Thermochemical Tomography of the Lithosphere from Multi-observable Probabilistic Inversions

MG3 Macquarie's Geophysics and Geodynamics Group

CCFS

GEMOC

Australian National University

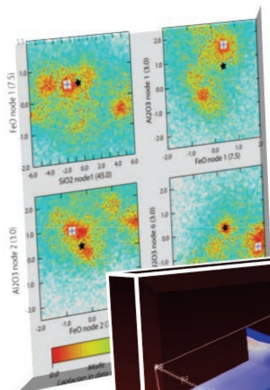
ETH

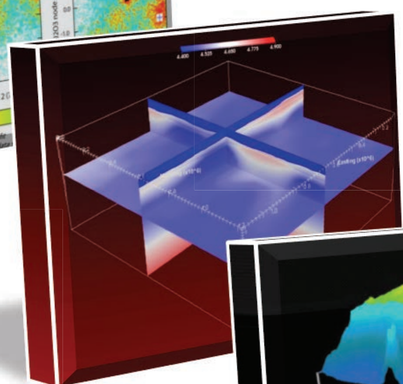
Juan Carlos Afonso

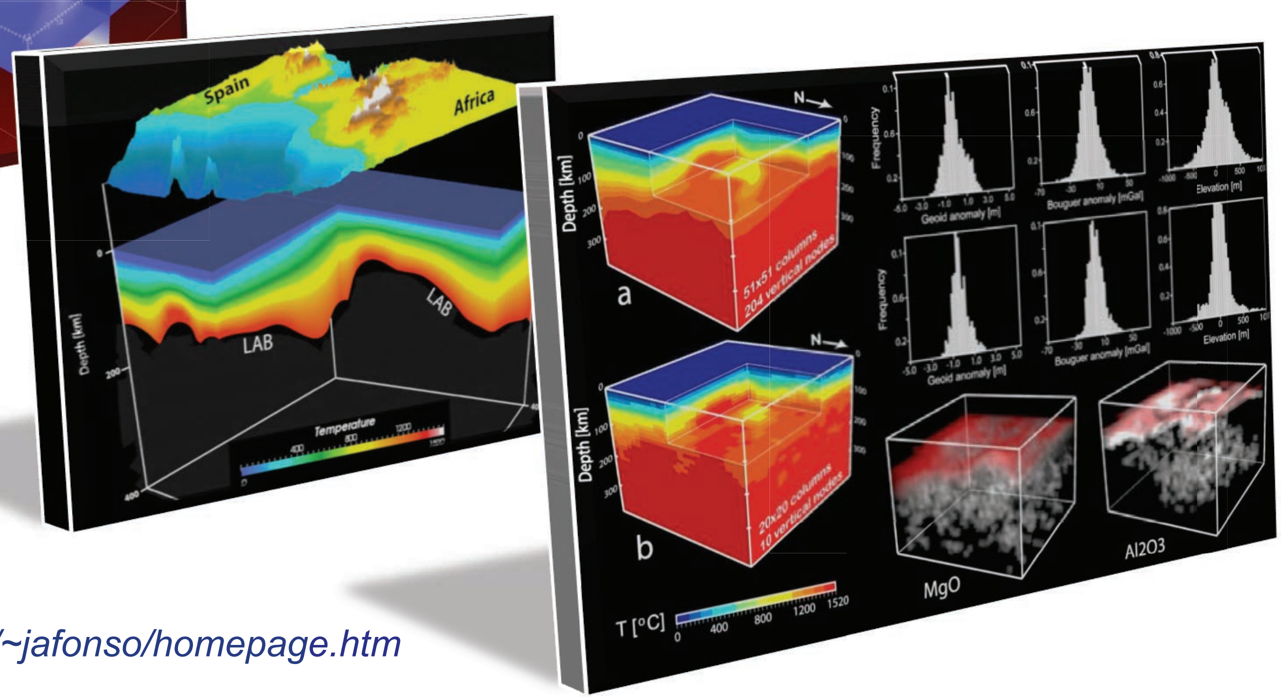
CCFS-GEMOC, Macquarie University, Sydney, Australia.

<u>In collaboration with</u>:

Javier Fullea, Yingjie Yang, Nick Rawlinson, James Connolly, Alan G. Jones, Bill Griffin and Sue O'Reilly

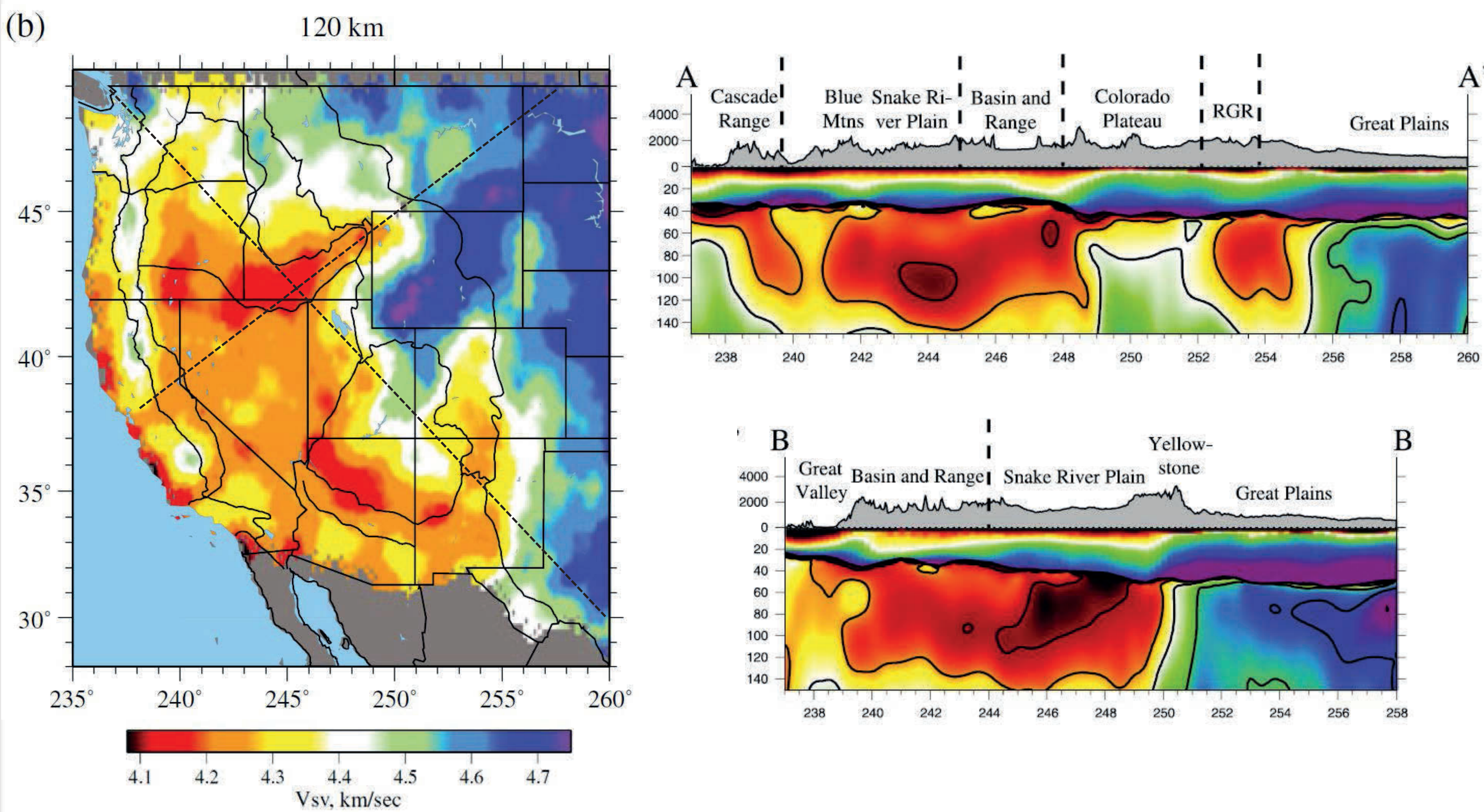






http://eps.mq.edu.au/~jafonso/homepage.htm

- What is the nature of the heterogeneity “observed” in the mantle?



Shen et al., 2013, JGR

1) An interesting problem

- What is the nature of the heterogeneity "observed" in the mantle?

Exploration, targeting systems *(cf. McCuaig et al., Ore Geol. Rev., 2010)*

Defining the LAB *(cf. Jones et al., Lithos, 2010)*

Geodynamic modeling (buoyancy from tomography models)

Lithospheric modeling and evolution (TopoEurope, crustal production

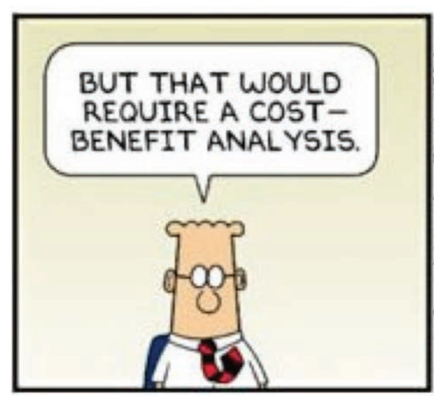
Dynamic topography (as we learned yesterday!!)

Craton stabilization… etc…etc…etc

2) The main goals…

- **Predictive and *more explicative* models at regional scales (<~ 1000 x 1000 km) and depths < 600 km.**
- **How much can we really extract from high-resolution geophysical datasets in terms of thermal and compositional anomalies?**
- **Realistic uncertainties affecting our predictions**

We would like to work within an *internally consistent, multi-observable, probabilistic* inverse framework



Why a *probabilistic* formalism?

Because the problem at hand is probabilistic in nature

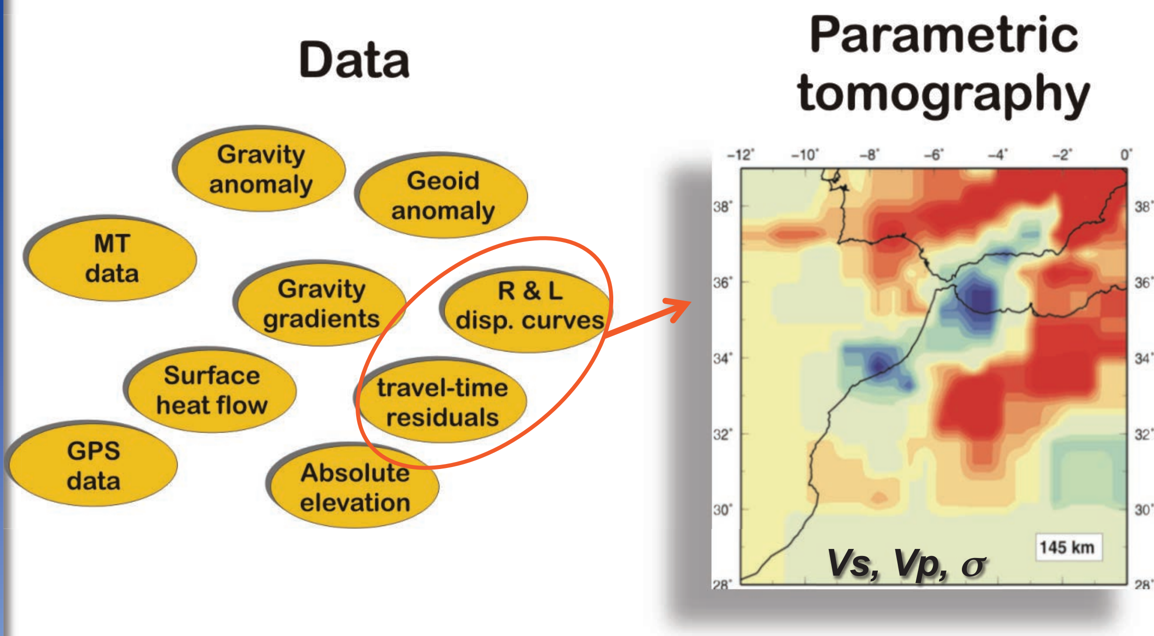
Why *multi-observable*?

Different observables provide information on different aspects of the problem

Why *internally consistent*?

So you cannot tweak parameters as you please to make your model look better!!

3) Multi-Observable Thermochemical Tomography: why and how?



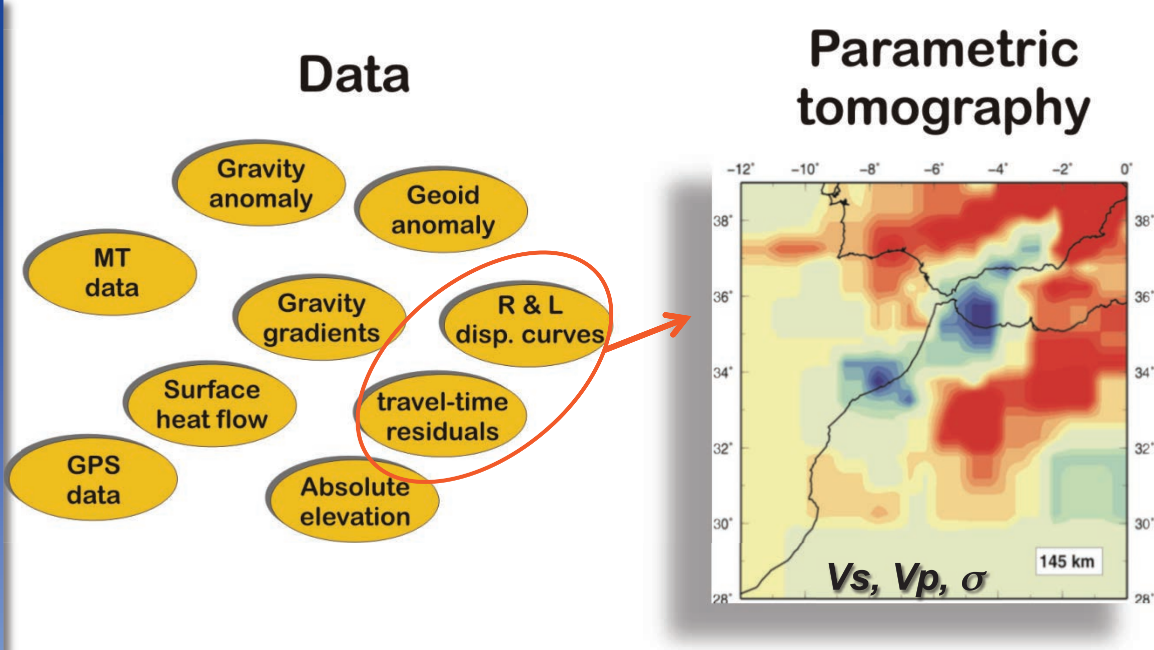
MG3 Macquarie's Geophysics and Geodynamics Group

GEMOC

Thermochemical Tomography of the Lithosphere from Multi-Observable Probabilistic Inversions

CCFS

3) Multi-Observable Thermochemical Tomography: why and how?



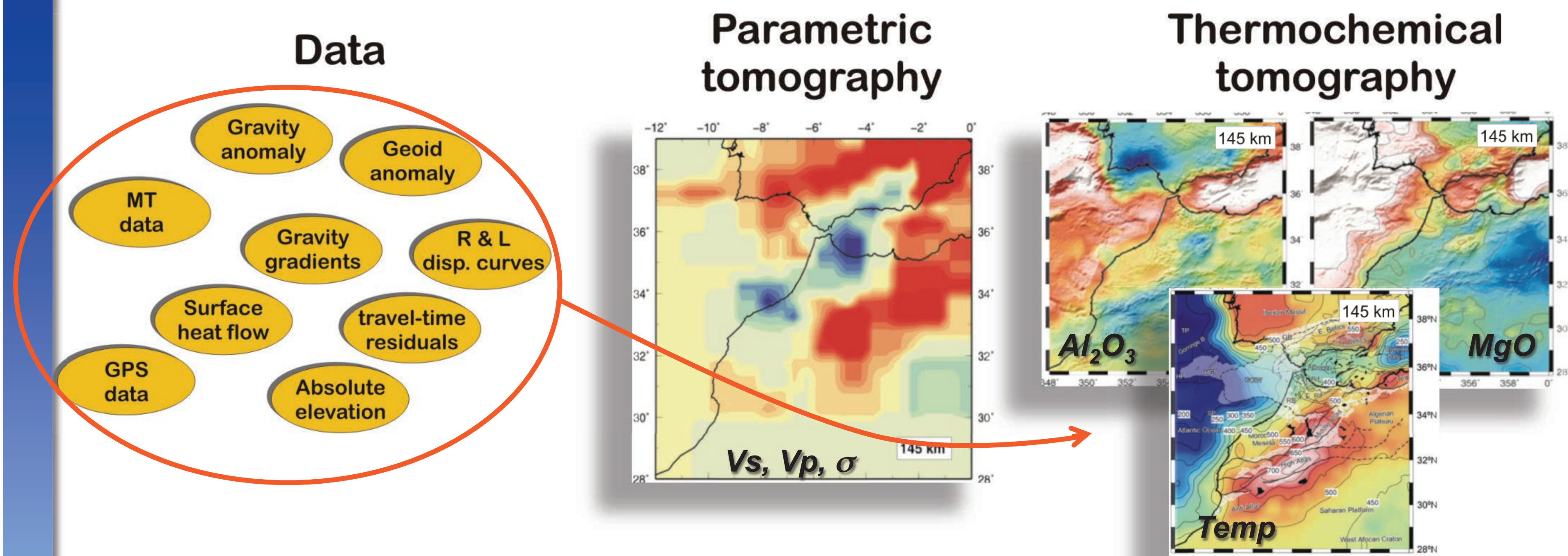
There is abundant complementary information available (e.g. satellite-based gravity, topography, geoid, etc)

Technology capabilities in seismology, mineral physics, geochemical analysis, geodynamics, potential fields, and computing power have reached the required stage of sophistication

*Take the next step: from **parametric tomography** to true **thermochemical multi-observable tomography***

Thermochemical Tomography of the Lithosphere from Multi-Observable Probabilistic Inversions

3) Multi-Observable Thermochemical Tomography: why and how?



