Multi-data and multi-scale probabilistic inversion for Imagining the physical and chemical state of the Earth's interior

MG3
Macquarie's Geophysics and Geodynamics Group

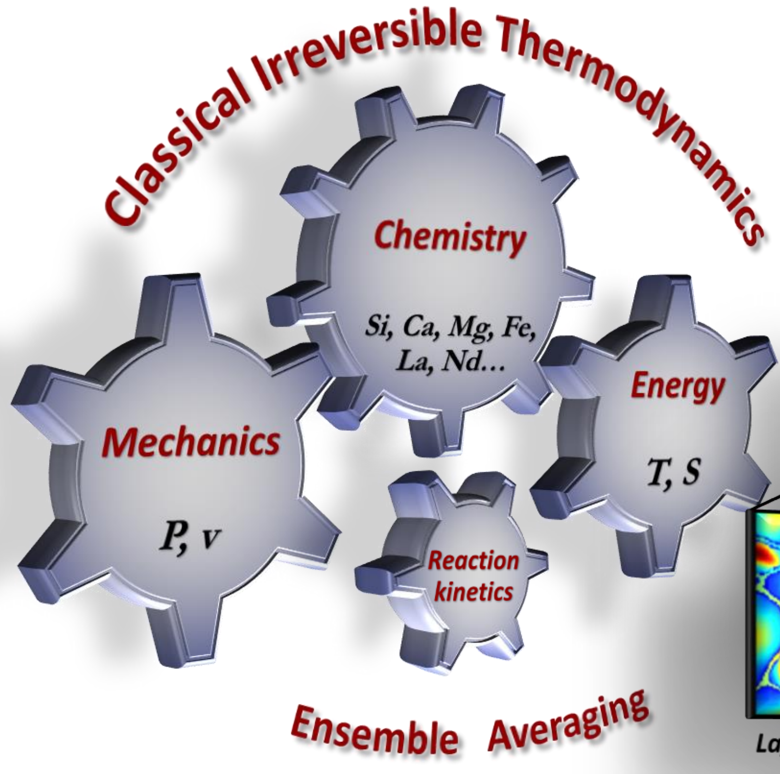
Juan Carlos Afonso[1,2]

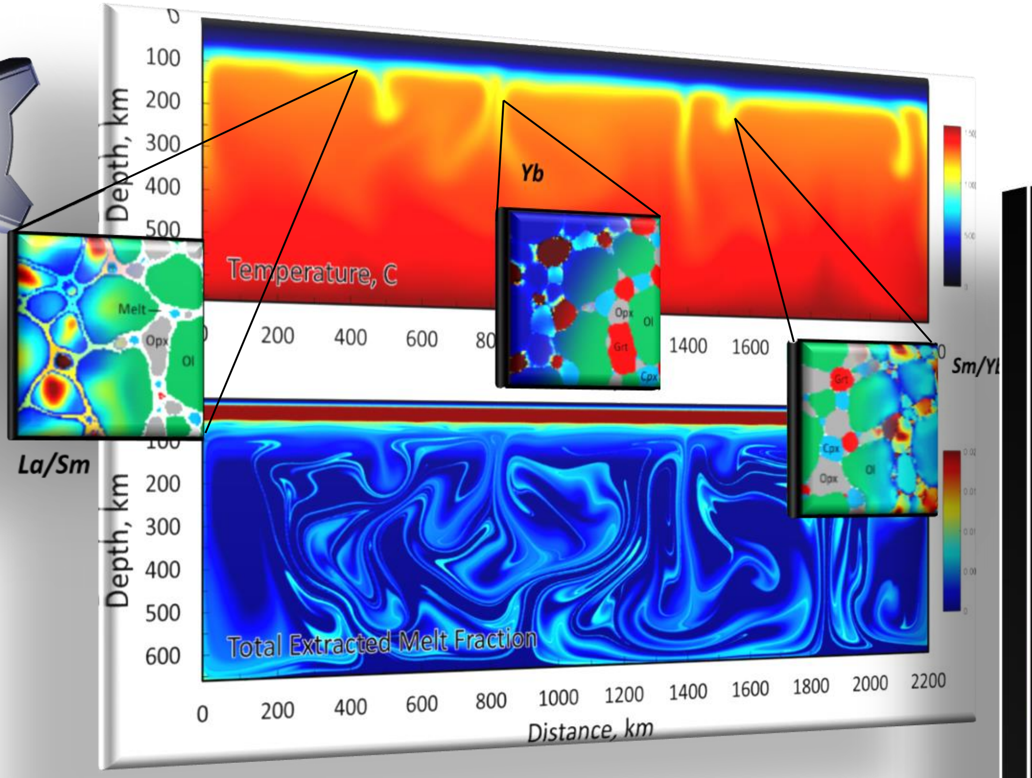
[1] MG3 and CCFS, Dept Earth and Environmental Sciences, Macquarie University, Sydney, Australia.

