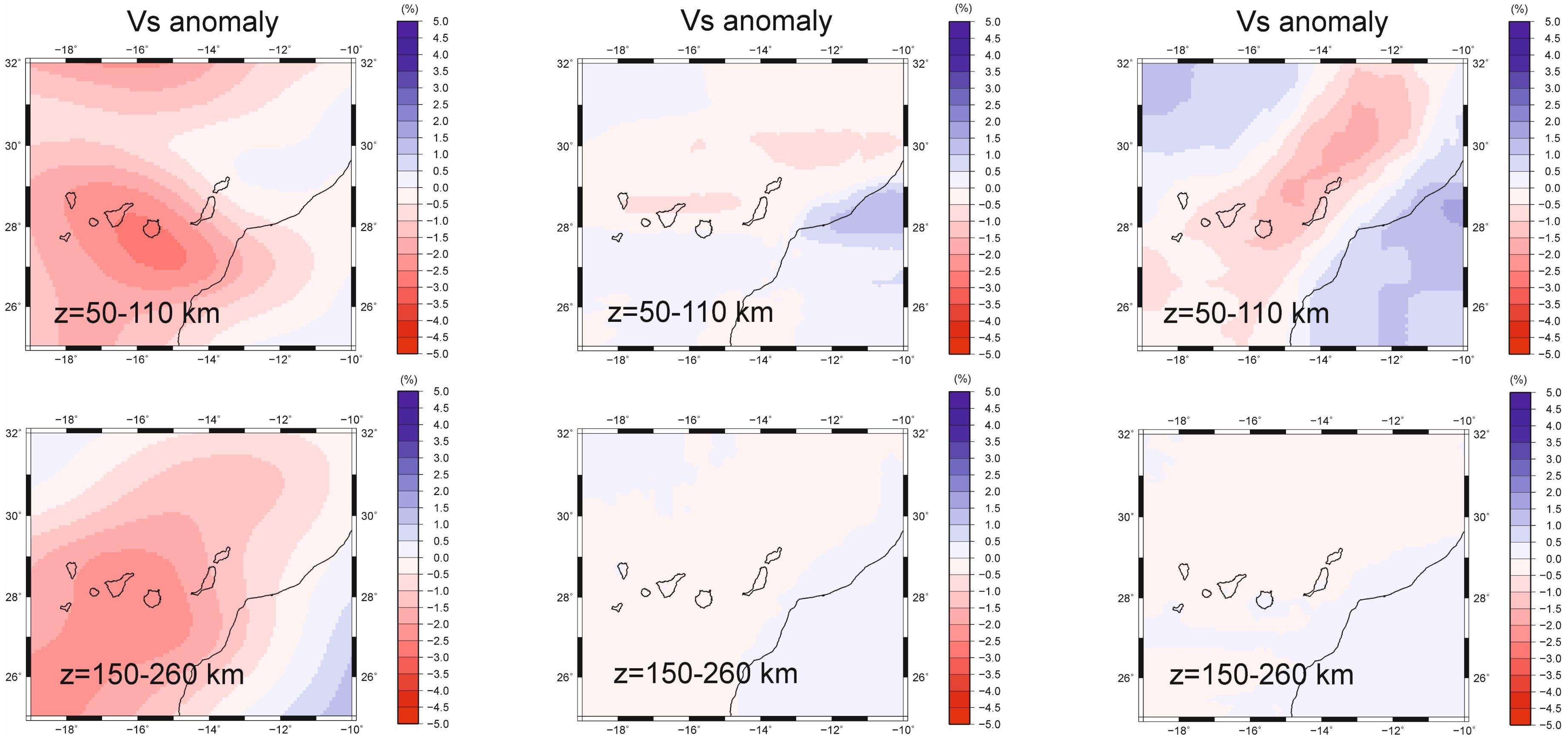
Canarian domain:

- ***Composition 2 (Tenerife HEXO)—depleted→ Model C1***
- ***Composition 4 (Tenerife HLCO)—depleted+metasomatised→ Model C2***



Moderate lithospheric thinning below the Canaries (LAB 80-100 km)
Compositional differences account for small LAB variations (15-20 km)

Lithospheric models: comparison with seismic tomography



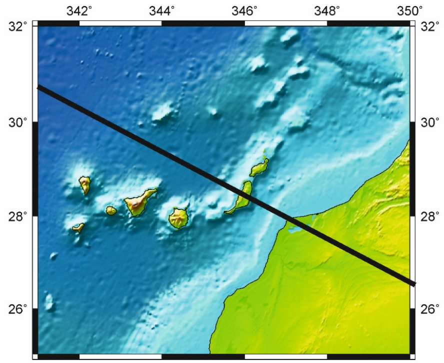
Surface-wave tomography model (Legendre et al., 2012)

Model C1

Model C2

Below the LAB (z>100 km) lithospheric models C1 and C2 are nearly homogeneous

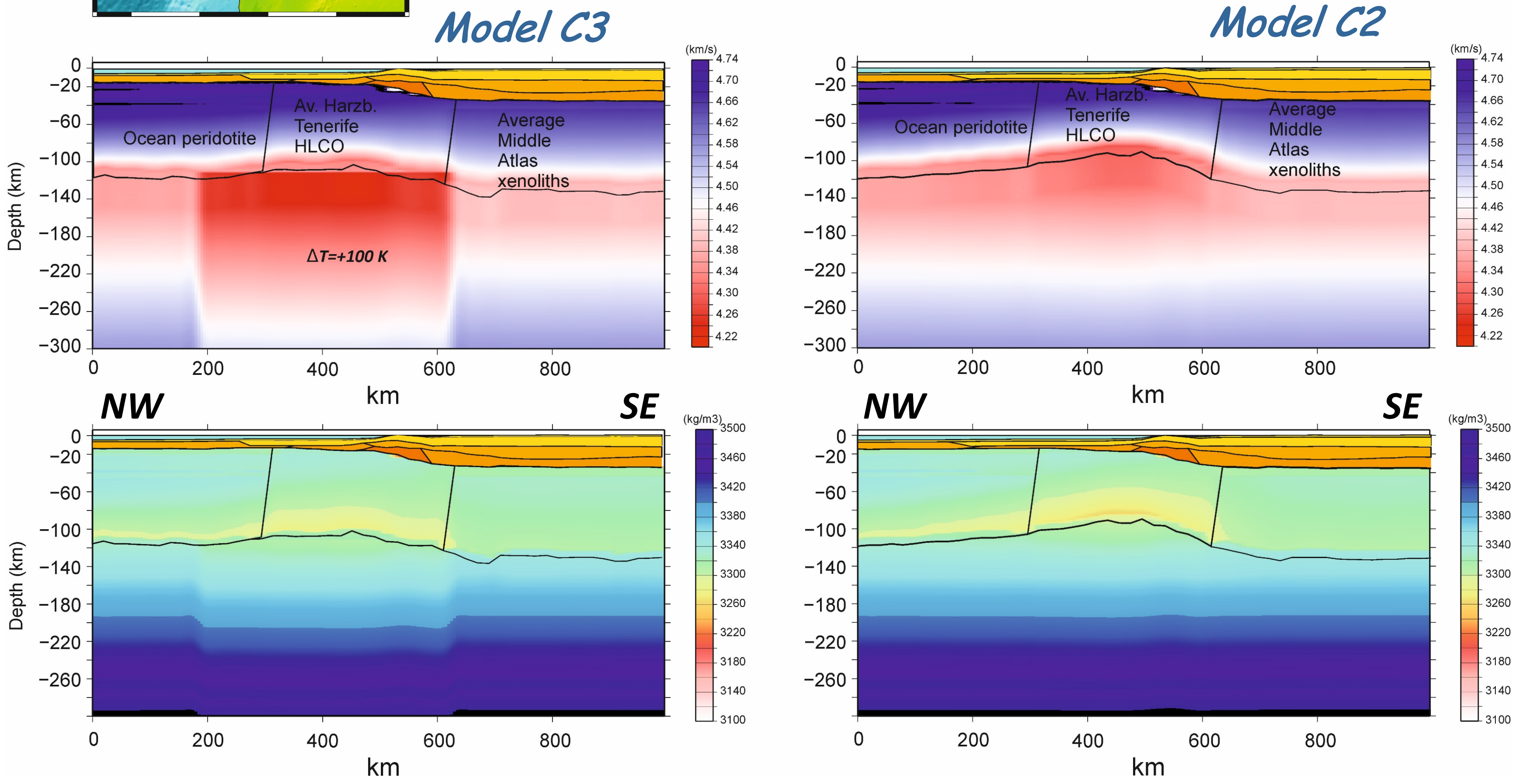
Lithospheric models



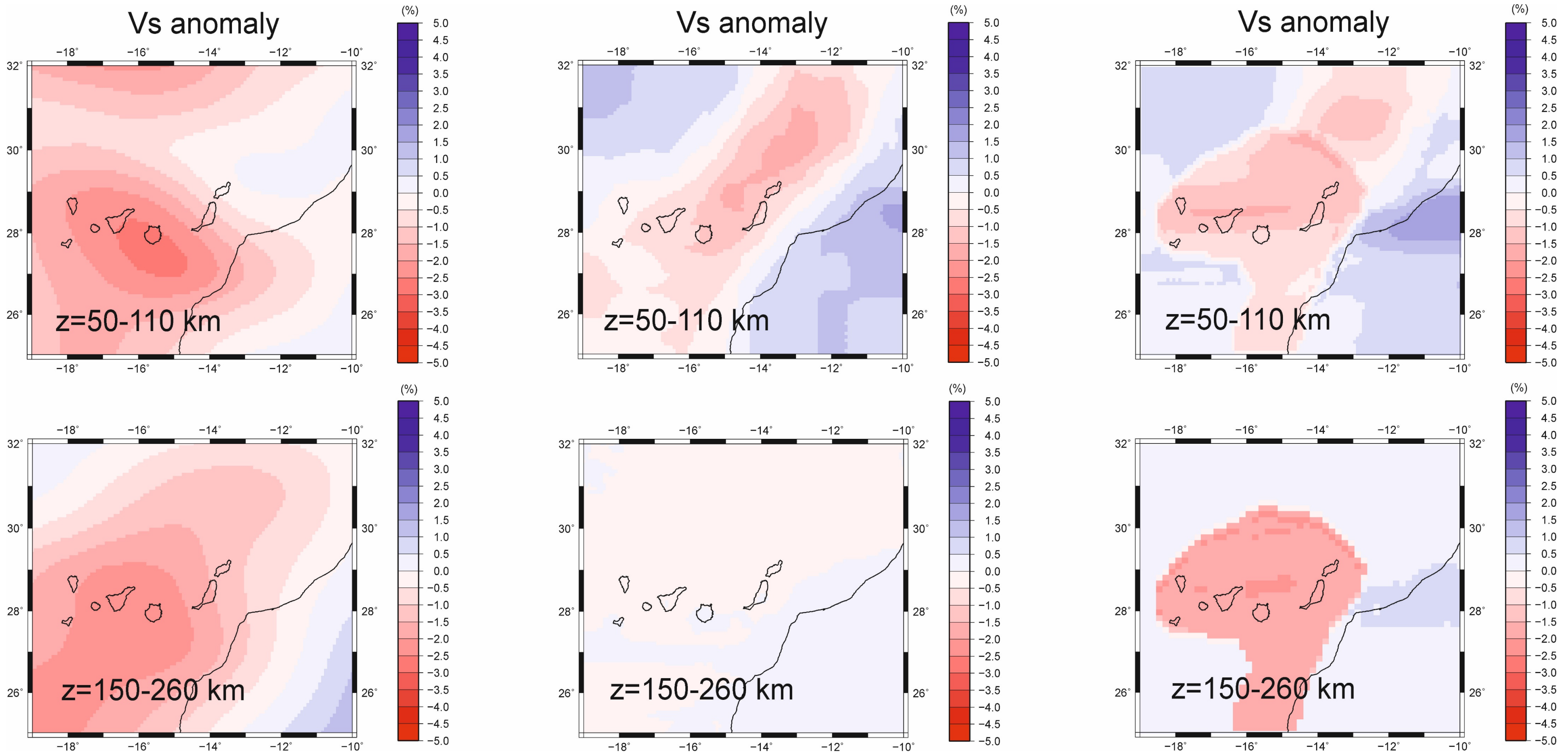
Model C3

Canarian domain: Composition 4 (Tenerife HLCO)+deep sublithospheric thermal anomaly (ΔT=+100 K)

The low density anomaly in the convective mantle is decupled in the isostatic elevation determination → C3 shows low misfits for elevation and potential field data



Lithospheric models: comparison with seismic tomography



Surface-wave tomography model (Legendre et al., 2012)

Model C2

Model C3

Below the LAB (z>150 km) lithospheric model C3 matches tomography models better than C2 (or C1)

Summary: imaging the Canarian lithosphere

*Moderate lithospheric thinning below the Canaries (LAB 80-100 km)

*Compositional differences in the Canarian domain (depleted to moderately depleted, metasomatised) account for small LAB variations (15-20 km)

*A sub-lithospheric thermal anomaly (+100 K) allows to fit elevation and the other observables simultaneously and reproduces seismic tomography models (z>150 km)

*The convection process producing the thermal anomaly (mantle plume?) is relatively weak or happened long time ago: the erosion at the base of the lithosphere is moderated.

Geophysical Journal International

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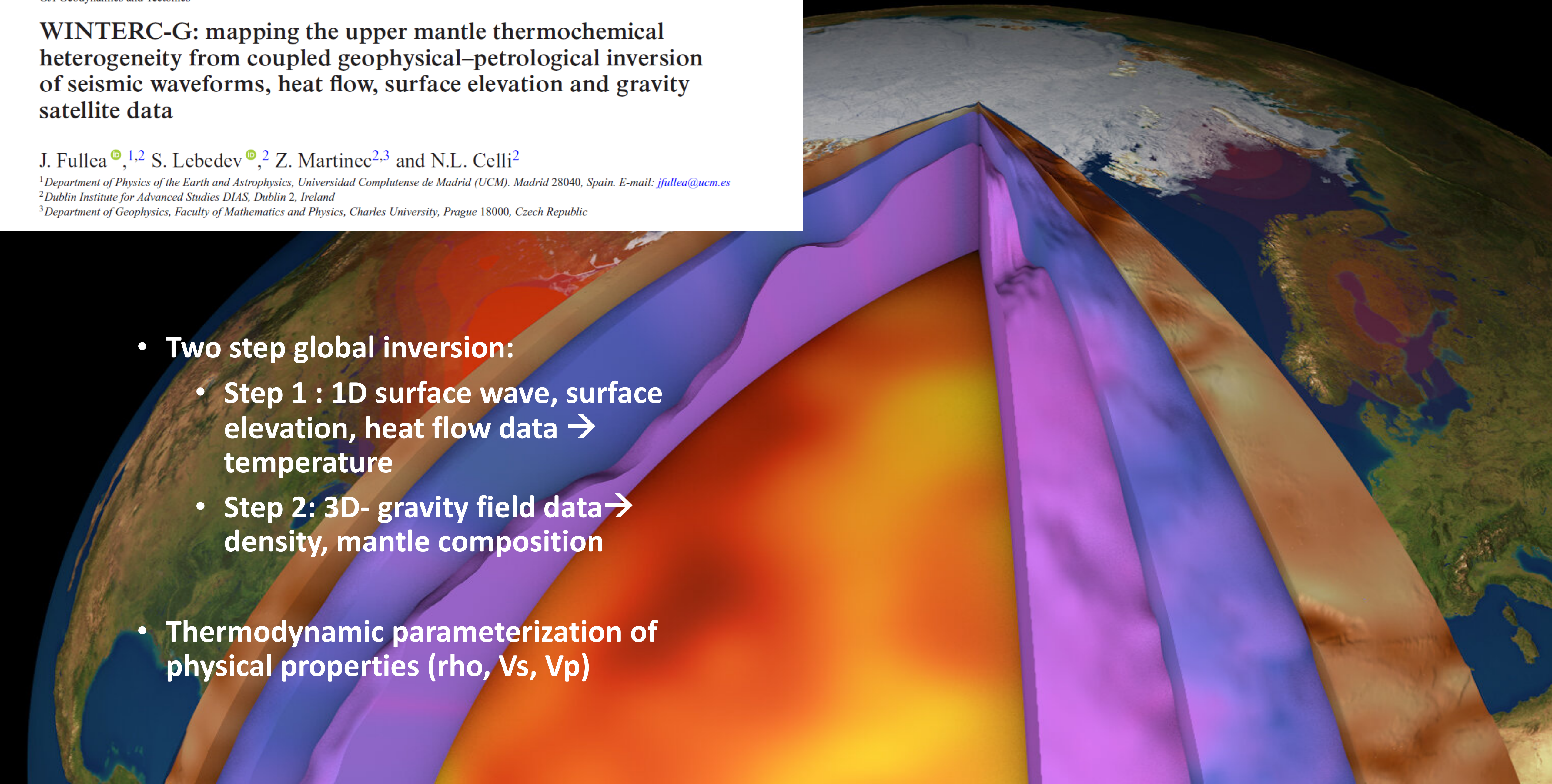
Advance Access publication 2021 March 10
GJI Geodynamics and Tectonics

WINTERC-G: mapping the upper mantle thermochemical heterogeneity from coupled geophysical–petrological inversion of seismic waveforms, heat flow, surface elevation and gravity satellite data

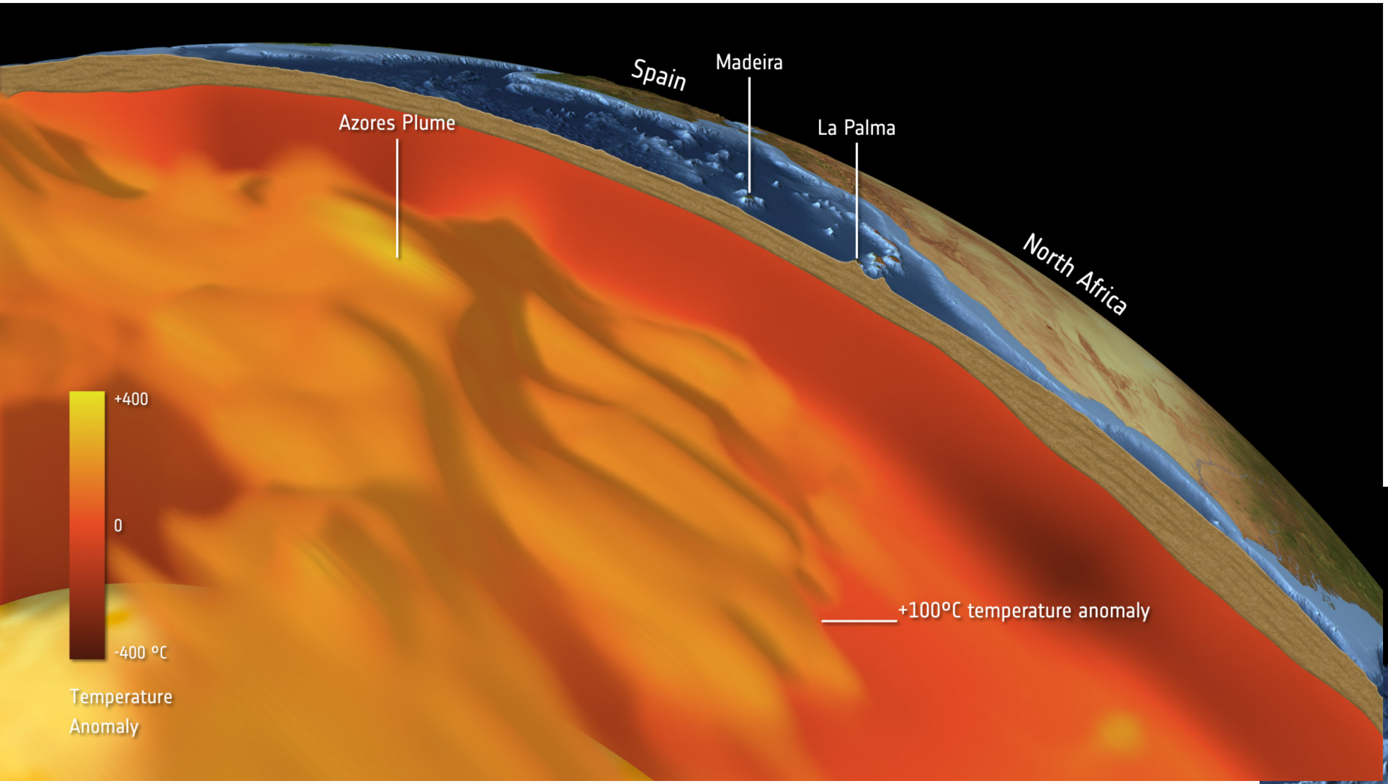
J. Fullea[1,2] S. Lebedev[2] Z. Martinec[2,3] and N.L. Celli[2]

