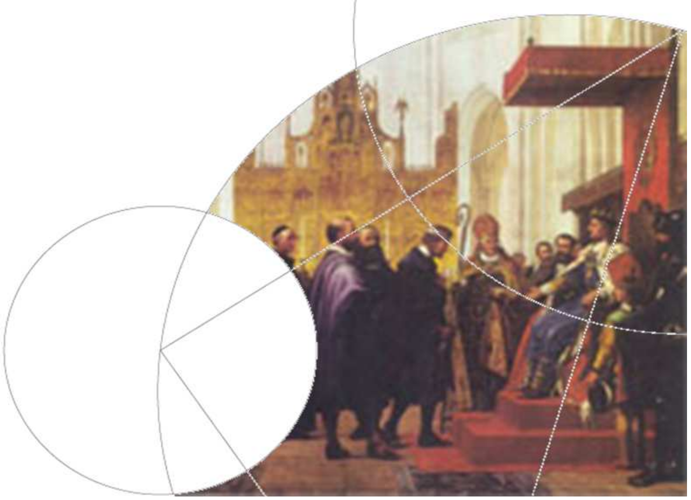
UNIVERSITY OF COPENHAGEN

Faculty of Science

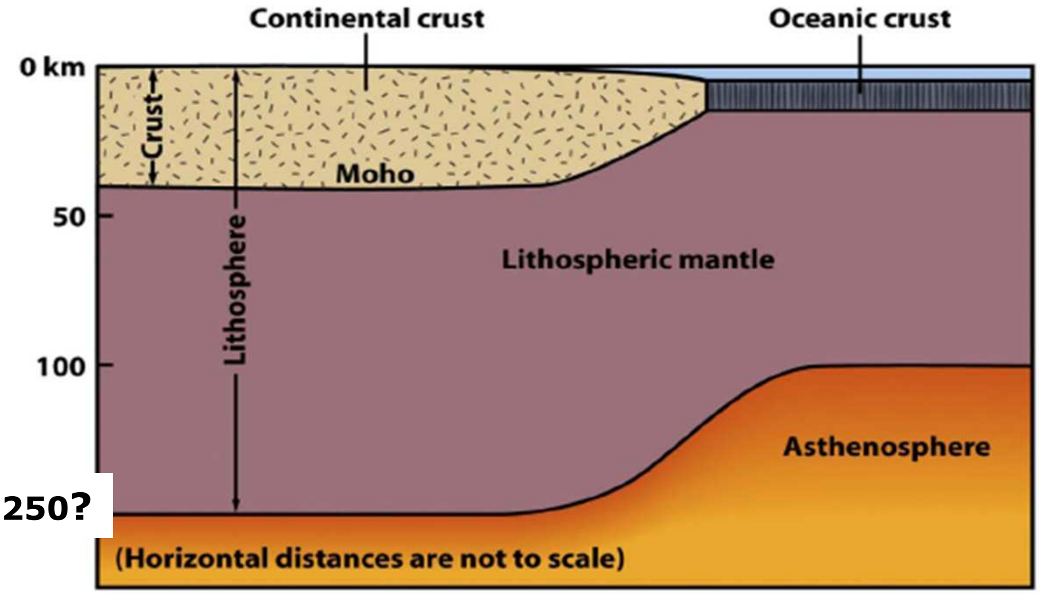
Gravity and topography signature of global petrological lithosphere

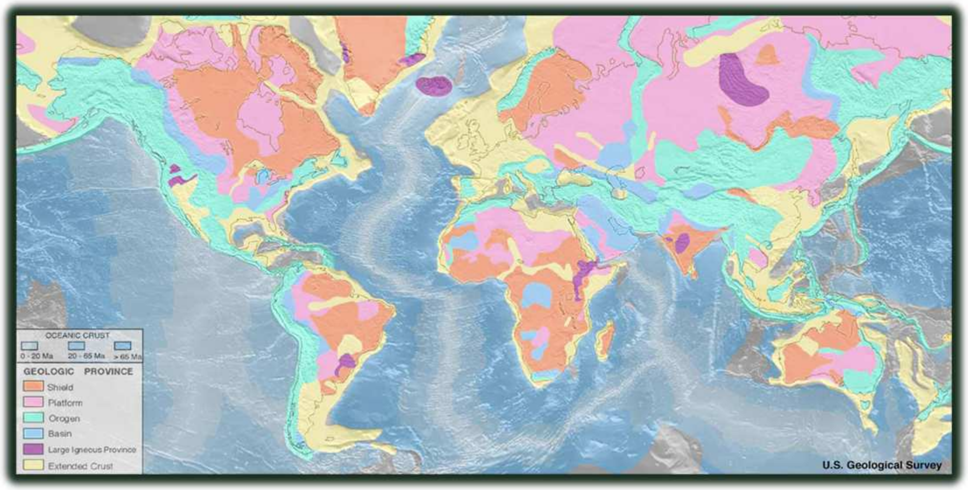
Fabio Cammarano
University of Copenhagen

GOCE- Solid Earth Workshop, October 17 2012



❖ Earth is a very dynamic system, yet the stable part of continents formed > 3 billion of years ago and, since then, survive destruction!





✓ **Continental lithosphere →** old, thick and chemically depleted compared to **oceanic lithosphere**

Why do we study the lithosphere?

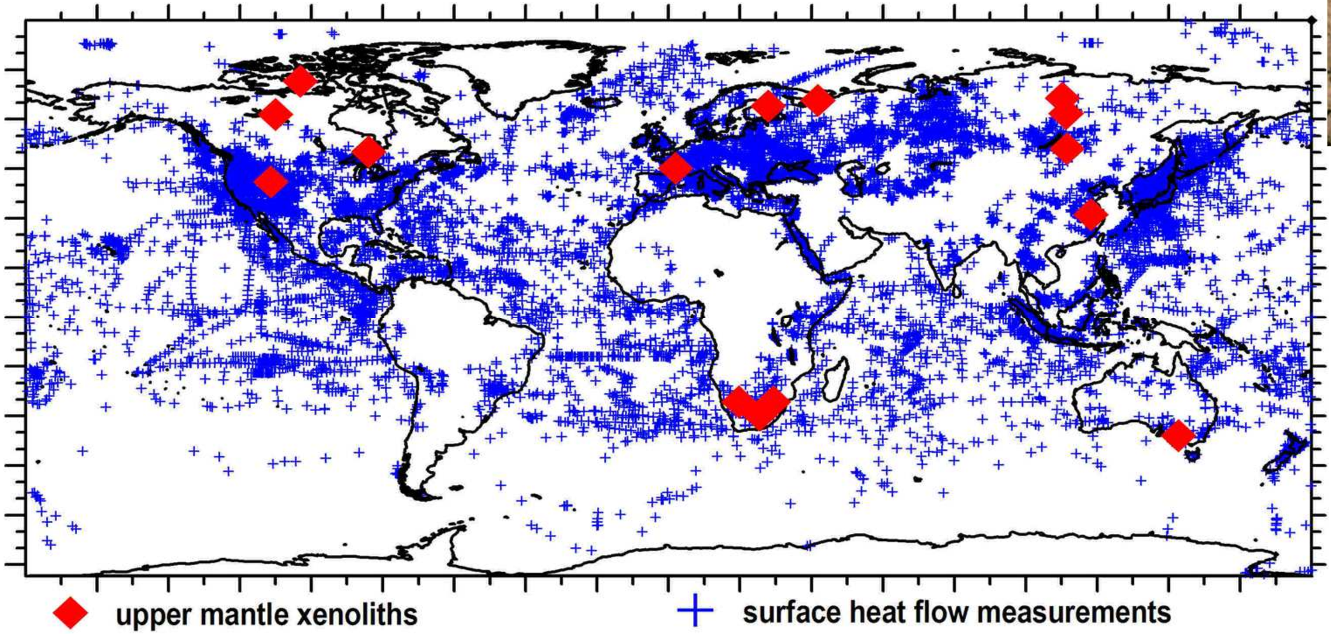
- ✓ Oceanic lithosphere ➔ understand plate-tectonics dynamics
- ✓ Understand the origin and evolution of stable continental regions ➔ understand evolution of our planet

❖ In order to do this, it is fundamental to determine the **thermal** and **compositional heterogeneity** of the lithosphere.

◆ Lithosphere is largely inaccessible.

Garnet-peridotite outcrop- SW Norway

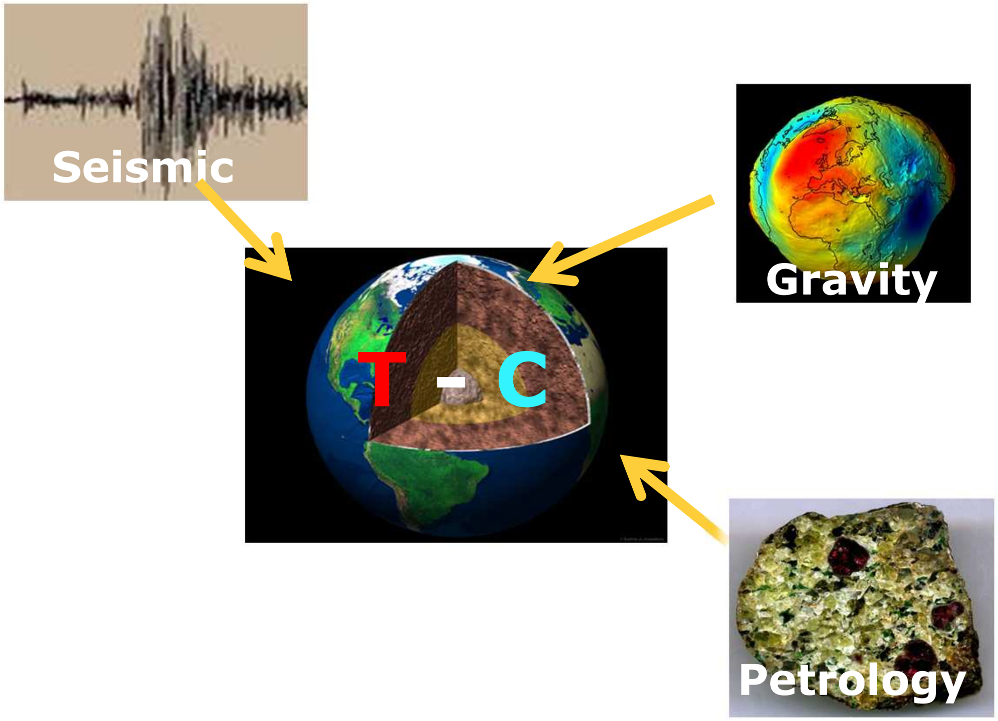
Garnet-peridotite in kimberlite



✓ Direct sampling (xenoliths) is sparse and not representing, perhaps, “normal” mantle

✓ Most of knowledge is indirect ➔ interpretation of geophysical data

…an interdisciplinary approach:



❖ Use seismic, gravity and petrological observations to obtain an insight on composition and temperature of Earth’s interior