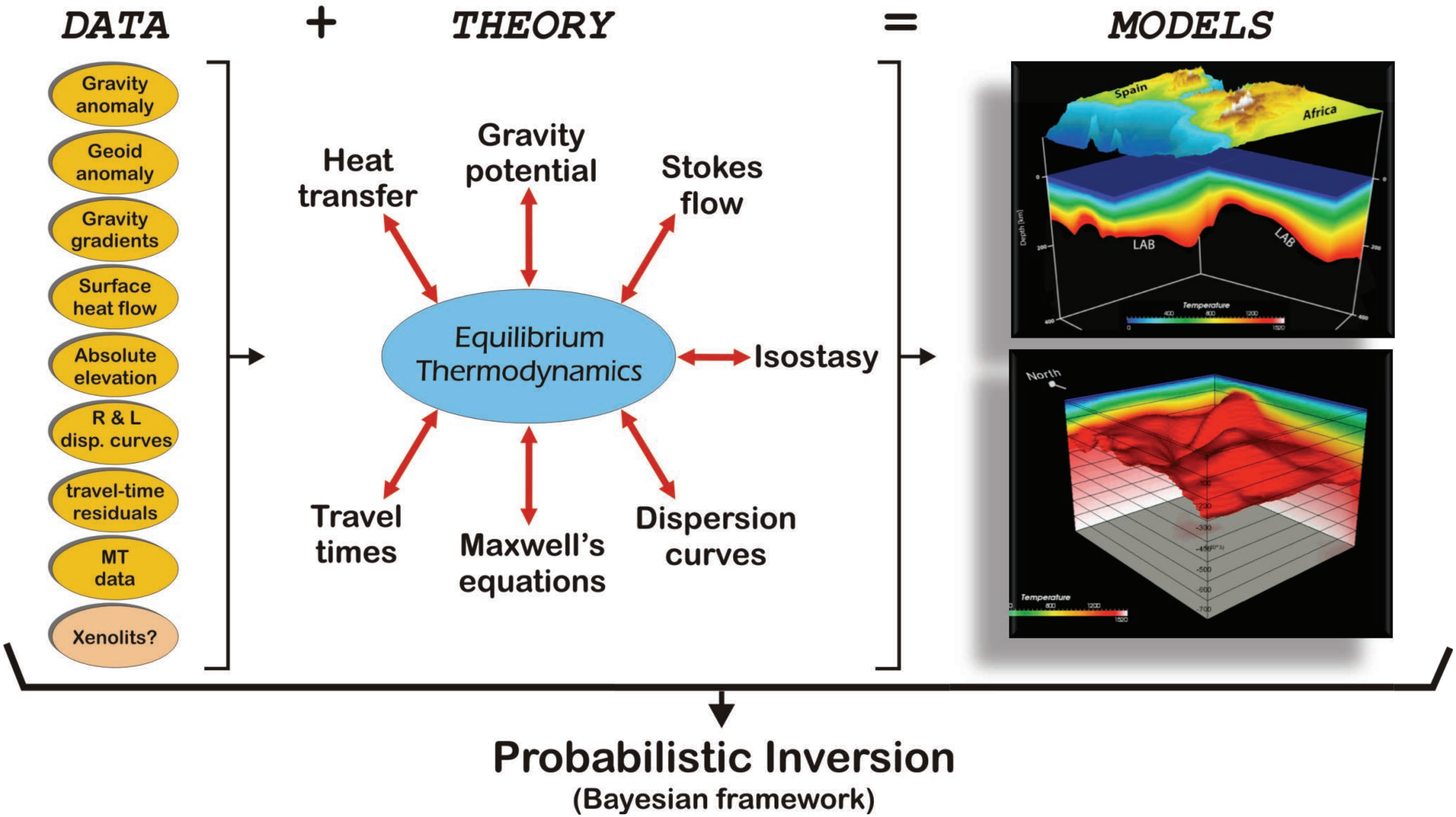
There is abundant complementary information available (e.g. satellite-based gravity, topography, geoid, etc)

Technology capabilities in seismology, mineral physics, geochemical analysis, geodynamics, potential fields, and computing power have reached the required stage of sophistication

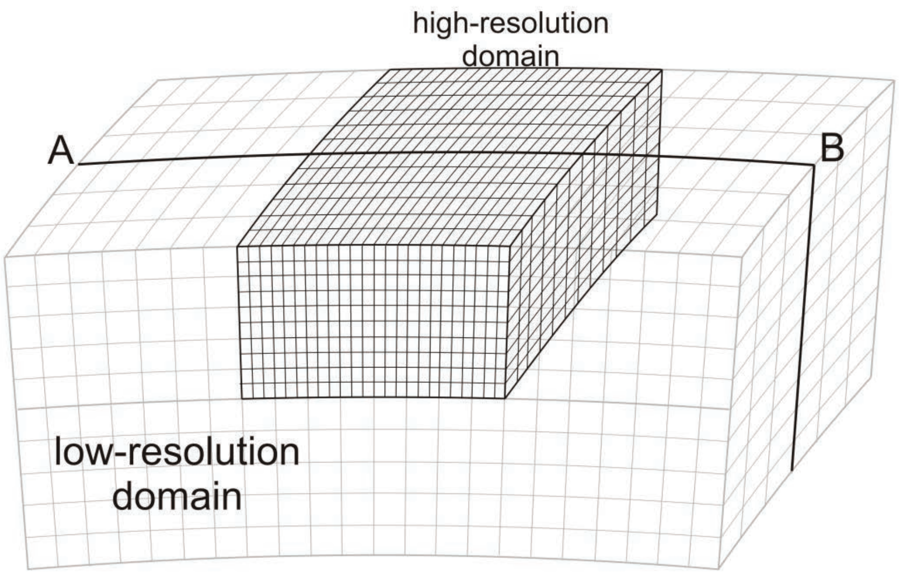
 # This is not a methodological competition, but rather a collaborative step forward in methodology

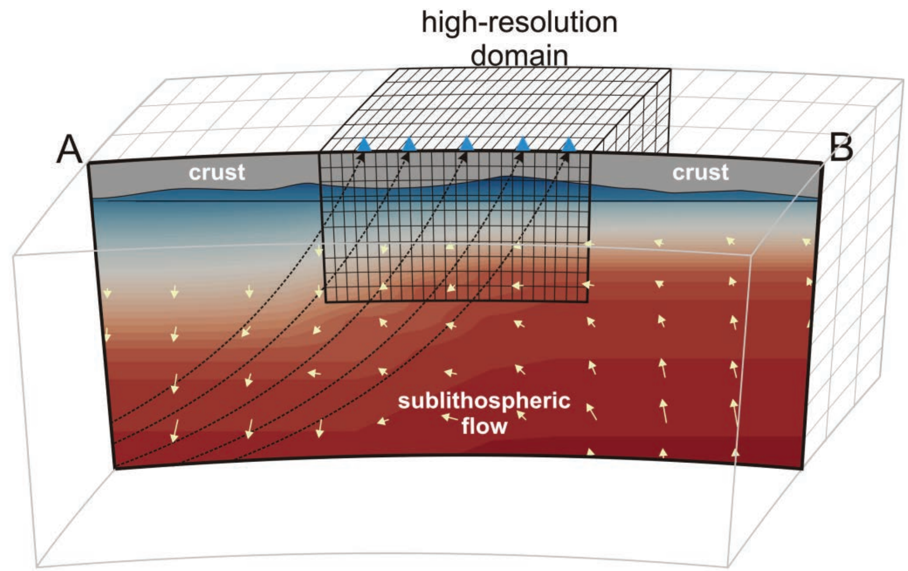
3) Multi-Observable Thermochemical Tomography: why and how?

LitMod_4INV



Body wave tomography and mantle flow… tough problems





The secret is SIMPLE! … not to solve a very complicated problem every time we draw a new model, but every *n* models … but check convergence!

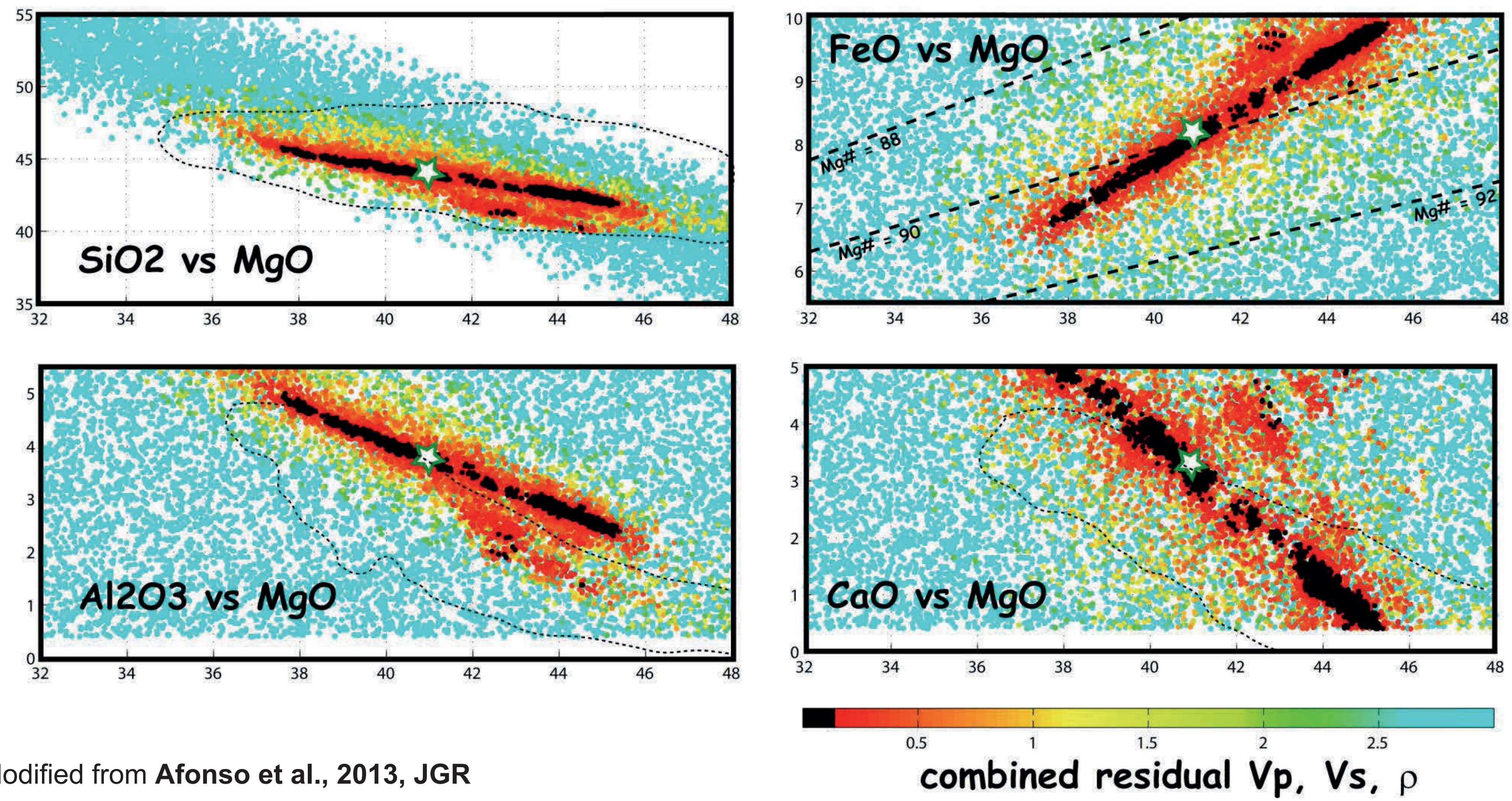
For BWT we're using teleseismic data and a modified version of the Fast Marching Method (Rawlinson and Sambridge, 2005) to compute synthetic travel-time residuals

For the Stokes' flow we are testing a new kind of ultra-fast Stokes solvers based on FEM (w/ G. Rozza & A. Patera, MIT)

Non-unique solutions in compositional space

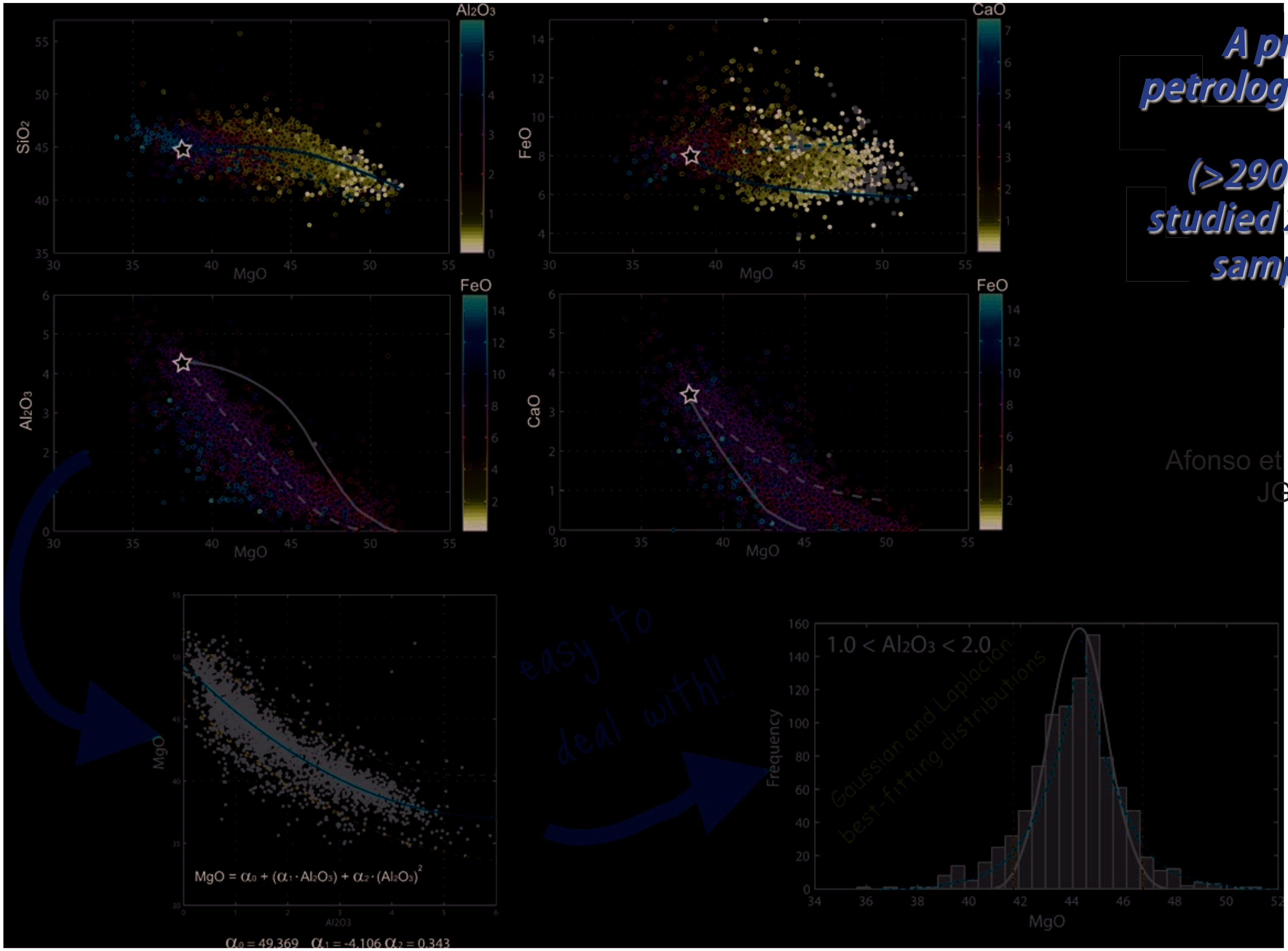
Let's take a "target" composition at T=900ºC and P=1.2 GPa