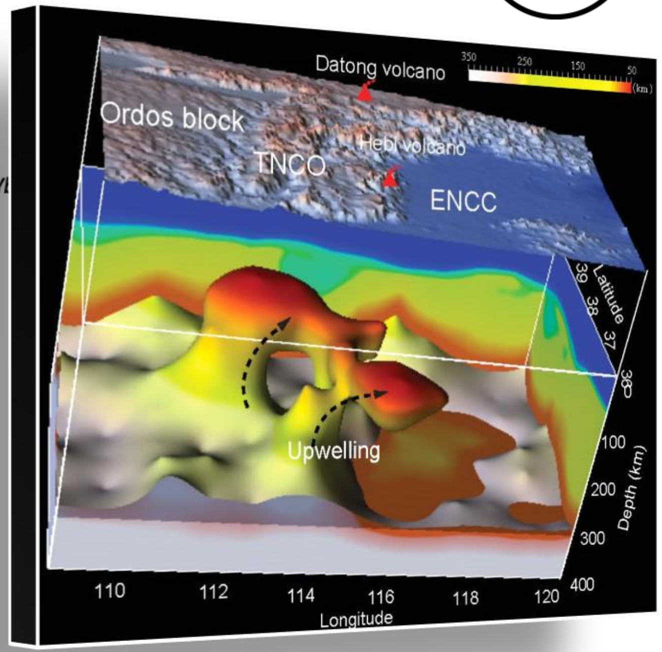
MACQUARIE University

CCFS

CEED
The Centre for Earth Evolution and Dynamics







https://www.juanafonso.com/

https://research.science.mq.edu.au/mg3/

The work I will present today is not only my own…

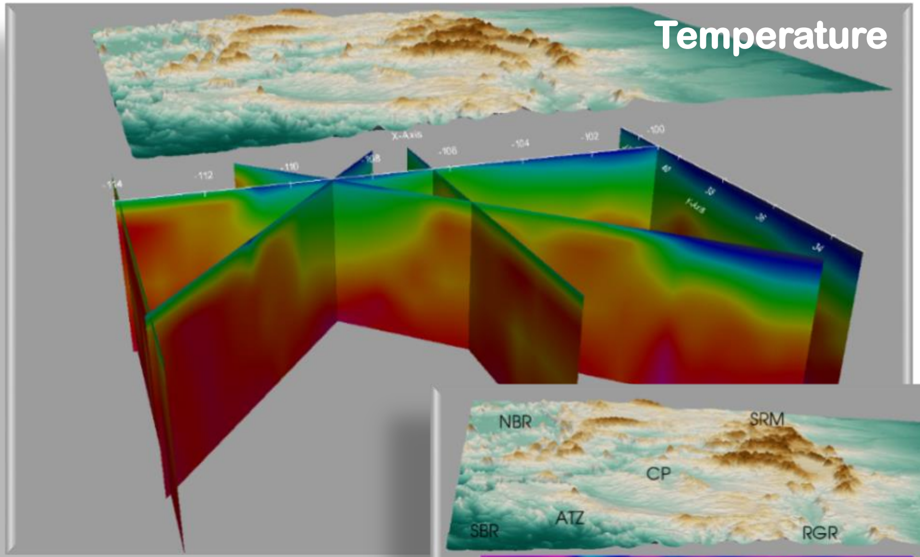
- *Special thanks to Farshad Salajegheh, Maria Manassero, Benat Oliveira, Ilya Fomin, Mehdi Qashqai, Walid Mansour, Anqi Zhang, Yingjie Yang and many others…*

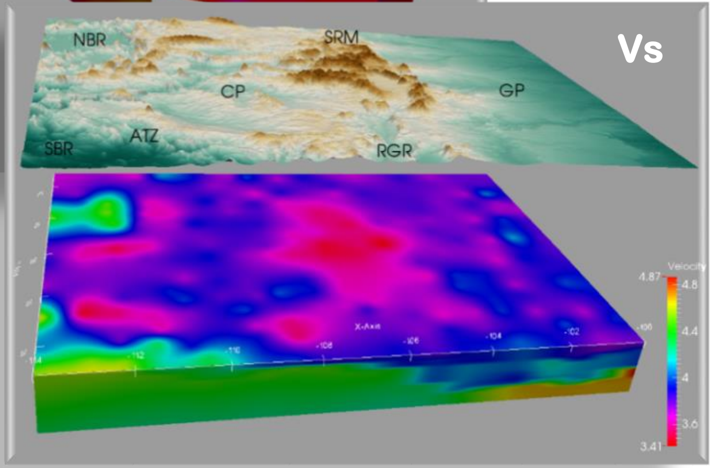
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

1) A bit about me and what I do

- *I am a geophysicist and geodynamicist (aka modeller)*
- *My own research is broadly divided into **two main streams**:*

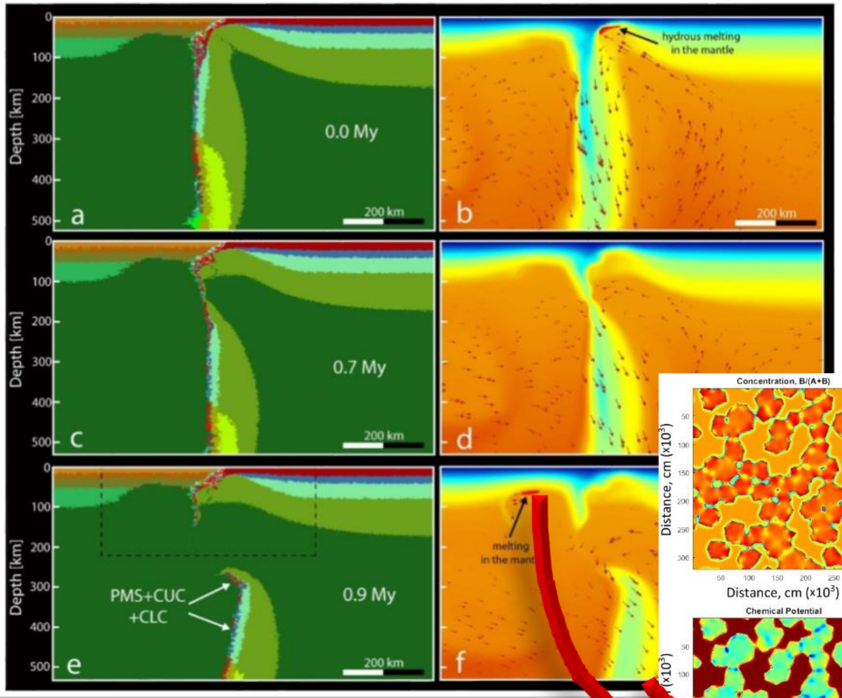
1) Geophysical modelling and inversion





Afonso et al., (2016), JGR
Qashqai, Afonso et al (2018), Tectonics

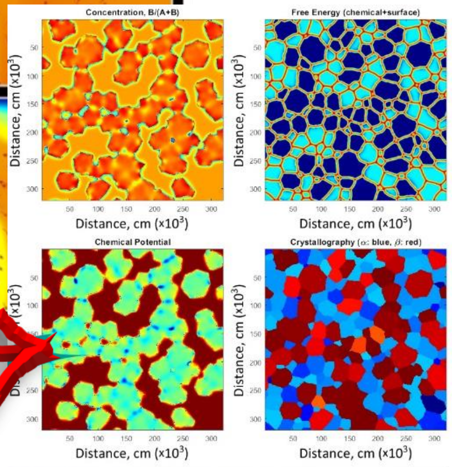
2) Numerical modelling of geological, geophysical and geochemical processes



Afonso and Zlotnik (2011)

Oliveira, Afonso et al., (2017), GJI

Grose and Afonso, (2019), J. Petrol.