[1] *Department of Physics of the Earth and Astrophysics, Universidad Complutense de Madrid (UCM). Madrid 28040, Spain. E-mail: jfullea@ucm.es*
[2] *Dublin Institute for Advanced Studies DIAS, Dublin 2, Ireland*
[3] *Department of Geophysics, Faculty of Mathematics and Physics, Charles University, Prague 18000, Czech Republic*

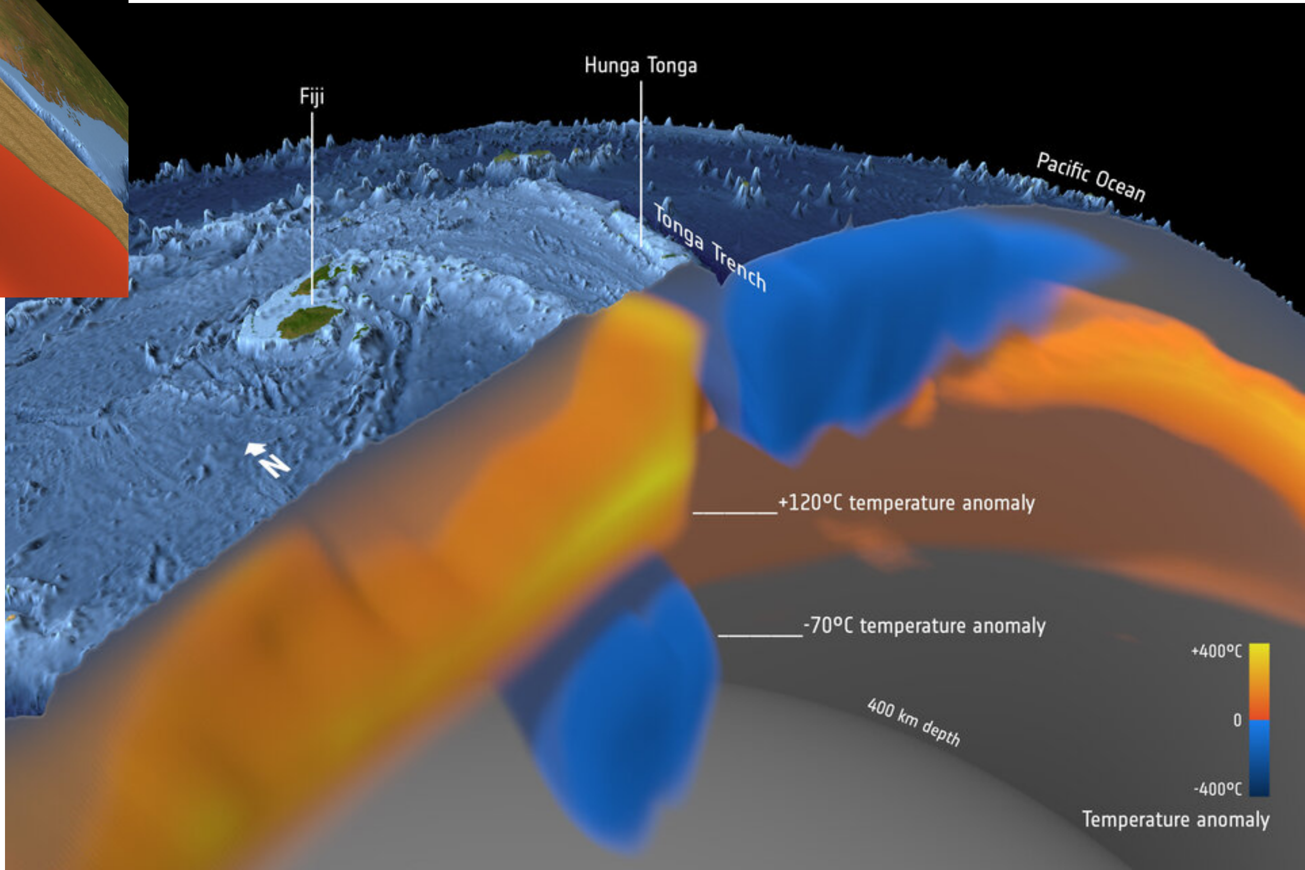


- **Two step global inversion:**
  - **Step 1 : 1D surface wave, surface elevation, heat flow data → temperature**
  - **Step 2: 3D- gravity field data→ density, mantle composition**
- **Thermodynamic parameterization of physical properties (rho, Vs, Vp)**

Direct temperature mapping of the crust and mantle



Hot mantle Plumes…



… and cold lithospheric slabs.

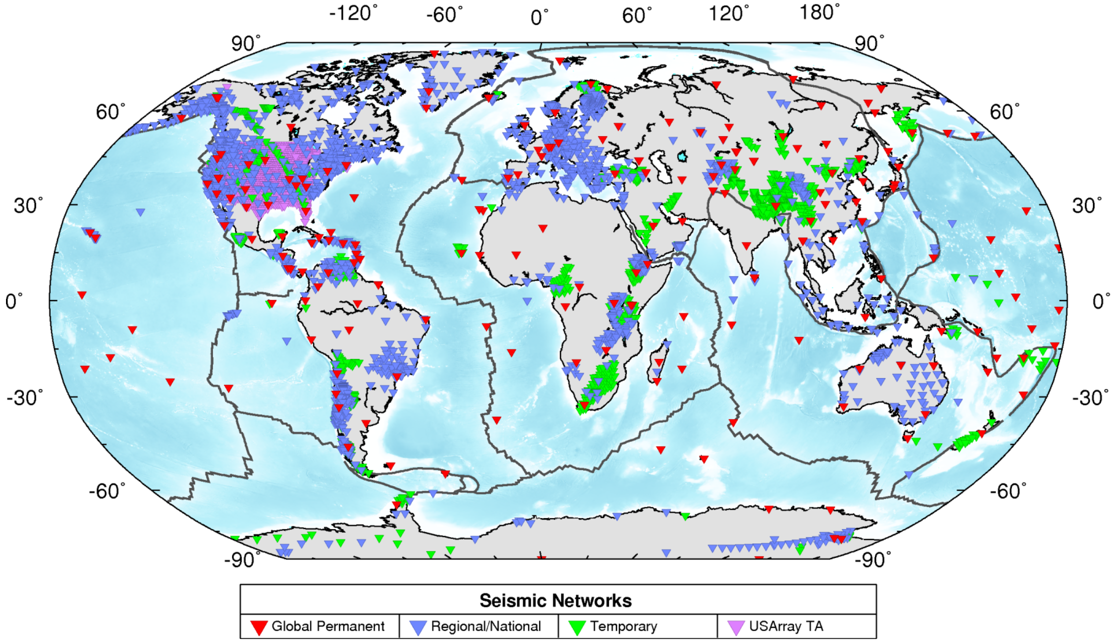
https://www.esa.int/Applications/Observing_the_Earth/FutureEO/GOCE/Deep_down_temperature_shifts_give_rise_to_eruptions?fbclid=IwAR3lr7YdwmDztLYqyPxhi-Brw5BgSUMfPsF7Kxwr2MbrMe6uEay2WpLUShs

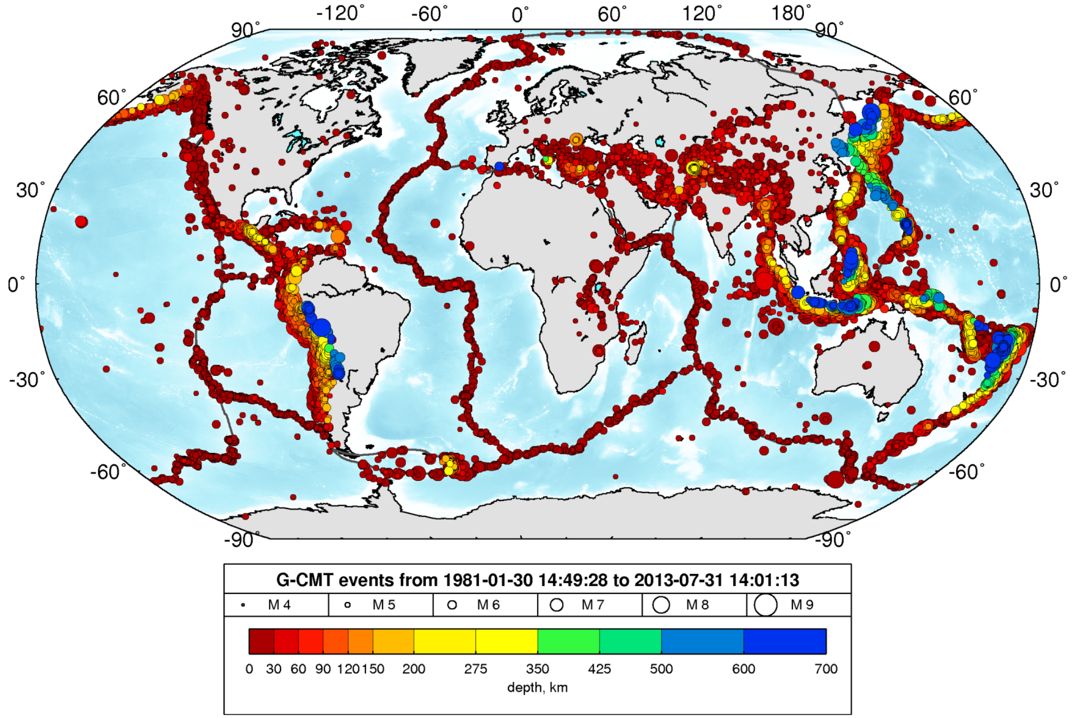
DATA: Global waveform tomography

- **Master dataset:**
  All broadband data available
  from IRIS, ORFEUS, GFZ, CNSN

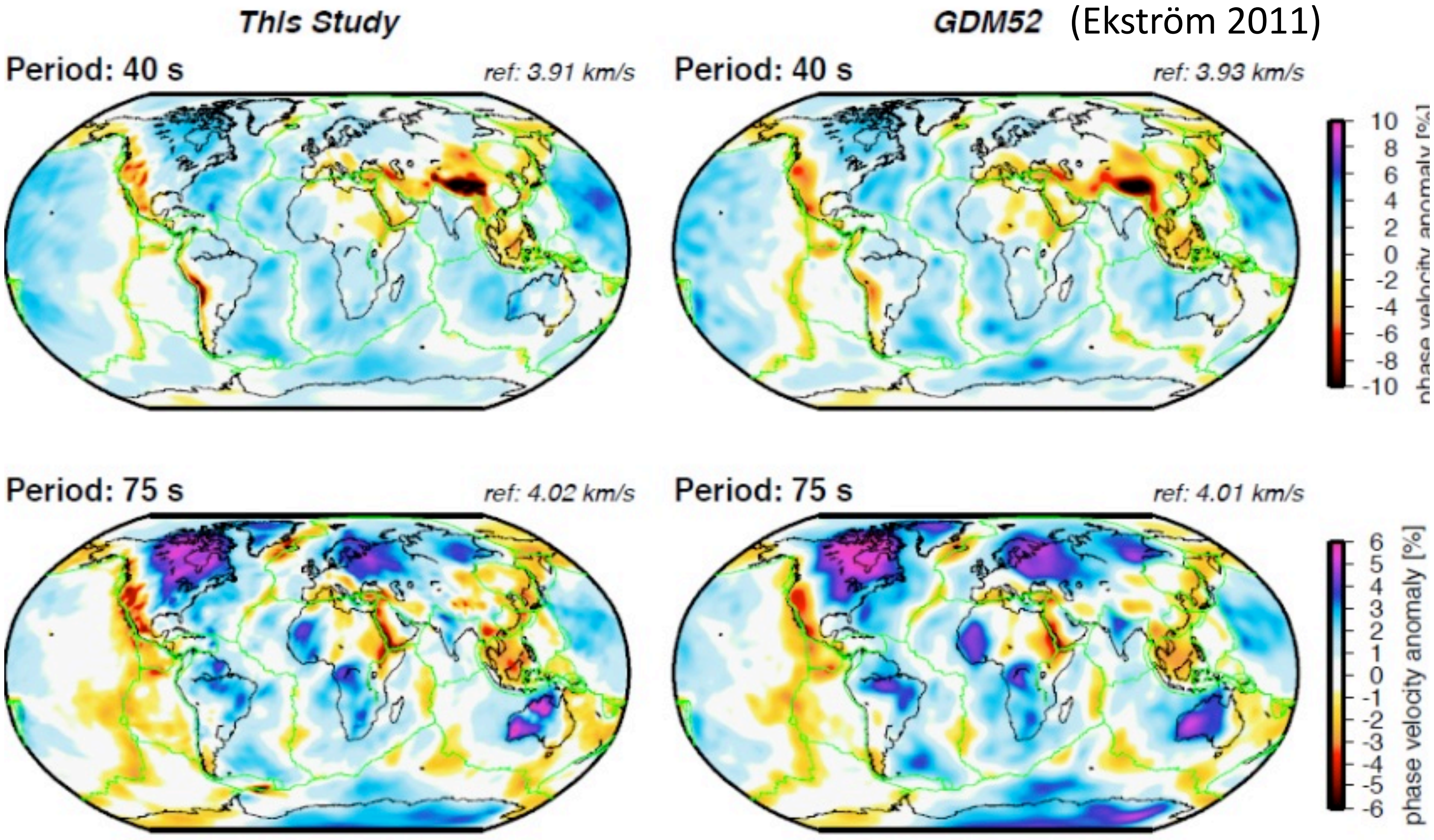
- **Inversion of surface-wave and S-wave waveforms**
  Waveform fits of
  >1,250,000 seismograms
  from **>5,000** stations

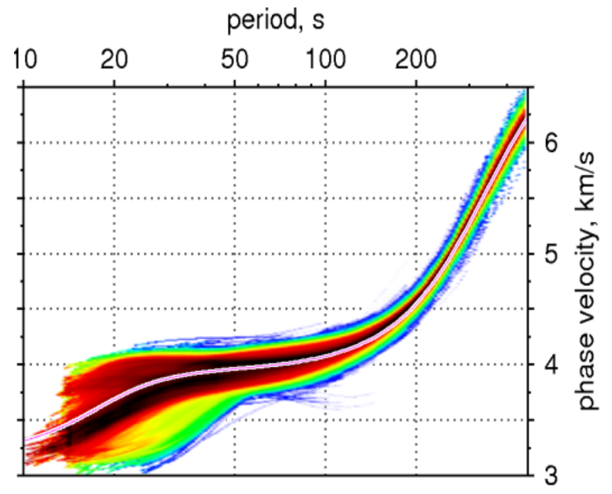
- **Outlier removal**
  Select most mutually consistent data
  Reduce effects of errors in the data





DATA: Global waveform tomography→phase velocity maps→dispersion curves (Rayleigh, Love fundamental mode)



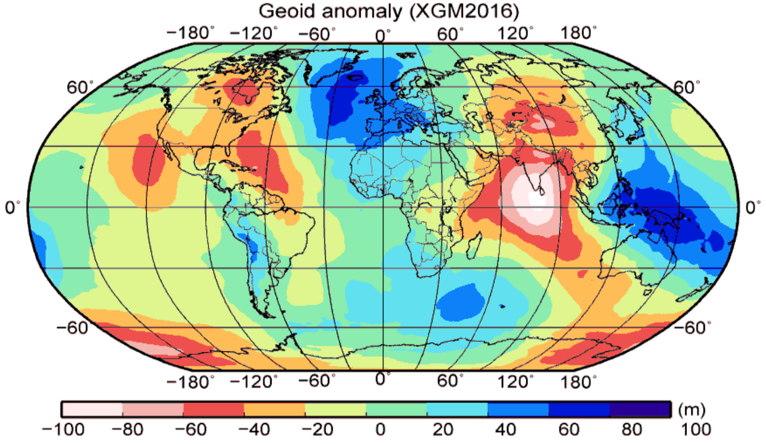


Phase velocity dispersion curves for each point (geographical coordinates grid).

✓ 12,500 1D Columns (about 225 km inter knot spacing)

DATA: gravity field data (GOCE, XGM2016)

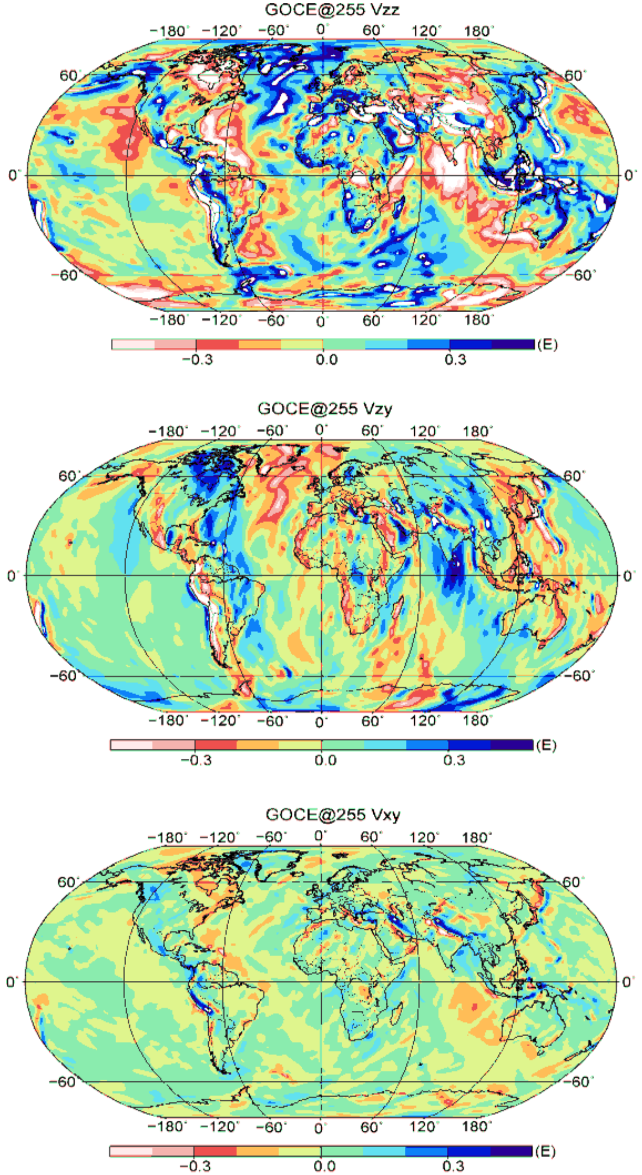
Geoid anomaly



(Pail et al., 2018)

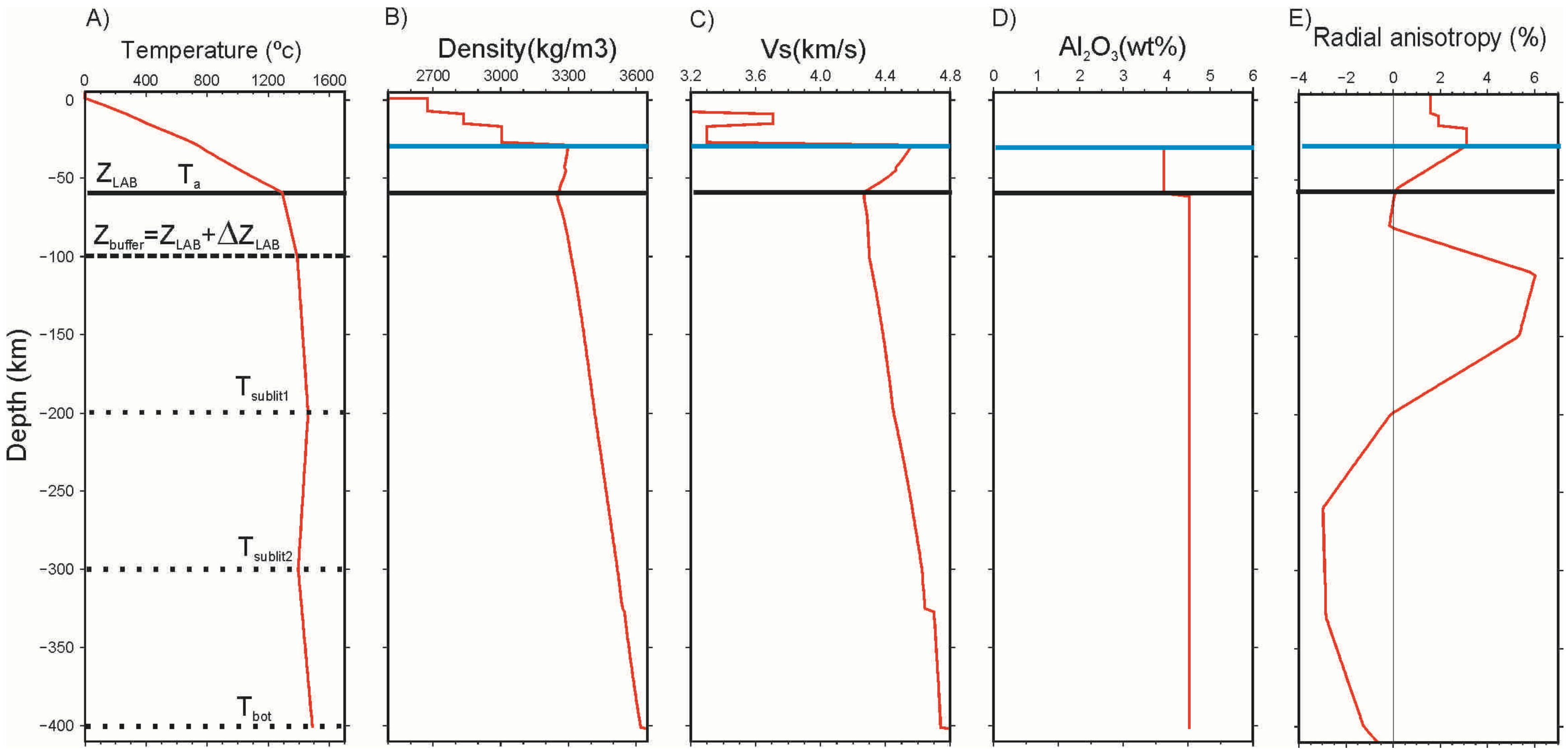
- ✓ Geoid anomaly constrains upper mantle density
- ✓ Gravity grads@255 km constrain crustal density

Gravity gradients @ 255 km



(Bouman et al., 2016.)