Acceptable models (NA) without a priori information



Modified from **Afonso et al., 2013, JGR**

Non-unique solutions in compositional space

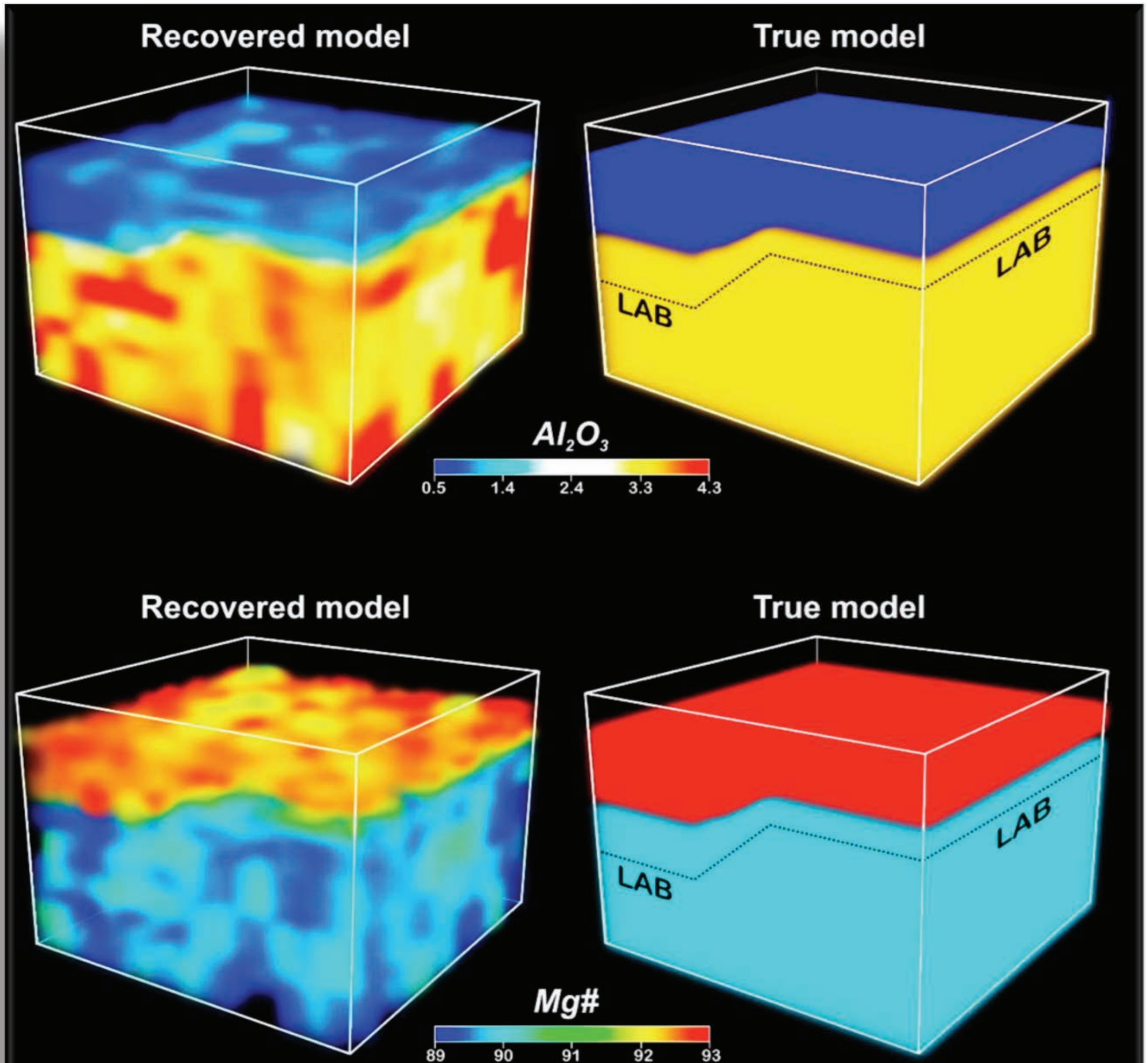


A priori petrological data

(>2900 well studied xenolith samples)

Afonso et al., 2013, JGR

A quick synthetic example:



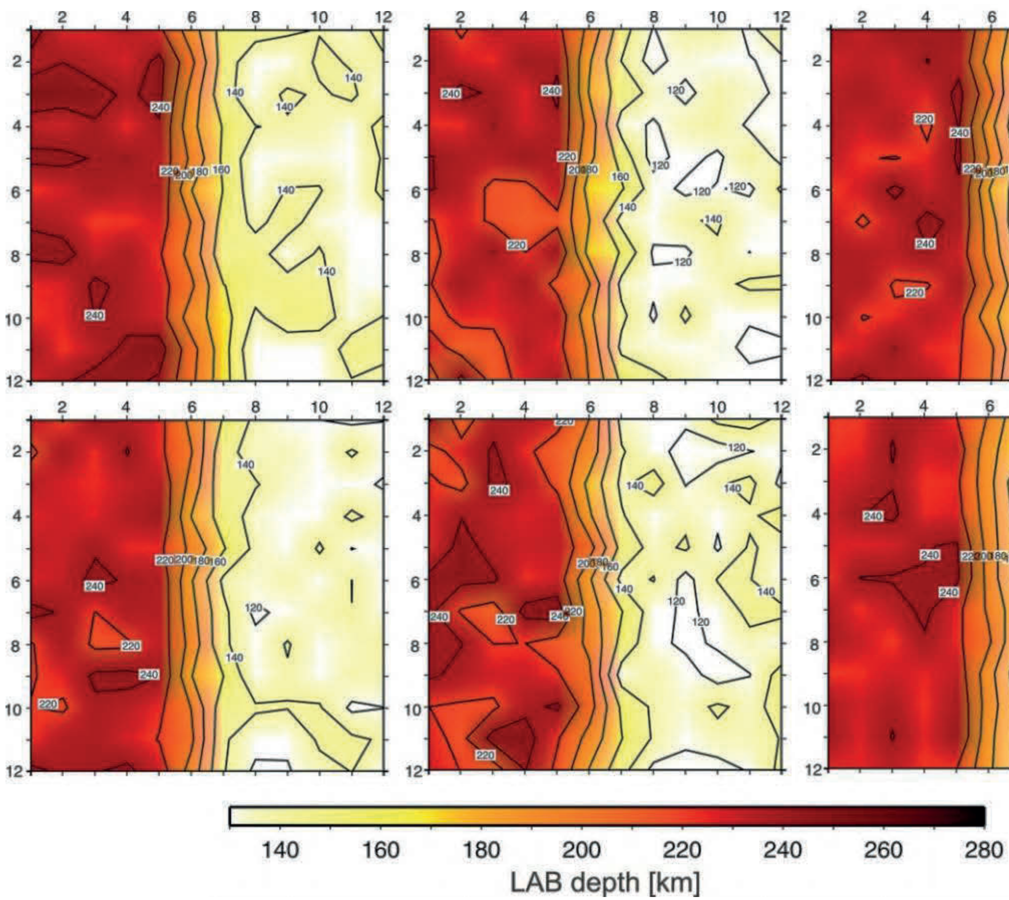
Shown recovered model is the ML only

Note the intrinsic variability associated with a unique model

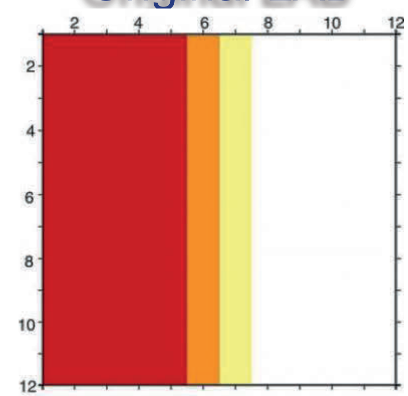
Averaging the PDF would reduce the variability but affects the absolute amplitudes as well

Results for LAB geometry

Six models taken randomly from within 1 STD of the total posterior PDF



Original LAB



Conclusions

Thermodynamically-constrained multi-observable probabilistic inversions are particularly well suited for providing reliable estimates of T and C in the upper mantle

This approach overcomes or minimizes most of the problems affecting more traditional inversion schemes when applied to the current problem

Thermochemical multi-observable tomography is a reality… a computationally expensive one, but we've got supercomputers!

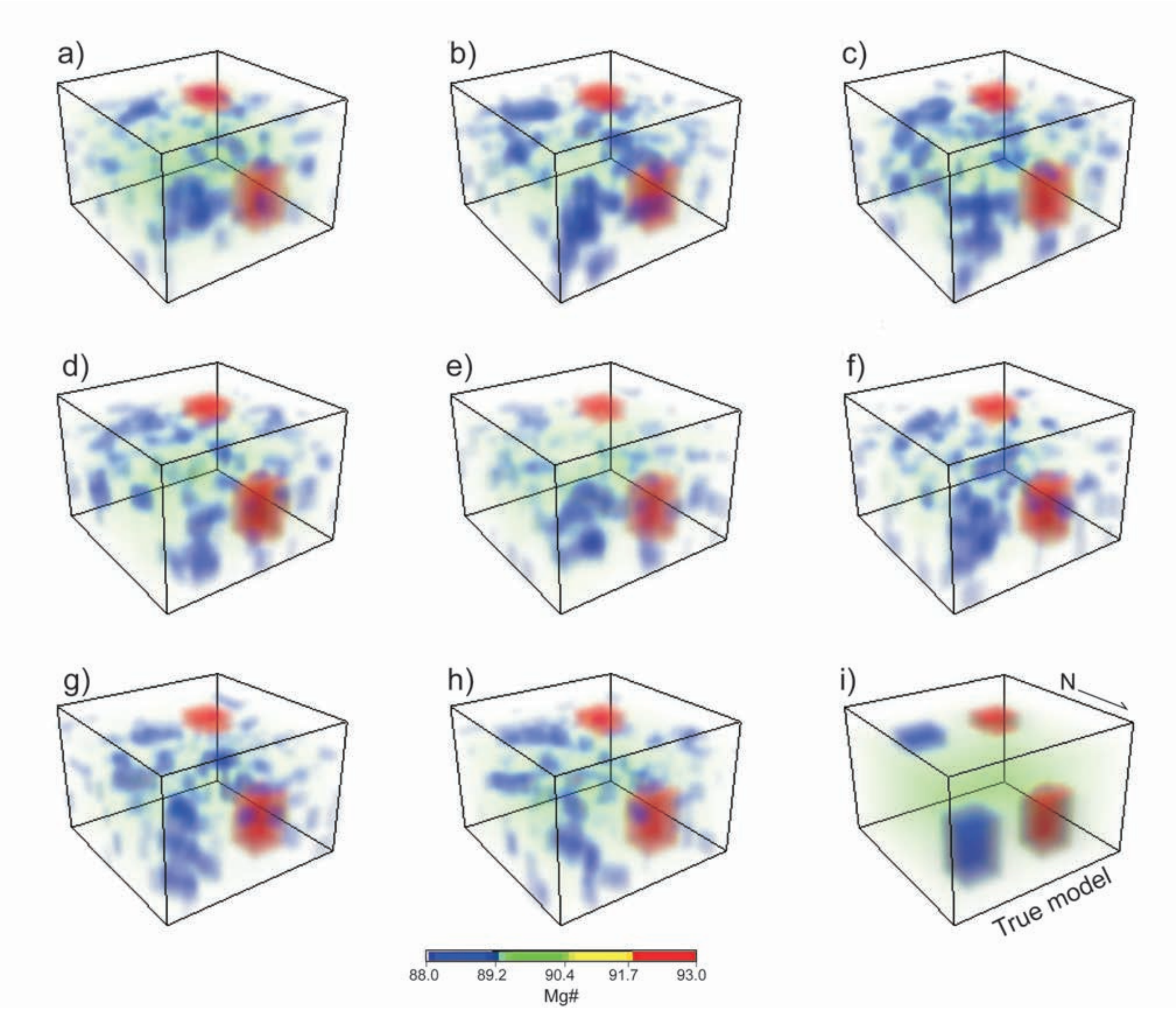
Compositional heterogeneities in the sublithospheric mantle… what do they mean?

4) A synthetic example

Results for Mg#

Mean models of 8 random ensembles with 500 samples each taken from the total posterior

Note the "persistent" features



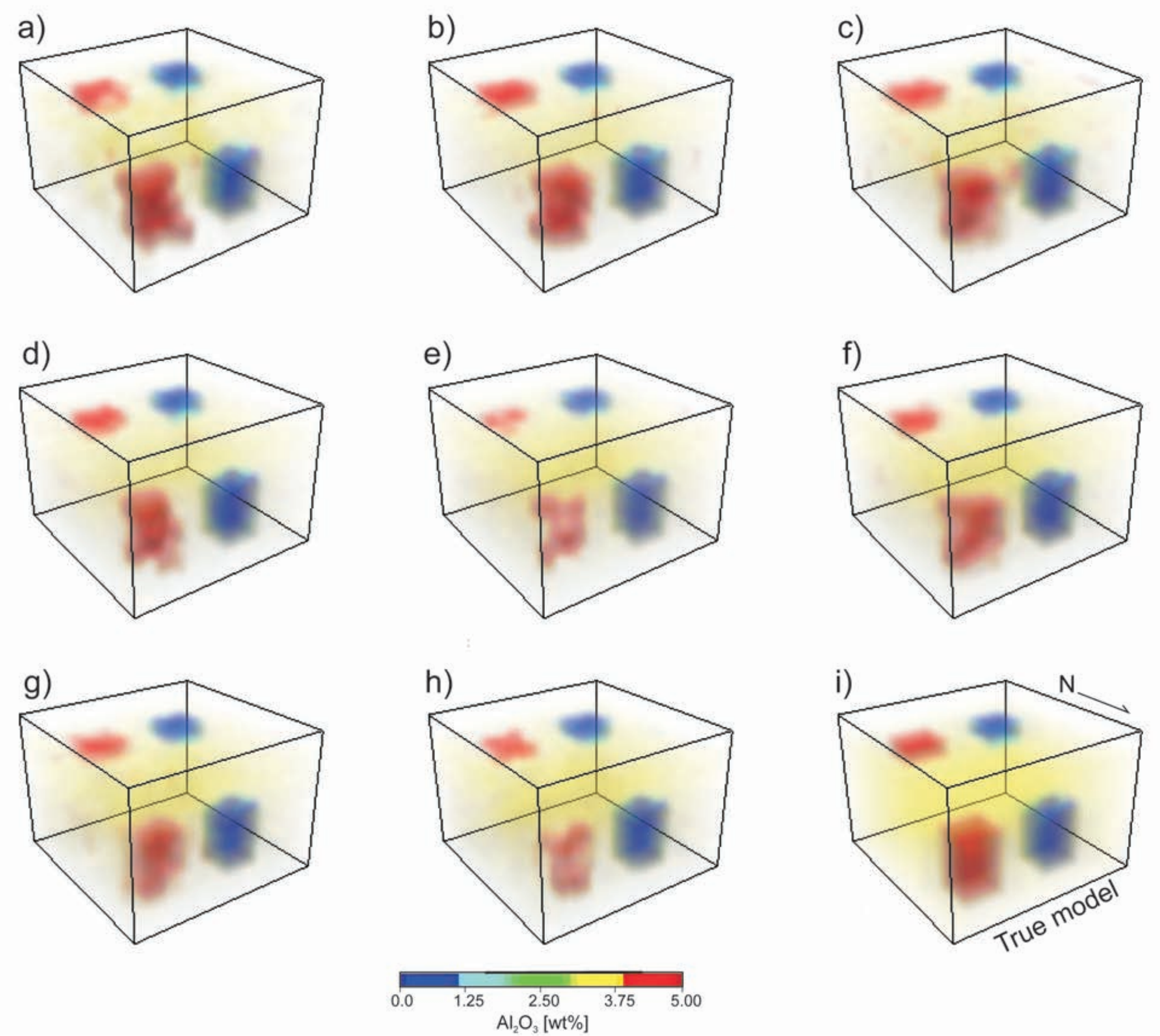
Afonso et al., JGR (in review).

4) A synthetic example

Results for bulk Al_2O_3

Mean models of 8 random ensembles with 500 samples each taken from the total posterior

Note the "persistent" features

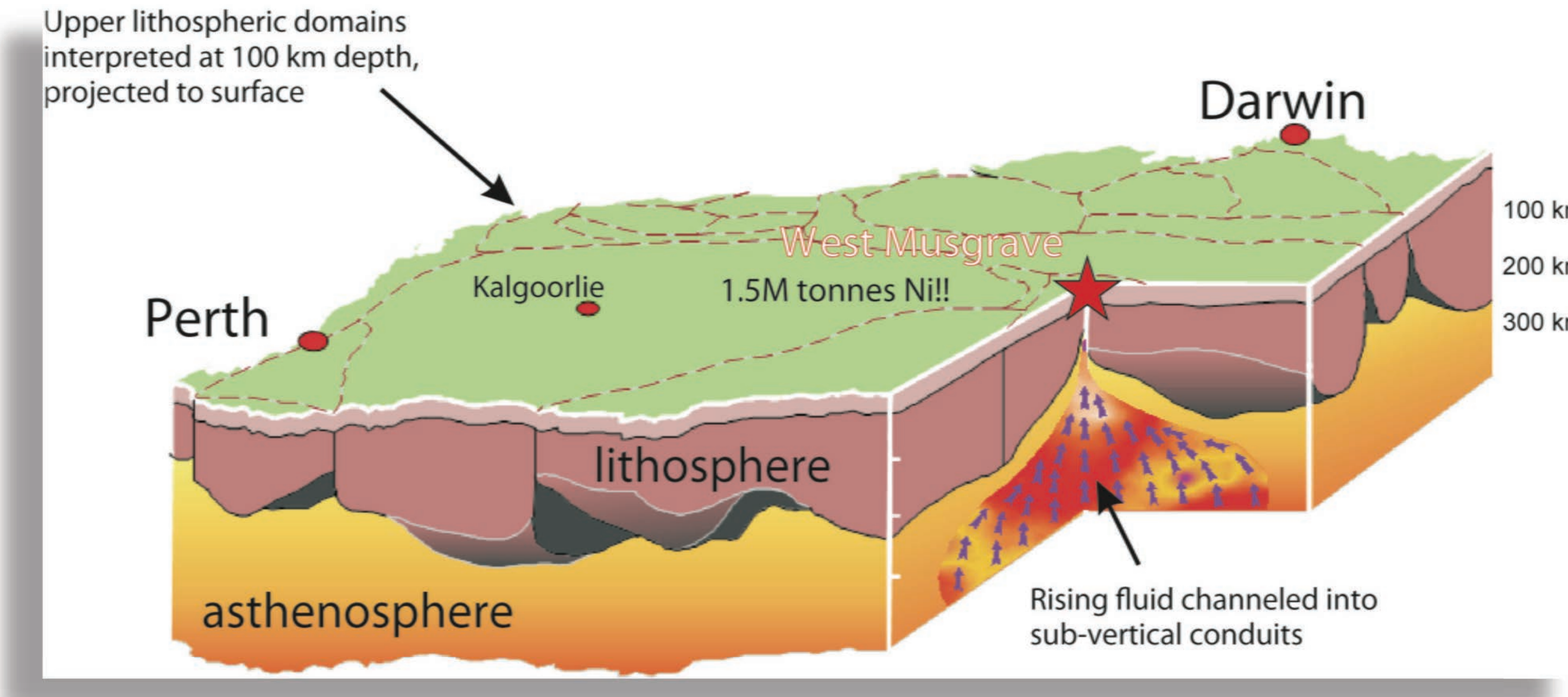


Afonso et al., JGR (in review).

1) An interesting problem...

- What is the nature of the heterogeneity "observed" in the mantle?