Model V_P,V_S,ρ (P, T, C) from mineral physics

Interpret seismic data or V_P, V_S models for T-C structure

Predict $\rho-\mu$ structure => compute geoid undulations and topography and compare with observed ones

✓ We do not use a scaling law from Velocity to ☐ and T, but knowledge from mineral physics

✓Allows to include, sequentially, different observables into the interpretation process

V_P, V_S, ρ (P, T, C) from MINERAL PHYSICS

Elasticity (P,T)

Laboratory + numerical data => equation of state

+

Phase equilibria (P,T) => C (P,T)

Experimental or thermodynamical modeling (Gibbs free energy minimization)

⇓

V_P, V_S, ρ (P, T, C)

Average rock properties (e.g., Voigt-Reuss-Hill averaging scheme)

+

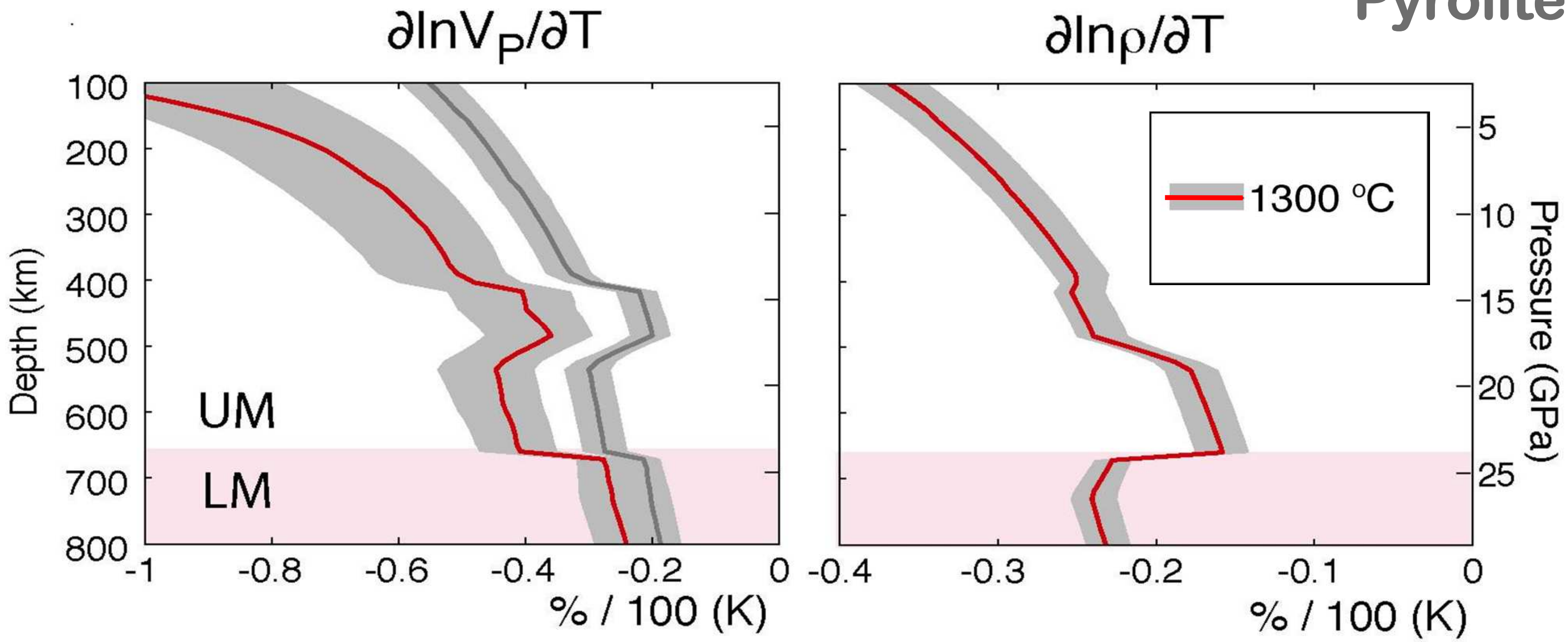
Anelasticity

Laboratory + analogy with rheology => $\partial V_{P,S}/\partial T$ function of T

MINERAL PHYSICS

Thermal Sensitivity

Pyrolite

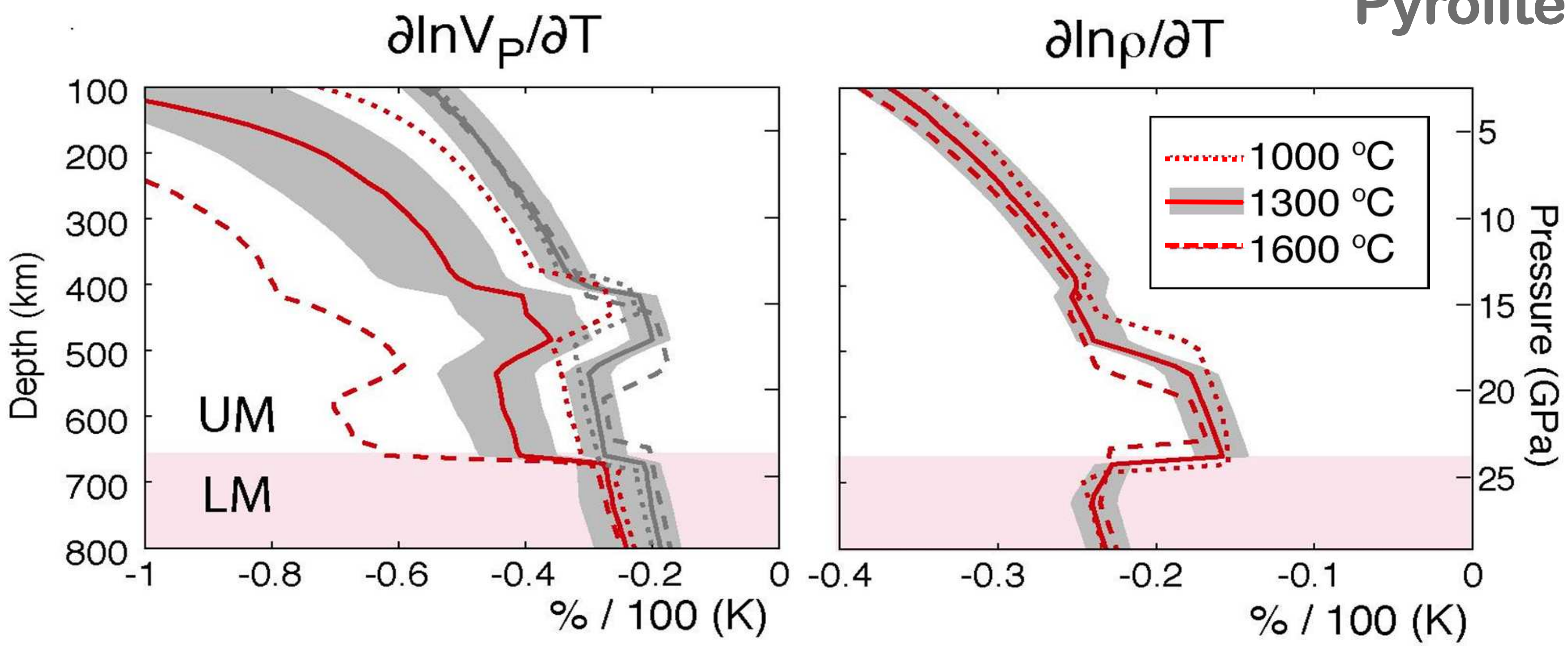


Cammarano et al., PEPI 2003

- T sensitivities decrease with depth
- ρ less sensitive than seismic velocities

Thermal Sensitivity

Pyrolite

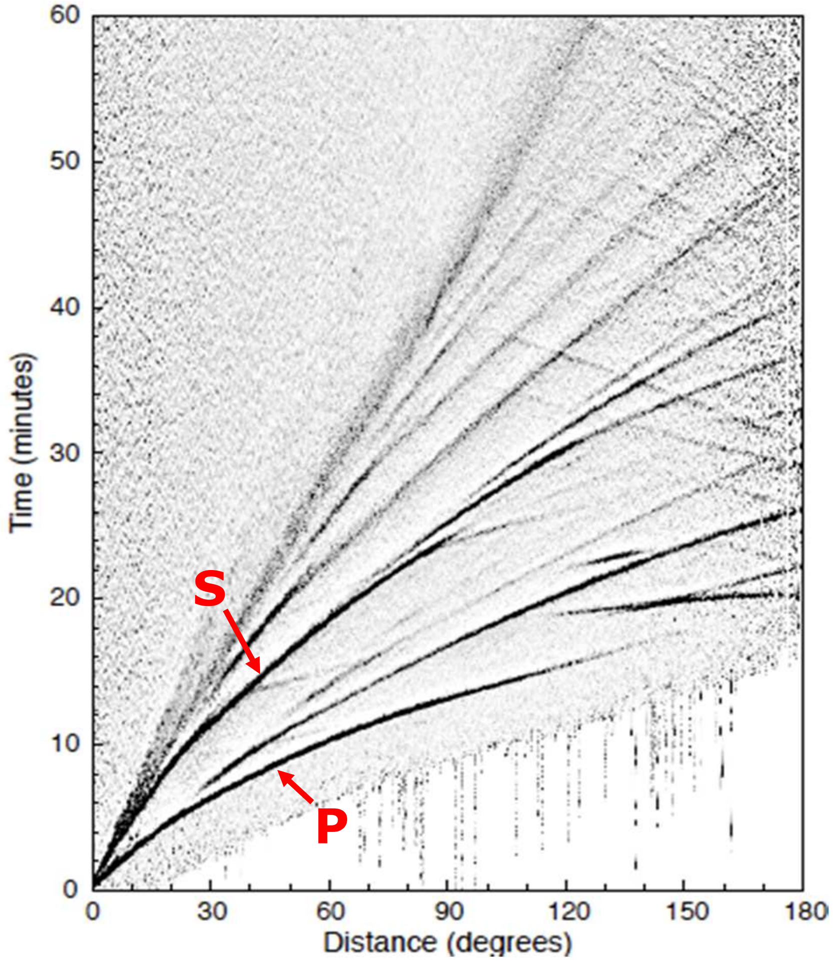


Cammarano et al., PEPI 2003

- T sensitivities decrease with depth
- ρ less sensitive than seismic velocities
- Q_S => $\partial V/\partial T(T)$ => need absolute velocities in UM