This is multiple-phase multi-component reactive flow flow

Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

1) A bit about me and what I do

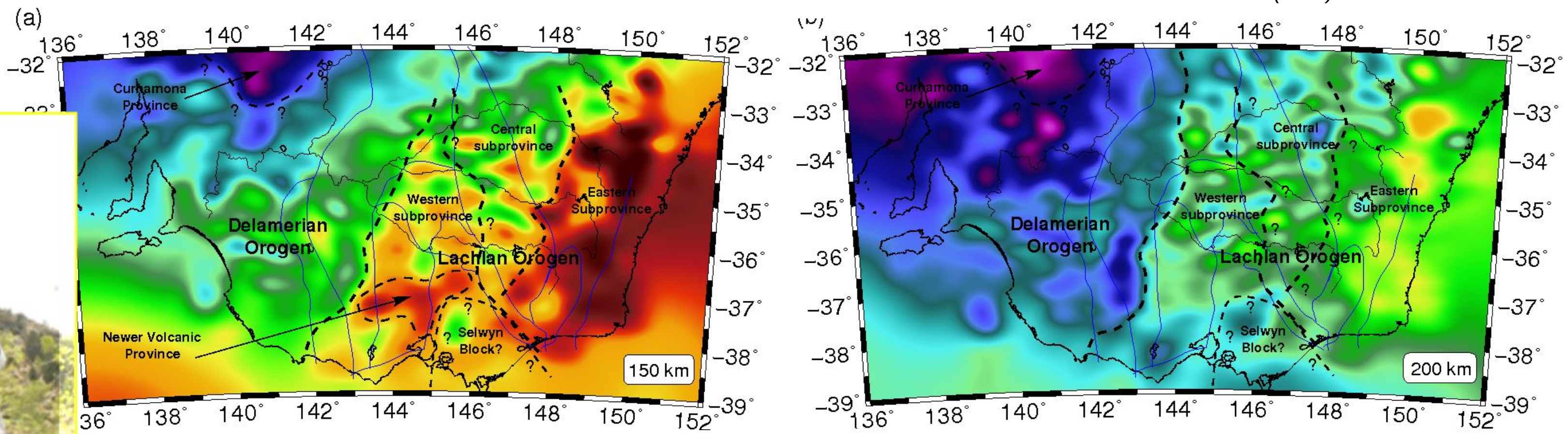
In outcrops

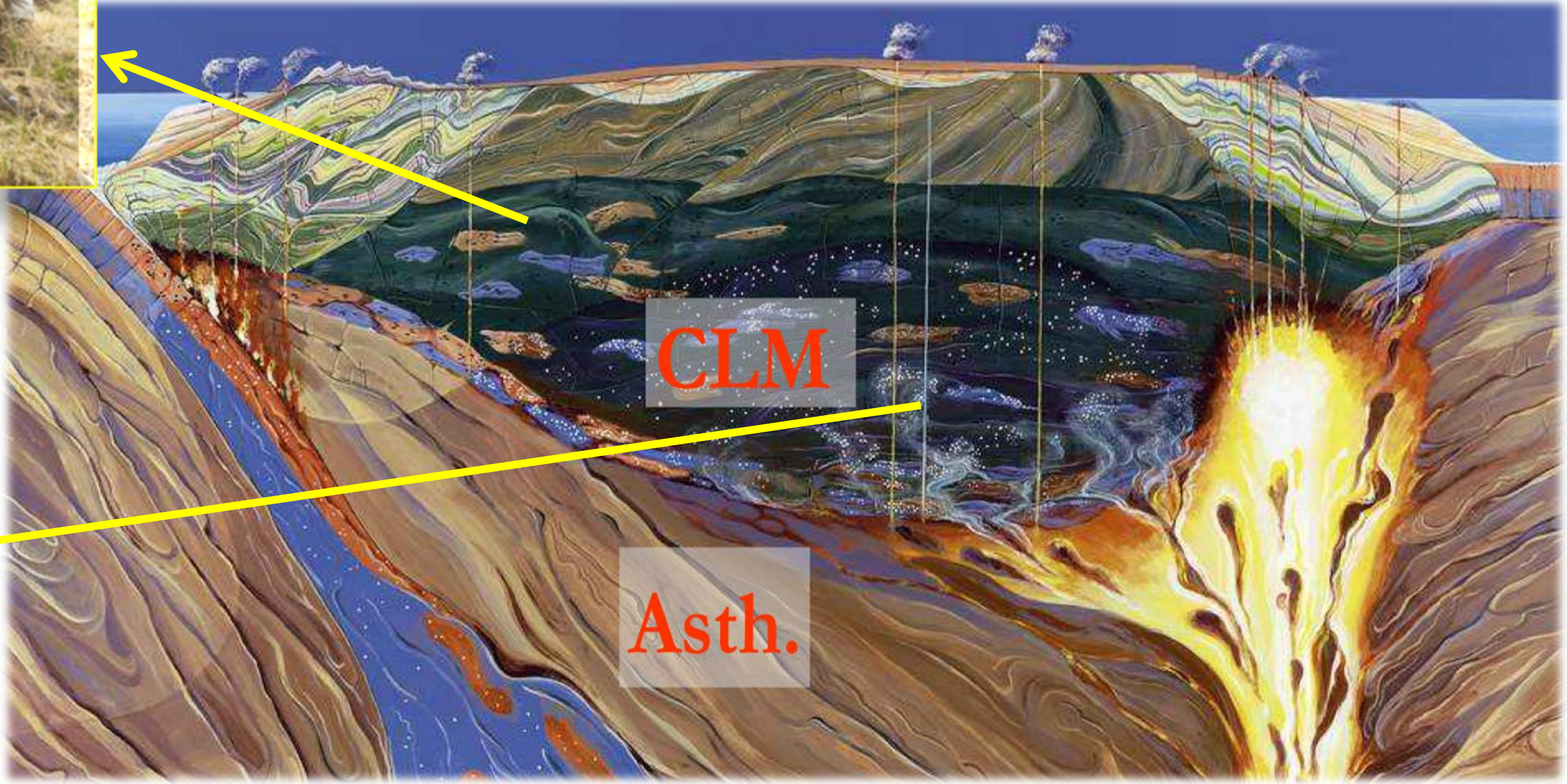
When we look in detail, the Earth looks very complicated …

… and the nature of the observed heterogeneity is uncertain.

In xenoliths

Fishwick and Rawlinson (2016)





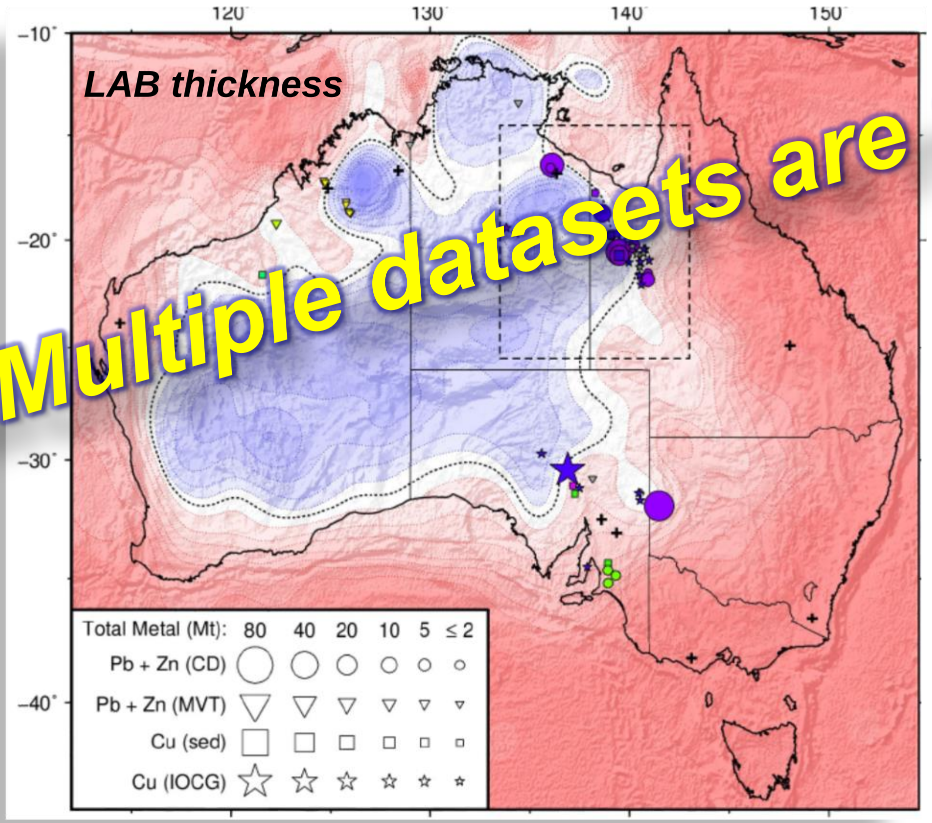
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