Exploration, targeting systems *(cf. McCuaig et al., Ore Geol. Rev., 2010)*



Courtesy of GEMOC

1) The main goals...

 # Why a *probabilistic* formalism?

Because the problem at hand is probabilistic in nature

 # Why *multi-observable*?

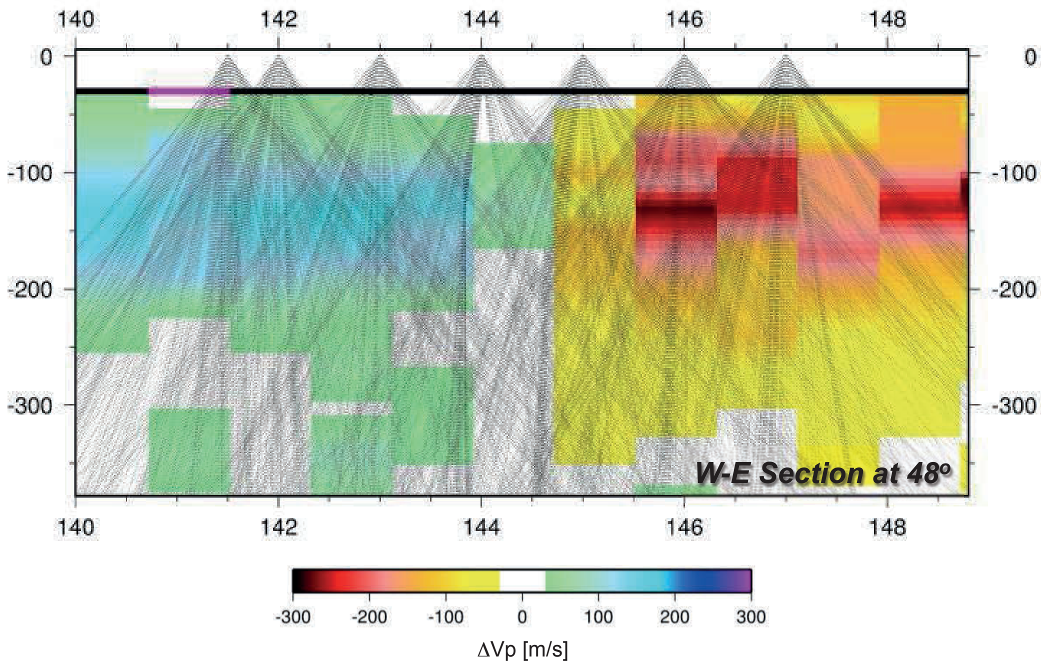
Different observables provide information on different aspects of the problem

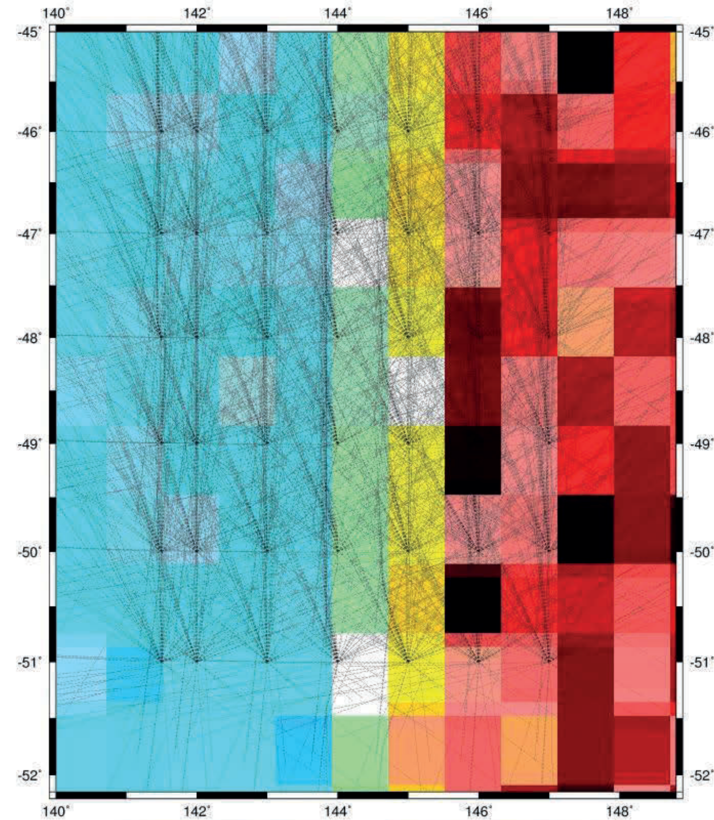
 # Why *internally consistent*?

So you cannot tweak parameters as you please to make your model look better!!

5) Another synthetic example

seismic tomography from posterior



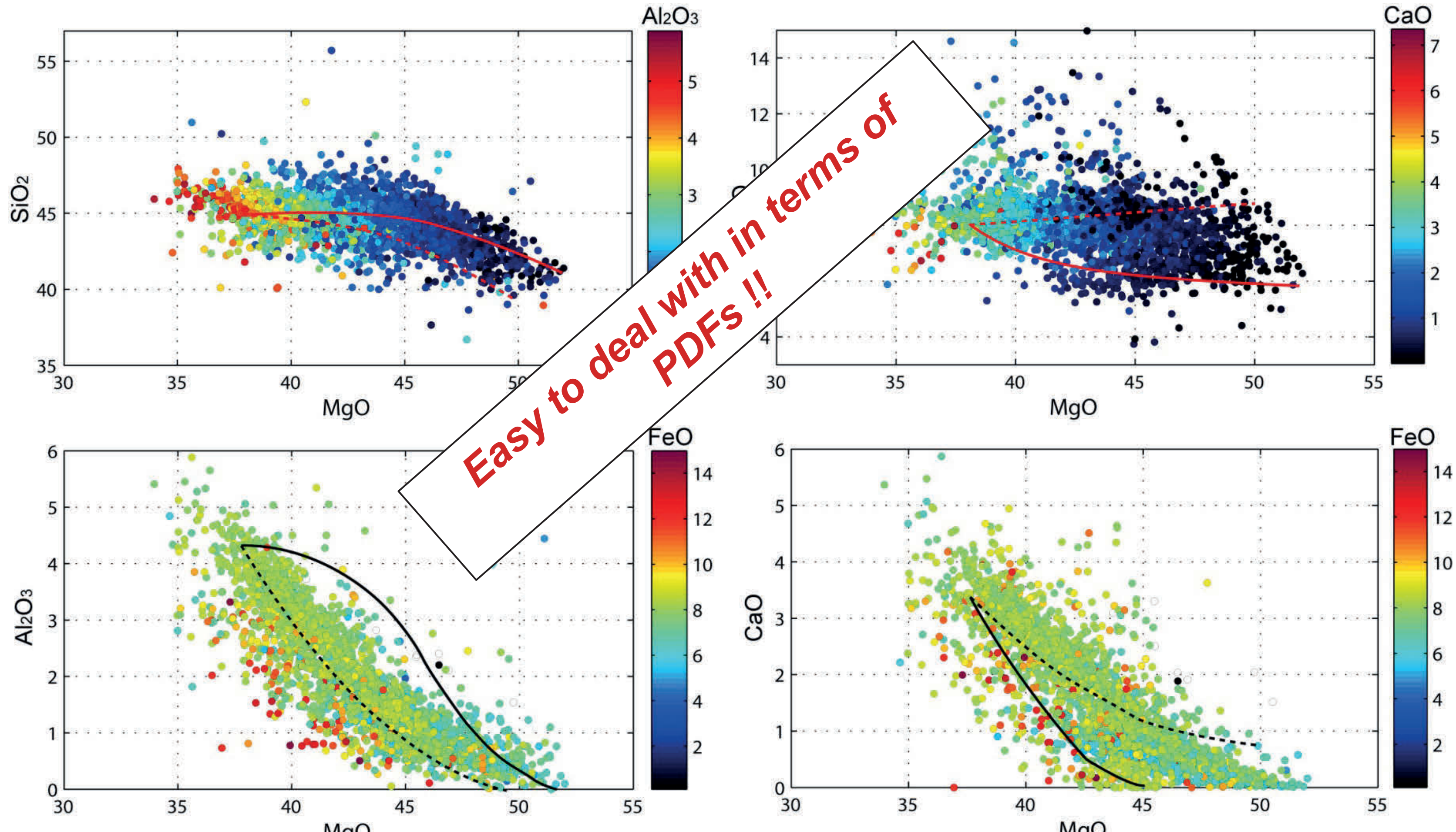


- Our test have been performed with a teleseismic dataset composed of 70 distant sources (from the EVA Array, Victoria) with mostly *P* and *PKiKP* phases (and a few *Pp* and *ScP*)
- The receivers array (42 stations) is synthetic.

3) Our (still preliminary) approach

The *a priori* petrological data

Over 3000 well studied mantle samples



Afonso et al., JGR (in review).

3) How do we do it?

a) Different observables are sensitive to different chemical-physical properties and depth ranges

b) Each method is designed to specific chemical-physical properties or perturbations of these properties

c) All thermophysical properties of interest ultimately depend on **T**, **P**, **C**

$$dG = V\,d\mathbf{P} - S\,d\mathbf{T} + \Sigma_i\, \mu_i\, d\mathbf{n}_i$$

$$V = \left(\frac{\partial \mathcal{G}}{\partial P}\right)_T \quad V\alpha = -\left(\frac{\partial \mathcal{S}}{\partial P}\right)_T = \left(\frac{\partial^2 \mathcal{G}}{\partial P \partial T}\right) \quad C_P = -T\left(\frac{\partial^2 \mathcal{G}}{\partial T^2}\right)_P \quad c_{ijkl} = \frac{1}{V}\left(\frac{\partial^2 \mathcal{G}}{\partial S_{ij} S_{kl}}\right)_{P,T}$$

All related to the free energy of the system (in equilibrium)

4) Our method

* There are two main parts

First Part
(search & appraisal in 1D)

Input
* *seismic velocities*
* *1D geoid anomaly*
* *xenolith data*
* *elevation*
* *MT data*
* *surface heat flow*

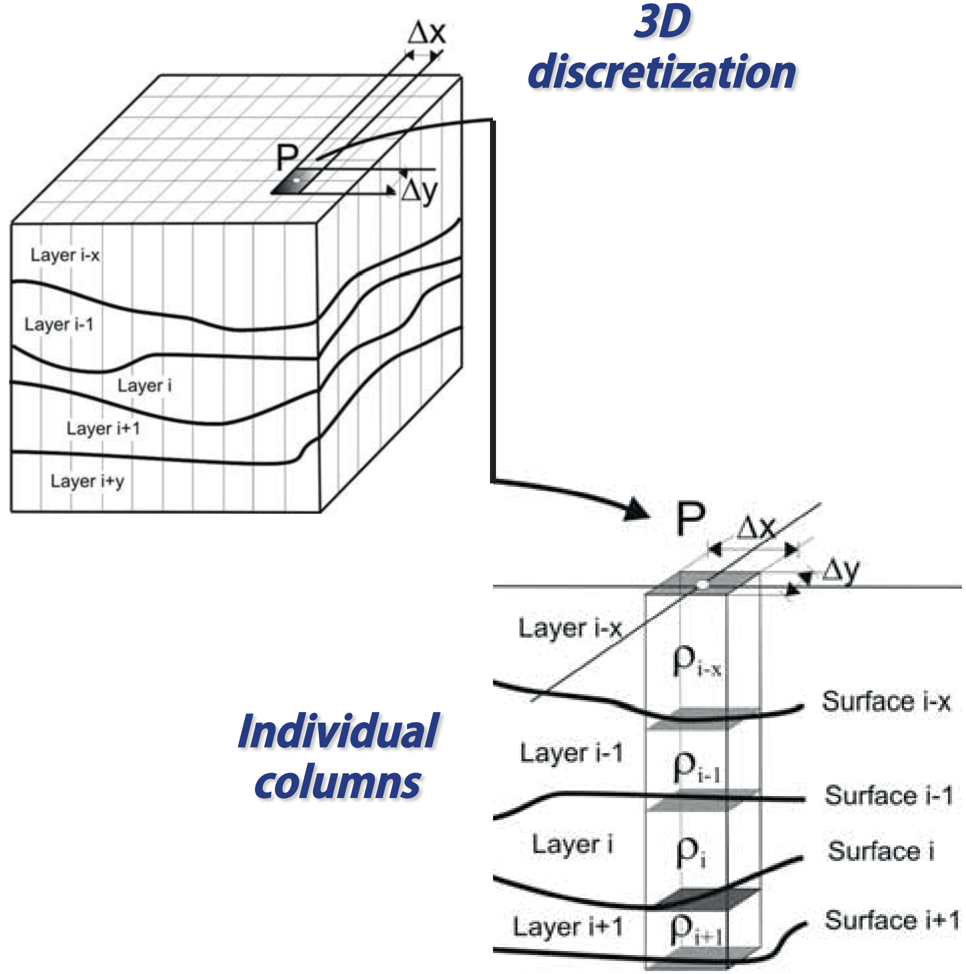
↓

Nonlinear inversion
(***Search*** for acceptable models "column by column" and their ***Bayesian appraisal*** using NA)

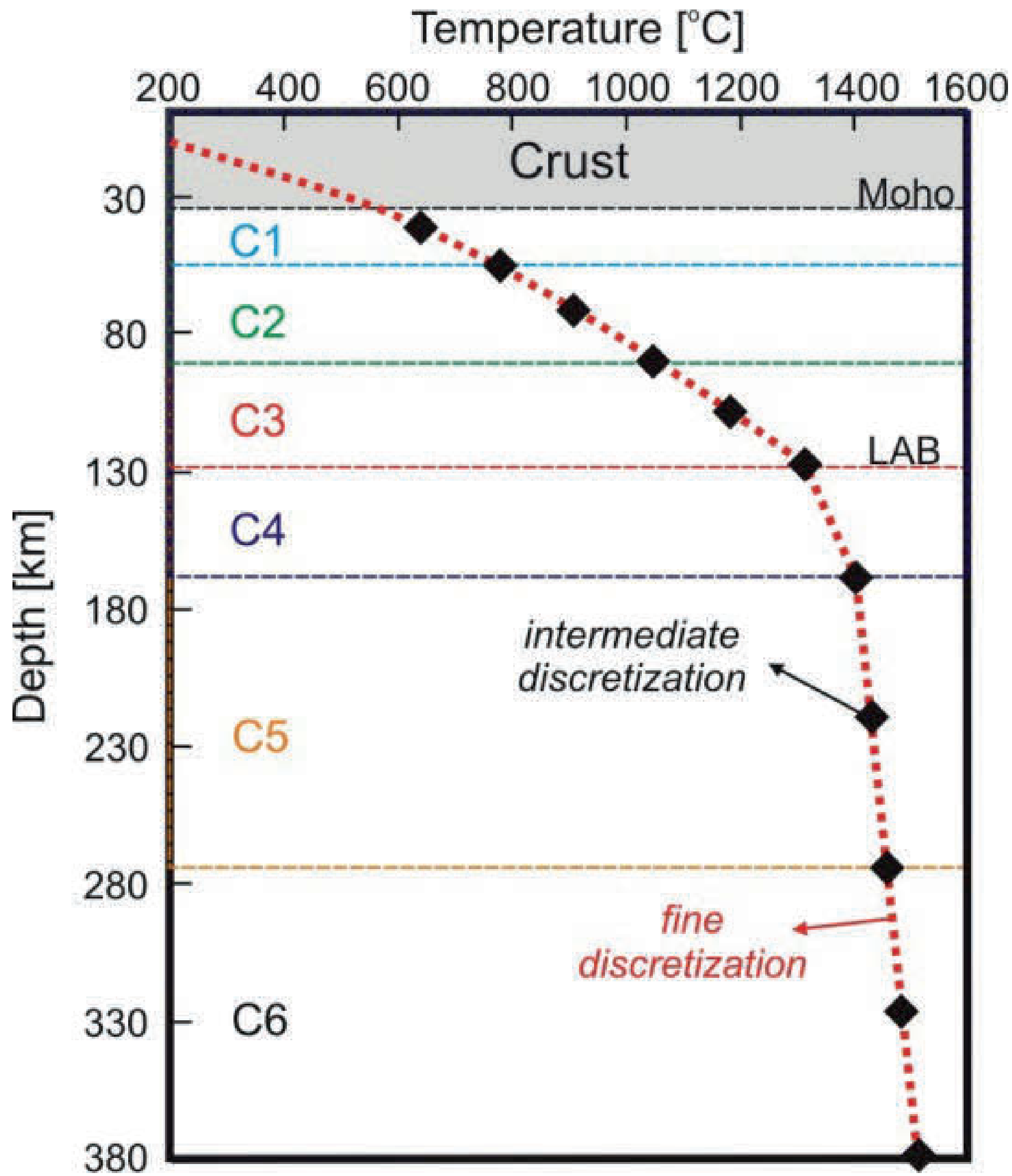
↓

Output
(Acceptable pseudo-3D models by assembling 1D best-fitting model columns)

3D discretization



Thermochemical Tomography of the Lithosphere from Multi-Observable Probabilistic Inversions



3) The main problems...

i) Nonlinearity of the problem at hand

ii) Thermodynamic modelling

iii) Trade-off between T and C in wave speeds

iv) T effect is much stronger than C effect (i.e. hard to isolate)