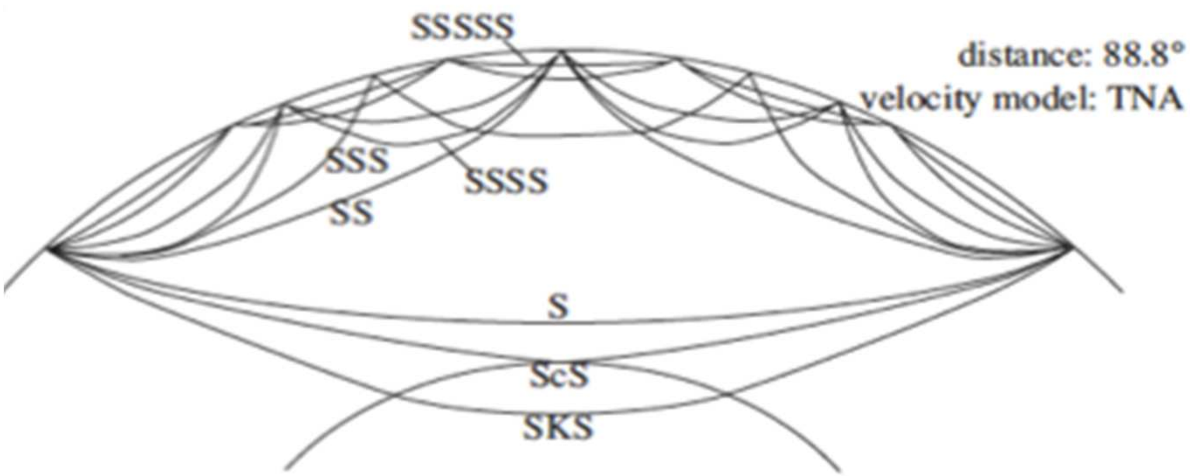
Seismic data for global models

- **Travel times** from ISC or EHB catalog (10^6 P, 10^5 S arrivals)
- Good lower mantle coverage, but only partial upper mantle coverage



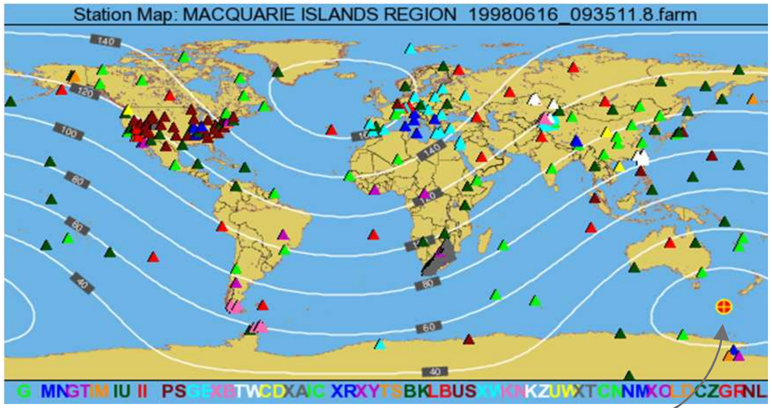
Seismic data for global models

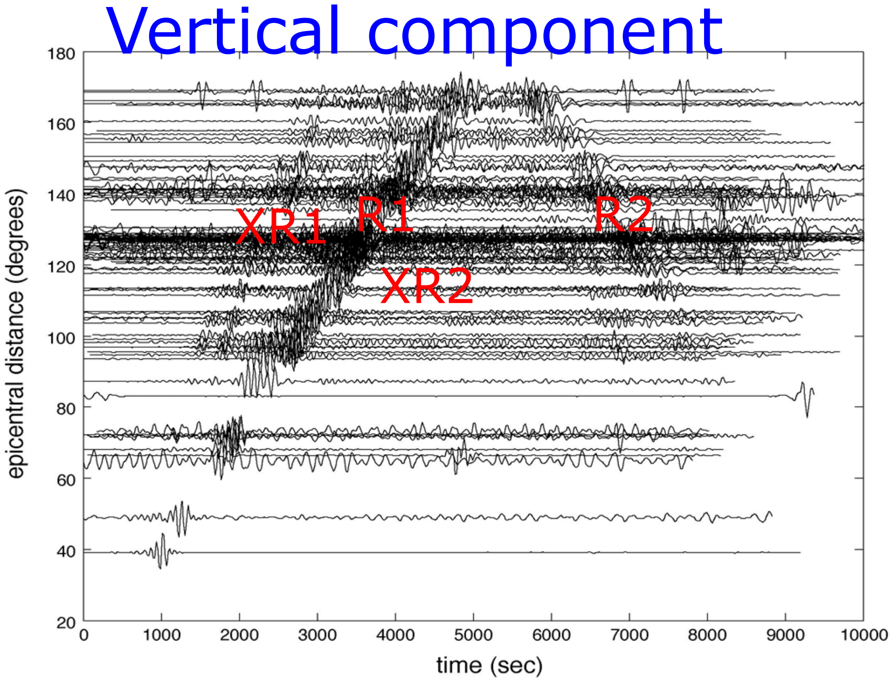
- **Travel times** from ISC or EHB catalog (10^6 P, 10^5 S arrivals)
- Good lower mantle coverage, but only partial upper mantle coverage
- Inclusion of diffracted and later arriving phases may increase resolution in the upper mantle (Grand 2000)

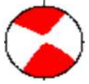


Seismic data for global models

- **Long period and broadband waveforms**
- Good global coverage
- Resolution better than 1000 km at surface
- V_S global models





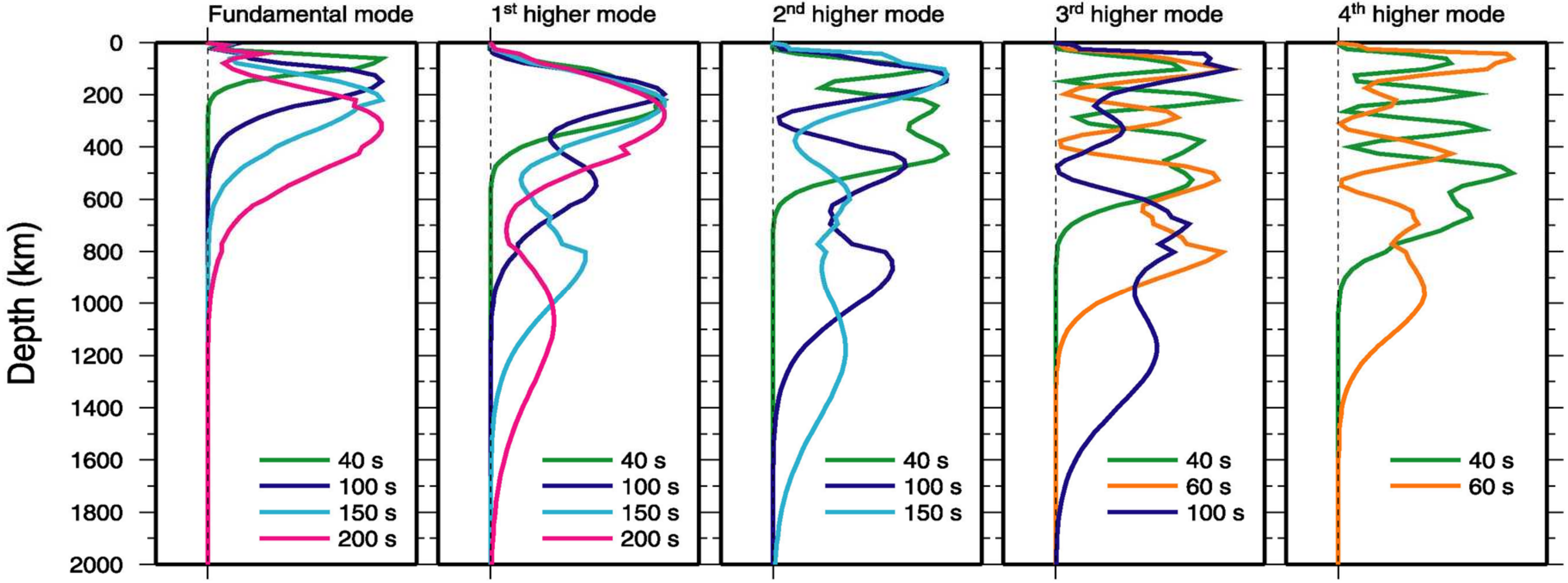


filtered: lp 60s (~16mHz) cutoff (80s corner frequency)
hp ~170s (~6mHz) (400s corner frequency)

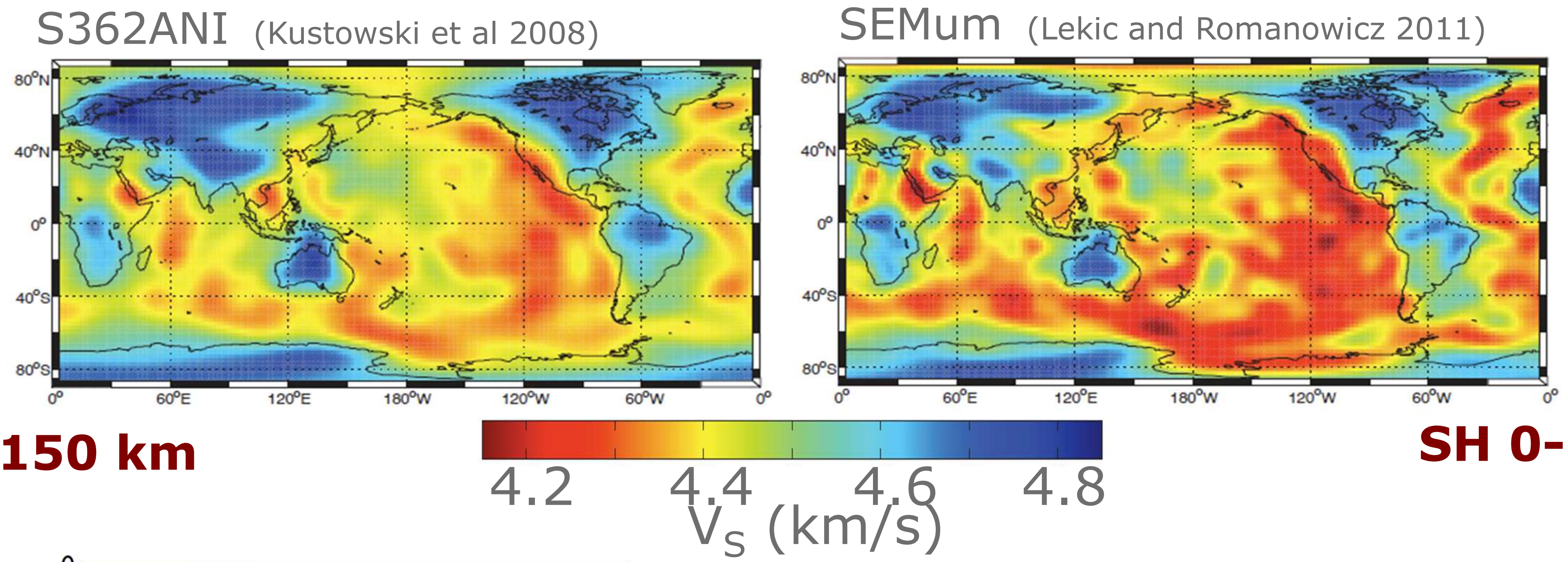
Seismic data for global models

- **Long period and broadband waveforms**
- Good global coverage
- Resolution better than 1000 km at surface
- V_S global models