Inversion setting step 1 (tomography+SHF+elevation)

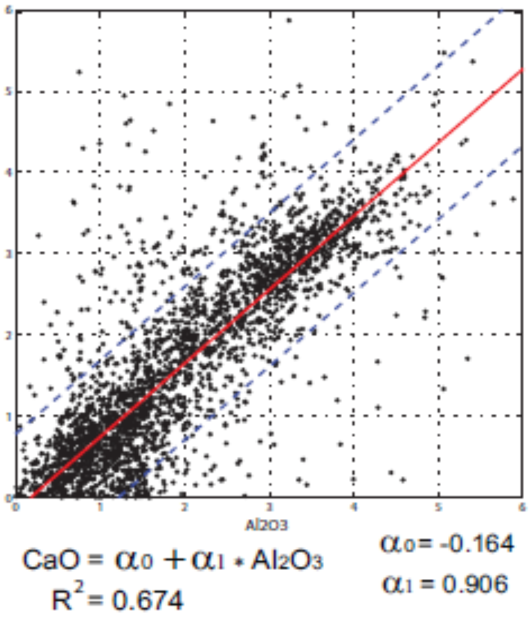


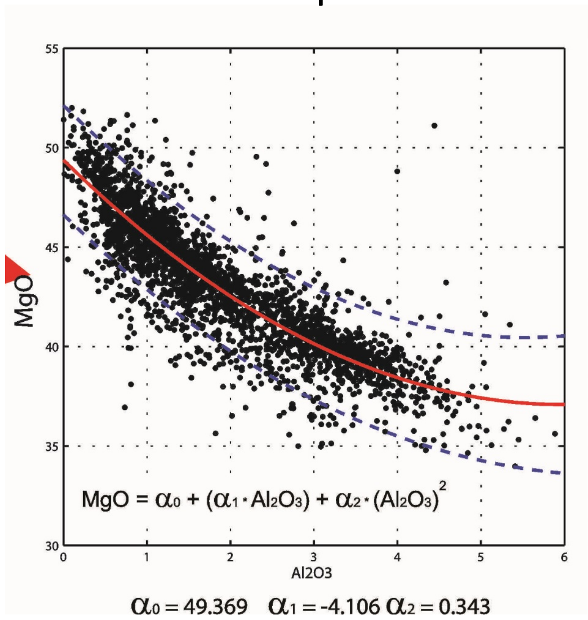
- ✓ 1D Inversion of surface wave tomography data, elevation and heat flow (12,500 columns)
- ✓ Crustal structure: density, seismic velocities, heat production and thickness
- ✓ Mantle structure: Thermal lithosphere (LAB) and sublithospheric temperature; mantle composition, melt, anisotropy

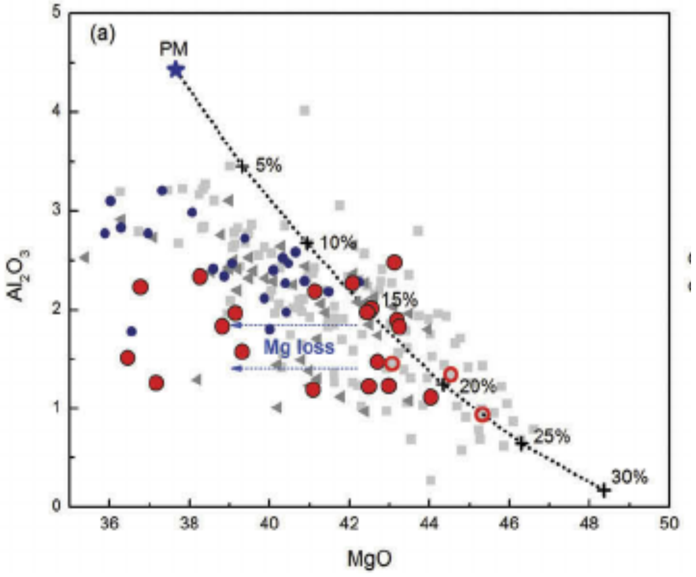
Inversion setting step 1

Major oxides correlations from xenoliths & per. massifs

Melting trend



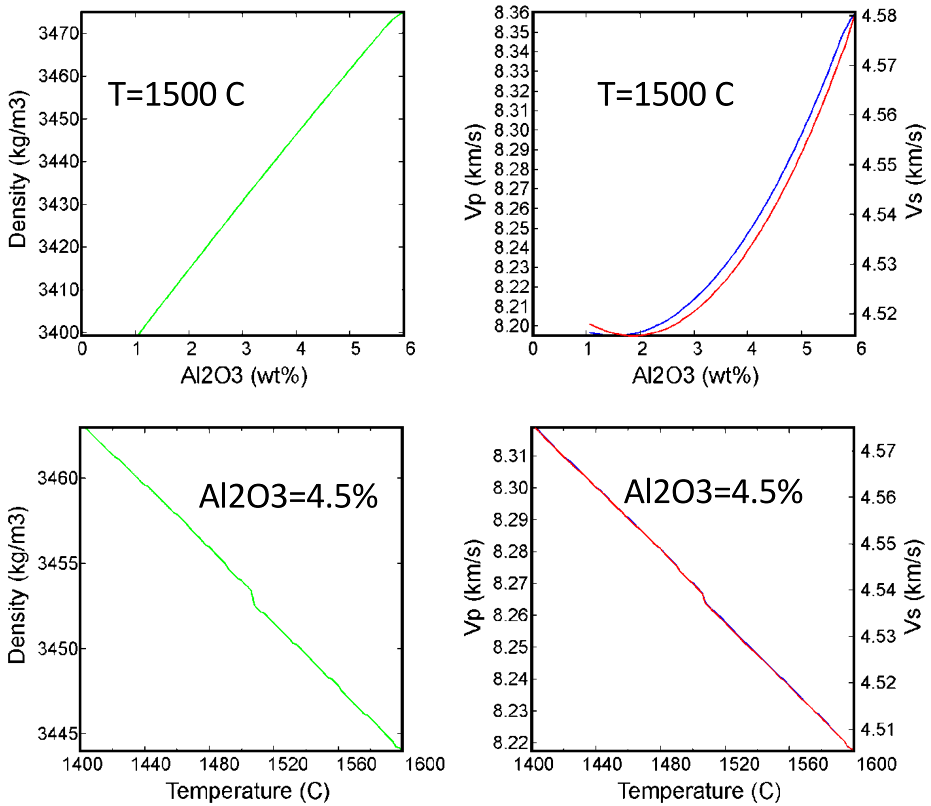




- ✓ Mantle composition described by **Al2O3** and FeO independent variables (CaO and MgO=F(Al2O3))
- ✓ Chemical parameterization following melting trend, analogous to pyrolite (Harz+basalt)

Sensitivity analysis

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%)

Temperature derivative
For drho=15 kg/m3→ dT=200 C(dVs=1.8%)

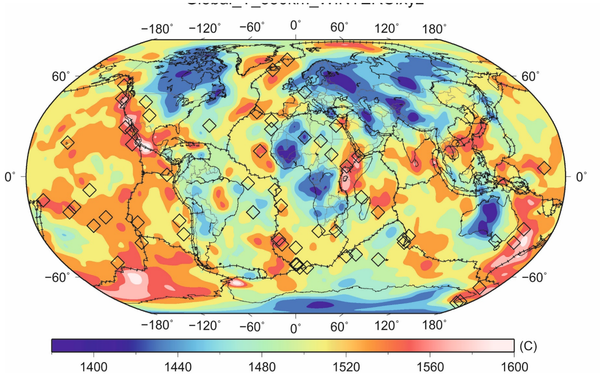
- For the same density variation, the associated thermally induced variation in Vs is about 2-12 times larger than the compositional induced Vs variation

Inversion setting, step 2 (gravity field)

- ✓ 3D Gravity data inversion regularized by temperature & composition from step1: surface wave, elevation and SHF data inversion

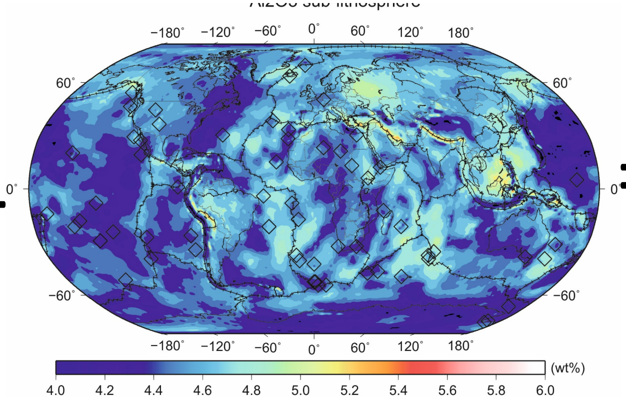
- ✓ Variables for the gravity inversion are the composition (Al2O3) of lithosphere and sublithosphere and crustal density

Temperature @330 km



+

Composition @330 km



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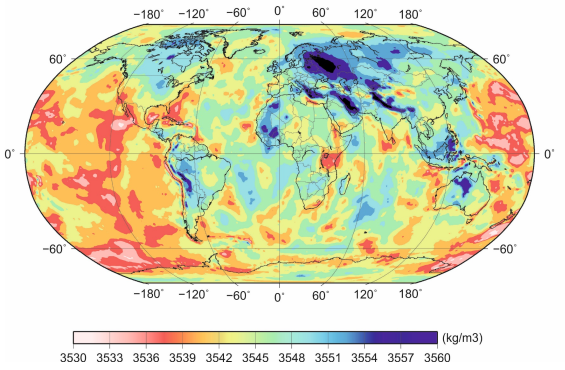
Density @330 km



Geoid in a dynamic Earth, viscosity and convection

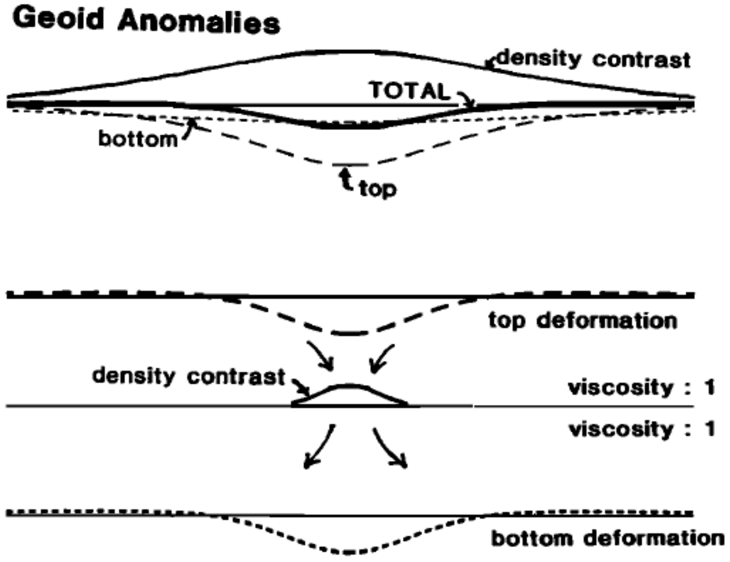


Fig. 1. Illustration of the components of the geoid anomaly from a cosine bell density contrast at the midpoint of a layer of uniform viscosity η. The total anomaly (heavy solid line) is the sum of the contributions from the density contrast itself (light solid line), from dynamic deformation of the upper boundary (long dashes), and from dynamic deformation of the lower boundary (short dashes). The total geoid anomaly is negative for a positive density anomaly.

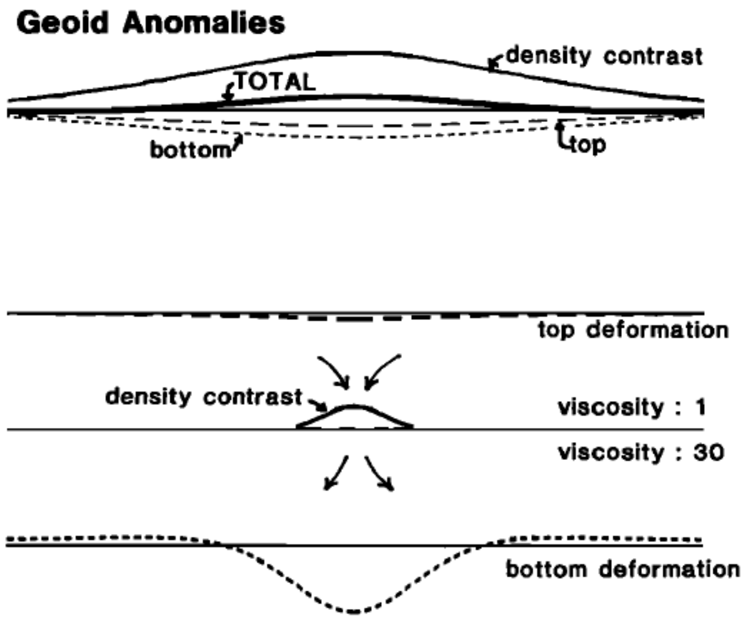
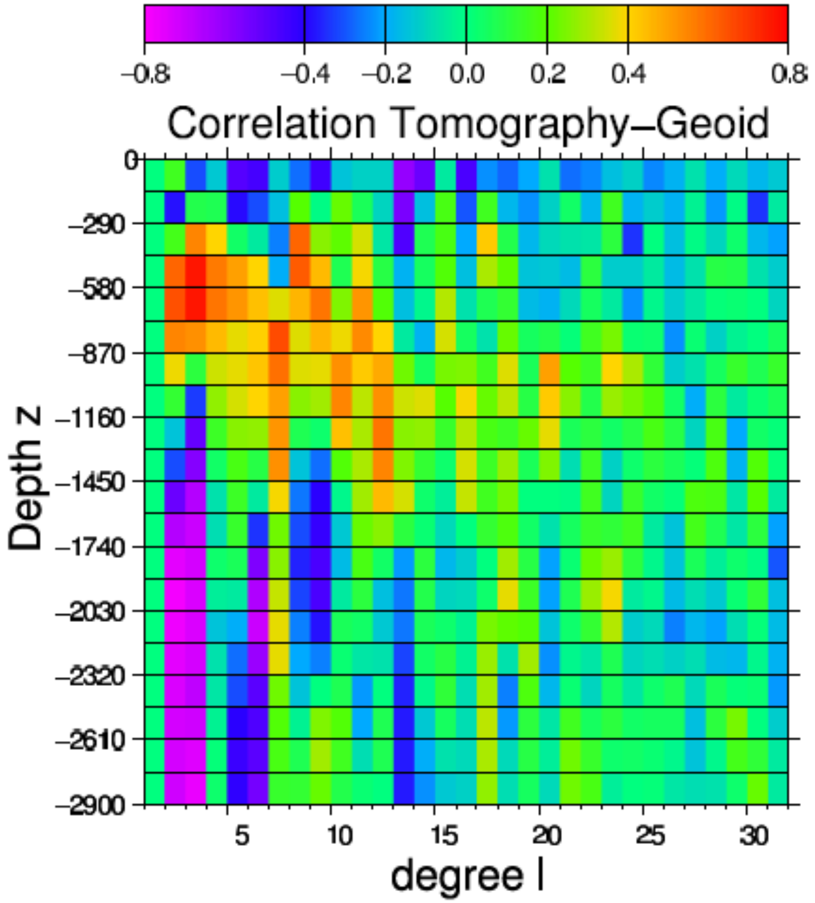
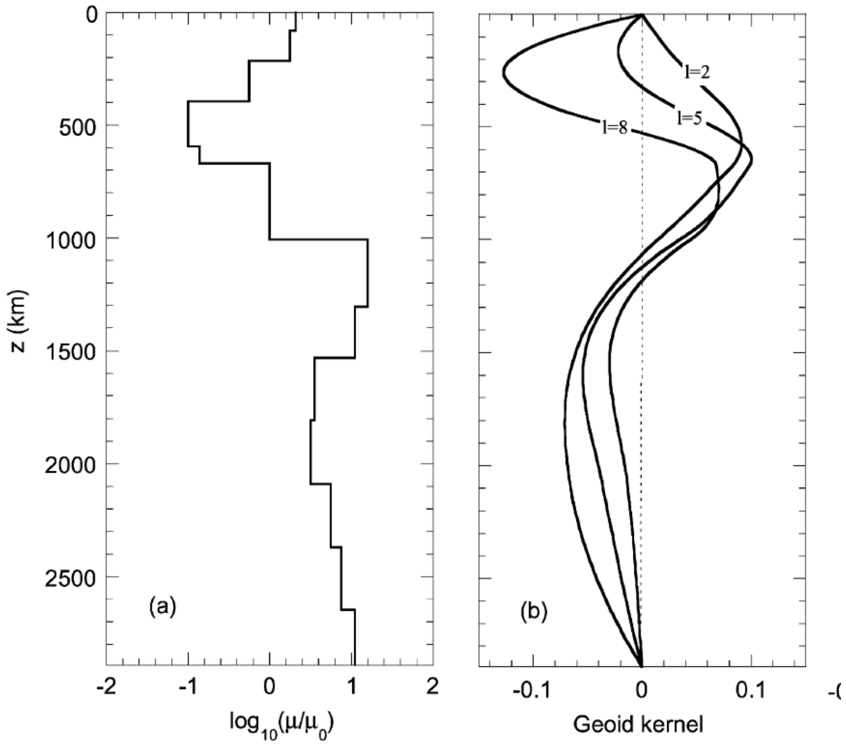


Fig. 2. As in Figure 1, but now the bottom half of the layer has a viscosity η a factor of 30 larger than the upper half. The sign of the total geoid anomaly is now positive.