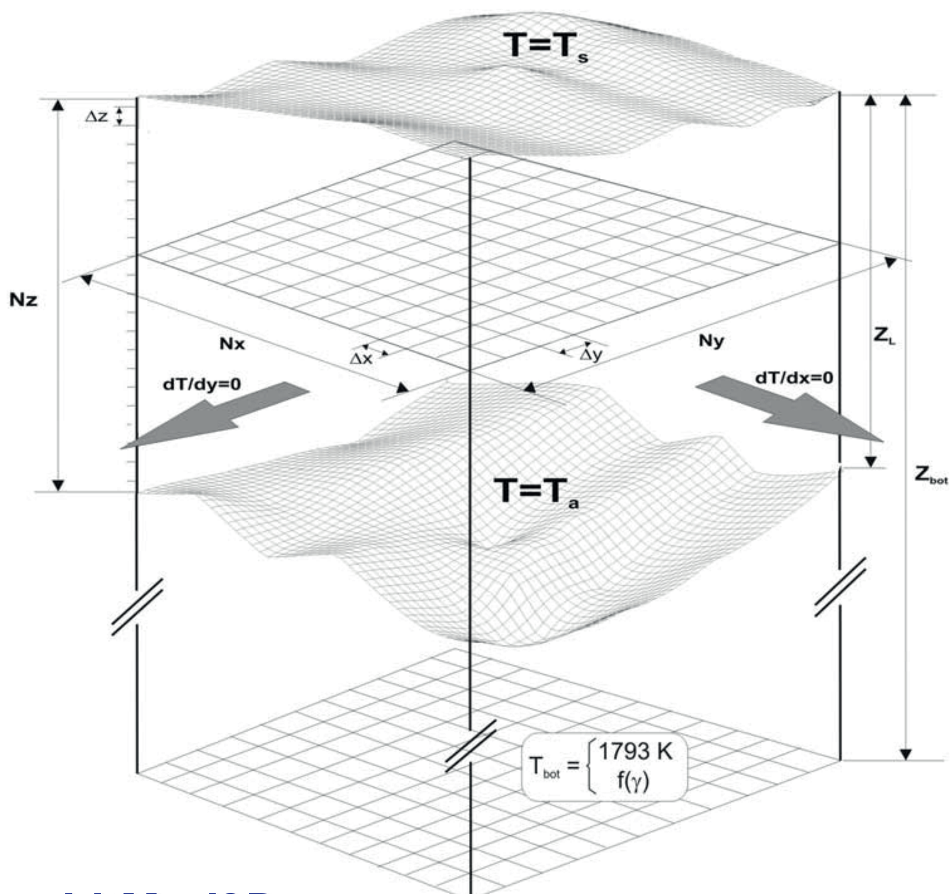
ELSEVIER
Contents lists available at ScienceDirect
Earth and Planetary Science Letters
journal homepage: www.elsevier.com/locate/epsl
EARTH & PLANETARY SCIENCE LETTERS

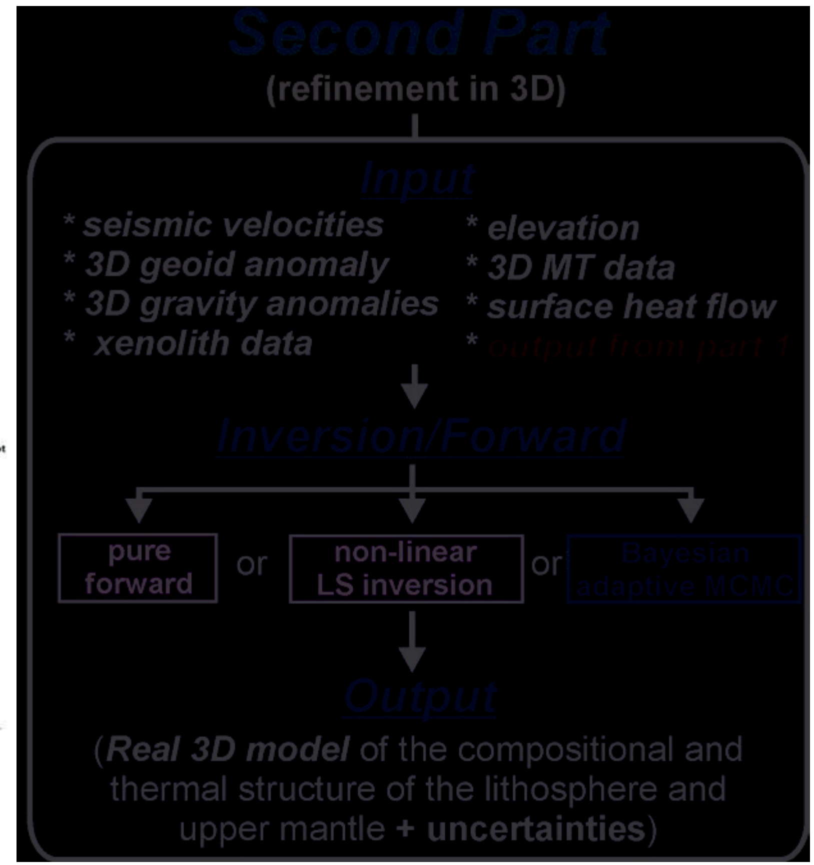
On the Vp/Vs–Mg# correlation in mantle peridotites: Implications for the identification of thermal and compositional anomalies in the upper mantle

Juan Carlos Afonso [a,*], Giorgio Ranalli [b], Manel Fernàndez [c], William L. Griffin [a], Suzanne Y. O'Reilly [a], Ulrich Faul [d]

4) Our method

* There are two main parts



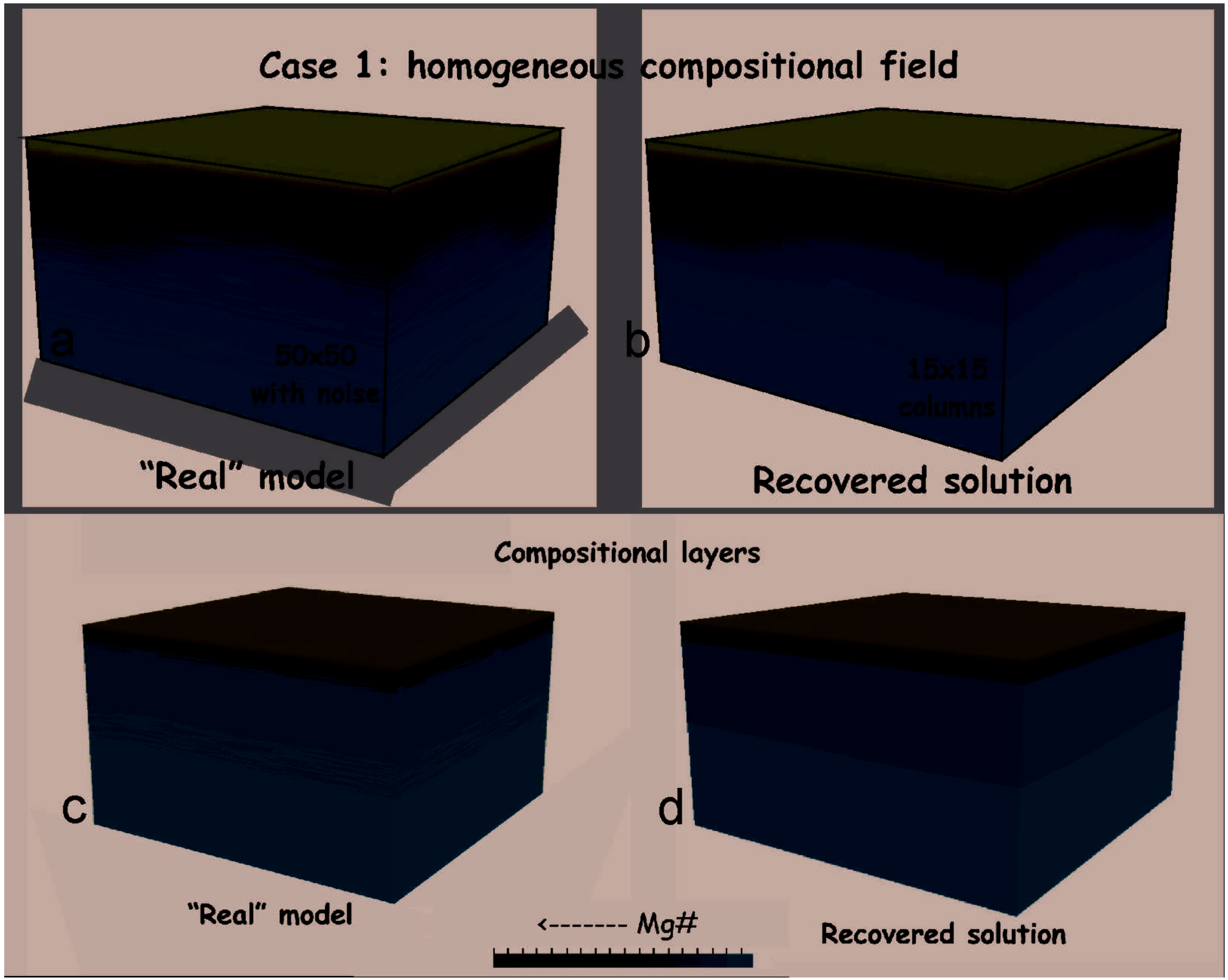


LitMod3D

http://www.eps.mq.edu.au/~jafonso/Software1.htm

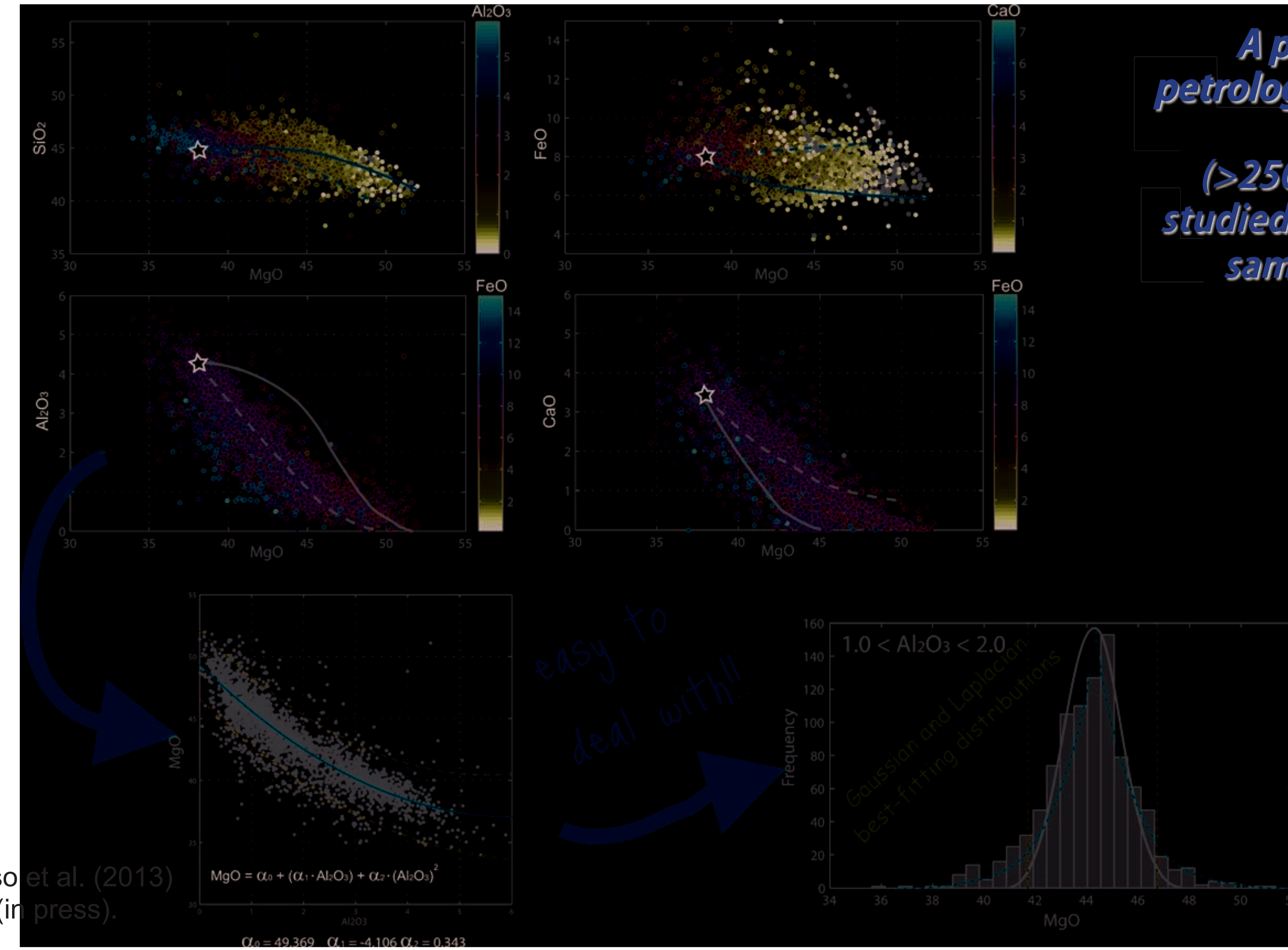
5) Preliminary results (synthetic cases)

Simulation run in a 90-CPU cluster for ~ 10 days



3) The main problems...

Non-unique solution in compositional space

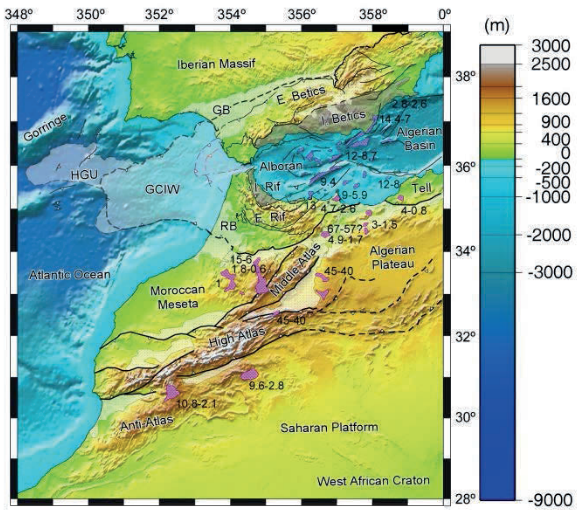


A priori petrological data

(>2500 well studied xenolith samples)

Afonso et al. (2013) JGR (in press).

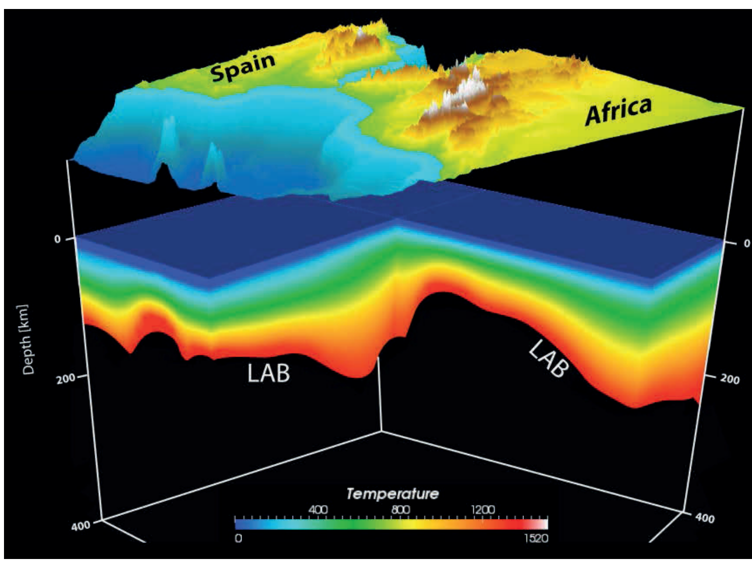
5) Preliminary results (real case)

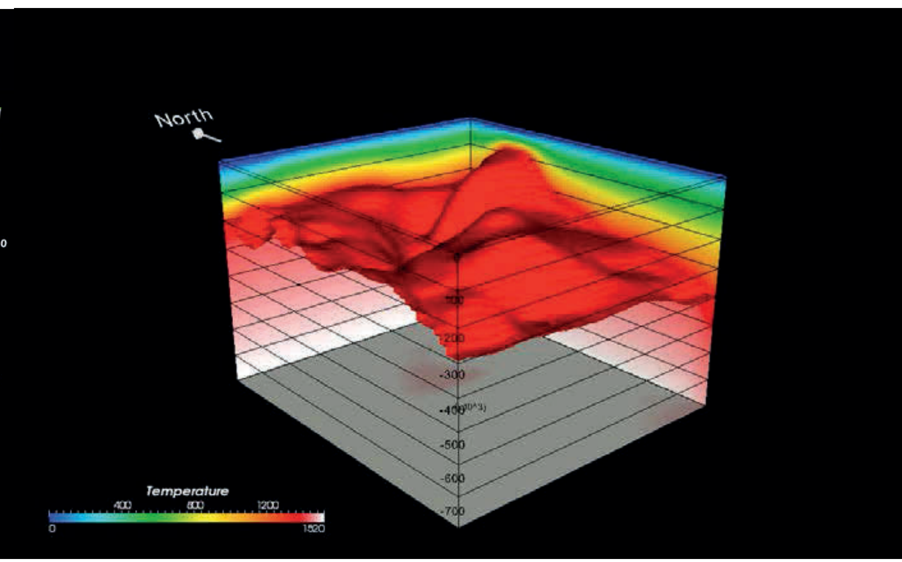


From Fullea et al., 2010, Lithos

An example...
the Atlantic-Mediterranean Transition Region

It's a highly complicated and interesting area





3) How do we do it?