Rayleigh waves 1-D sensitivity kernels



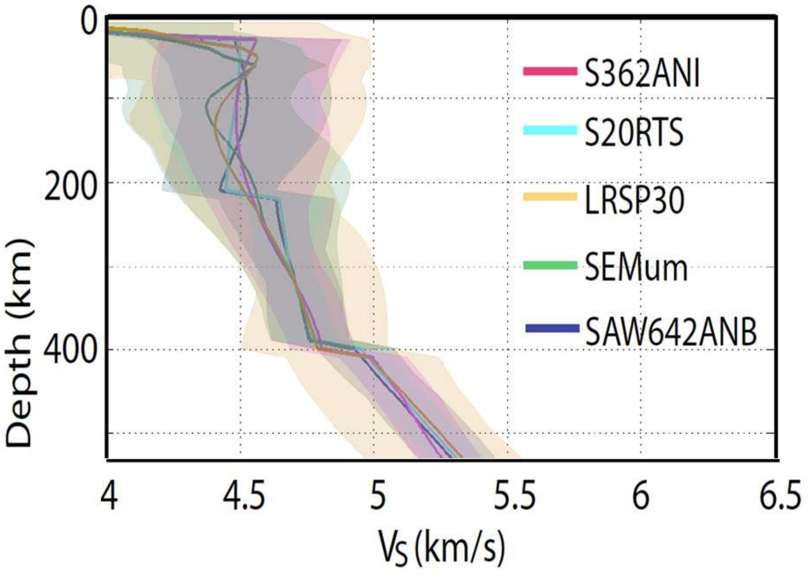
✓ **Top 300 km structure well constrained by fundamental modes.** Including higher order modes improves deeper resolution


S362ANI (Kustowski et al 2008)

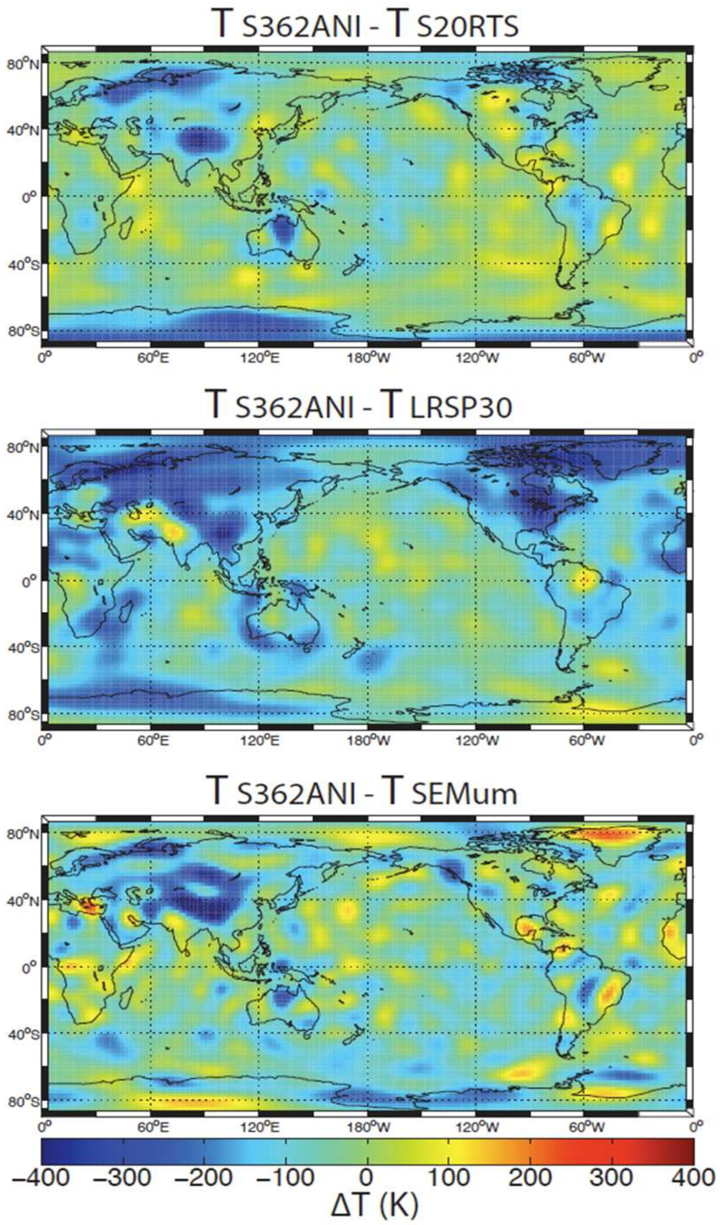
SEMum (Lekic and Romanowicz 2011)

150 km

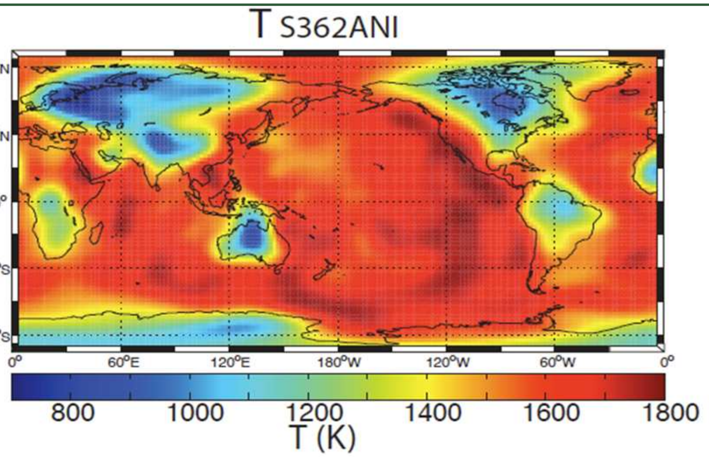
SH 0-24



- **Long Wavelength structure is well constrained, but ΔV_S depend on regularization schemes**
- **$\langle V_S \rangle(z)$ depends on starting reference model (Cammarano et al. 2005, 2007, 2009, Cobden et al. 2009)**



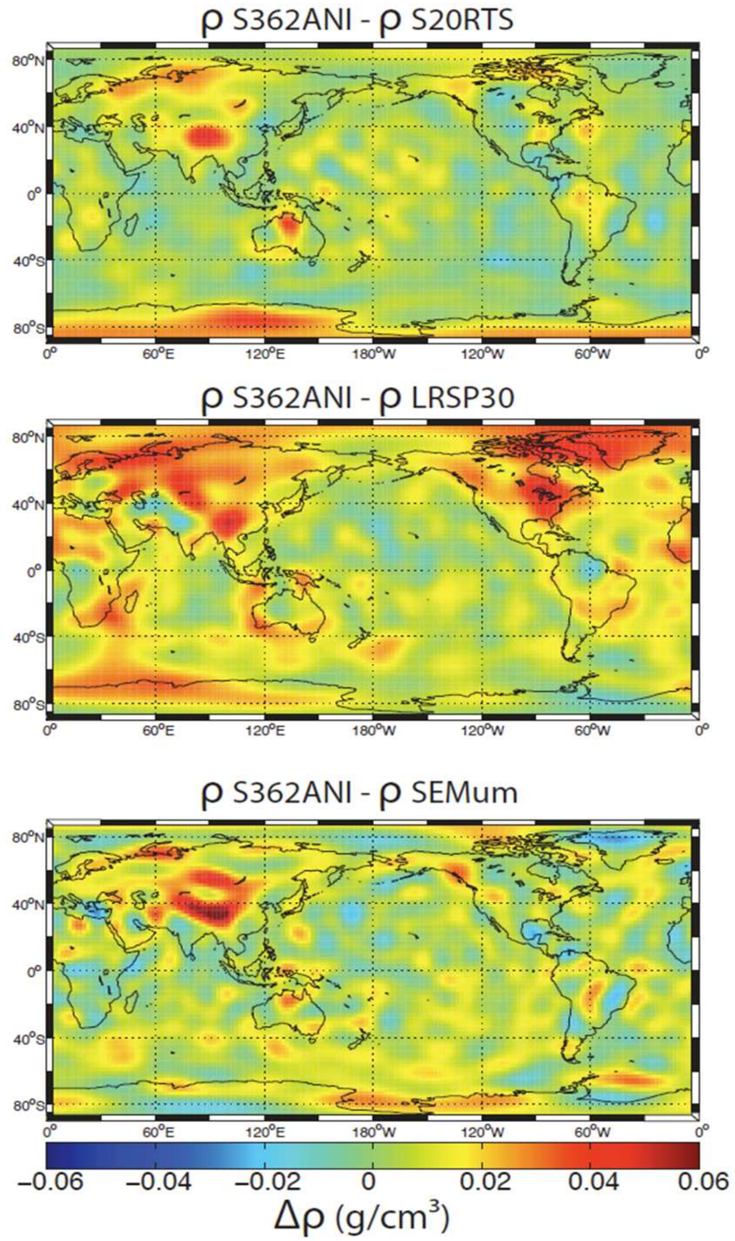
Cammarano et al., GJII 2011



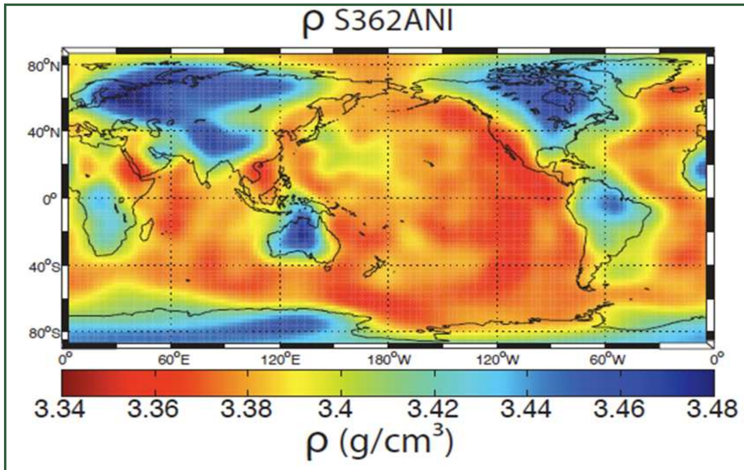
Pyrolite Composition

150 km

- **ΔT between different V_S models can go as high as ±400K**



Cammarano et al., GJII 2011

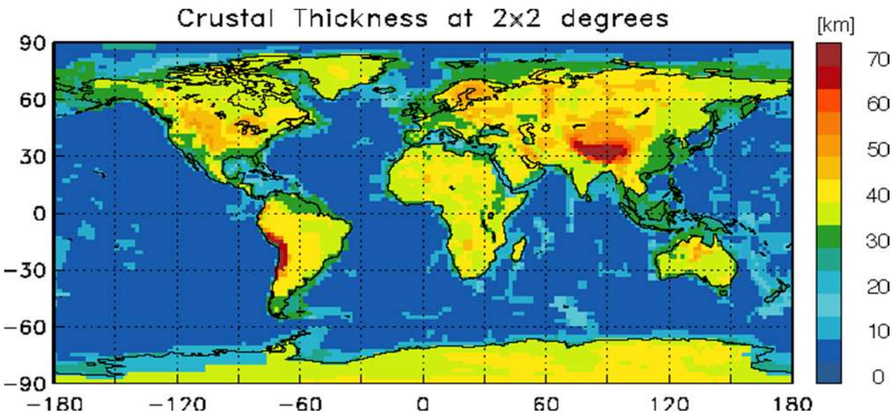


Pyrolite Composition

150 km

- **ΔT between different V_S models can go as high as ±400K**
- **densities vary of ±0.06 g/cm3**