Bibliography: Hager (1984)

Geoid in a dynamic Earth, viscosity and convection

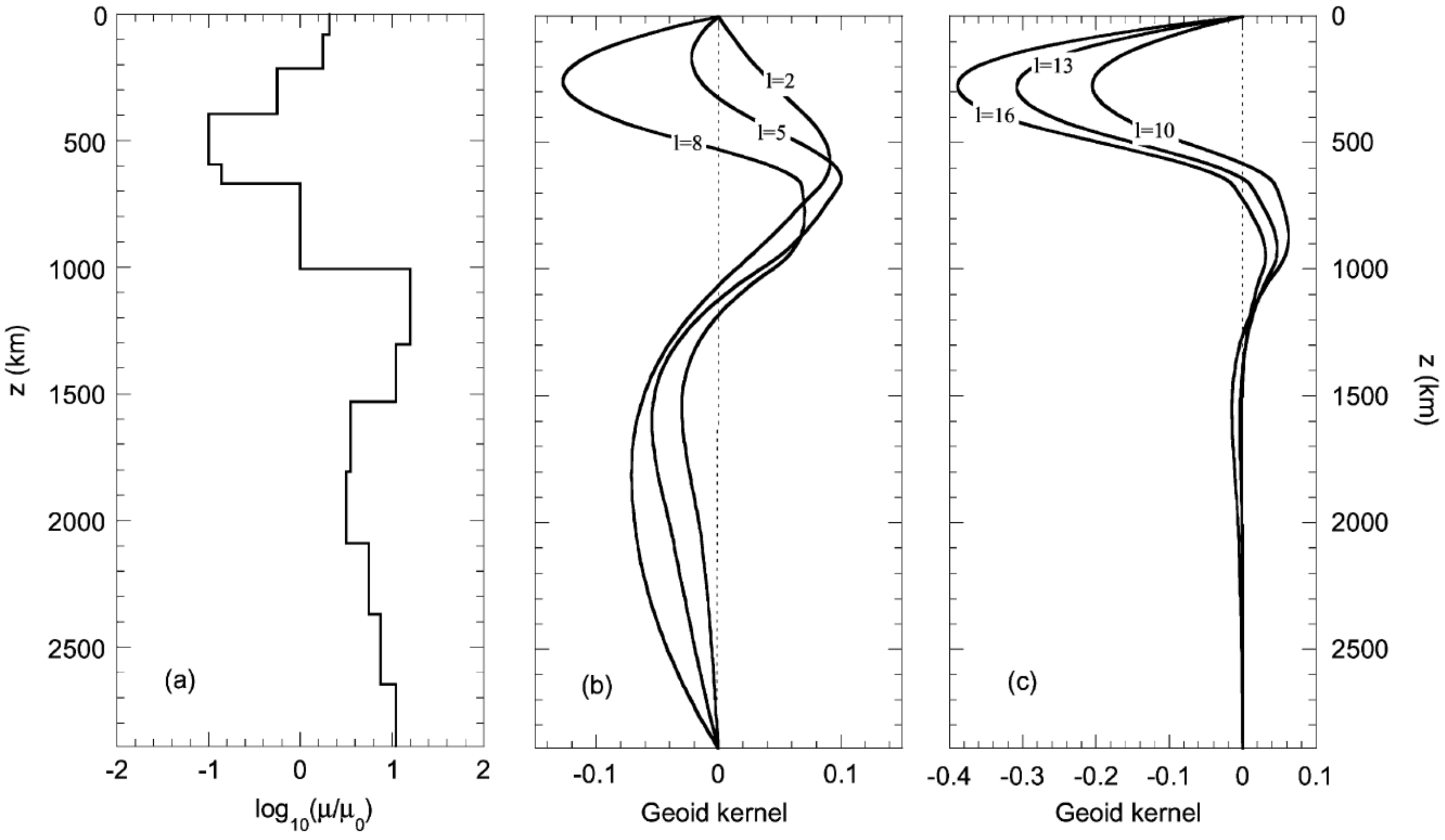




Bibliography: Ricard et al. CRAS (2006), Deschamps et al. (2001)

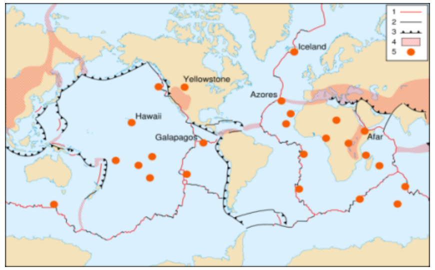
Geoid in a dynamic Earth, viscosity and convection

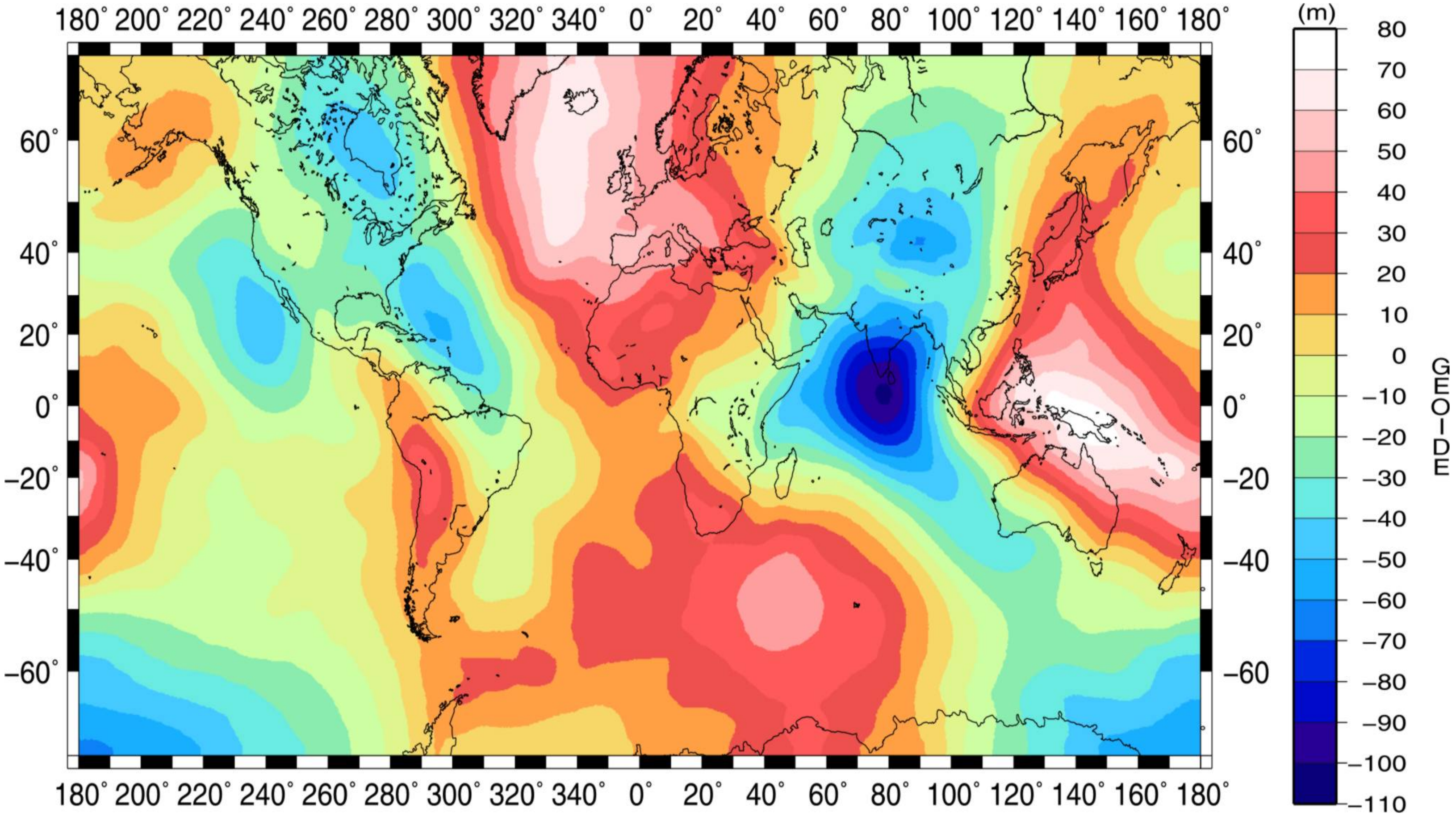
Geoid sensitivity kernels



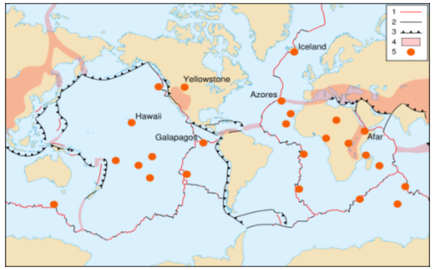
Bibliography: Deschamps et al. (2001)

Total geoid anomaly



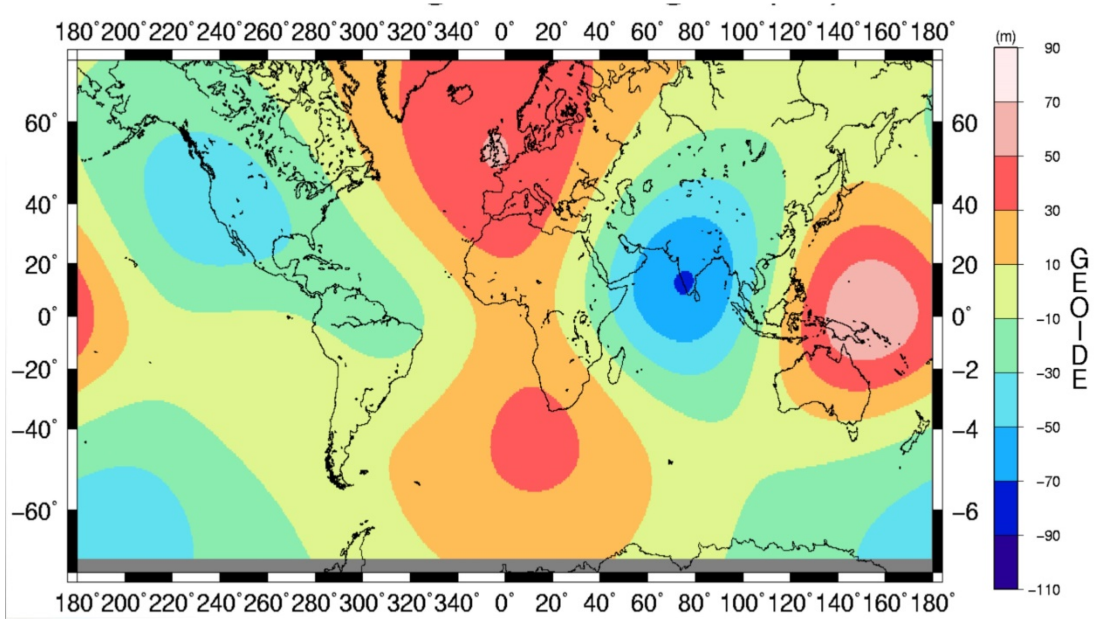


Geoid anomaly n=2-3

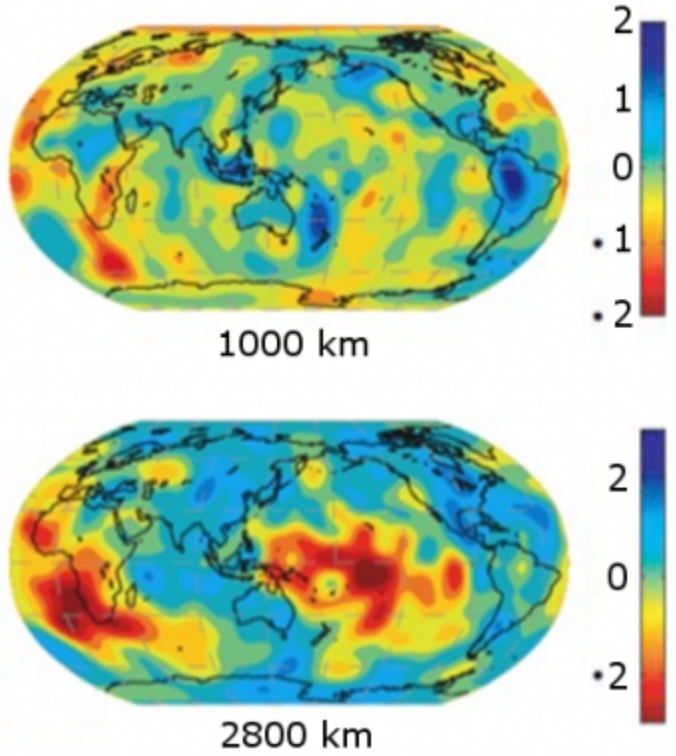


Harmonic degrees 2-3 are not correlated with plate tectonics: Core-mantle boundary and lower mantle signal

Degrees 2-3 represent 60 % of the total geoid signal.



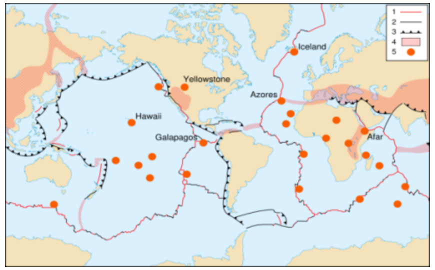
Global tomography



Bibliography: Bowin (2000)

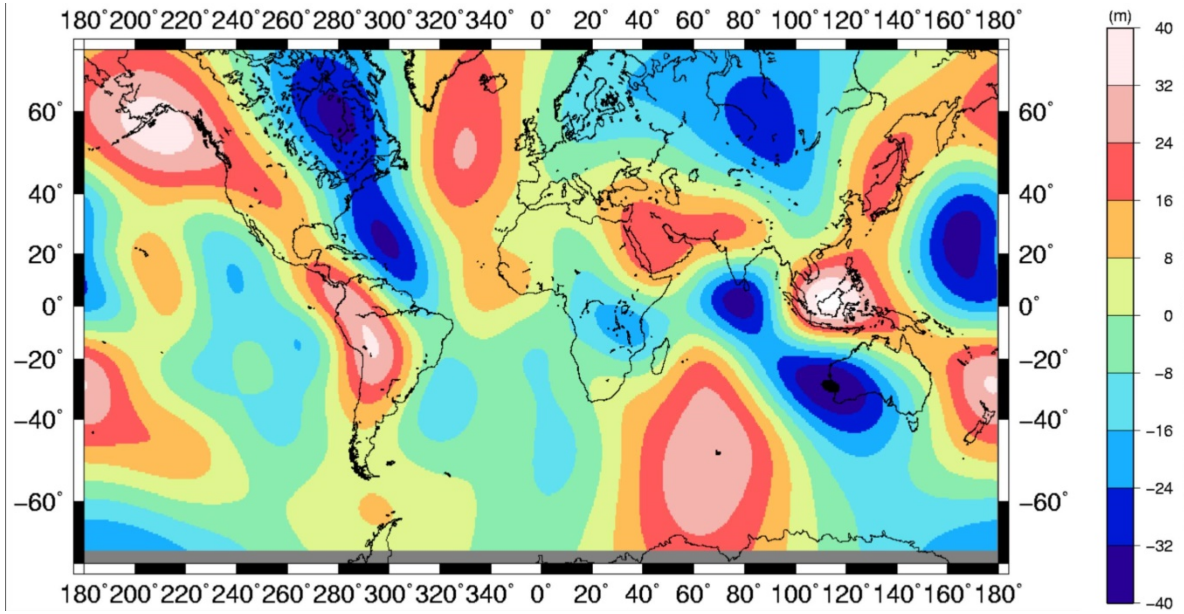
Kustowski *et al.* (2008)

Geoid anomaly n=4-10

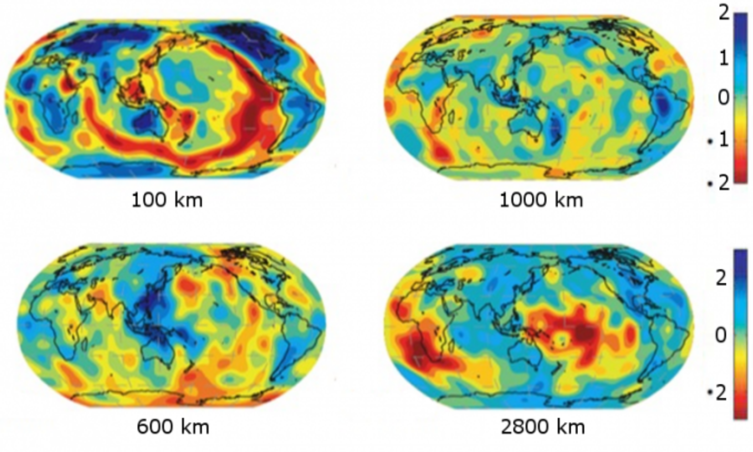


Harmonic degrees 4-10 correlate with subduction zones and mantle plumes

Degrees 4-10 represent 30% of total geoid signal



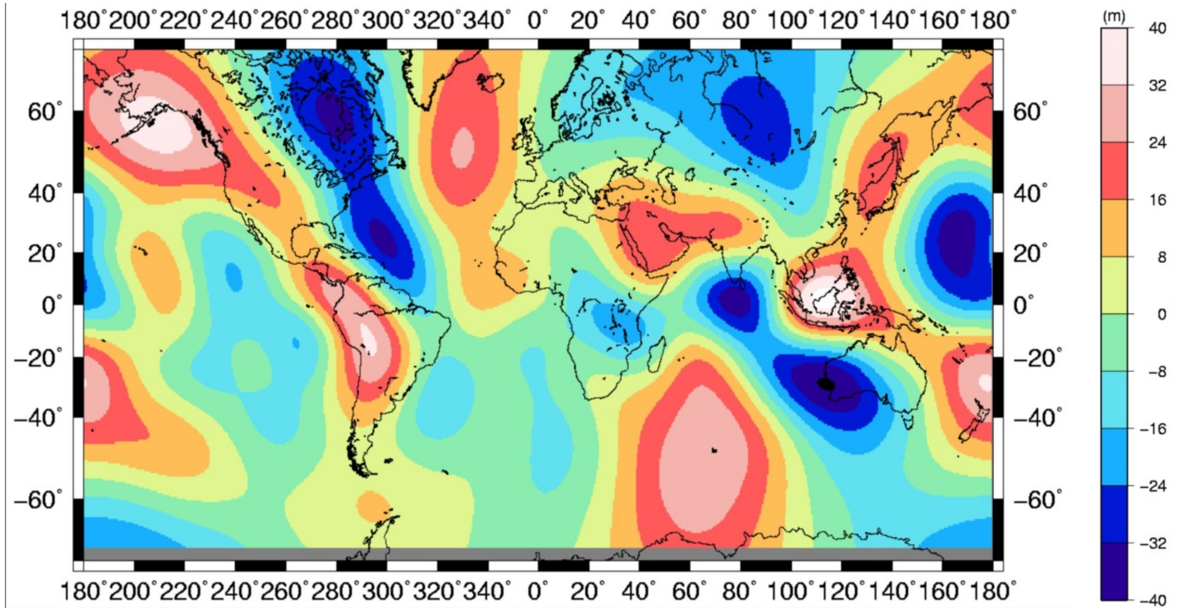
Global tomography



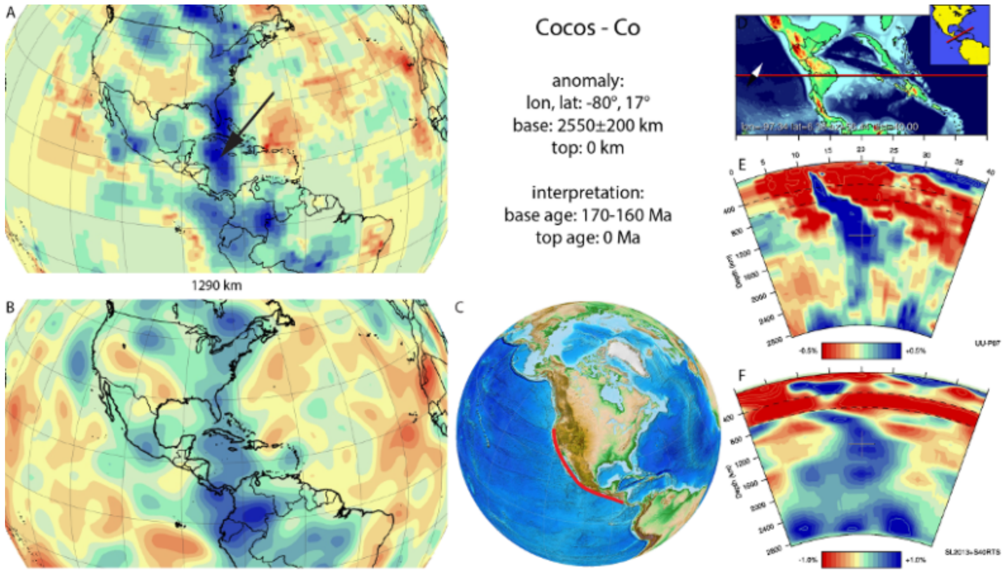
Kustowski *et al.* (2008)

Bibliography: Bowin (2000)

Geoid anomaly n=4-10



UNIVERSIDAD COMPLUTENSE MADRID



Global tomography van der Meer, D.G et al. ‘Atlas of the Underworld

Geoid anomaly n>10 (wavelengths <4100 km)