First Part
(search & appraisal in 1D)

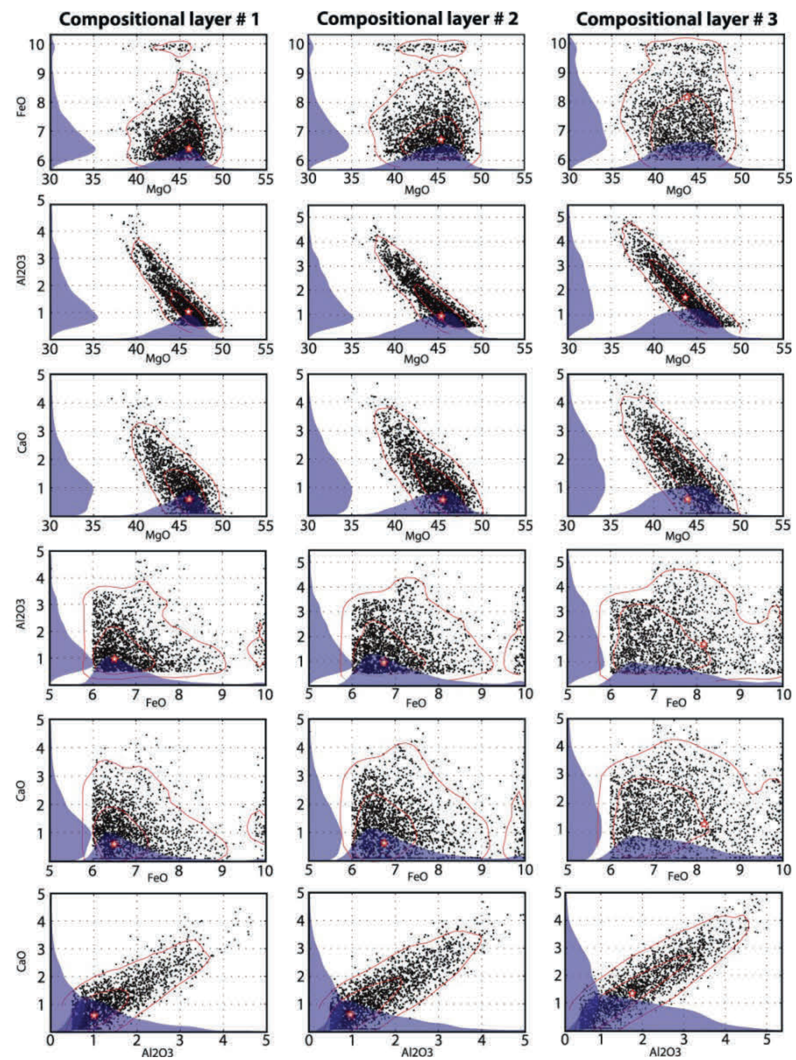
Input
* Dispersion curves
* 1D geoid anomaly
* xenolith data
* Vp structure
* elevation
* MT data
* surface heat flow

↓

Nonlinear inversion
(**Search** for acceptable models "column by column" and their PDFs using NA)

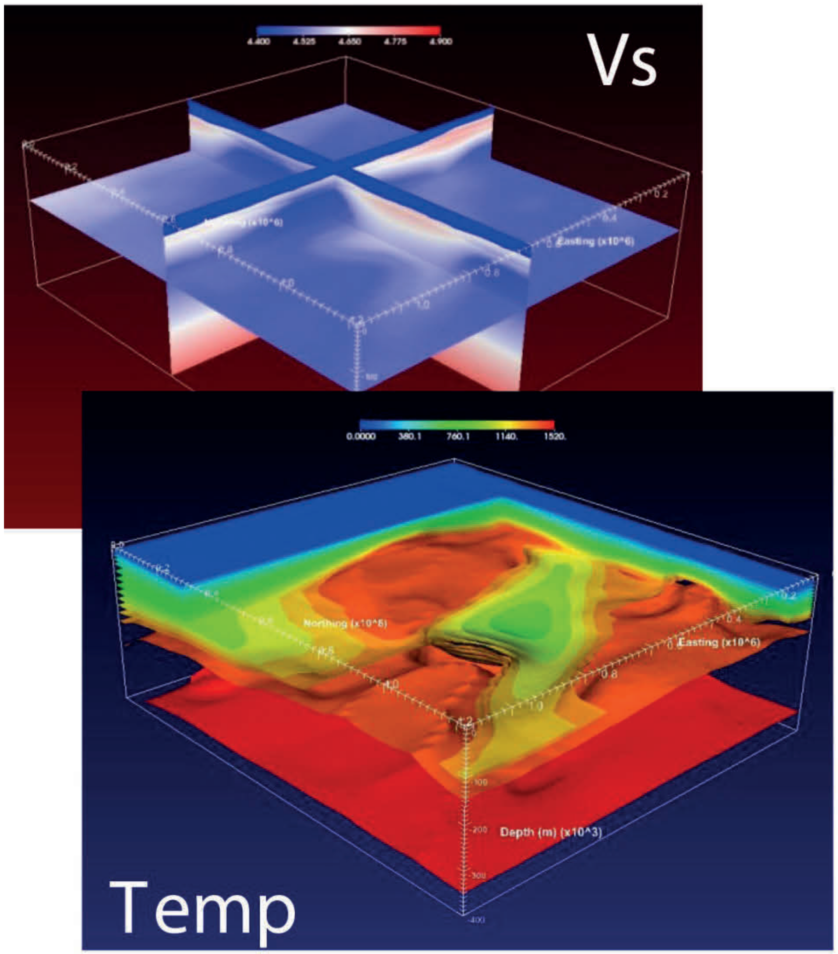
↓

Output
(**PDFs for all parameters in all individual columns**)



Afonso et al., in prep.

3) How do we do it?



Afonso et al., in prep.

Second Part
(refinement in 3D)

Input
- * Dispersion curves
- * 3D geoid anomaly
- * 3D gravity anomalies
- * xenolith data
- * Vp structure
- * elevation
- * MT data
- * surface heat flow
- * output from part 1

↓

Inversion/Forward

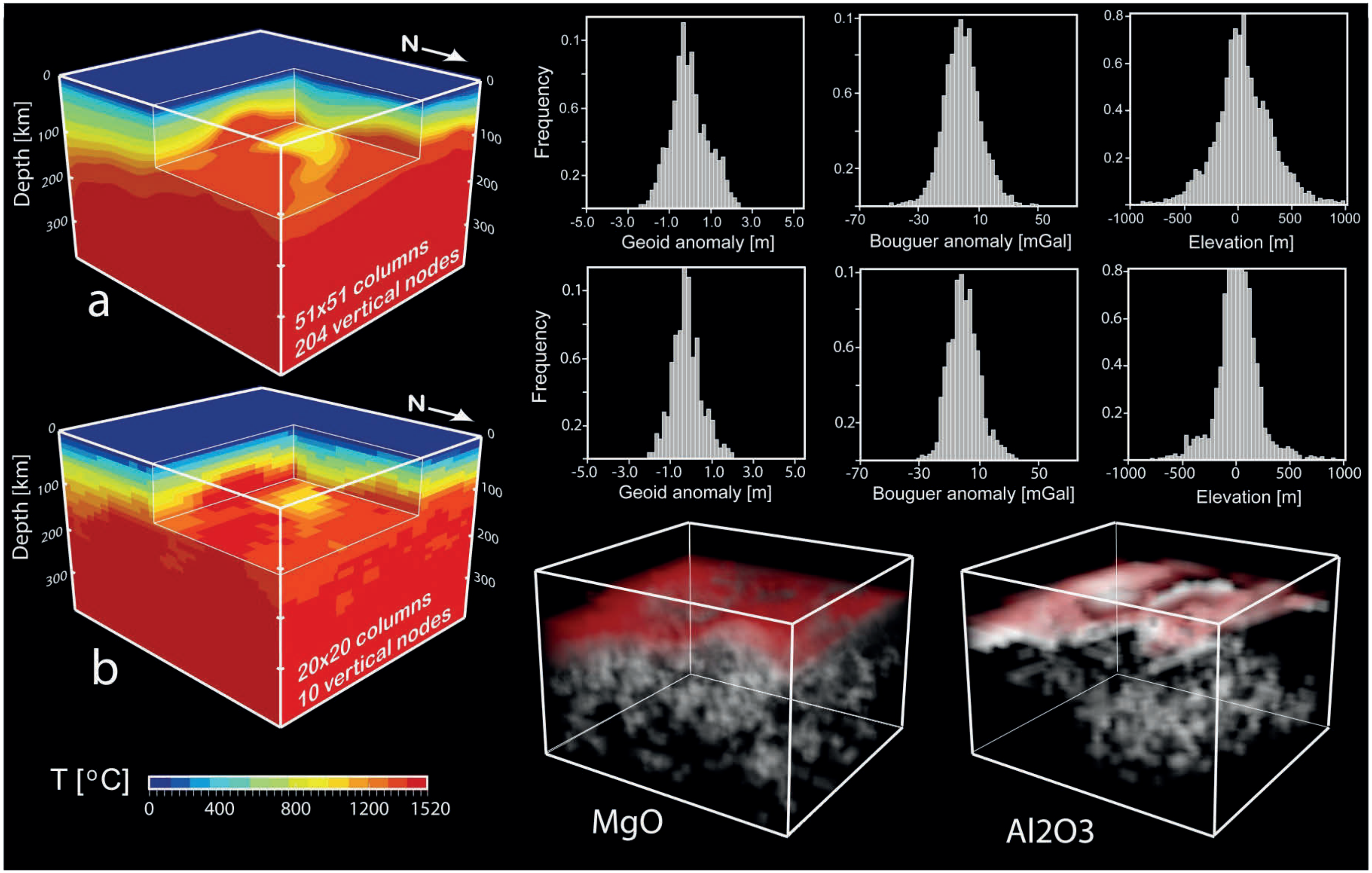
pure forward | or | non-linear LS inversion | or | Bayesian MCMC

↓

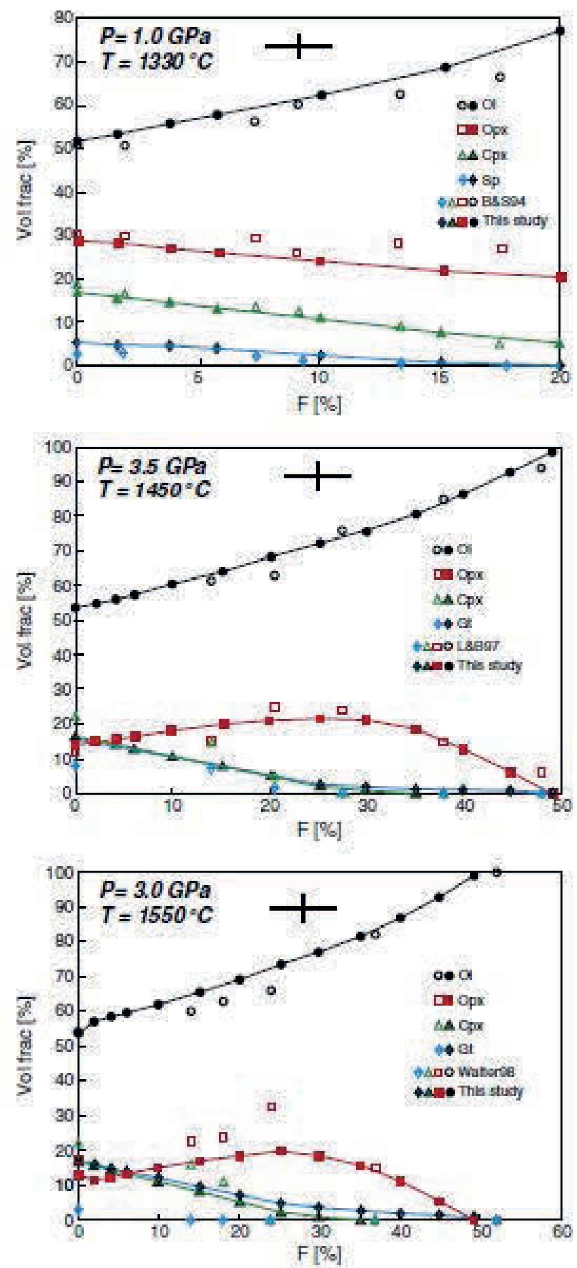
Output
(Posterior PDF of the 3D compositional and thermal structure of the lithosphere and sublithospheric upper mantle + uncertainties)

5) Preliminary results

A comparison between the results of Fullea et al. (2010) and our new method

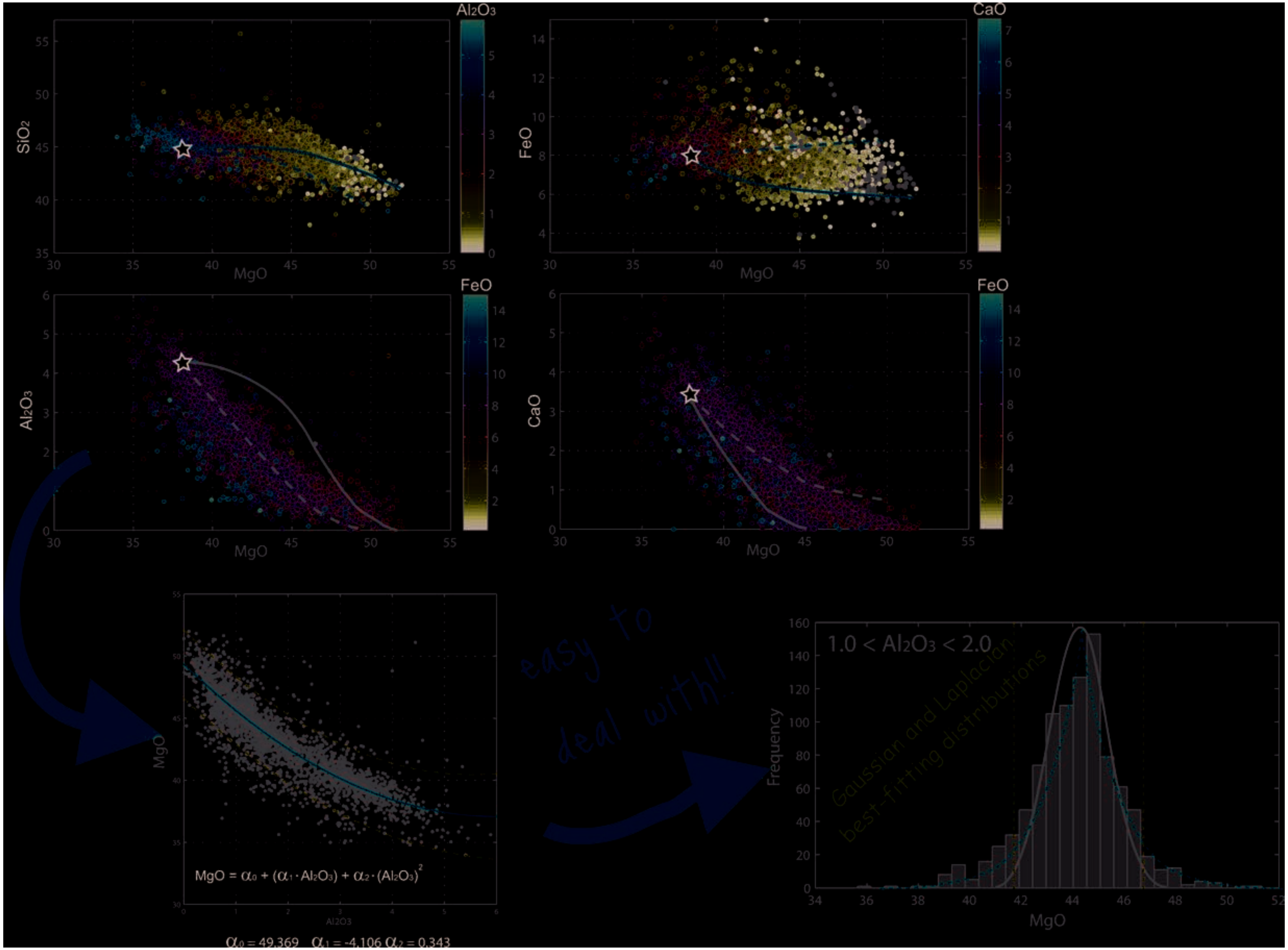


Thermodynamics



From Afonso and Schutt., Lithos (2012)

2) How do we do it?



2) Why bother with this?