Modeling the petrological lithosphere

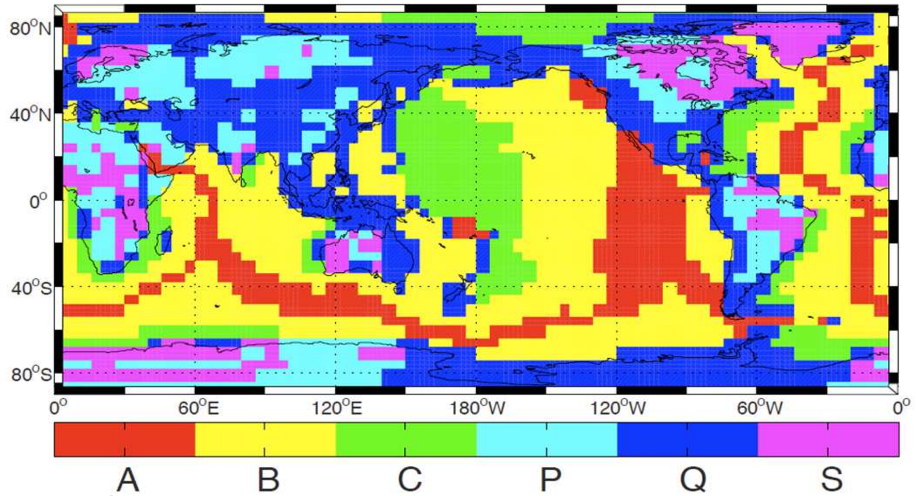


INGREDIENTS:

- **Crustal structure: CRUST2.0 (Bassin et al., 2000)**
- Tectonic regionalization on continents
- Compositions for lithosphere from petrology (Griffin et al. 2009, Workman & Hart 2005)
- Lithosphere (LAB) thickness based on T inversion and/or age-dependent LAB for oceans

Modeling the petrological lithosphere

GTR1 regionalization



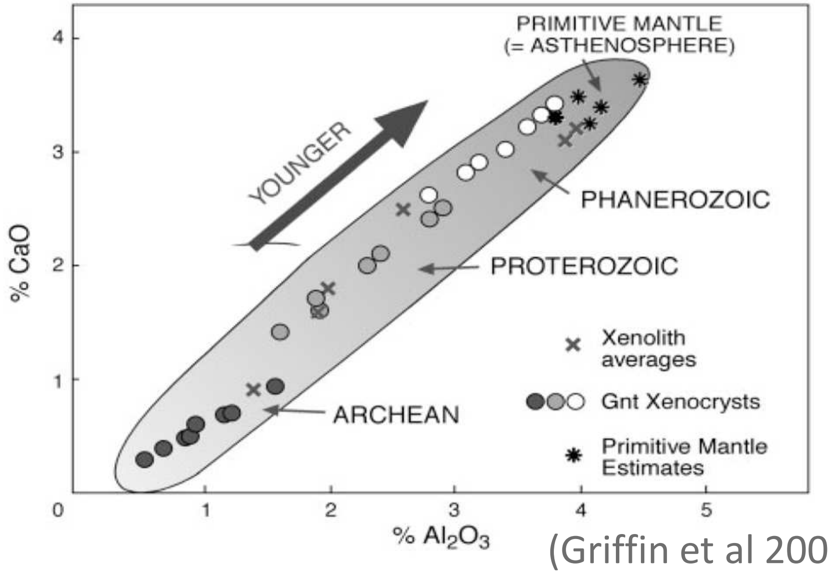
Jordan, 1981

S = Precambrian shield and platforms
Q = Phanerozoic orogenic zones and magmatic belts
P = Phanerozoic platforms

INGREDIENTS:

- **Crustal structure: CRUST2.0 (Bassin et al., 2000)**
- **Tectonic regionalization on continents**
- **Compositions for lithosphere from petrology** (Griffin et al. 2009, Workman & Hart 2005)
- **Lithosphere (LAB) thickness based on T inversion and/or age-dependent LAB for oceans**

Modeling the petrological lithosphere



(Griffin et al 2009)

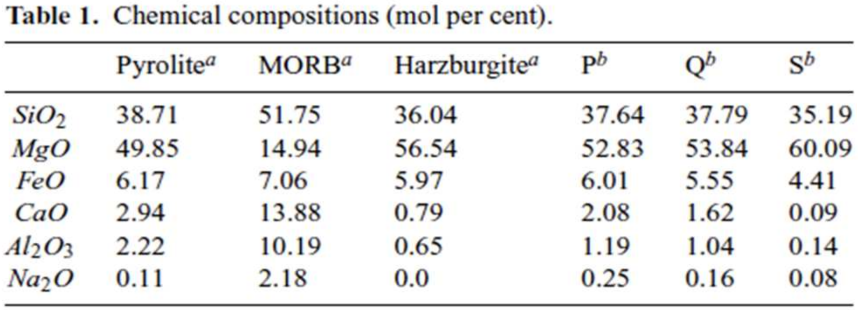


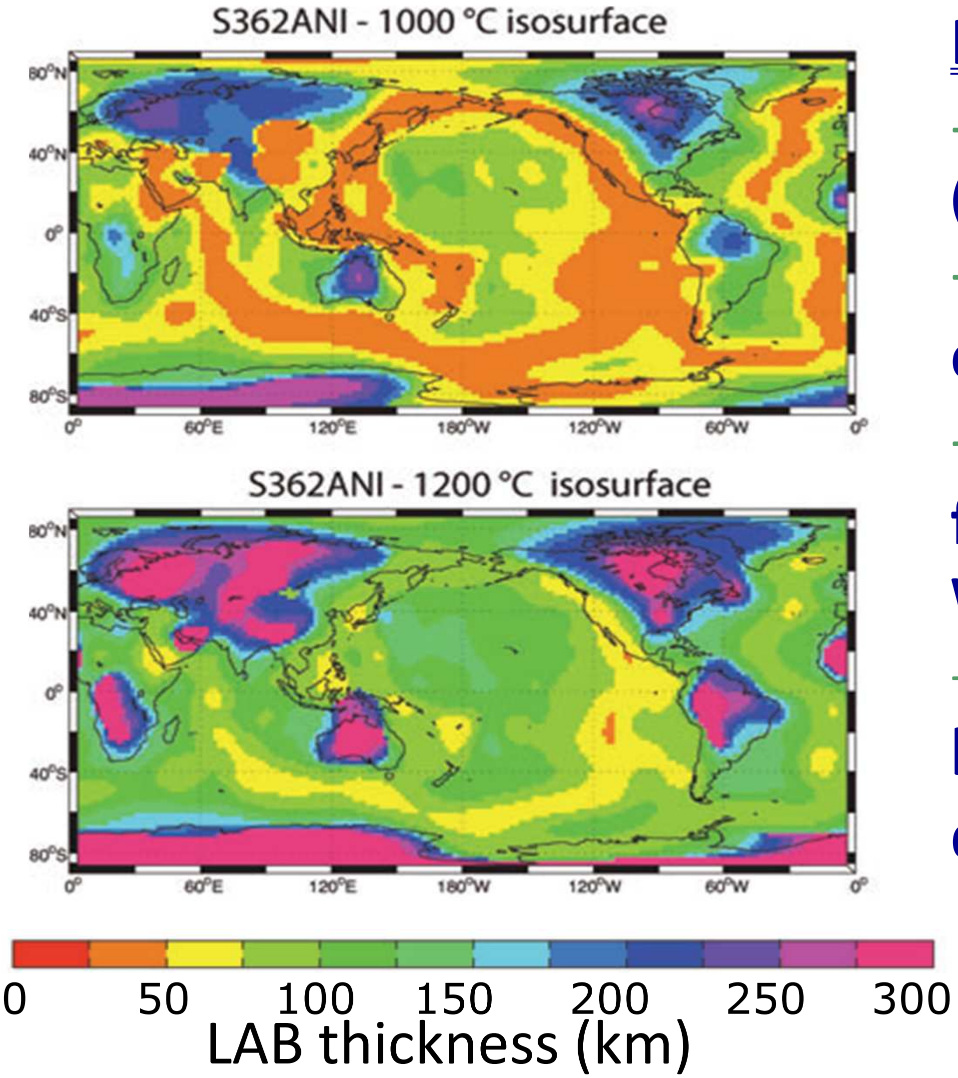
Table 1. Chemical compositions (mol per cent).

	Pyrolite[a]	MORB[a]	Harzburgite[a]	P[b]	Q[b]	S[b]
SiO_2	38.71	51.75	36.04	37.64	37.79	35.19
MgO	49.85	14.94	56.54	52.83	53.84	60.09
FeO	6.17	7.06	5.97	6.01	5.55	4.41
CaO	2.94	13.88	0.79	2.08	1.62	0.09
Al_2O_3	2.22	10.19	0.65	1.19	1.04	0.14
Na_2O	0.11	2.18	0.0	0.25	0.16	0.08

INGREDIENTS:

- **Crustal structure: CRUST2.0 (Bassin et al., 2000)**
- **Tectonic regionalization on continents**
- **Compositions for lithosphere from petrology (Griffin et al. 2009, Workman & Hart 2005)**
- **Lithosphere (LAB) thickness based on T inversion and/or age-dependent LAB for oceans**