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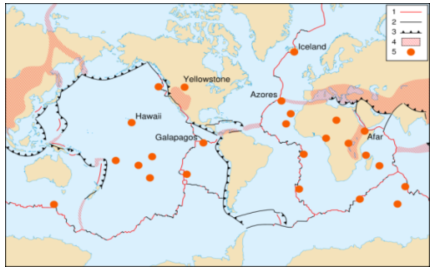
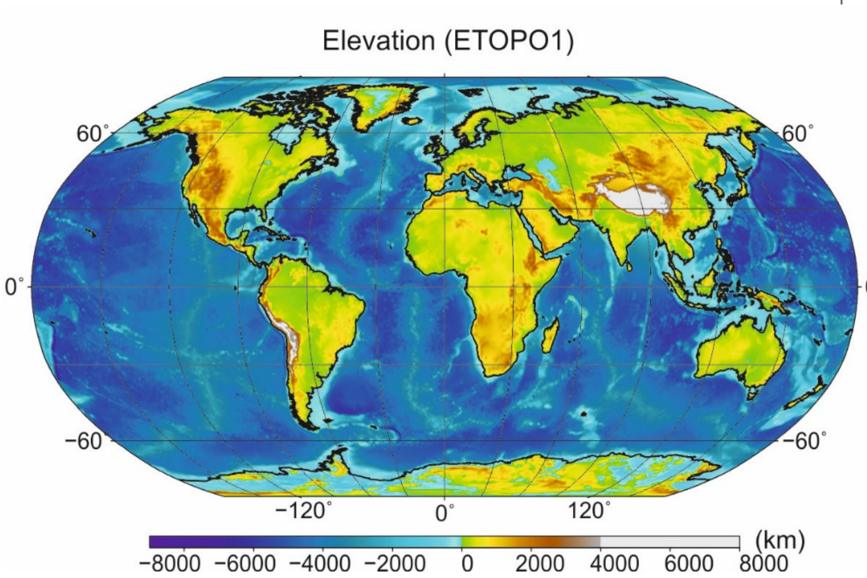
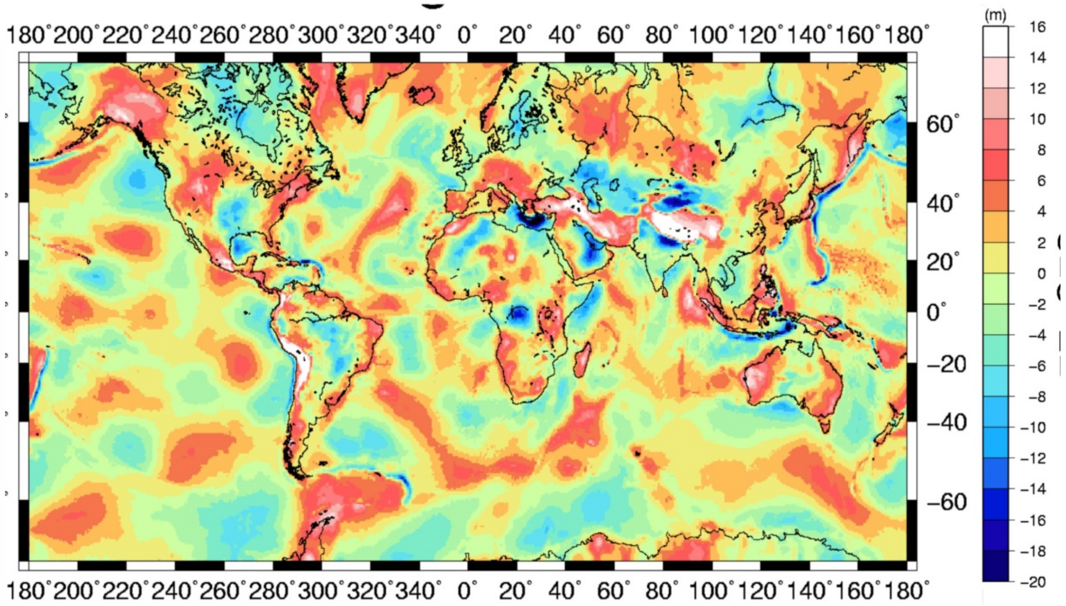
COMPLUTENSE
MADRID



Harmonic degrees >10 correlate with lithospheric scale features (e.g., mid oceanic ridges, cratons, orogenic belts…)

Degrees >10 represent 10% of total geoid signal

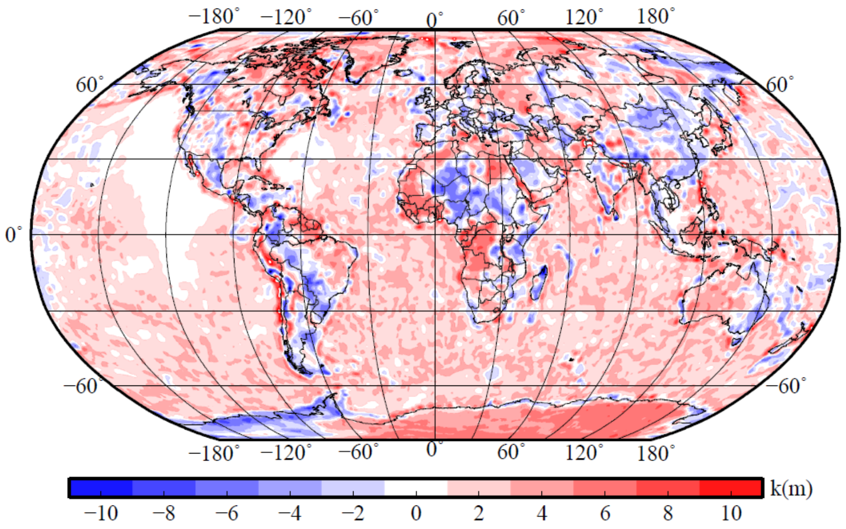


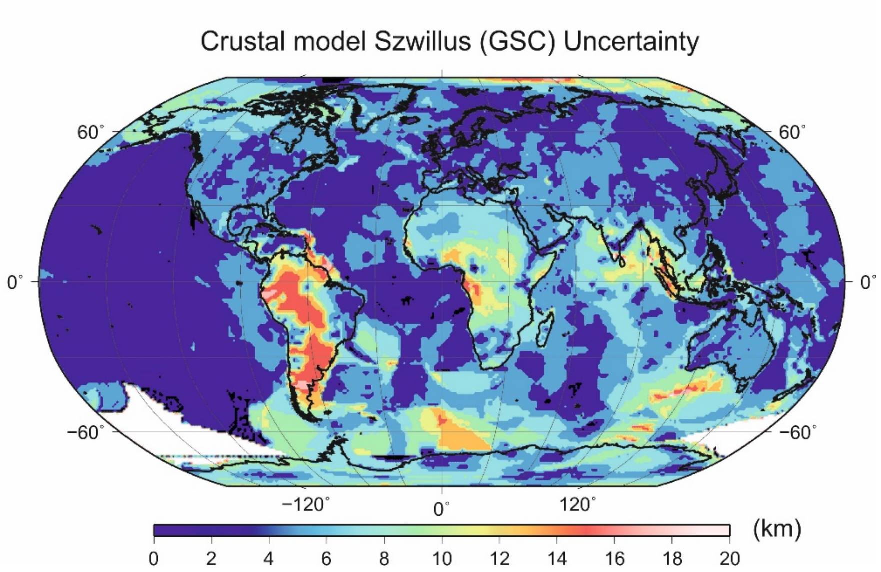


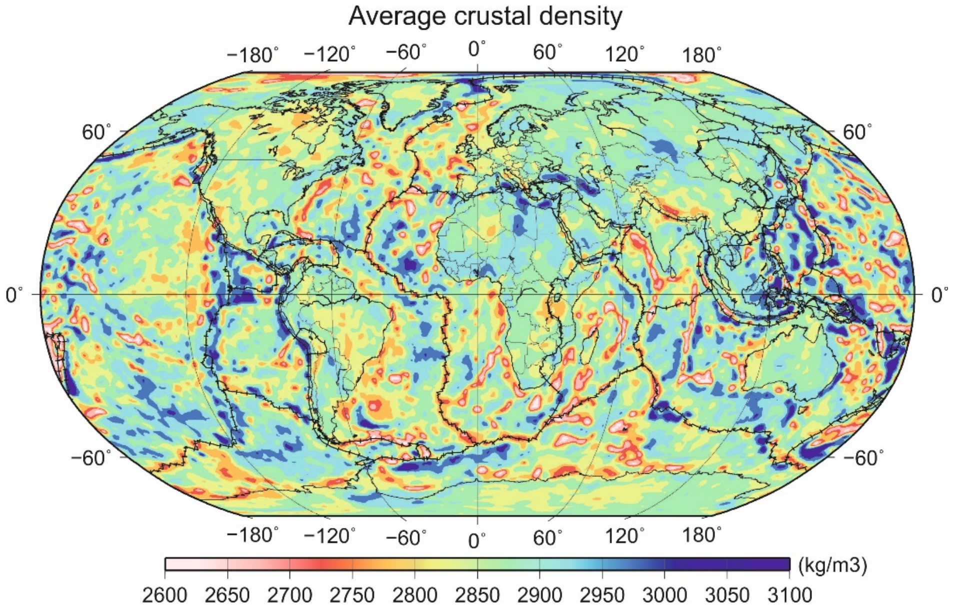
Bibliography: Bowin (2000)

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)



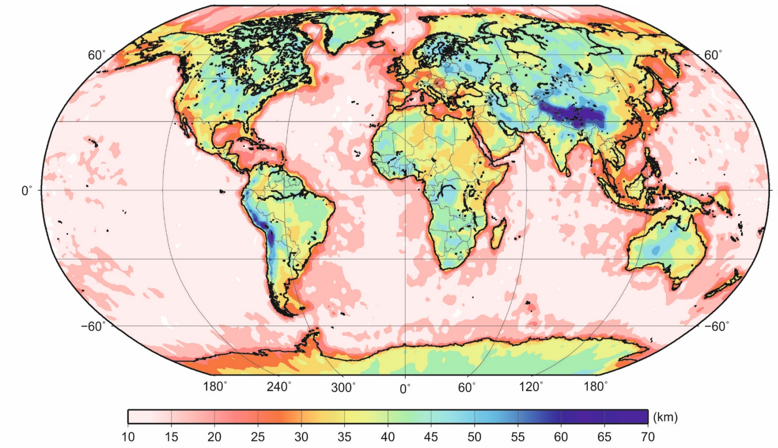




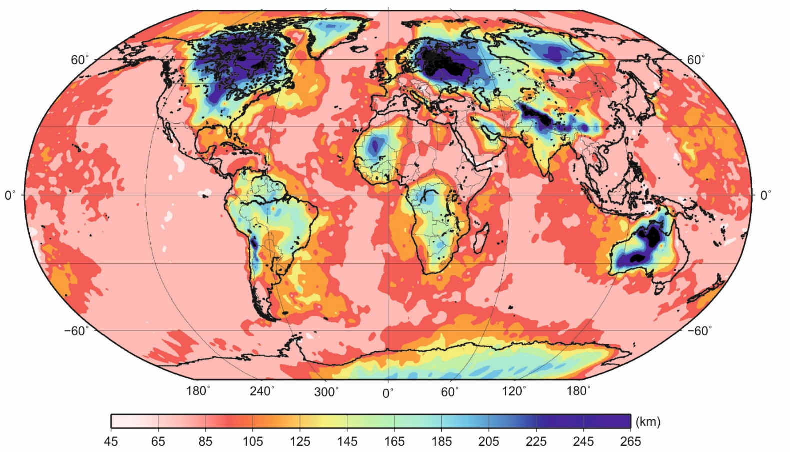
- ✓ Geometry (Moho depth, upper-mid/lower crust)variations
- ✓ Vs, Vp upper-mid/lower crust
- ✓ Average density

WINTERC-G: Lithosphere & mantle composition

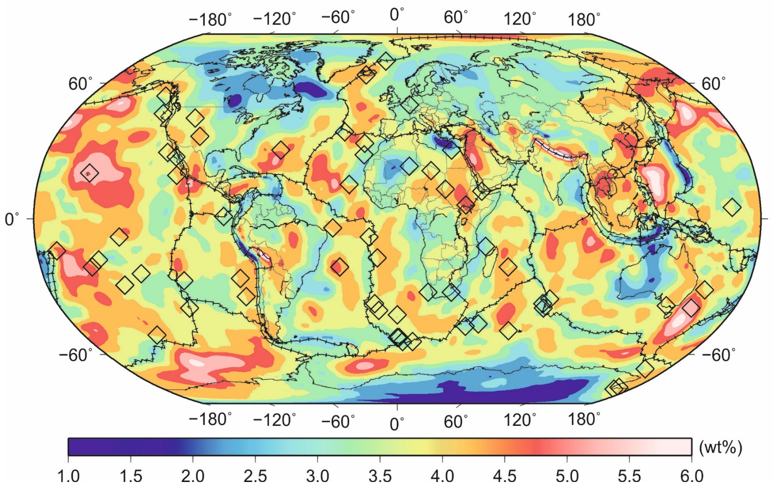
Moho depth



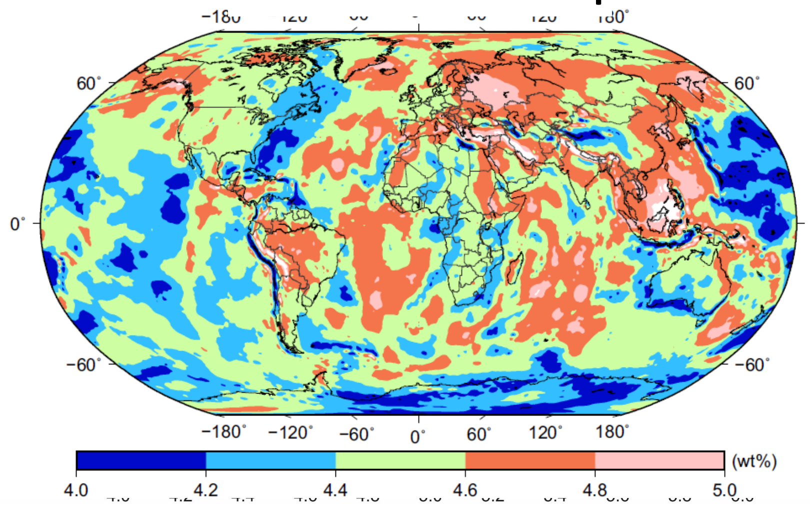
Lithospheric thickness



Al2O3 lithosphere

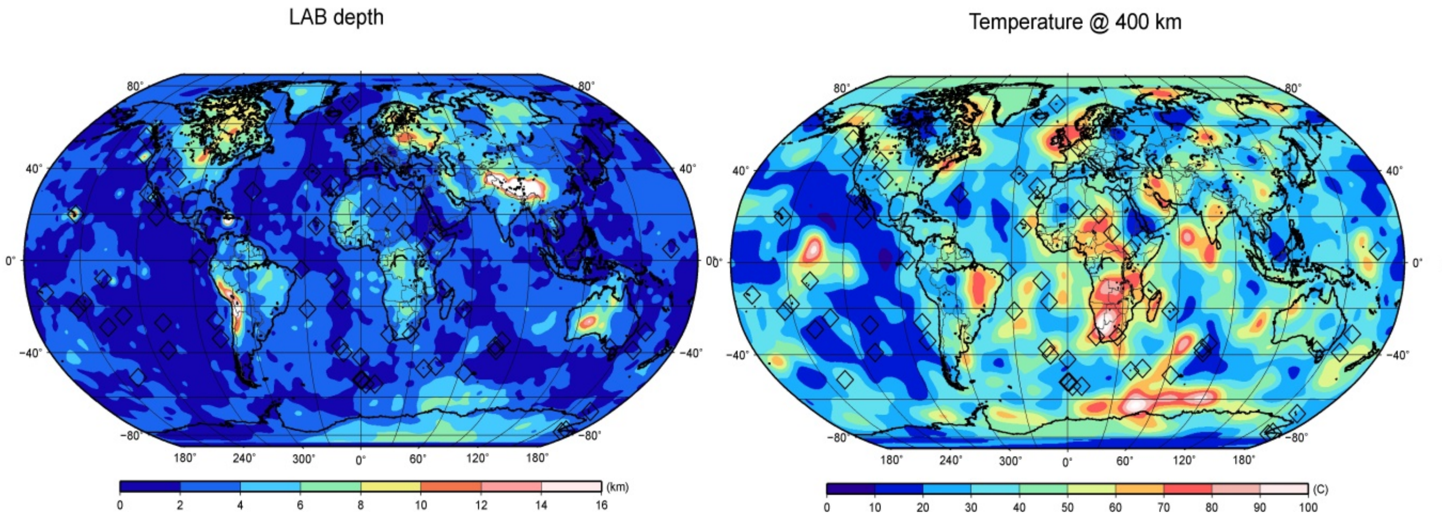


Al2O3 sublithosphere



- ✓ 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

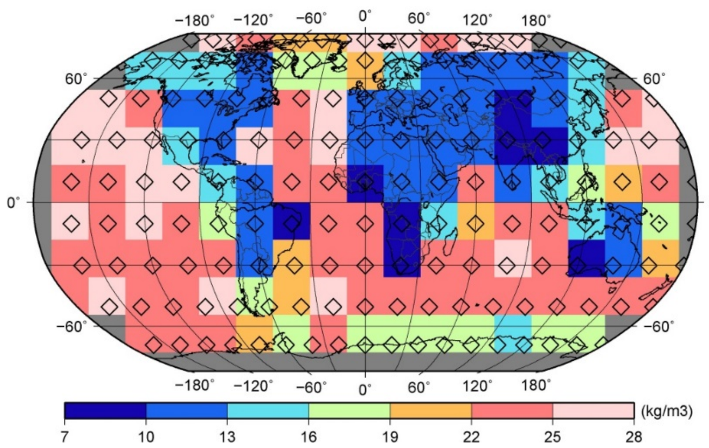
Uncertainties, step 1:
Waveform tomography+elevation+SHF



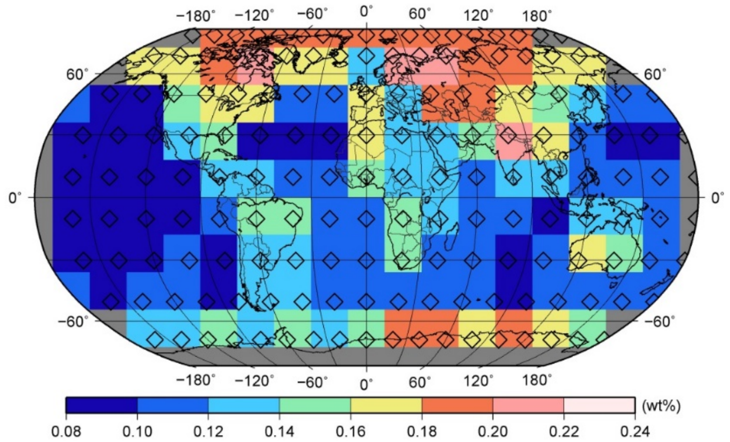
- ✓ Each model column: full covariance matrix
- ✓ Thermal lithospheric thickness is the best resolved parameter
- ✓ Uncertainty increases with depth (temperature, composition)