1) An interesting problem

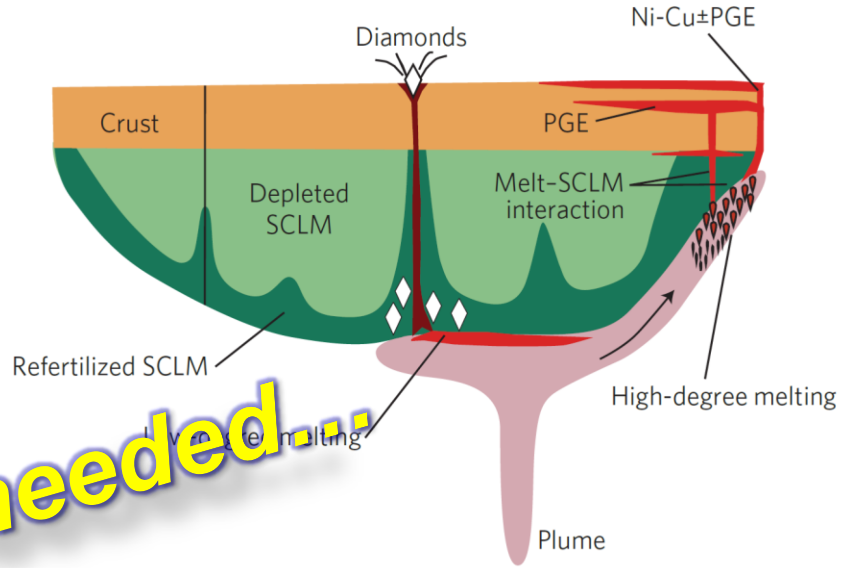
Industry interest!!!

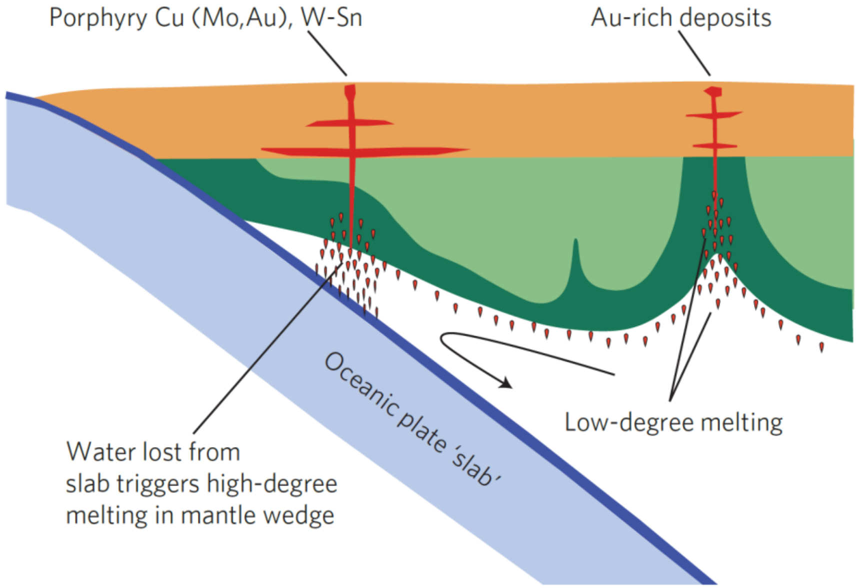
- Biggest deposits show direct connection to lithospheric architecture.
- Deposits concentrate along prominent trans-lithospheric structures
- Deposits involve both mantle and crust

Hoggard et al., 2020, Nat. Geosci.