Modeling the petrological lithosphere

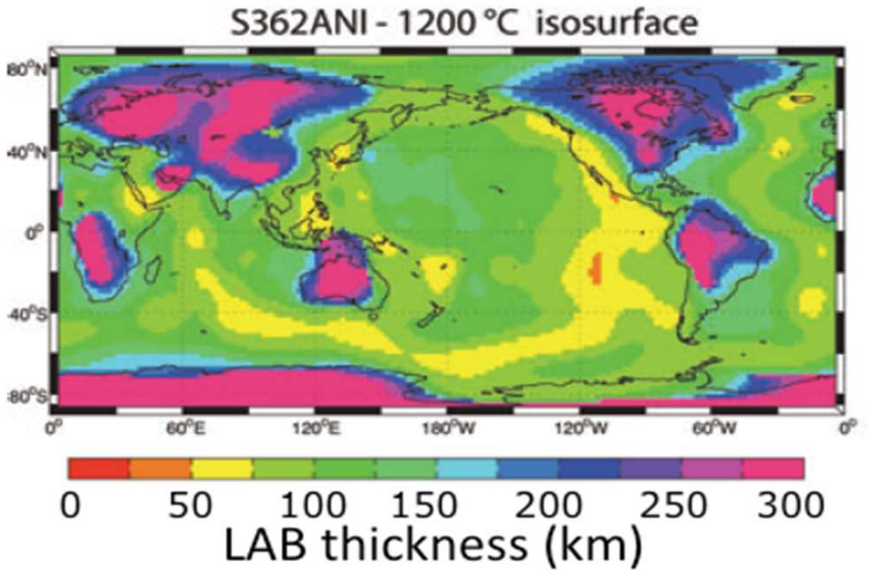


Cammarano et al., GJII 2011

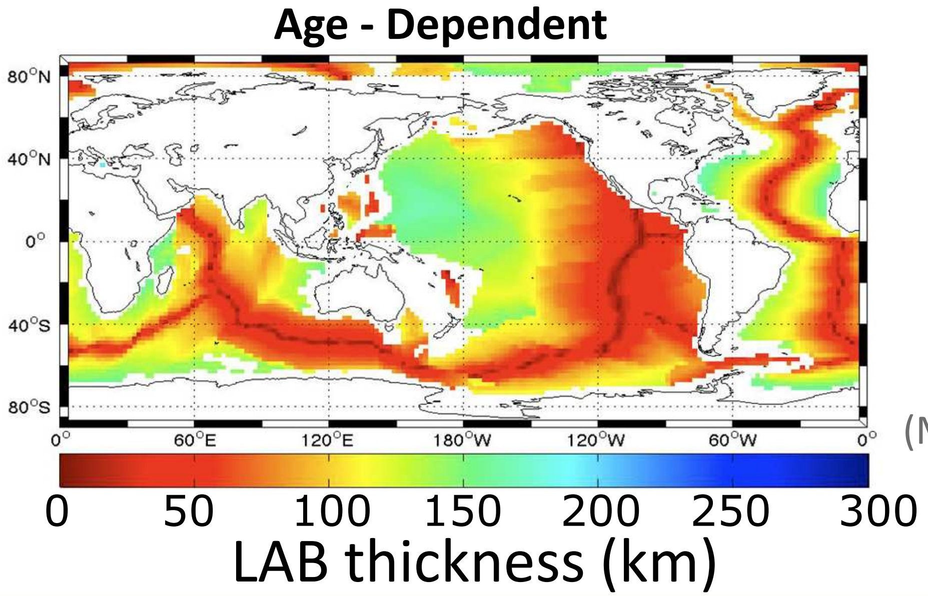
INGREDIENTS:

- **Crustal structure: CRUST2.0 (Bassin et al., 2000)**
- **Tectonic regionalization on continents**
- **Compositions for lithosphere from petrology (Griffin et al. 2009, Workman & Hart 2005)**
- **Lithosphere (LAB) thickness based on T inversion and/or age-dependent LAB for oceans**

Modeling the petrological lithosphere



Cammarano et al., GJII 2011

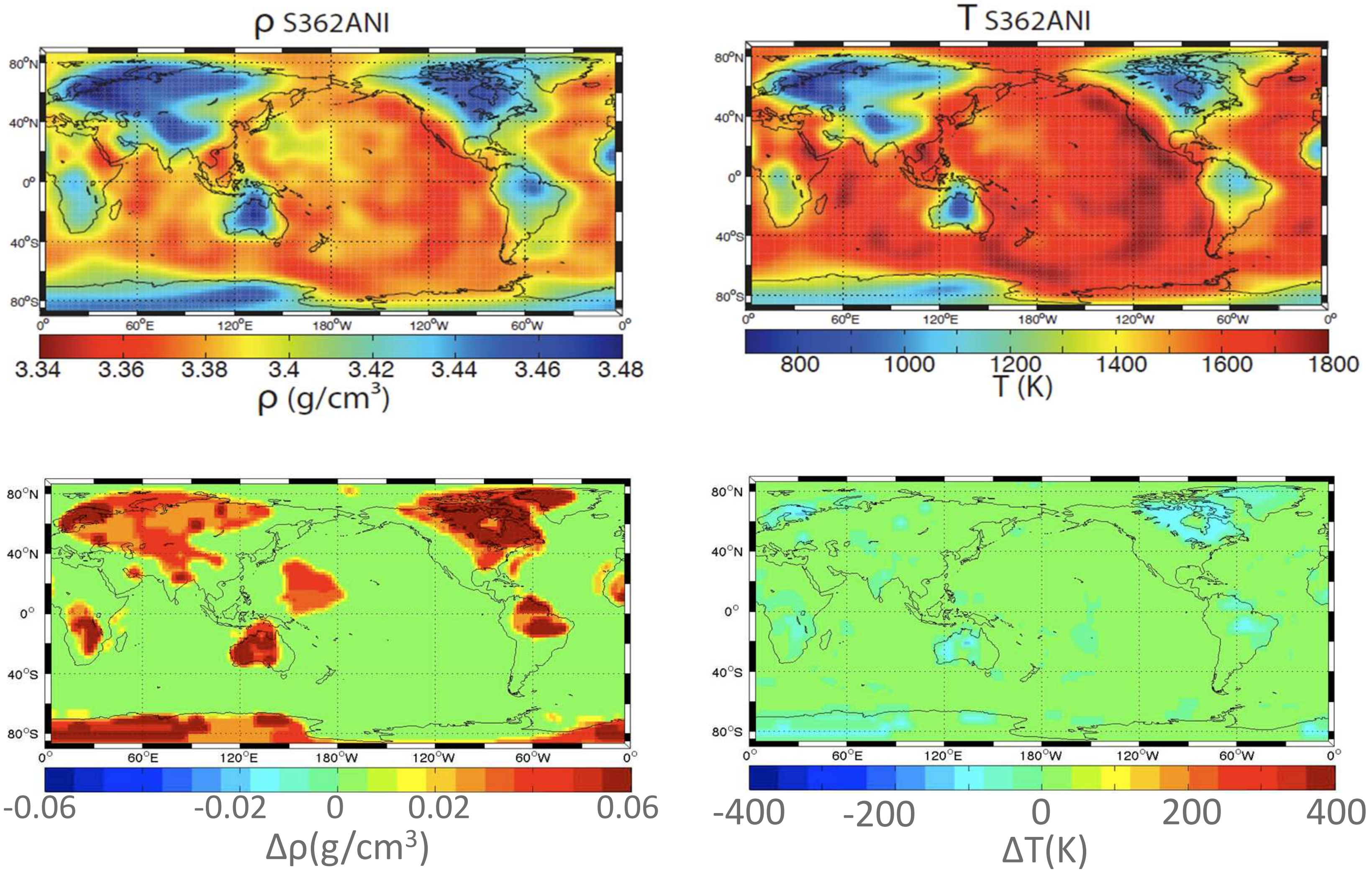


(Müller et al 2008)

INGREDIENTS:

- **Crustal structure: CRUST2.0 (Bassin et al., 2000)**
- **Tectonic regionalization on continents**
- **Compositions for lithosphere from petrology (Griffin et al. 2009, Workman & Hart 2005)**
- **Lithosphere (LAB) thickness based on T inversion and/or age-dependent LAB for oceans**

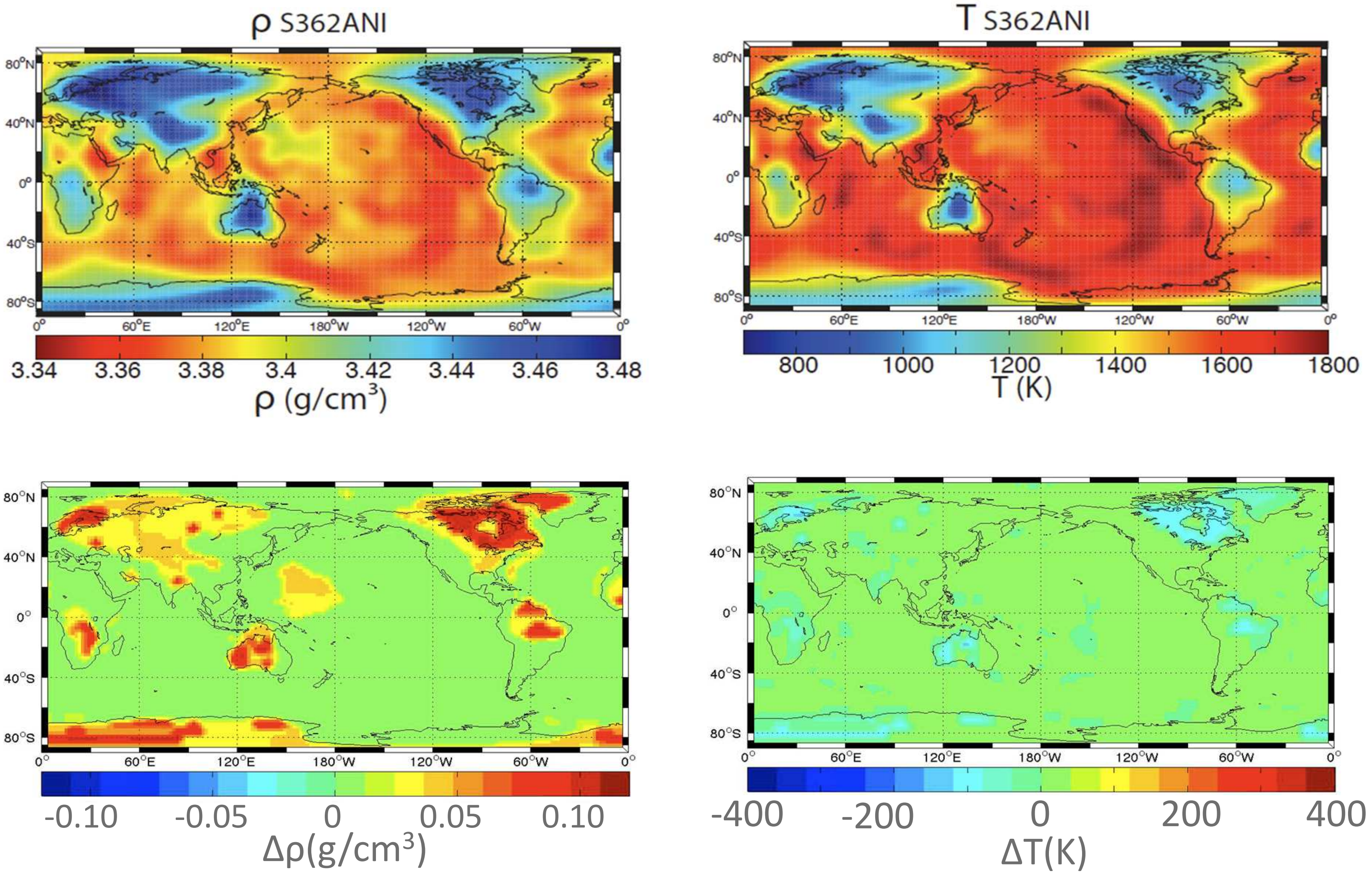
150 km



Cammarano et al., GJI 2011

- ➢ Modeling the depleted compositions of continental lithosphere does not change significantly T interpretation (> ~100K), but has a large effect on ρ (< ~ $0.1 g/cm^3$) in cratonic areas