Uncertainties, step 2:
Gravity field data

Average crustal density

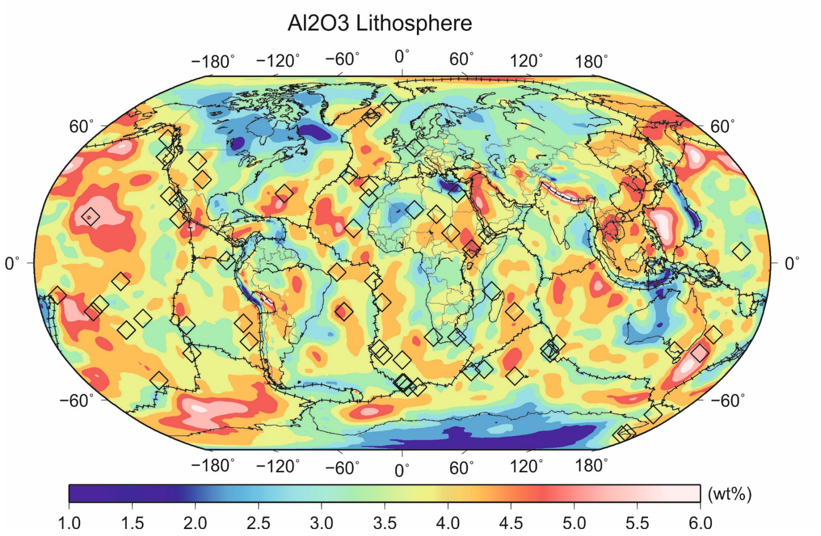


Average mantle composition

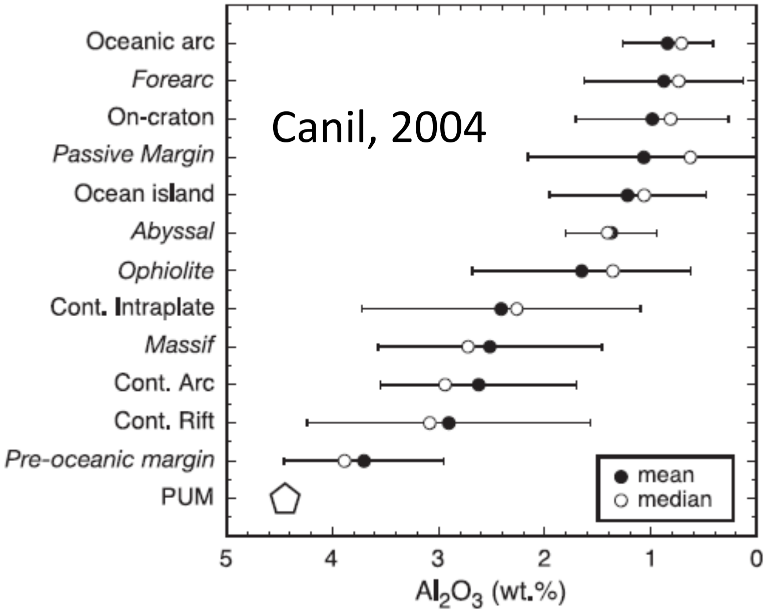


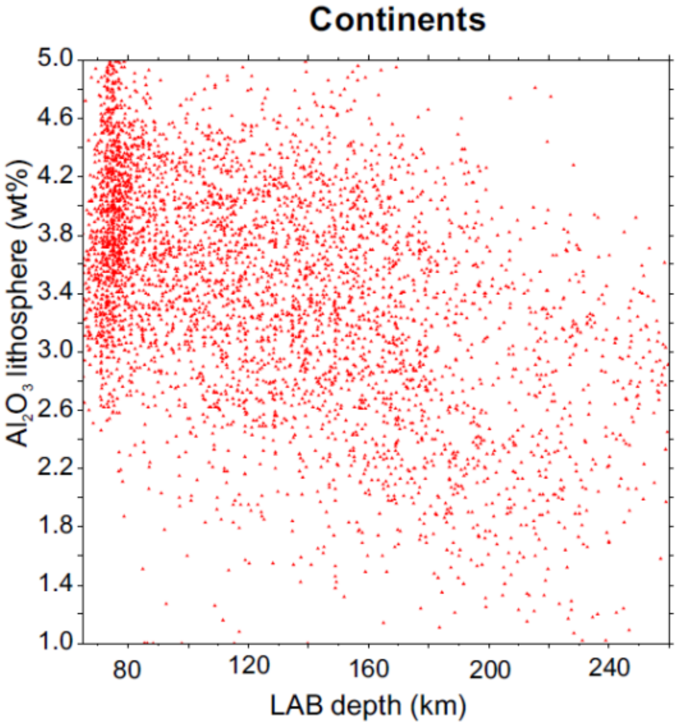
- ✓ Covariance matrix computed at coarser model resolution (20 deg) but full resolution at observations $G_{ij} = \left(\frac{\partial g_{\mathbf{3D}}(m_{post})_i}{\partial m_j}\right)$
- ✓ Crust density better resolved in continents than in oceans
- ✓ Mantle composition better resolved in oceans than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

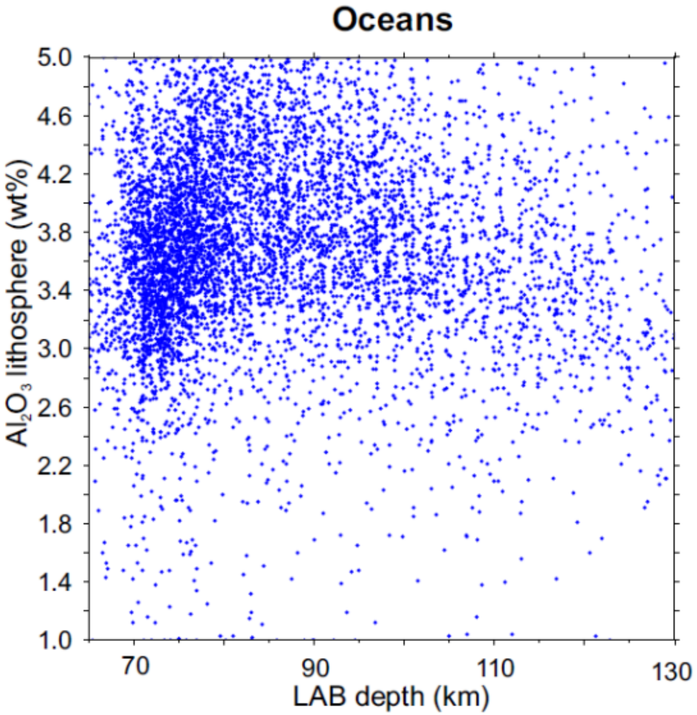
WINTERC-G: lithospheric composition



Global petrological data base



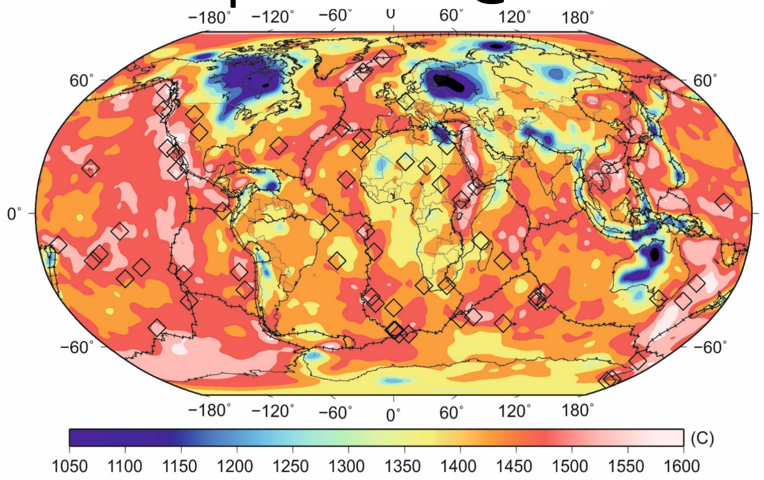




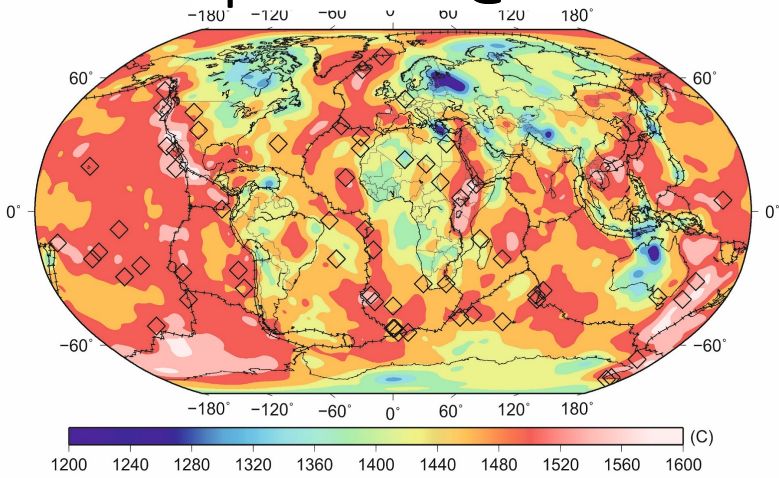
- ✓ General trend continents: lithospheric thickening (age increasing) fertility decrease
- ✓ Oceans: MOR's are depleted, fertility peaks at intermediate age

WINTERC-G: temperature

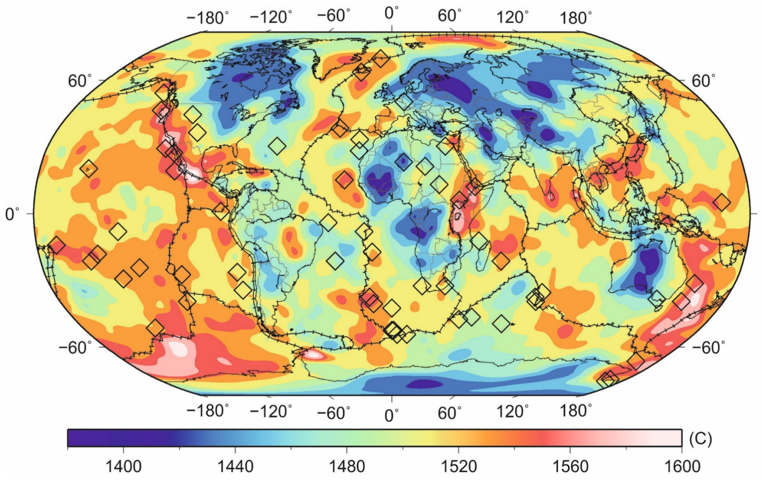
Temperature @200 km



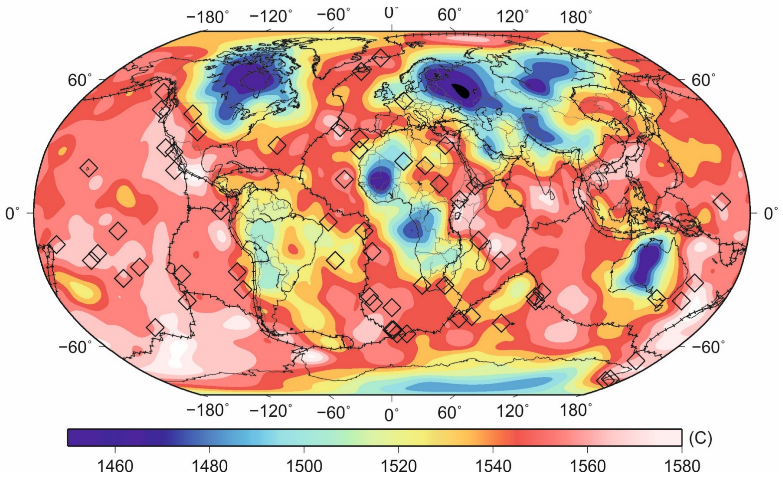
Temperature @260 km



Temperature @330 km

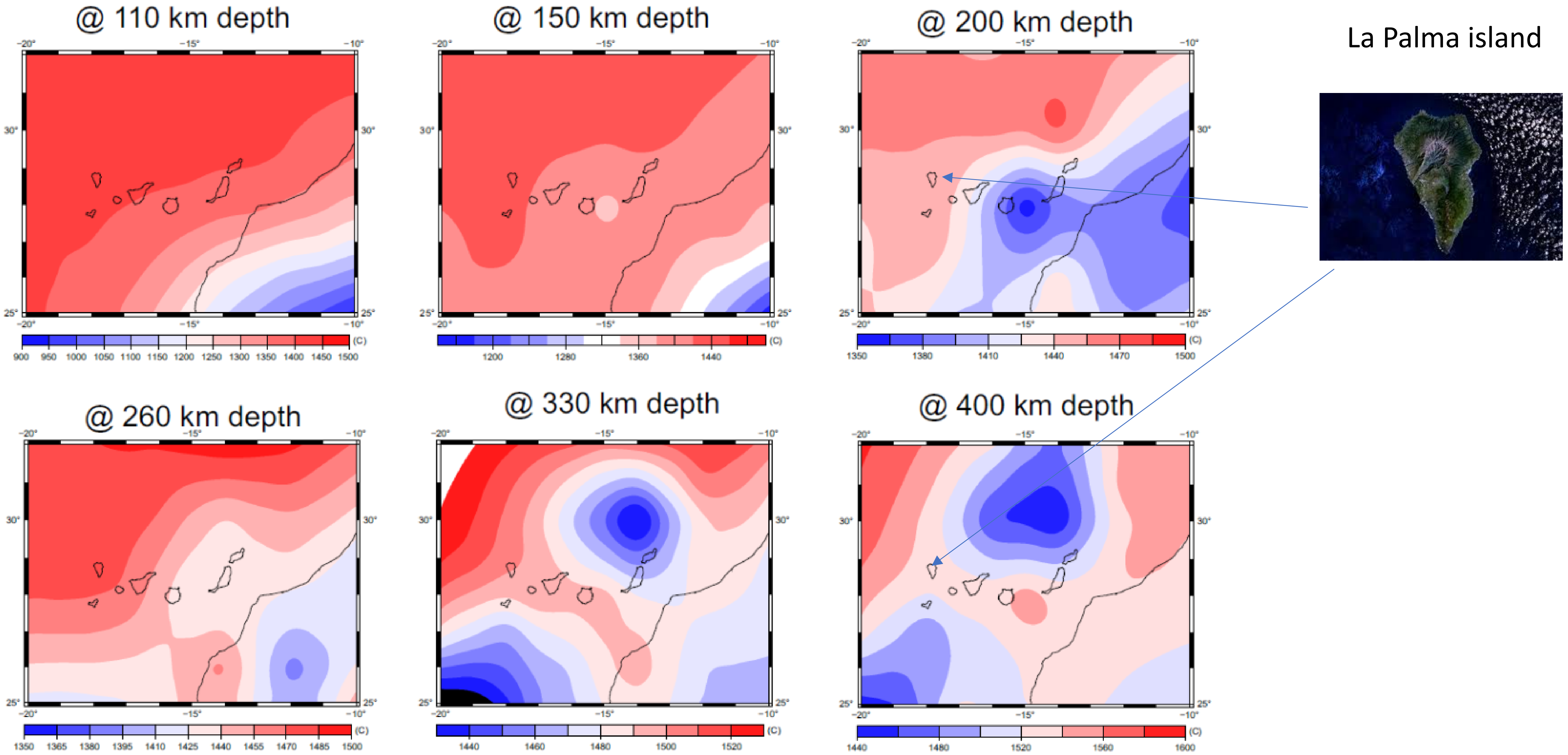


Temperature @400 km

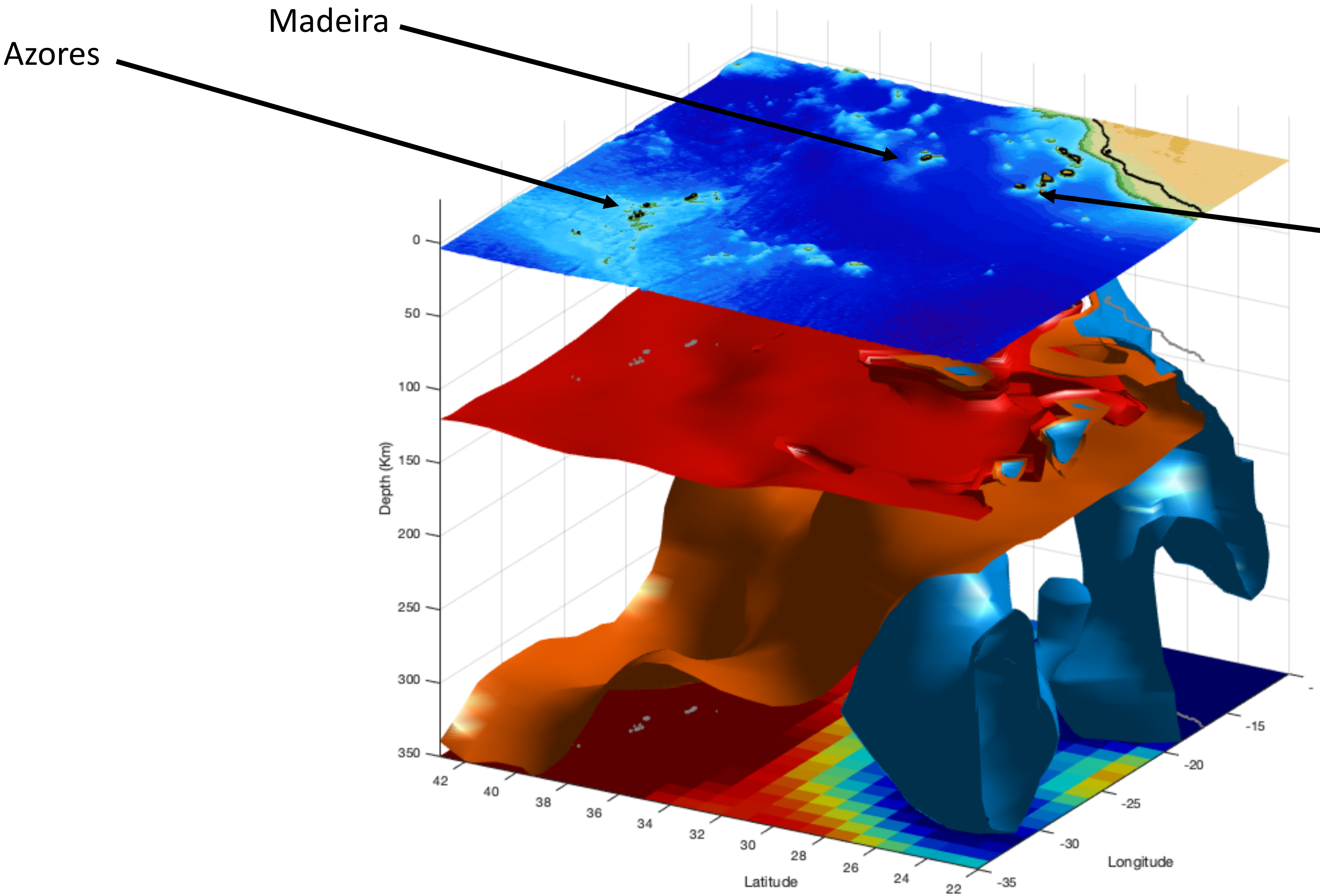


- ✓ Mantle plumes are warmer than ambient mantle
- ✓ Continental cratonic cores remain cold down to the transition zone (Specially N America, E Europe and W Australia)