Multiple datasets are needed…



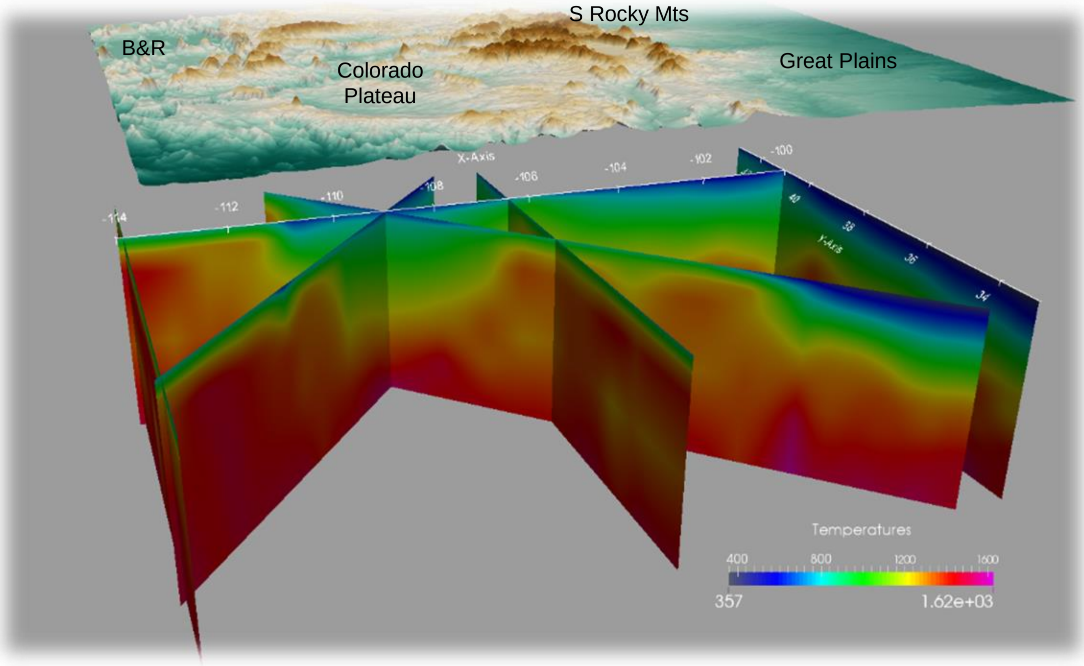


2) Motivation

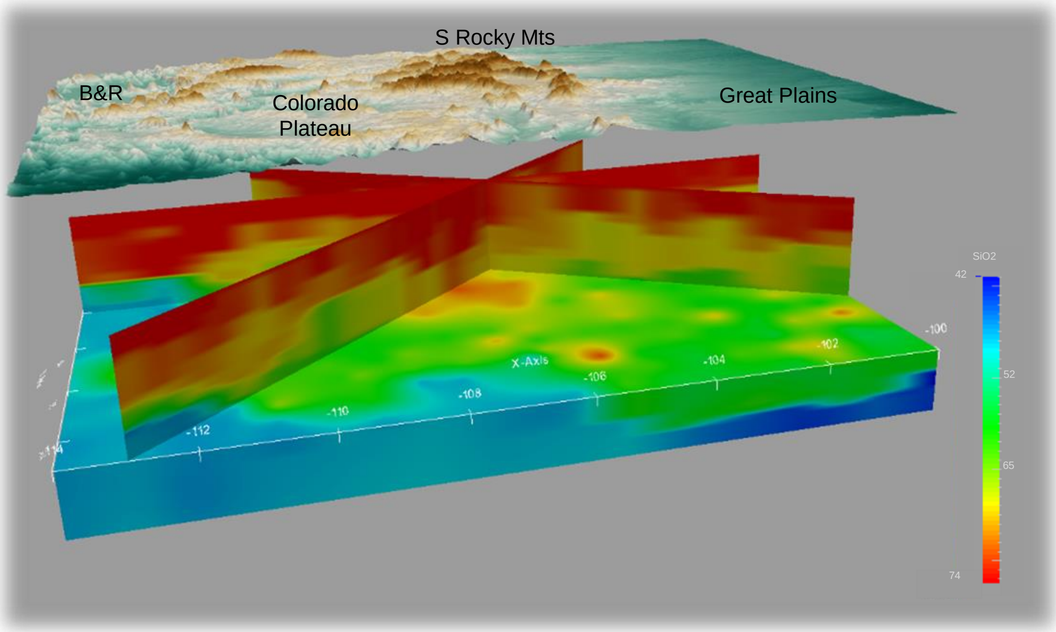
Two different but related problems

1) We need to map the thermochemical structure of the lithosphere and upper mantle

Temperature



SiO_2 content



2) Motivation

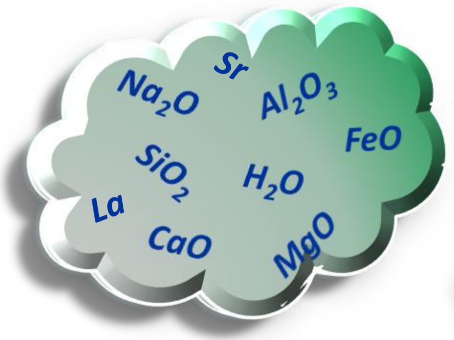
Two different but related problems

1) We need to map the thermochemical structure of the lithosphere and upper mantle

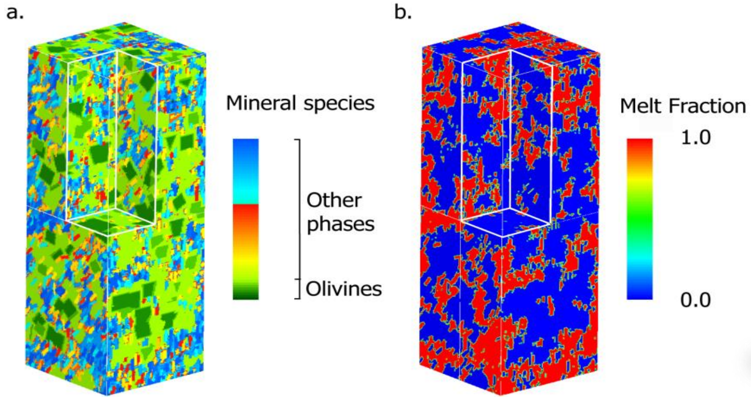
2) We need to be able to model processes of interest (e.g. melting, melt-rock interaction, etc) and their geophysical signatures

MPMCRT

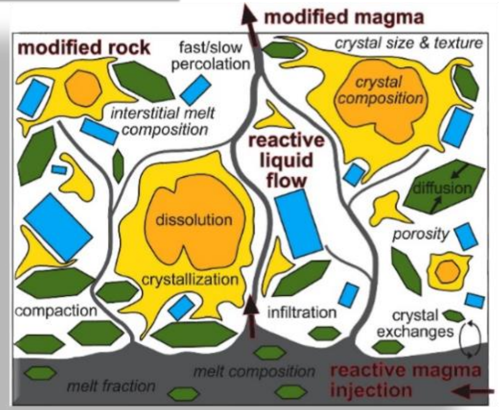
Multi-component



Multi-phase



Reactive



2) Motivation

Two different but related problems

1) We need to map the thermochemical structure of the lithosphere and upper mantle

2) We need to be able to model processes of interest (e.g. melting, melt-rock interaction, etc) and their geophysical signatures

Chemical Disequilibria, Lithospheric Thickness, and the Source of Ocean Island Basalts

Christopher J Grose, Juan C Afonso

Journal of Petrology, egz012, https://doi.org/10.1093/petrology/egz012
Published: 02 March 2019 **Article history** ▾

Abstract

We examine REE (Rare-Earth Element) and isotopic (Sr-Hf-Nd-Pb) signatures in OIB (Ocean Island Basalts) as a function of lithospheric thickness and show that the data can be divided into thin- (<12 Ma) and thick-plate (>12 Ma) sub-sets. Comparison to geophysically constrained thermal plate models indicates that the demarcation age (~12 Ma) corresponds to a lithospheric thickness of about 50 km. Thick-plate OIB show incompatible element and isotopic enrichments, whereas thin-plate lavas show MORB-like or slightly enriched values. We argue that enriched signatures in thick-plate OIB originate from

Numerical modelling of multiphase multicomponent reactive transport in the Earth's interior

Beñat Oliveira, Juan Carlos Afonso, Sergio Zlotnik, Pedro Diez

Geophysical Journal International, Volume 212, Issue 1, 1 January 2018, Pages 345–388, https://doi.org/10.1093/gji/ggx399
Published: 22 September 2017 **Article history** ▾

Cite Permissions Share ▾

SUMMARY

We present a conceptual and numerical approach to model processes in the Earth's interior that involve multiple phases that simultaneously interact thermally, mechanically and chemically. The approach is truly multiphase in the sense that each dynamic phase is explicitly modelled with an individual set of mass, momentum, energy and chemical mass balance equations coupled via