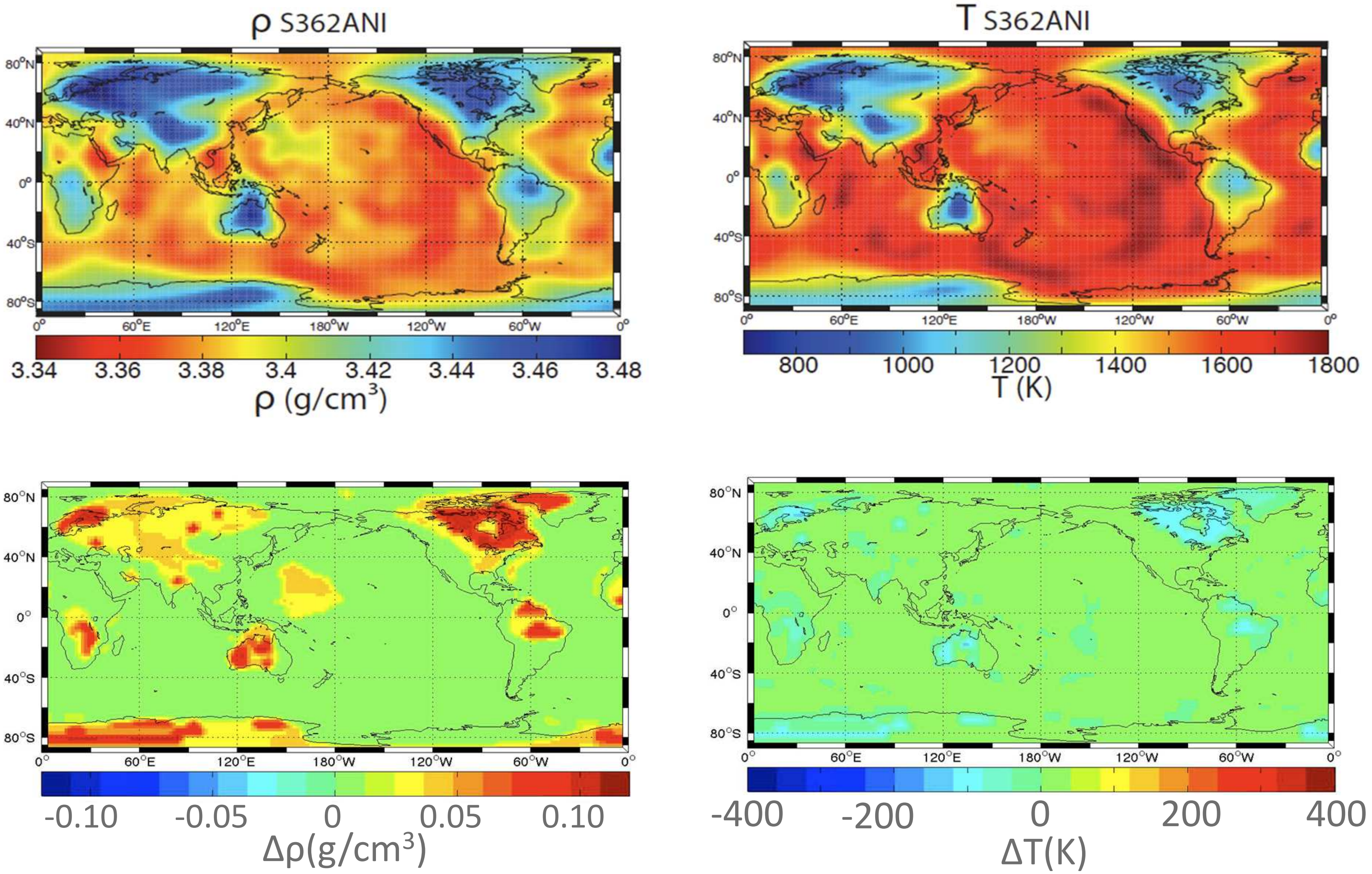
150 km



Cammarano et al., GJI 2011

- ➢ Modeling the depleted compositions of continental lithosphere does not change significantly T interpretation (> ~100K), but has a large effect on ρ (< ~ $0.1 g/cm^3$) in cratonic areas