WINTERC-G: temperature in the Canary archipelago

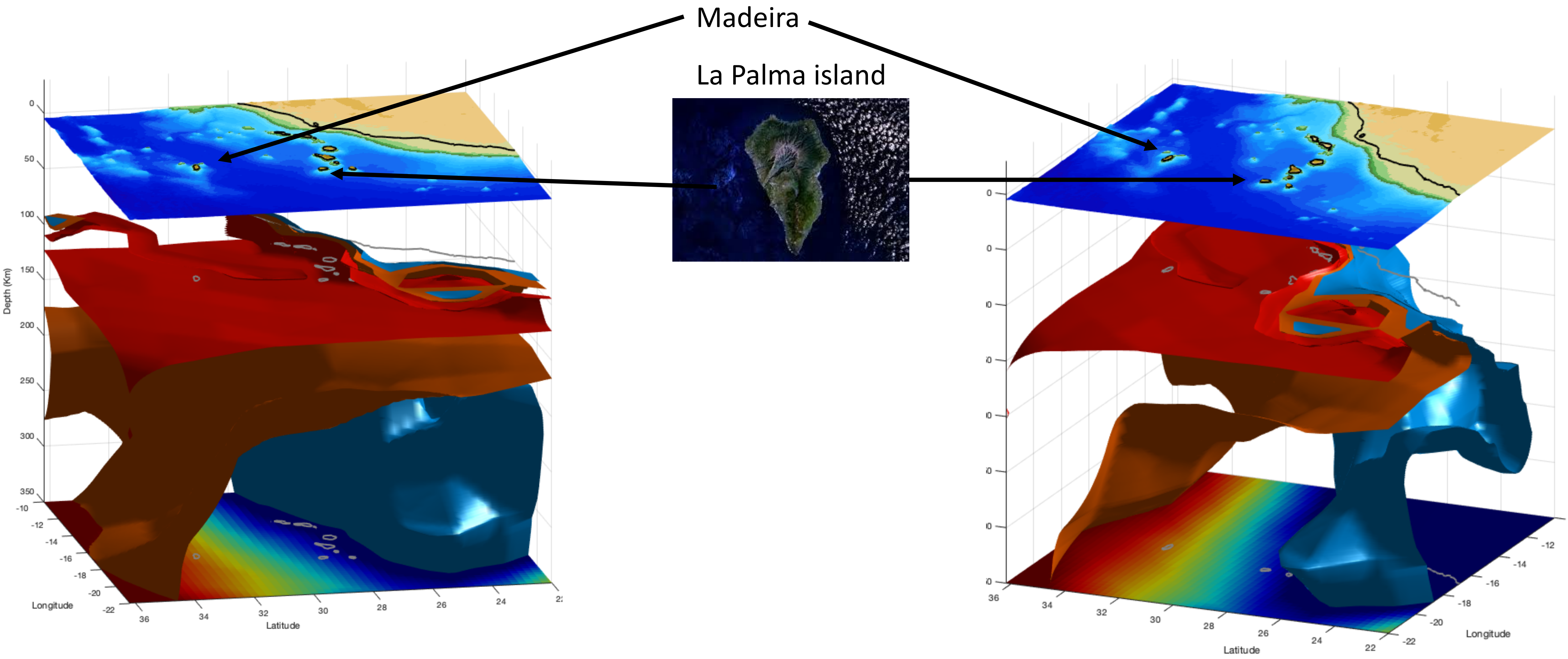


WINTERC-G: temperature in the Canary archipelago

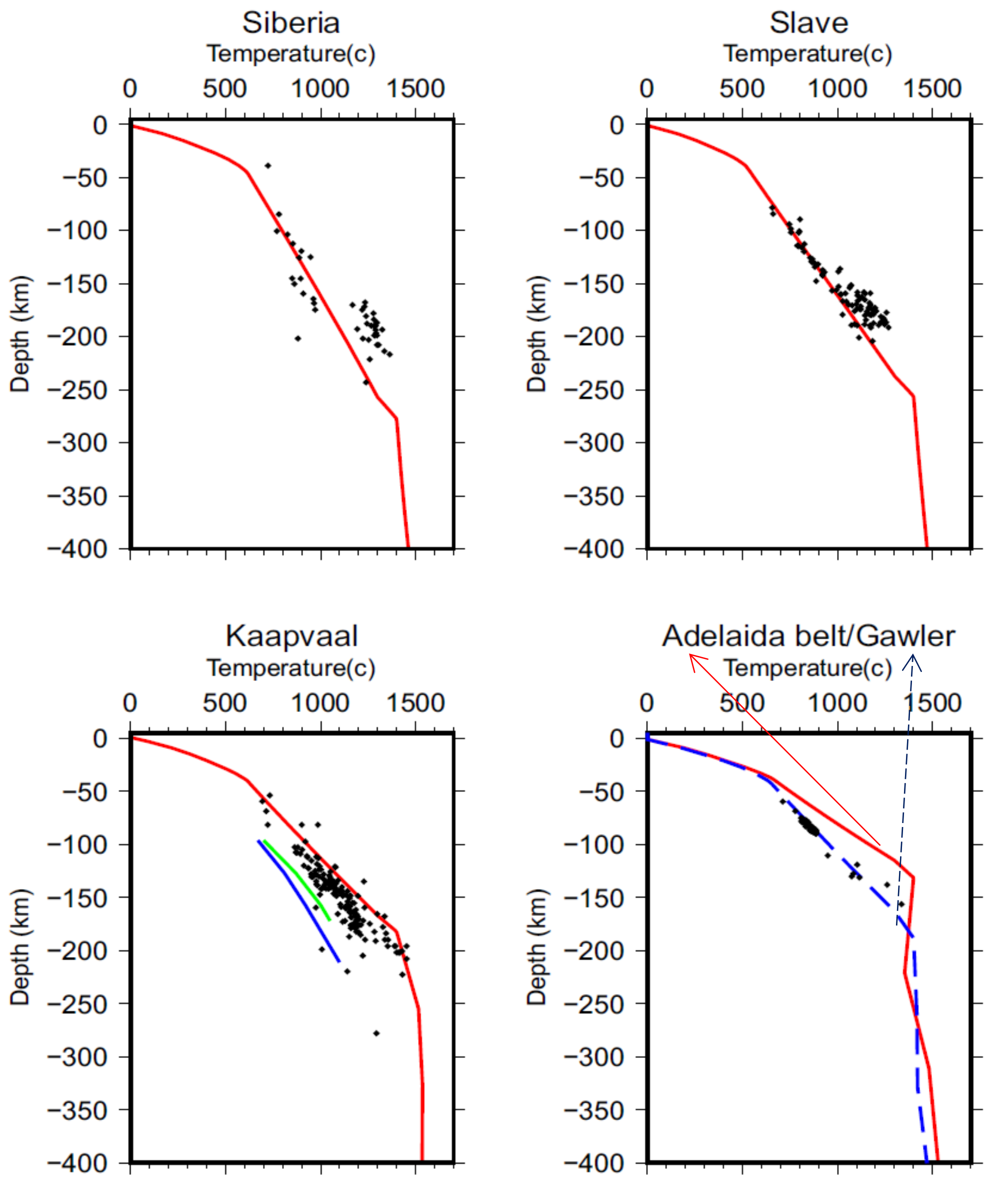


La Palma island

WINTERC-G: temperature in the Canary archipelago

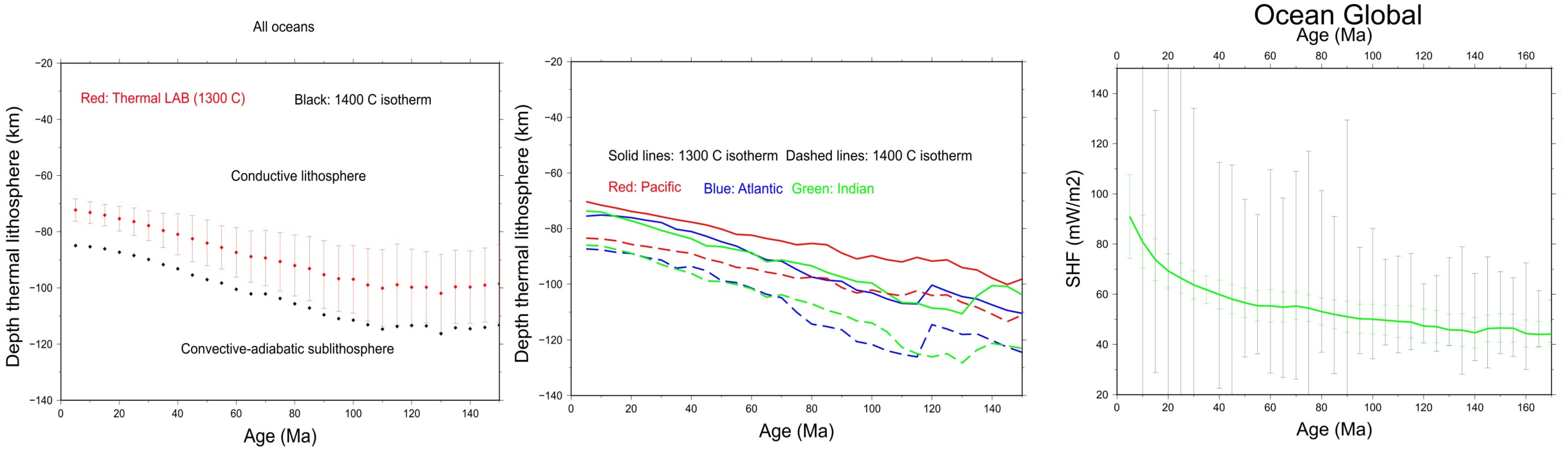


WINTERC-G: comparison with thermobarometry in cratons



Thermal oceanic lithosphere: cooling mechanism

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

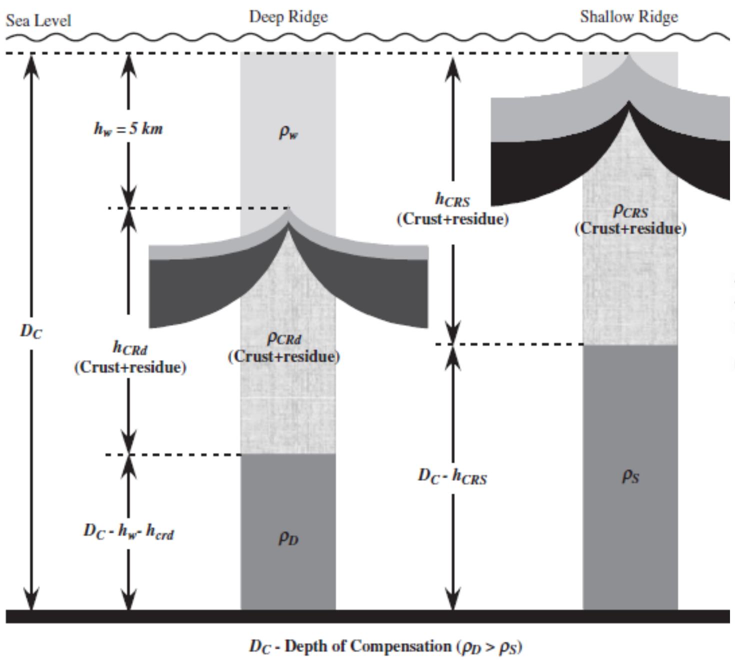


✓ Oceans cool at different rates with lithospheric age

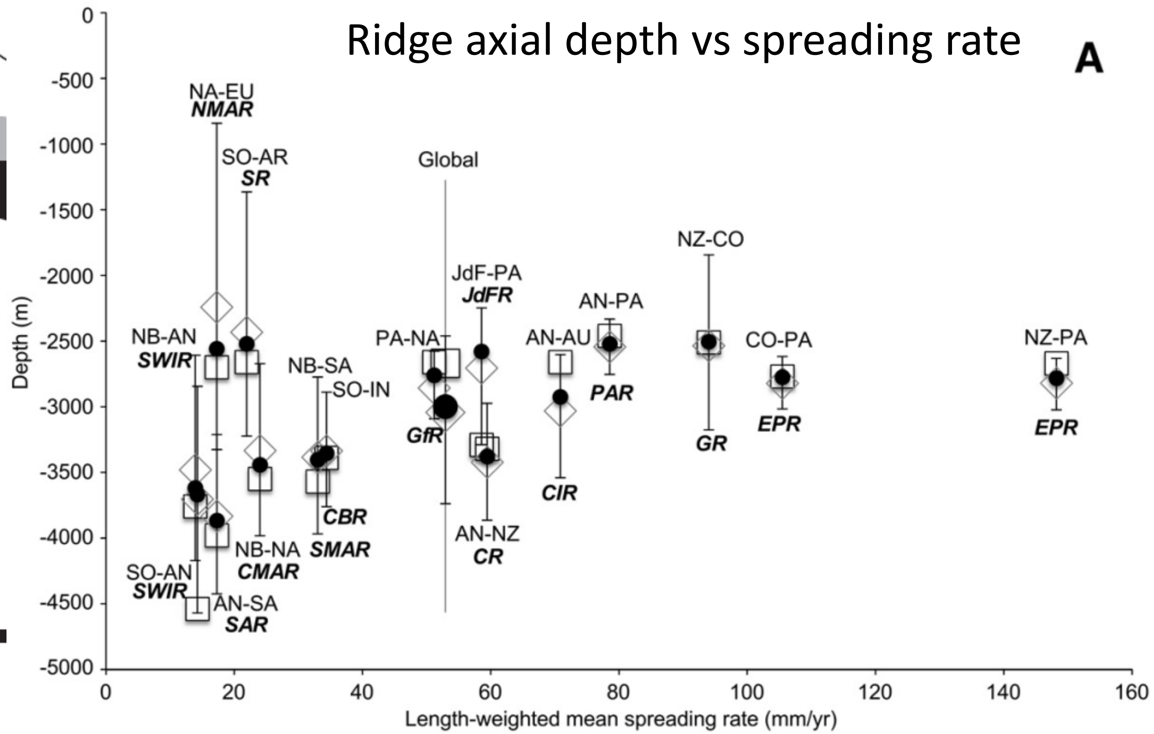
✓ No apparent flattening after 80 Ma

✓ Ocean SHF predictions match data except for lithospheric age<15 Ma approx.

Mid Oceanic Ridges



Rowley, 2018

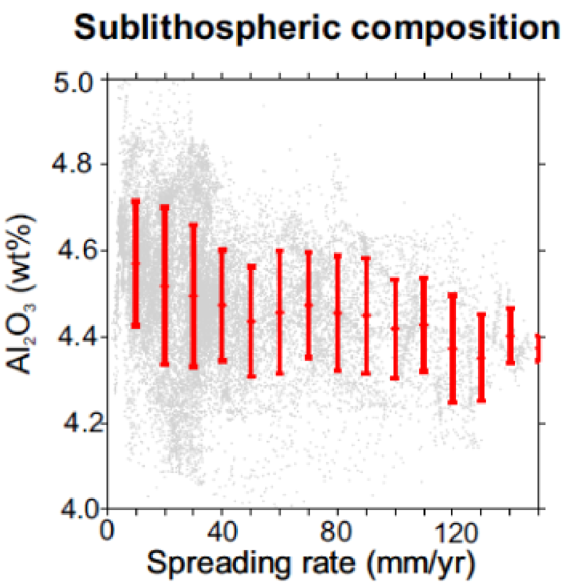


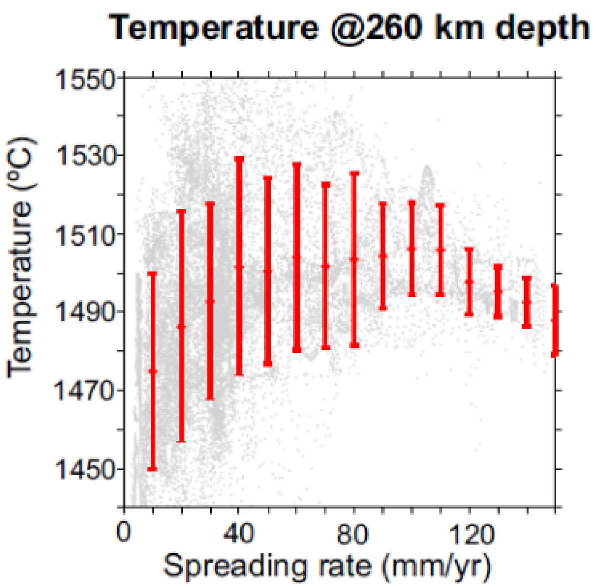
Niu and O'Hara, 2008

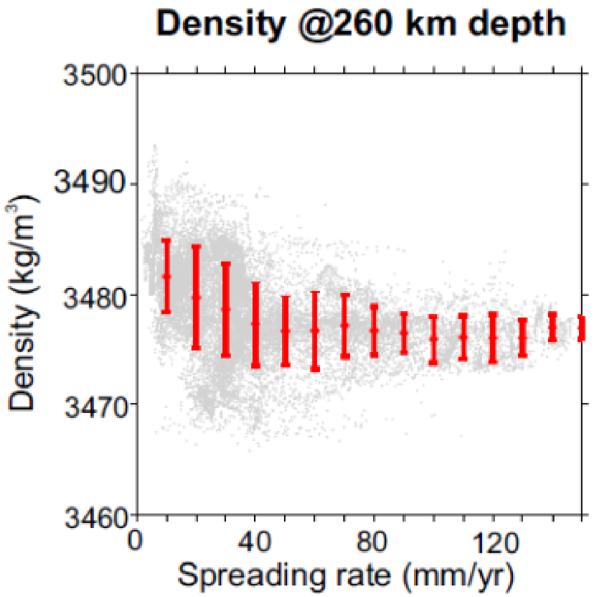
- ✓ Shallow ridges spread faster than deep ones
- ✓ Fertility of mantle melt source (based on MORB) increases with ridge depth (Niu and O'Hara, 2008)

WINTERC-G vs spread rate

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



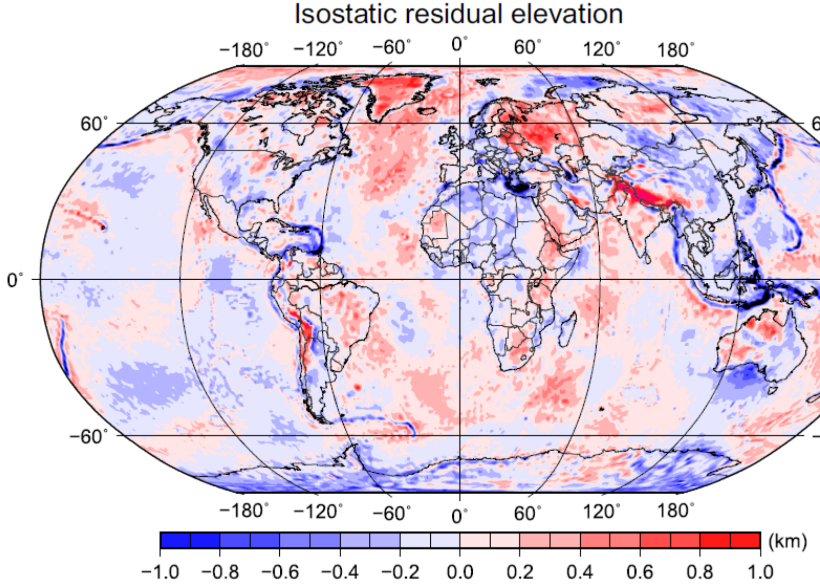




- ✓ Mantle fertility and density decrease and temperature increase with spreading rate (up to 50-60 mm/yr).

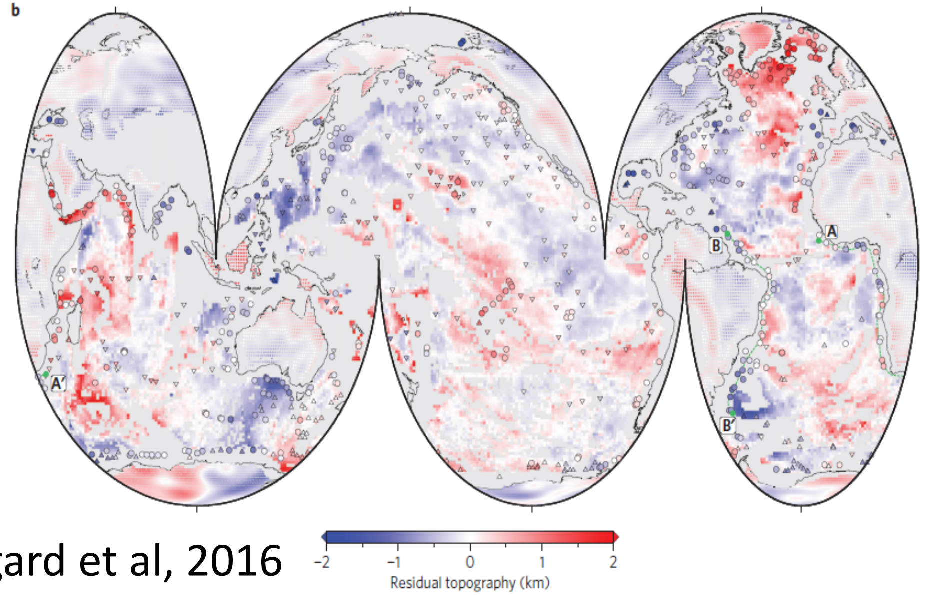
WINTERC-G: Isostatic/dynamic elevation

Isostatic residual elevation-WINTERC-G

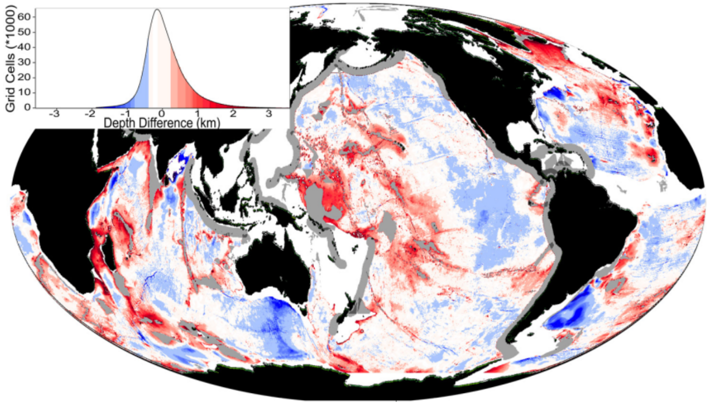


- ✓ Good agreement in oceans with independently derived residual maps
- ✓ In continents residual/dynamic published models show more dispersion