EDITOR'S CHOICE

A Disequilibrium Reactive Transport Model for Mantle Magmatism FREE

Beñat Oliveira, Juan Carlos Afonso, Romain Tilhac

Journal of Petrology, Volume 61, Issue 9, September 2020, egaa067, https://doi.org/10.1093/petrology/egaa067
Published: 18 June 2020 **Article history** ▾

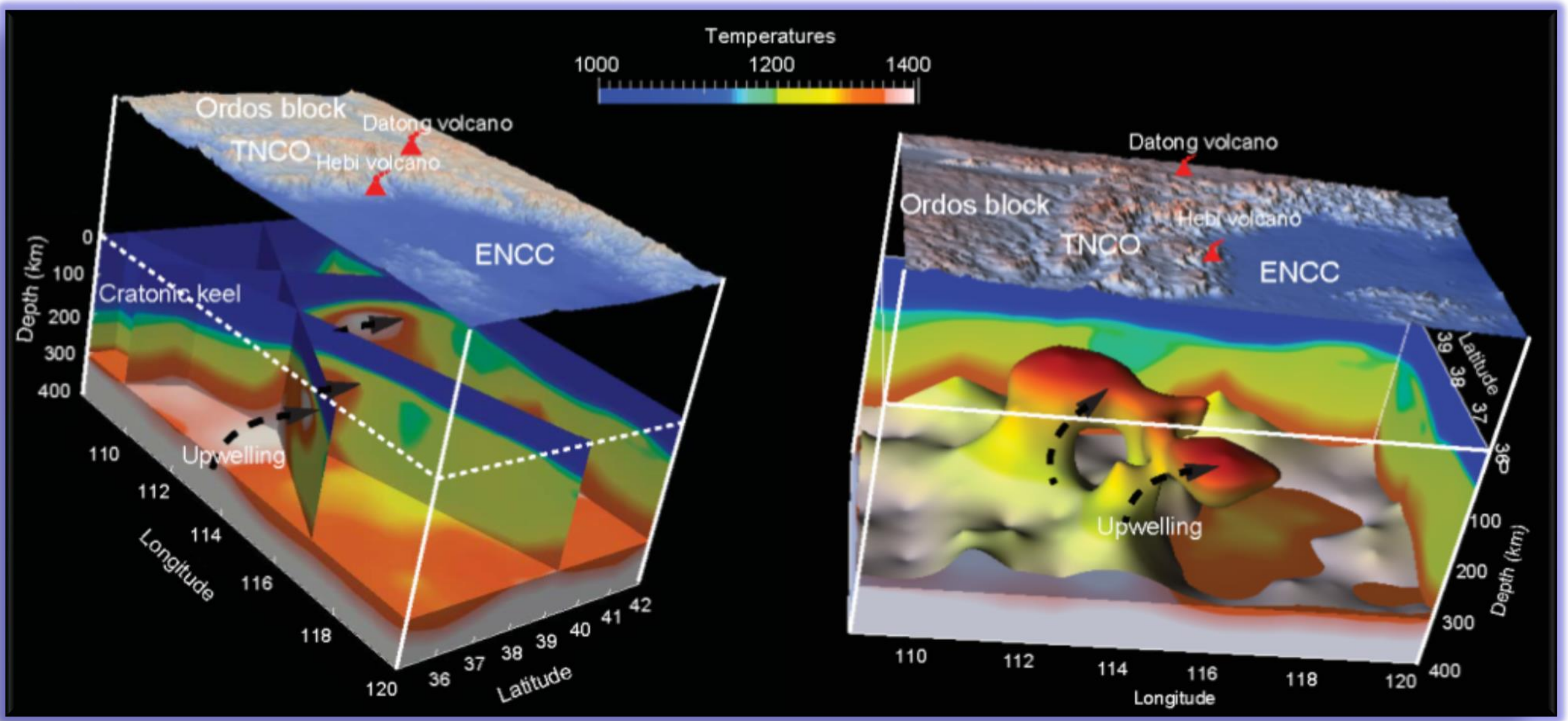
PDF Split View Cite Permissions Share ▾

Abstract

Besides standard thermo-mechanical conservation laws, a general description of mantle magmatism requires the simultaneous consideration of phase changes (e.g. from solid to liquid), chemical reactions (i.e. exchange of chemical components) and multiple dynamic phases (e.g. liquid percolating through a deforming matrix). Typically, these processes evolve at different rates, over multiple

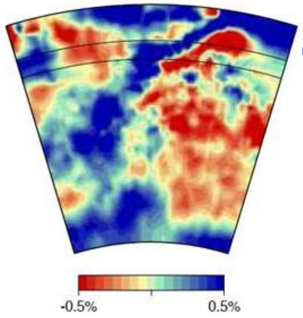
3) Multi-observable Thermochemical Tomography (MTT)

Architecture

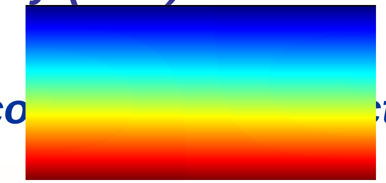


Guo, Z., Afonso, J.C. et al., GR, 2016

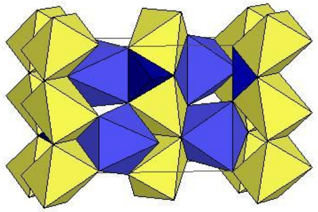
3) Multi-observable Thermochemical Tomography (MTT)



methods are co



tions should b



Geodynamics
processes

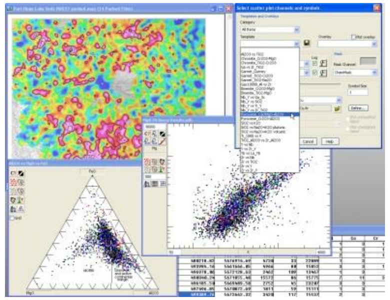
Geophysics
space field

Mineral Physics
fundamental

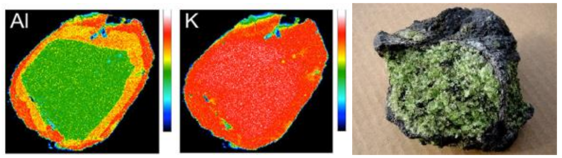
Geochemistry
groundtruth

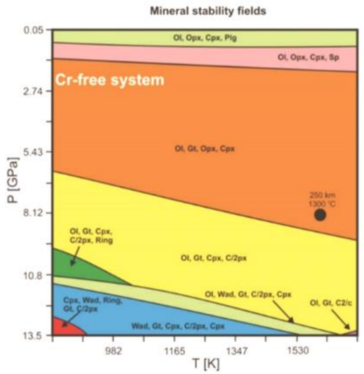
probabilistic, multi-observable, internally-consistent
inverse framework