150 km

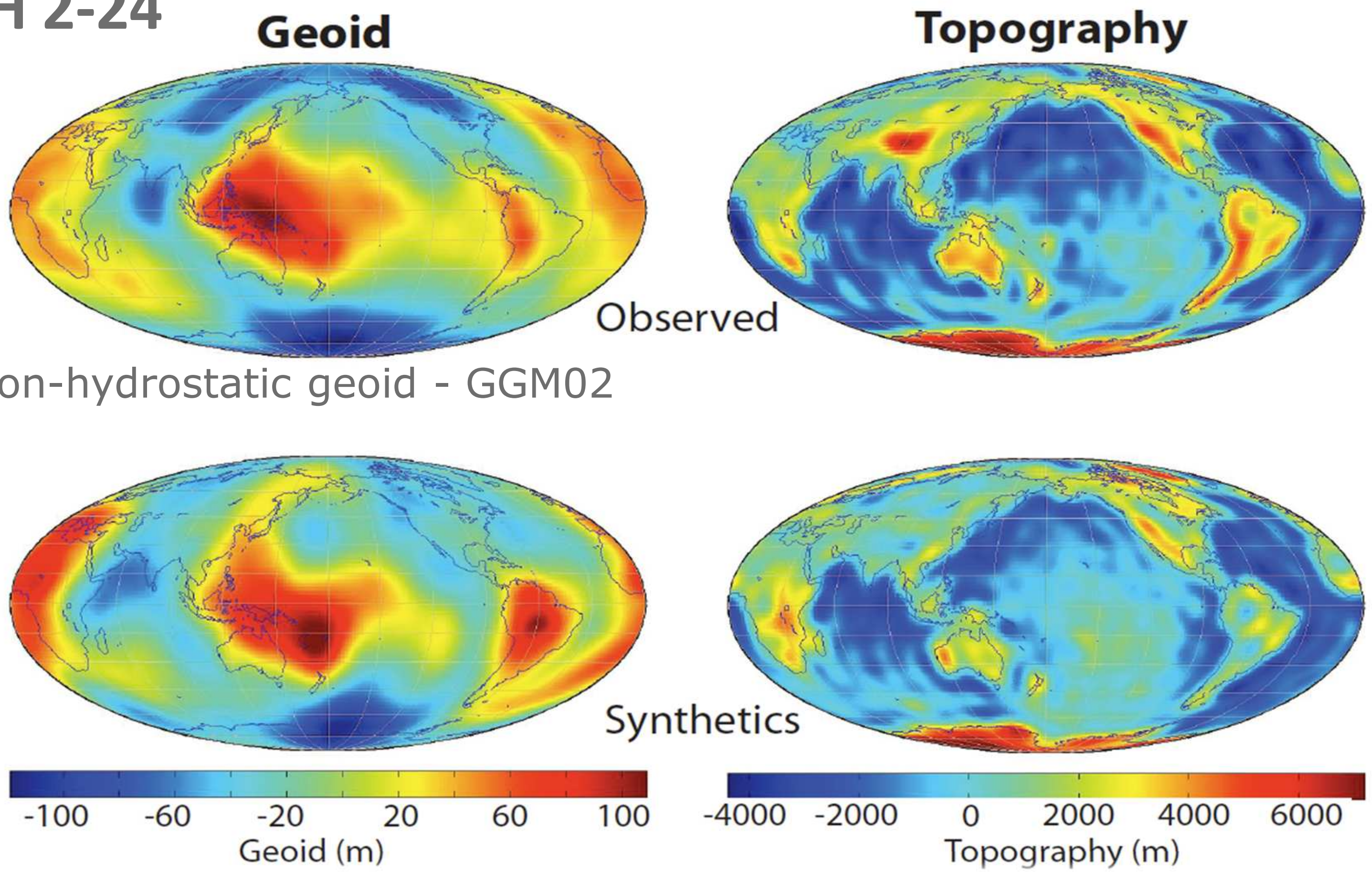


Cammarano et al., GJI 2011

- **How these 3-D ρ structures fit gravity data?**

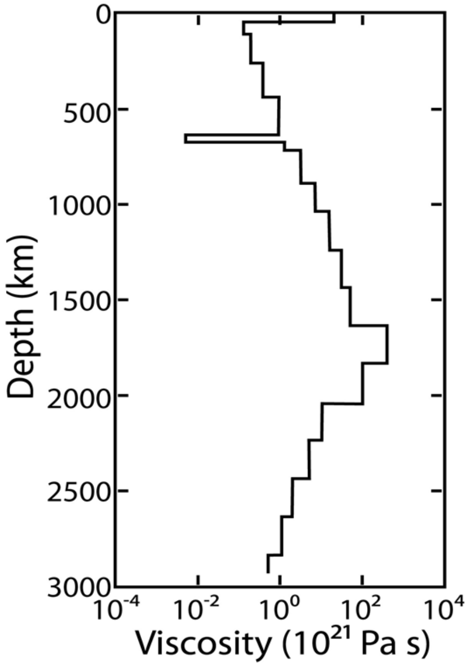
TESTING GEOID AND TOPOGRAPHY

SH 2-24



non-hydrostatic geoid - GGM02

V1



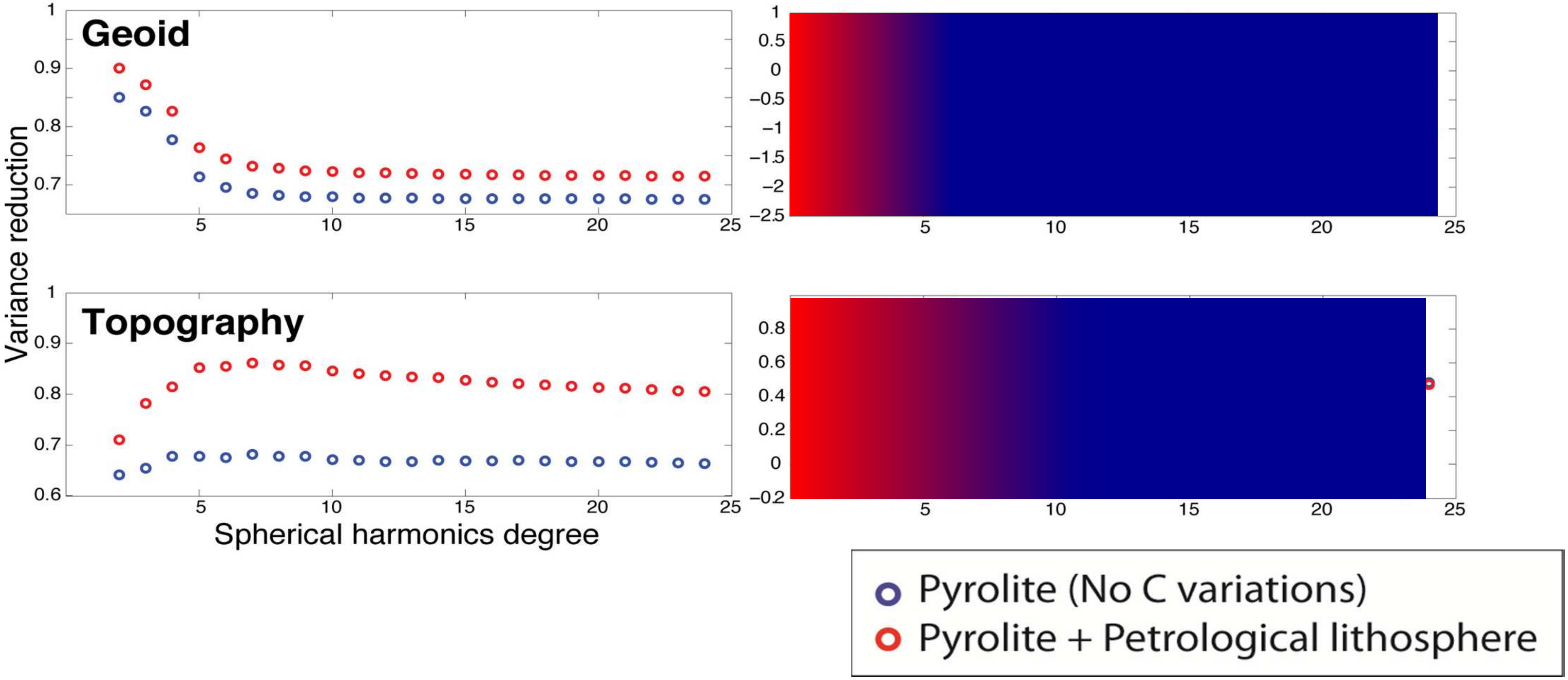
Mitrovica & Forte 2004

S362ANI with pyrolite + petrological lithosphere

- ✓ **Instantaneous mantle flow computed with StagYY** (Tackley 2008)

TESTING GEOID AND TOPOGRAPHY

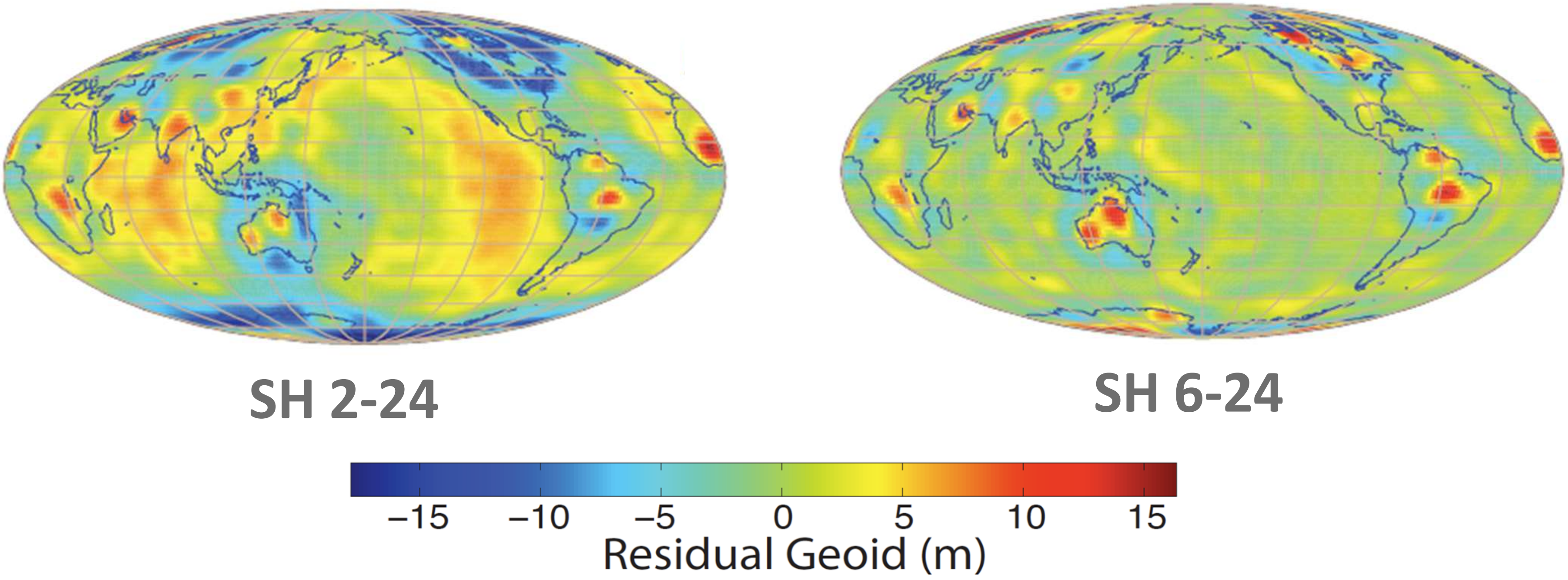
Effects of petrological lithosphere



- **Fits overall improves**, but situation **changes** if we do not consider long wavelength.

Testing geoid and topography

Geoid with petrological lithosphere – Geoid without



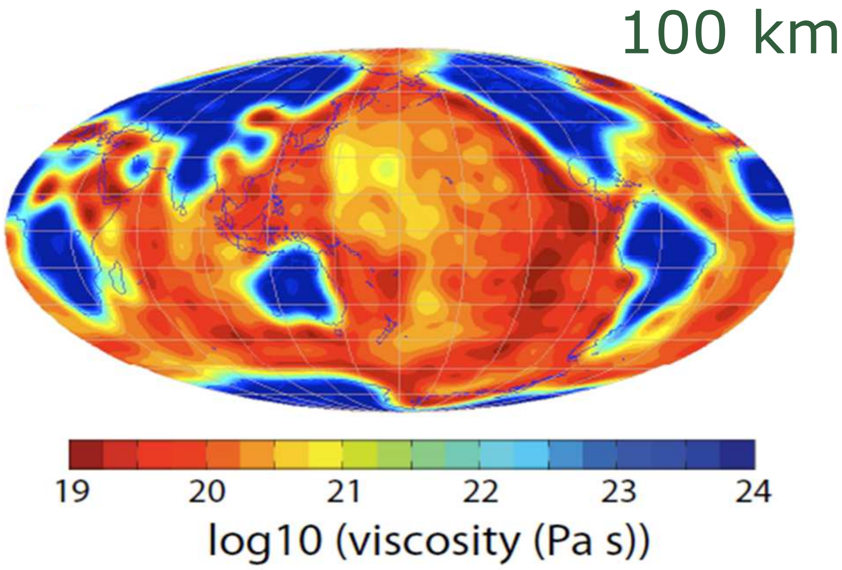
SH 2-24

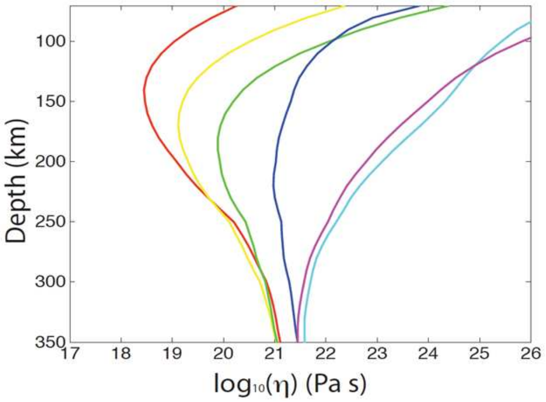
SH 6-24

- Longest λ signal is mainly associated with oceanic lithosphere ➔ this improves the fit

- Signal at SH degree > 5 is associated with continents ➔ this reduces the fit

- ➢ Lateral variations in viscosity cannot explain the discrepancy
➔
even extreme 3-D viscosity structures (up to 6 orders of magnitude of lateral variations) do not change the trend due to the density structure of the petrological lithosphere





- ➢ Average Composition of the continental lithosphere is less depleted (less chemical buoyant) of what modeled here, based on petrological constraints.

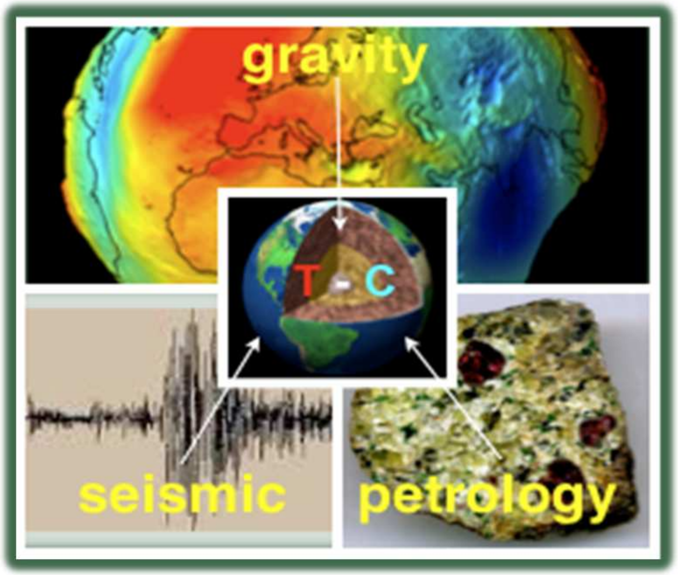
Conclusions

- **Introducing lateral C variations** (with a petrological lithosphere) **does not affect much the thermal interpretation** of seismic models, but modifies the density distribution → **Adding gravity** is crucial

- **The largest uncertainties on T structure of the lithosphere are due to limited seismic resolution**
  - ✓ Differences between models translate into large T and ρ variations

- **Accounting for a petrological lithosphere improves fit to geoid and topography**, but a first-order continental lithosphere worsens the fit
  - ⇒**average composition of continental lithosphere is less depleted (less chemical buoyant)** than what inferred from petrological constraints

An interdisciplinary approach is fundamental



❖ Mapping the thermal and compositional structure of the continental lithospheric mantle

-**Improve T-C interpretation with a combined, iterative, inversion of seismic waveforms and gravity data** (including anisotropy and accounting for non-linear crustal corrections)

-**Forward tests of effects of C variations** (including mineralogical phase transitions) on high-frequency seismic data

PhDs: Andrea Tesoniero, Mattia Guerri
Plus several external collaborations:
Mark van der Meijde, Lapo Boschi, Tarje Nissen-Meyer, Paul Tackley, Sergio Speziale, Hauke Marquardt, …