Defining the LAB (cf. Jones et al., Lithos, 2010)

Exploration, targeting systems (cf. McCuaig et al., Ore Geol. Rev., 2010)

Geodynamic modeling (buoyancy from tomography models)

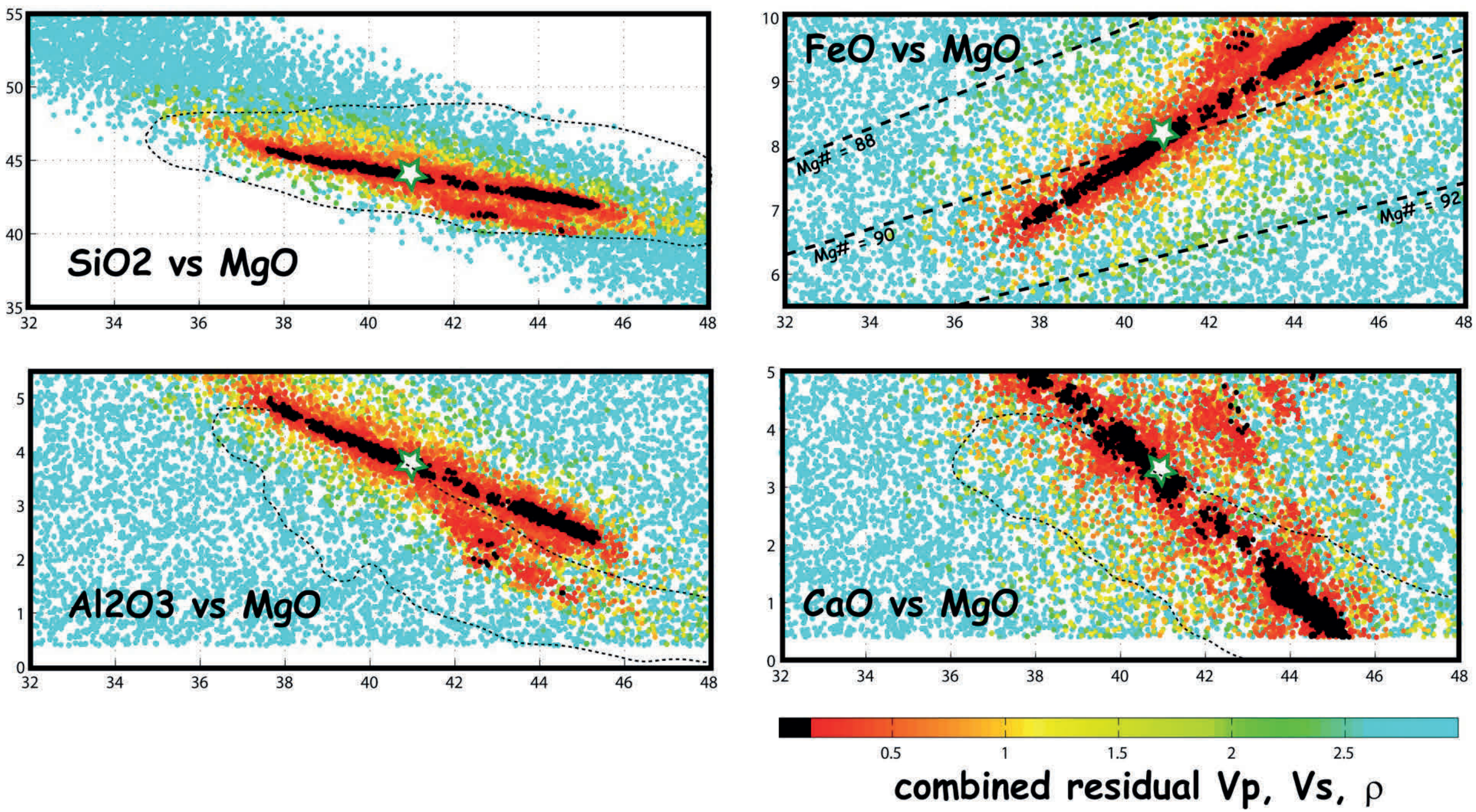
Lithospheric modeling and evolution (TopoEurope, crustal production trough time)

Craton stabilization… etc…etc…etc

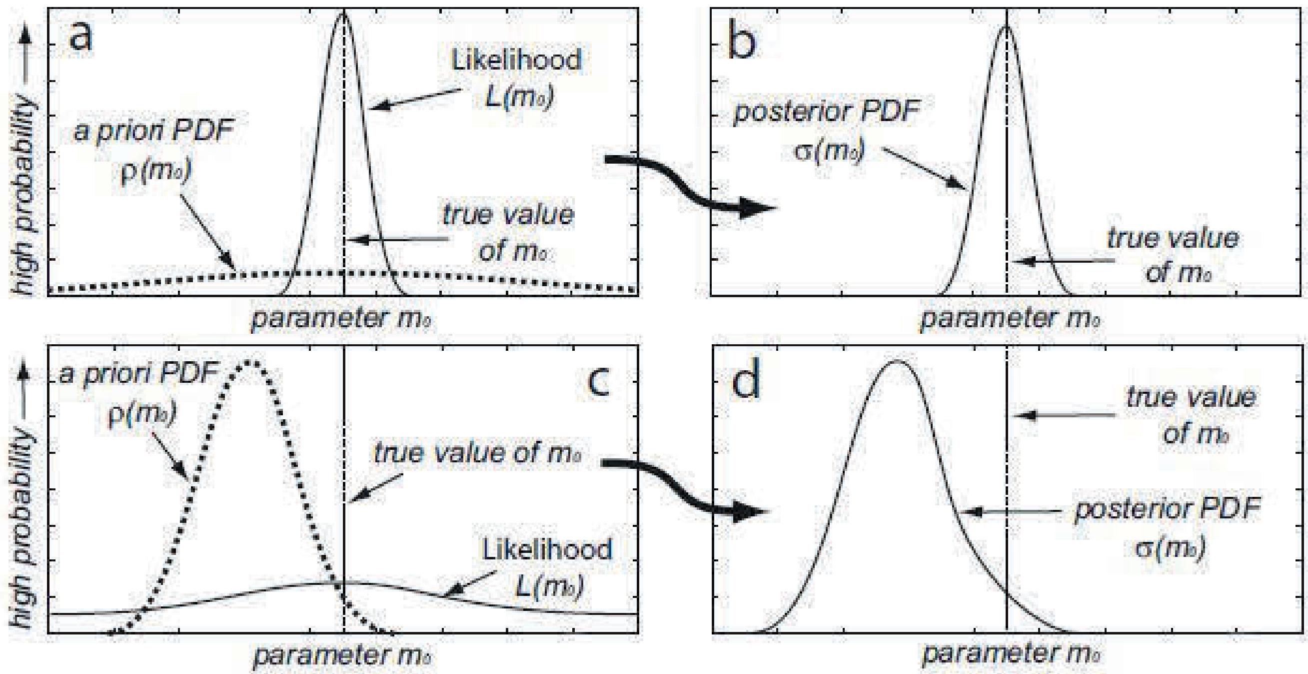
3) Should it work?

Let's take a "target" composition at T=900 °C and P=1.2 GPa

Acceptable models (NA) without any a priori information

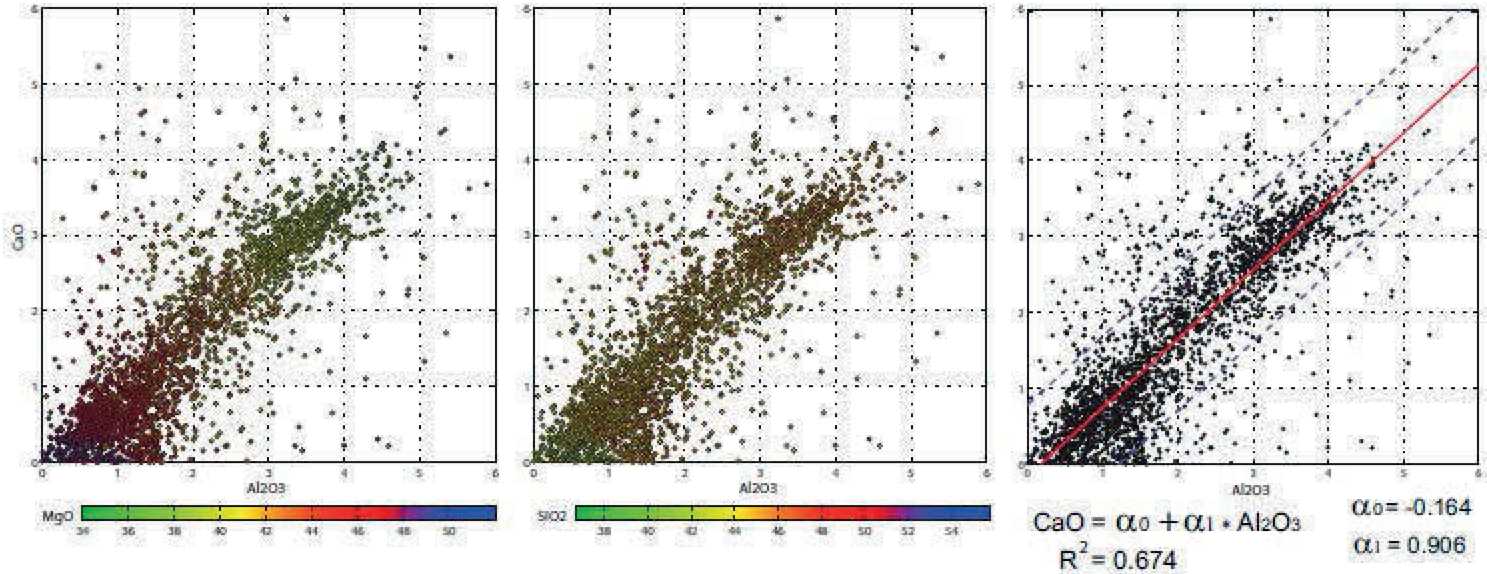


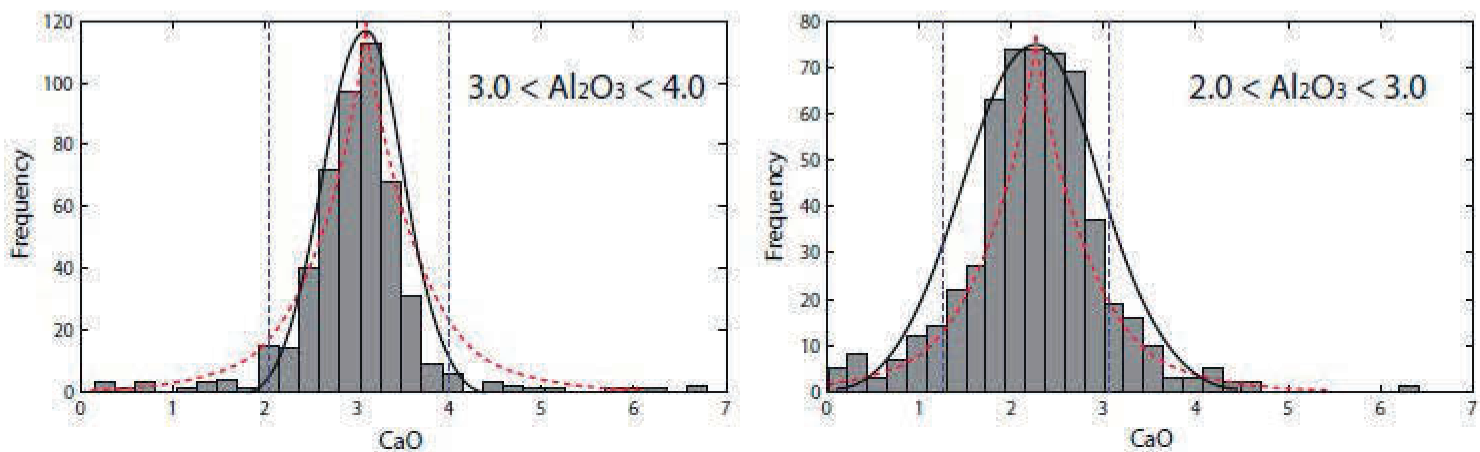
$$\sigma(\mathbf{m}) = k\rho(\mathbf{m})L(\mathbf{m})$$



$$\rho(\mathbf{d},\mathbf{m}) = const.\,exp\left\{-\frac{1}{2}(\mathbf{d}-\mathbf{g}(\mathbf{m}))^T C_t^{-1}(\mathbf{d}-\mathbf{g}(\mathbf{m}))\right\}$$

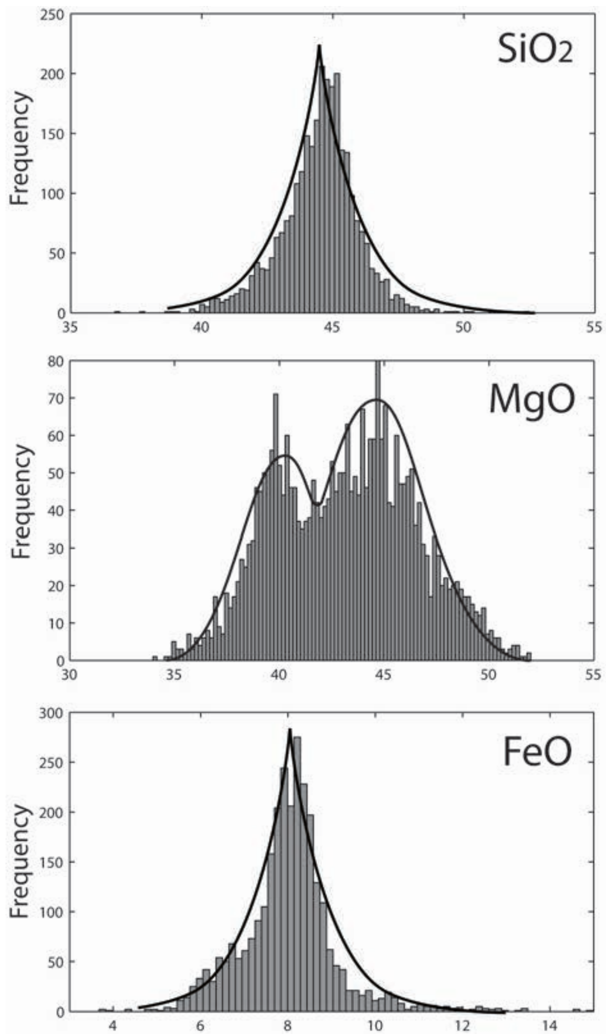
Thermochemical Tomography of the Lithosphere from Multi-Observable Probabilistic Inversions

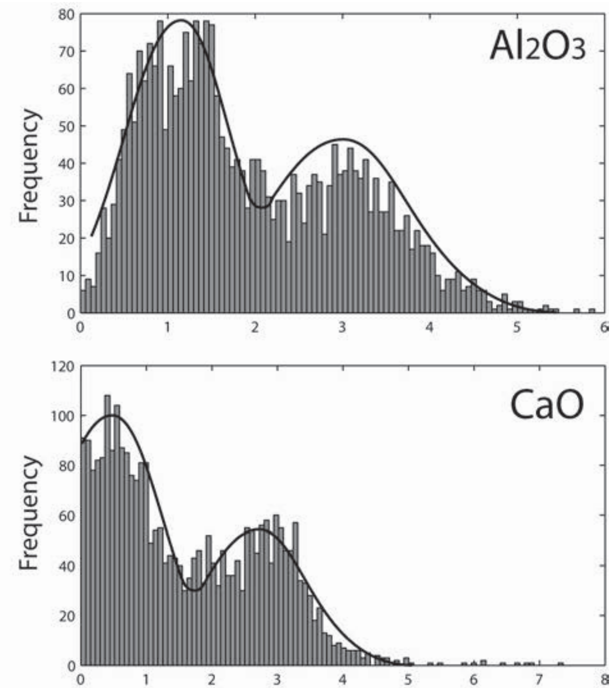




2) How do we do it?

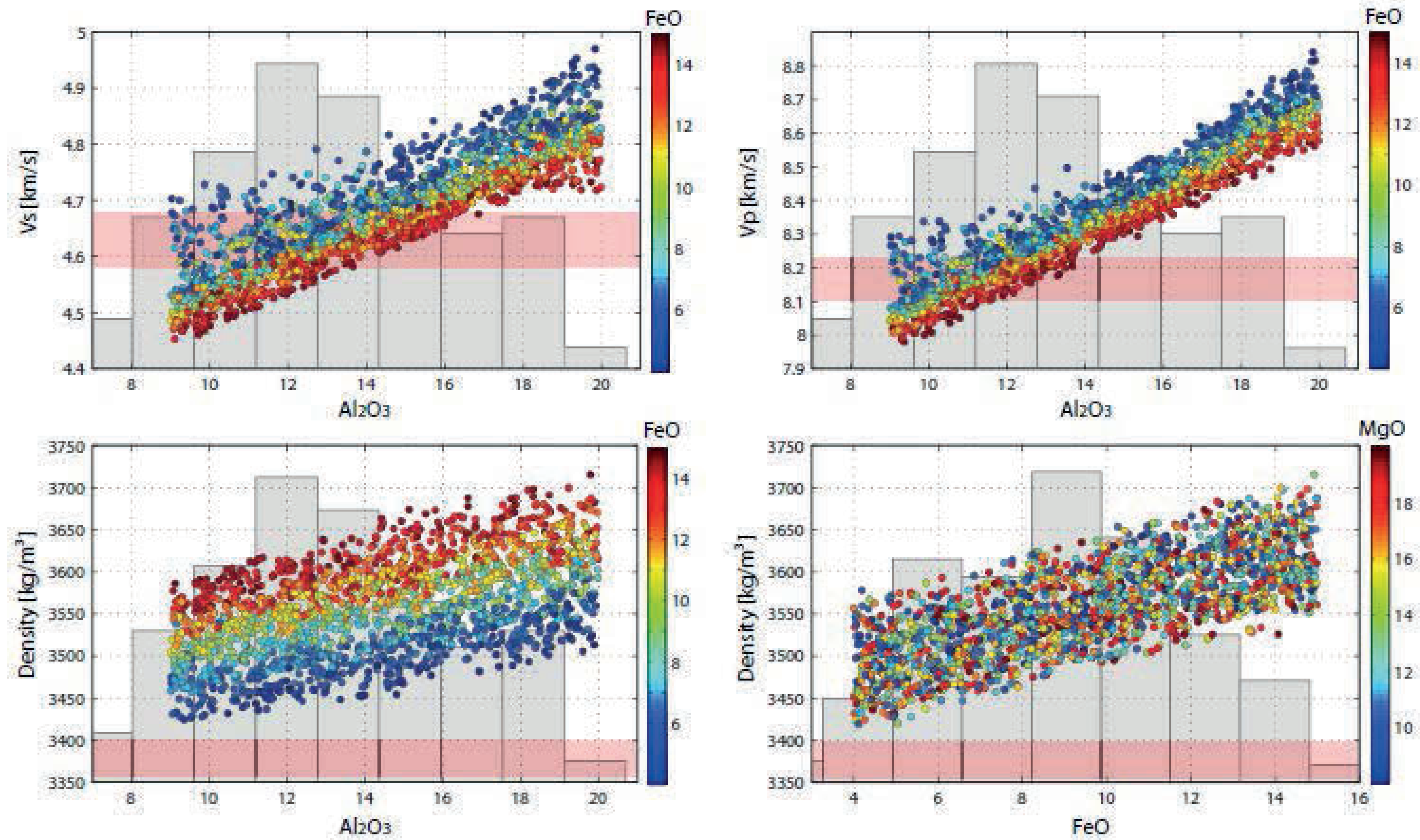
Be careful!! the distribution can be biased!





The two peaks in our distributions could be an artifact of the sampling

Thermochemical Tomography of the Lithosphere from Multi-Observable Probabilistic Inversions



3) Our approach …so far

LitMod_4INV

DATA

- Gravity anomaly
- Geoid anomaly
- Surface heat flow
- Absolute elevation
- R & L disp. curves
- travel-time residuals
- MT data
- Xenolits?