Thermodynamics
fundamental



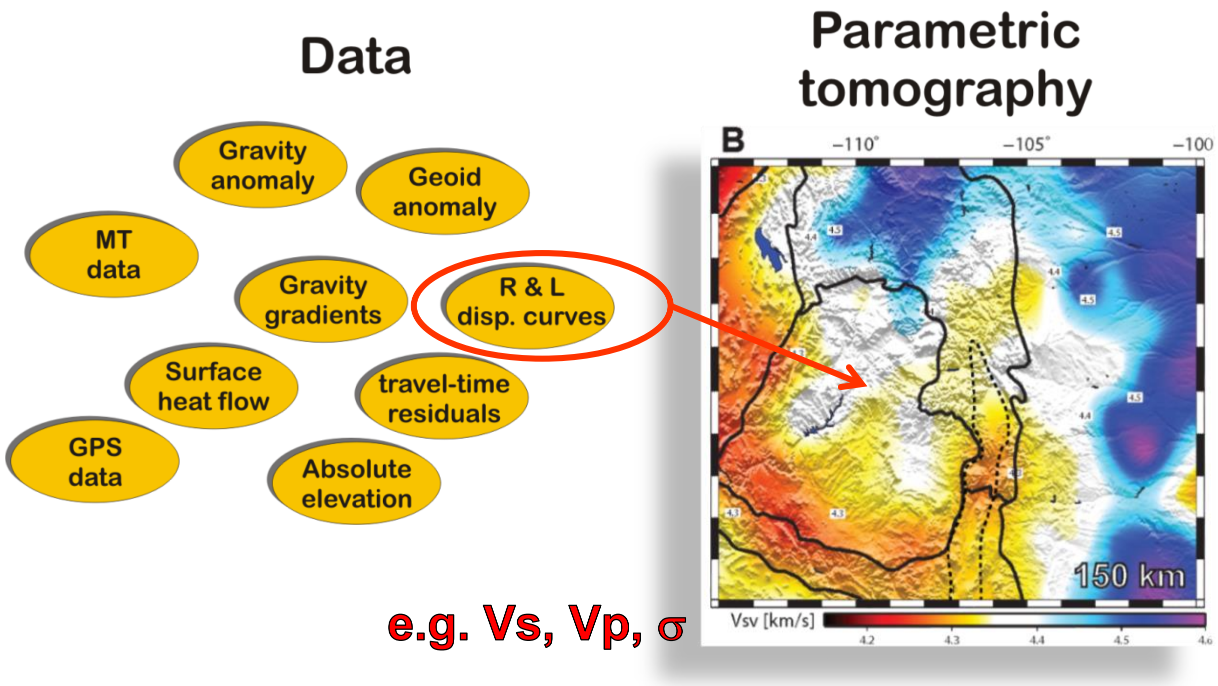
Petrology and mineralogy
groundtruth





3) Multi-observable Thermochemical Tomography (MTT)

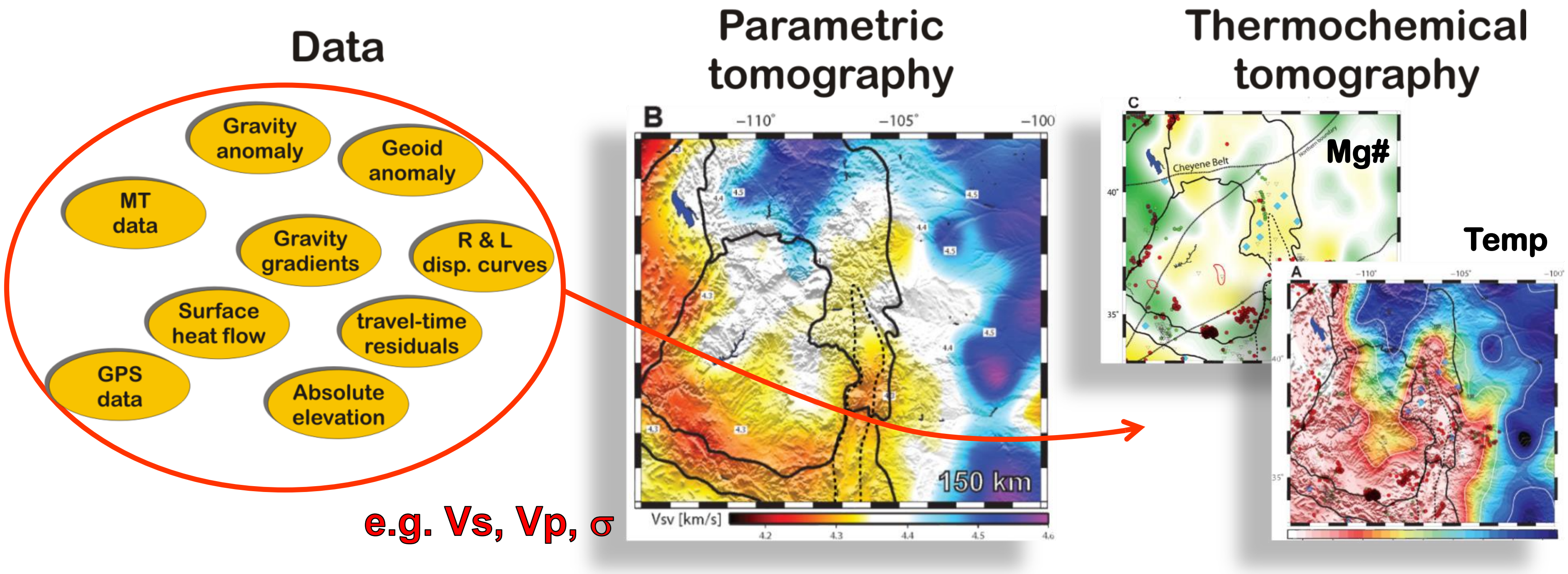
We'd prefer to work under a simulation-based (i.e. T-P-C parameter space) framework



e.g. Vs, Vp, σ

3) Multi-observable Thermochemical Tomography (MTT)

We'd prefer to work under a simulation-based (i.e. T-P-C parameter space) framework



*Make the most of what you've got…move from **parametric tomography** to true **multi-observable thermochemical tomography***

…We can all contribute!

3) Multi-observable Thermochemical Tomography (MTT)

JOURNAL OF GEOPHYSICAL RESEARCH: SOLID EARTH, VOL. 118, 2586–2617, doi:10.1002/jgrb.50124, 2013

3-D multiobservable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. I: *a priori* petrological information and geophysical observables

J. C. Afonso,[1] J. Fullea,[2,3] W. L. Griffin,[1] Y. Yang,[1] A. G. Jones,[2] J. A. D. Connolly,[4] and S. Y. O'Reilly[1]

JOURNAL OF GEOPHYSICAL RESEARCH: SOLID EARTH, VOL. 118, 1650–1676, doi:10.1002/jgrb.50123, 2013

3-D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle. II: General methodology and resolution analysis

J. C. Afonso,[1] J. Fullea,[2,3] Y. Yang,[1] J. A. D. Connolly,[4] and A. G. Jones[2]

93 pages!