Isostatic residual elevation- Oceans

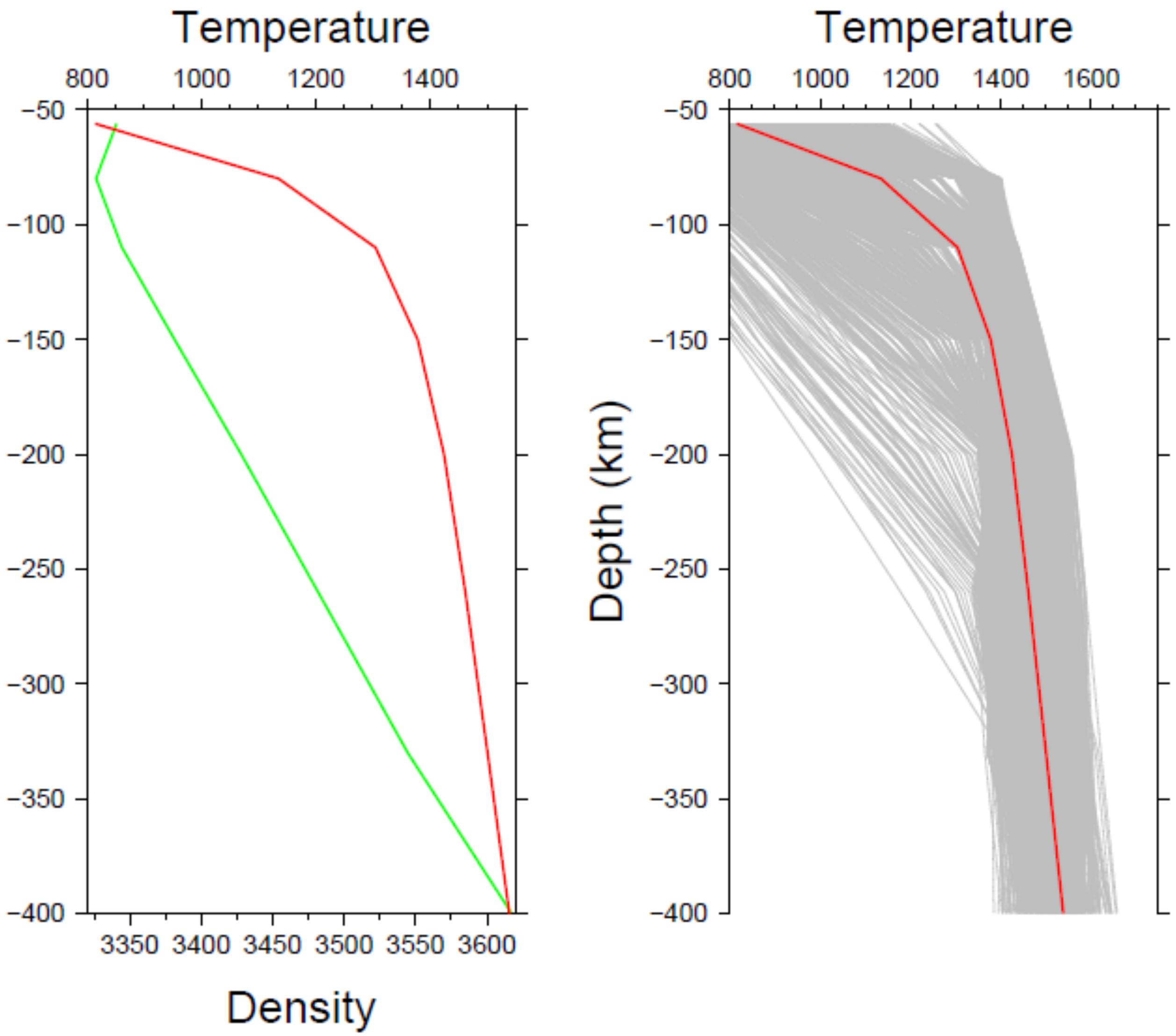


Hoggard et al, 2016



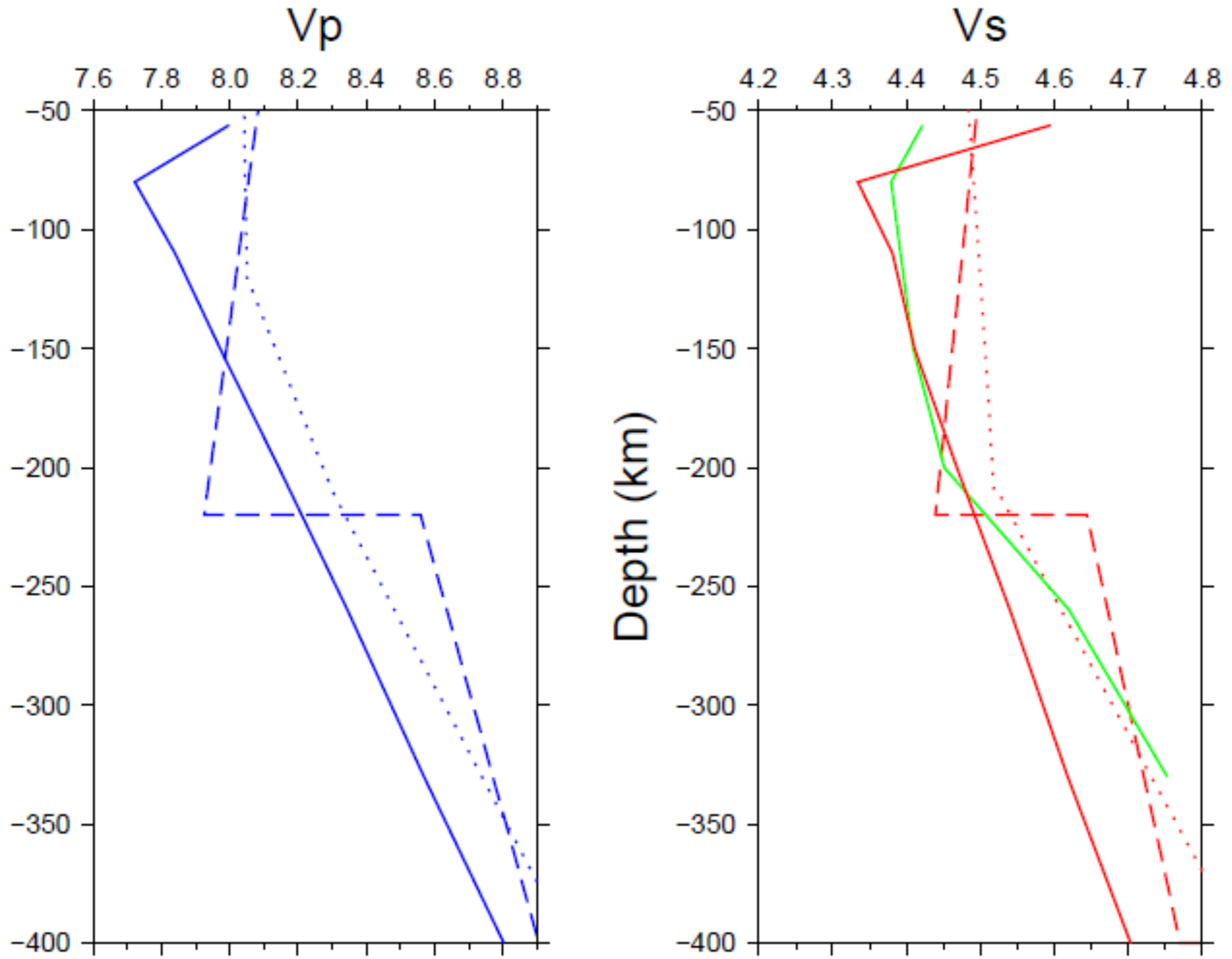
Rowley, 2018

WINTERC-grav: 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

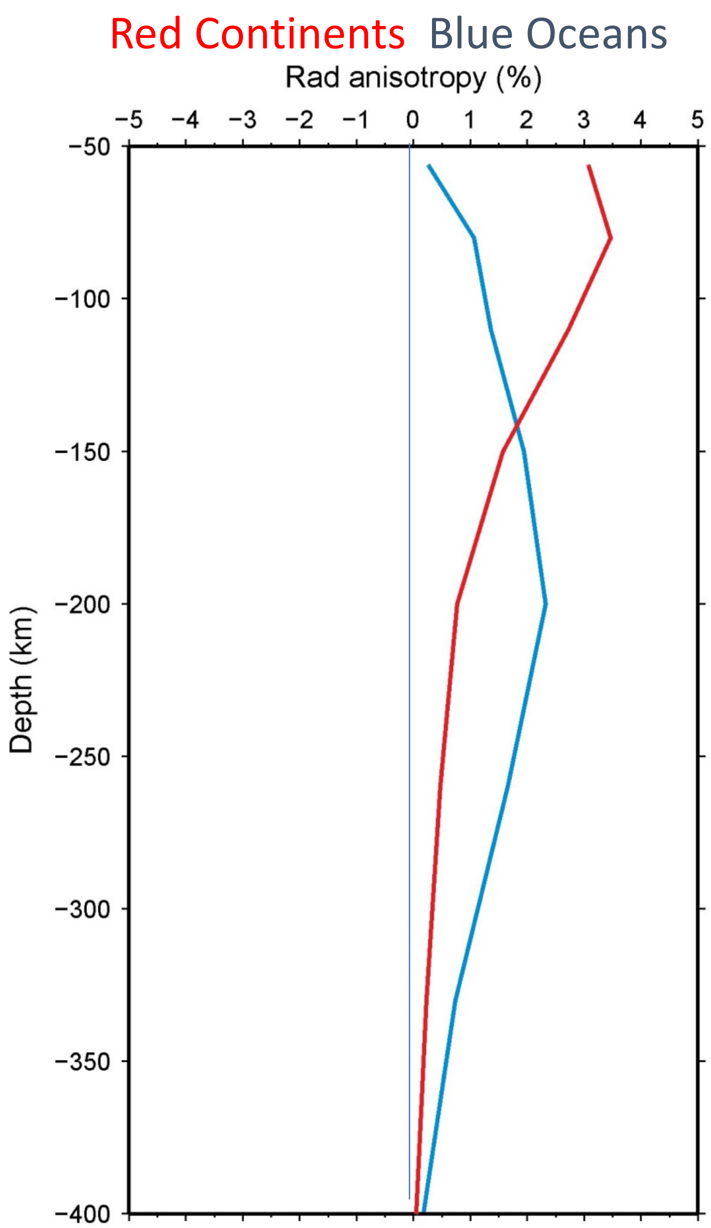


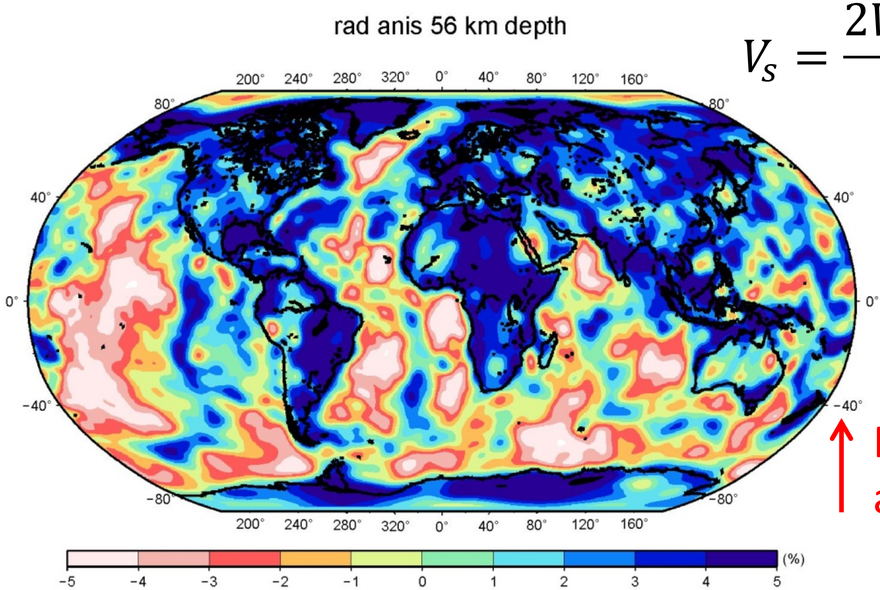
- ✓ Solid line WINTERC-grav, dashed line: AK135, dotted line PREM, solid green Vs: Schaeffer&Lebedev 2013
- ✓ Uniform Vs gradien throughout the upper mantle (no need for 200 km discontinuity or gradient increase)

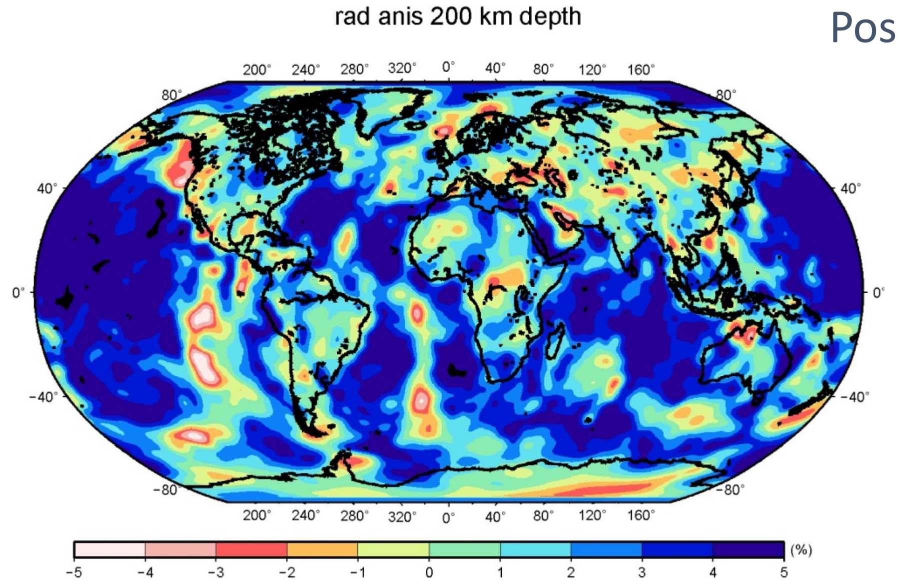
WINTERC-grav: Average radial anisotropy

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

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



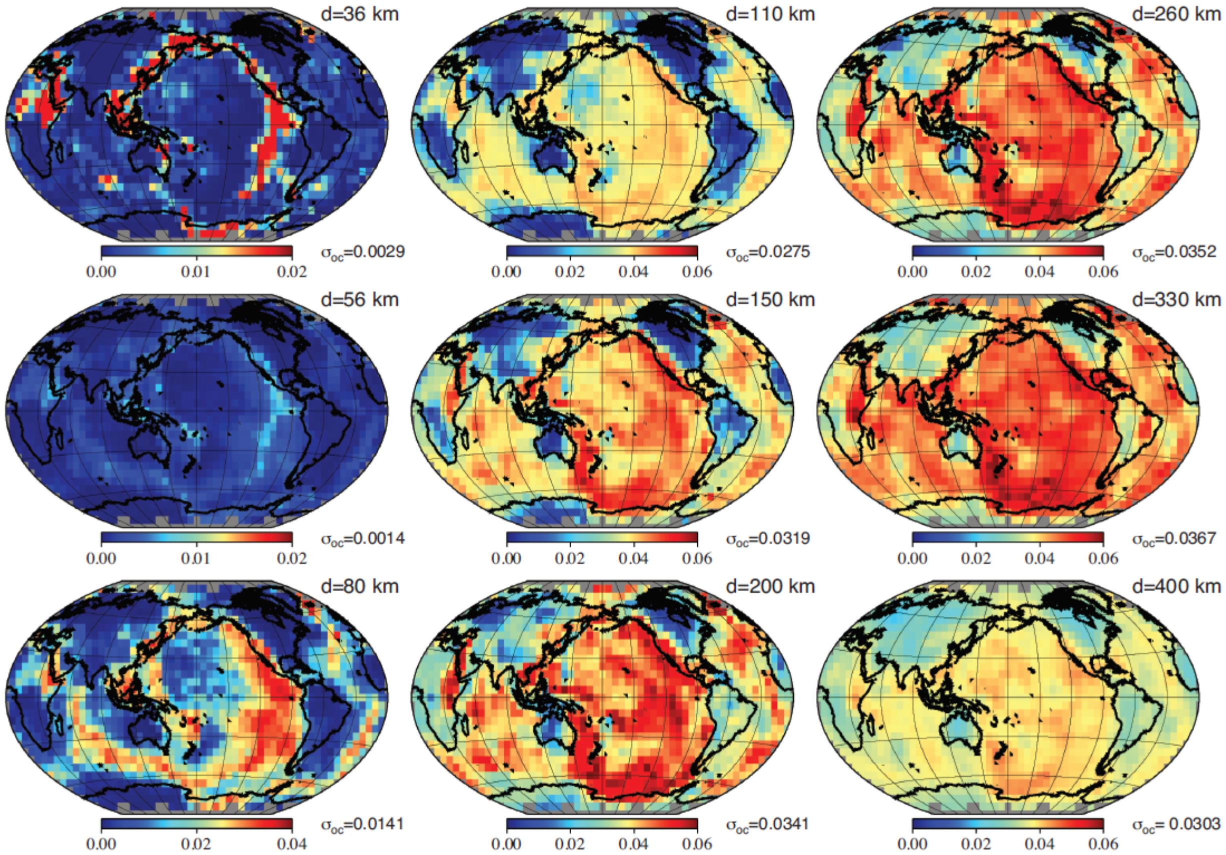




↑ Negative anis

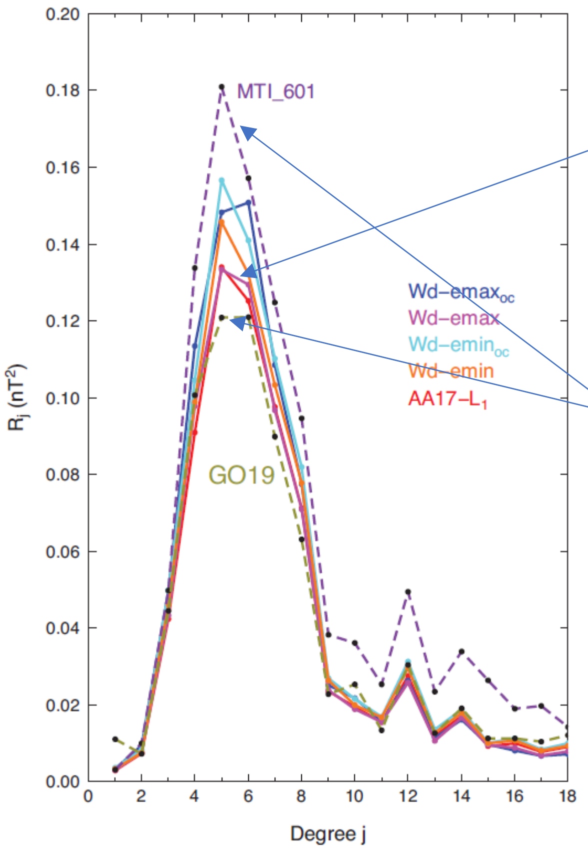
→ Positive anis

WINTERC-e: electrical conductivity



Martinec et al. (2021)

Spectrum of the time-averaged oceanic M2 tidal magnetic field



WINTERC-G based models (no magnetic data)

Swarm magnetic data constrained models

Magnetic field from satellite

Martinec et al. (2021)

Conclusions (so far…)

- ✓ WINTERC-G: new global lithospheric/upper mantle thermochemical model integrating waveform tomography, SHF, isostasy, satellite gravity and petrology

- ✓ 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 plate oceanic lithosphere cooling model

- ✓ Mid Oceanic Ridges: mantle fertility-spreading rate

WINTERC-G: global lithospheric/upper mantle thermochemical model

(Fullea et al. , 2021, GJI)

- **Outreach from ESA: https://www.esa.int/ESA_Multimedia/Videos/2021/03/GOCE_helps_create_new_model_of_crust_and_upper_mantle#.YV2wAmt9Y_0.link**
- **https://www.esa.int/Applications/Observing_the_Earth/FutureEO/GOCE/Deep_down_temperature_shifts_give_rise_to_eruptions?fbclid=IwAR3lr7YdwmDztLYqyPxhi-Brw5BgSUMfPsF7Kxwr2MbrMe6uEay2WpLUShs**

- **Full model available (3D thermal, compositional, Vp, Vs, density fields) in:**

https://zenodo.org/record/5771863
(DOI:10.5281/zenodo.5771863)

This study has been done in the framework of the project '3D Earth—A Dynamic Living Planet' funded by European Space Agency (ESA) as a Support to Science Element (STSE). Work supported an Atracción de Talento senior fellowship (2018-T1/AMB/11493) funded by Comunidad Autonoma de Madrid (Spain).