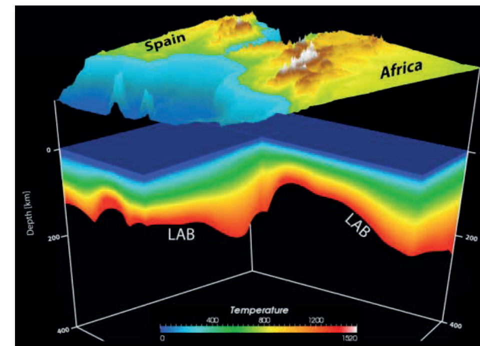
→

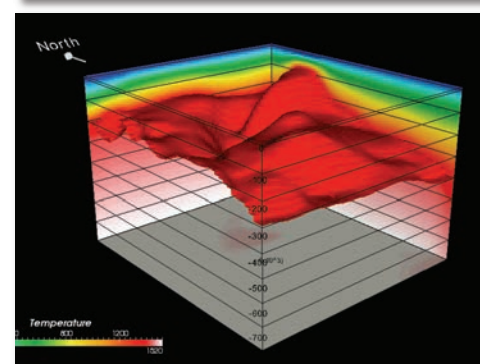
THEORY

Equilibrium Thermodynamics ↔ Heat transfer, Gravity potential, Stokes flow, Isostasy, Dispersion curves, Maxwell's equations, Travel times

→

MODELS



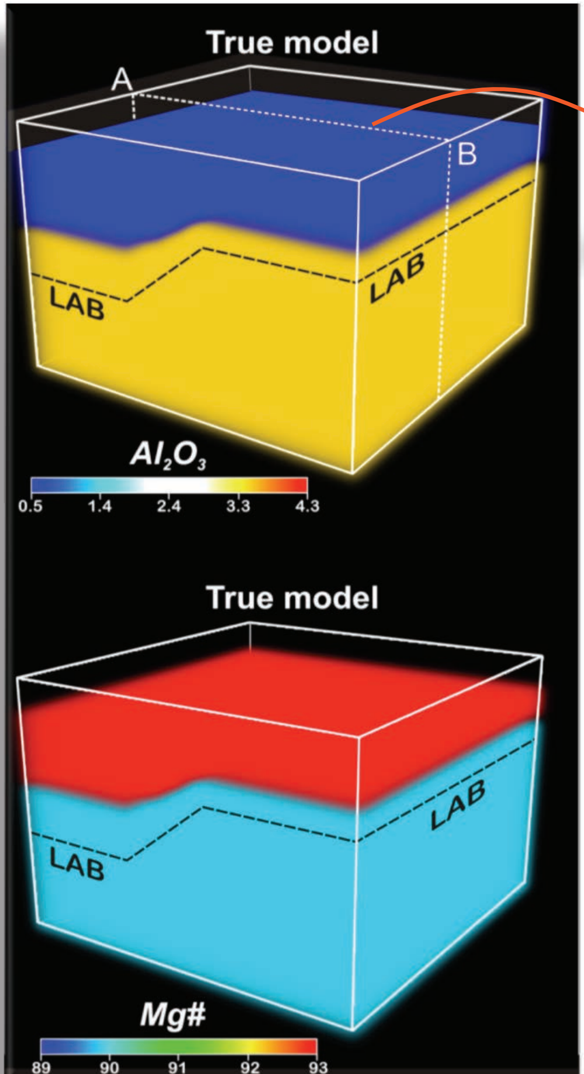


↓

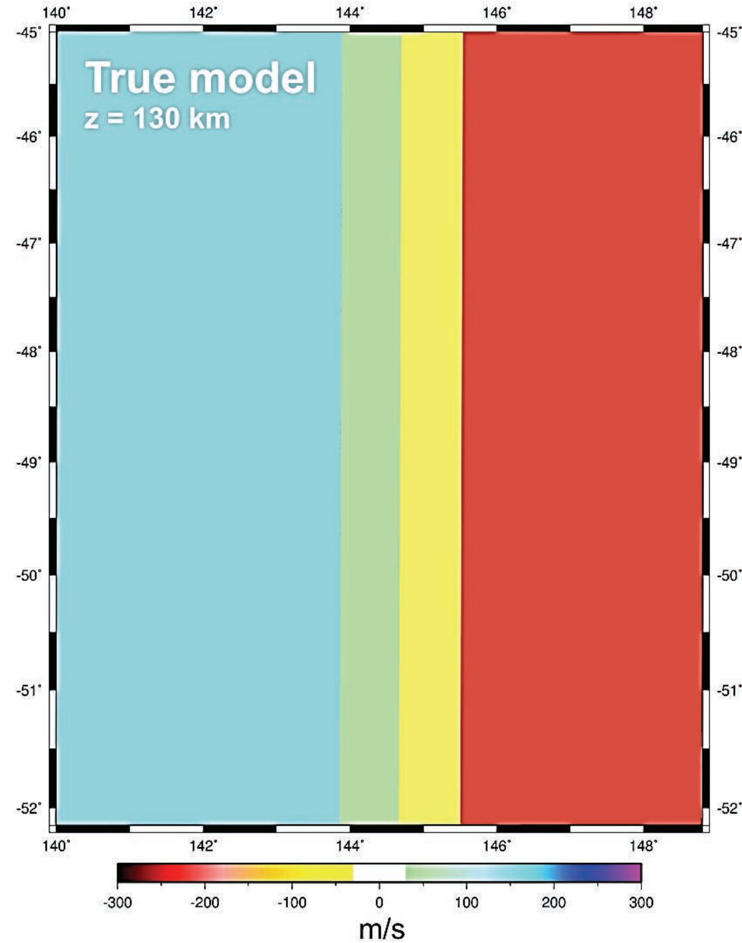
Probabilistic Inversion
(Bayesian framework)

3) Our approach …so far

Let's look at a simple example…

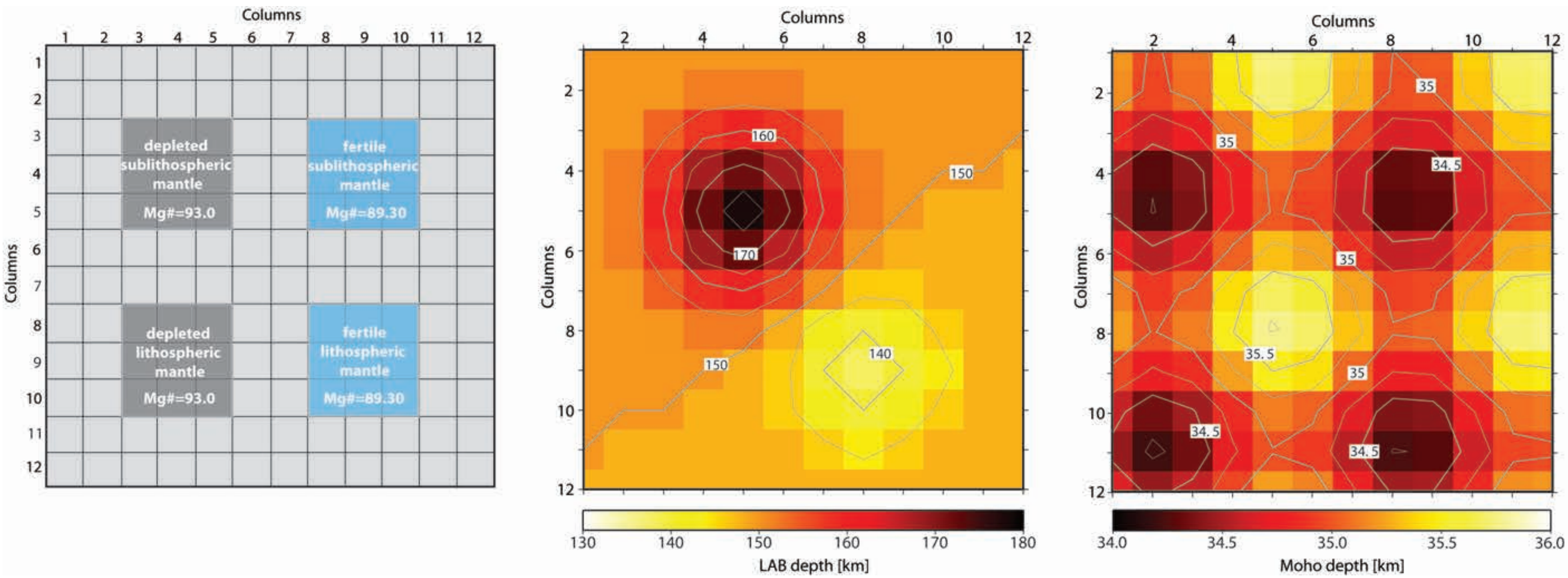


Vp anomalies relative to horizontal average



4) A synthetic example

We created a 3D model with *LitMod3D* and used its predictions + noise as input data for the inversion

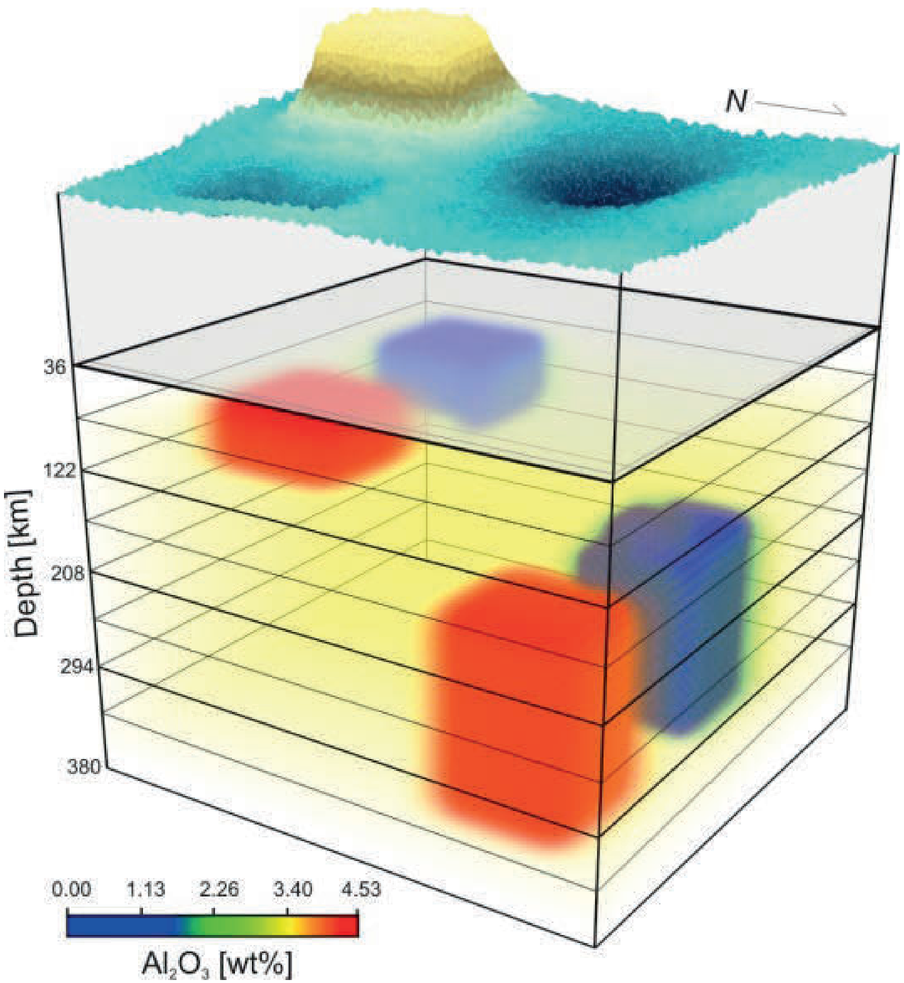


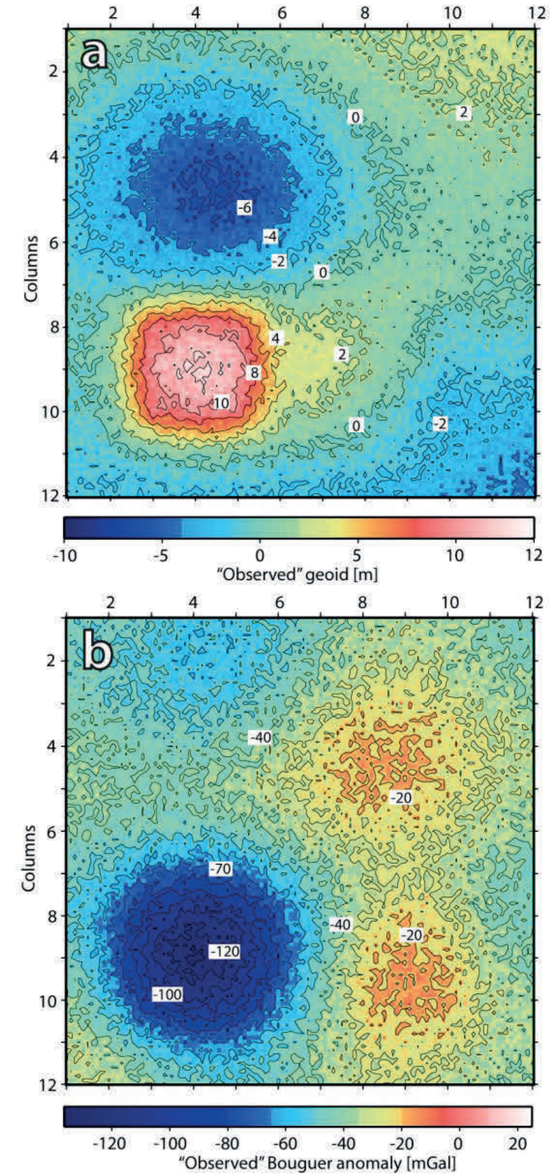
Domains **LAB** **Moho**

Afonso et al., JGR (in review).

4) A synthetic example

Examples of inputs (predictions + noise) used in the inversion





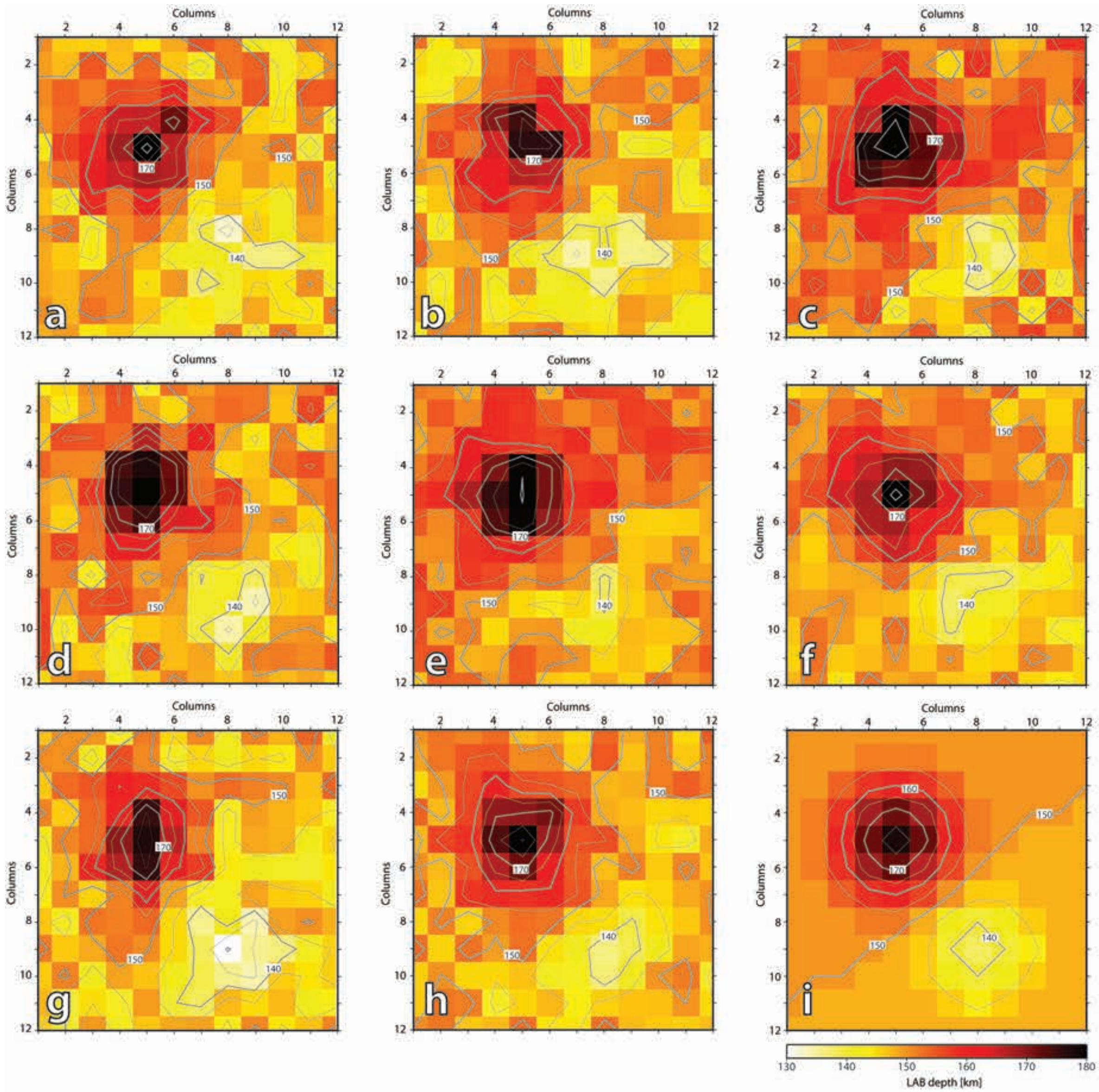
Afonso et al., JGR (in review).

4) A synthetic example

Results for LAB geometry

Mean models of 8 random ensembles with 500 samples each taken from the total posterior

Note the "persistent" features



Afonso et al., JGR (in review).