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE
10.1002/2016JB013049

This article is a companion to *Afonso et al.* [2013] doi:10.1002/jgrb.50124 and *Afonso et al.* [2013] doi:10.1002/jgrb.50123.

Key Points:
- We present a novel multiobservable probabilistic tomography method to image the thermochemical structure

3-D multiobservable probabilistic inversion for the compositional and thermal structure of the lithosphere and upper mantle: III. Thermochemical tomography in the Western-Central U.S.

Juan Carlos Afonso[1], Nicholas Rawlinson[2], Yingjie Yang[1], Derek L. Schutt[3], Alan G. Jones[4,5], Javier Fullea[5], and William L. Griffin[1]

Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

MG3 Macquarie's Geophysics and Geodynamics Group

MACQUARIE University

3) Multi-observable Thermochemical Tomography (MTT) … … the Western-Central US

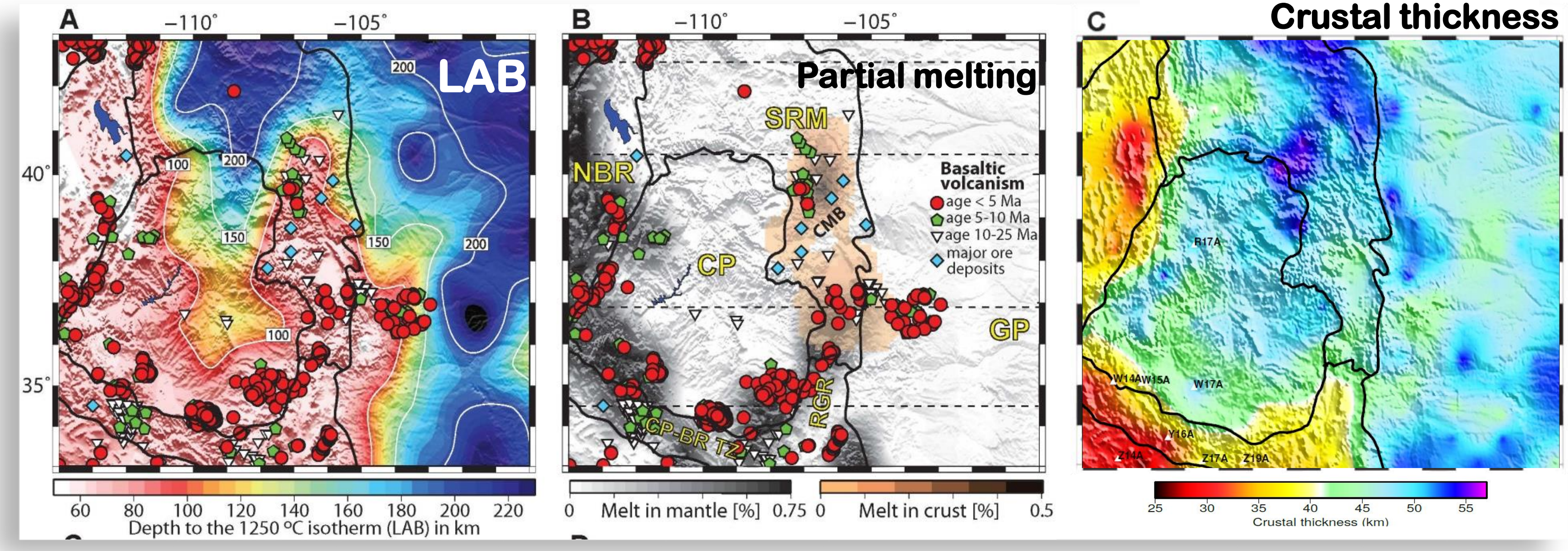
Afonso et al., JGR, 2016; Qashqai et al., Tectonics, 2018

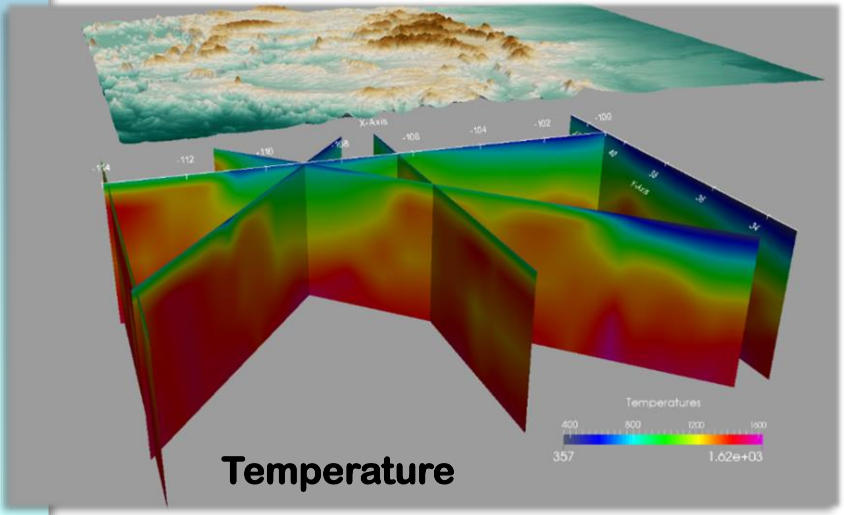
Multi-observable Thermochemical Tomography (MTT) of the Central/Western US

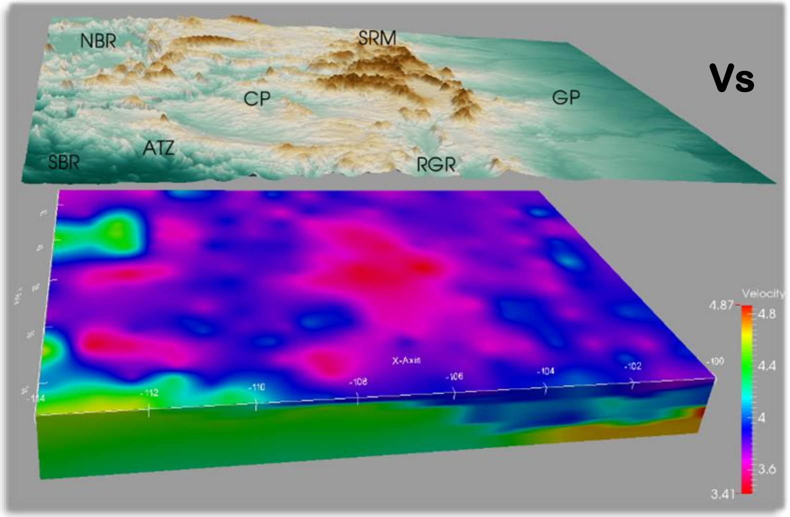
Eight datasets jointly inverted:

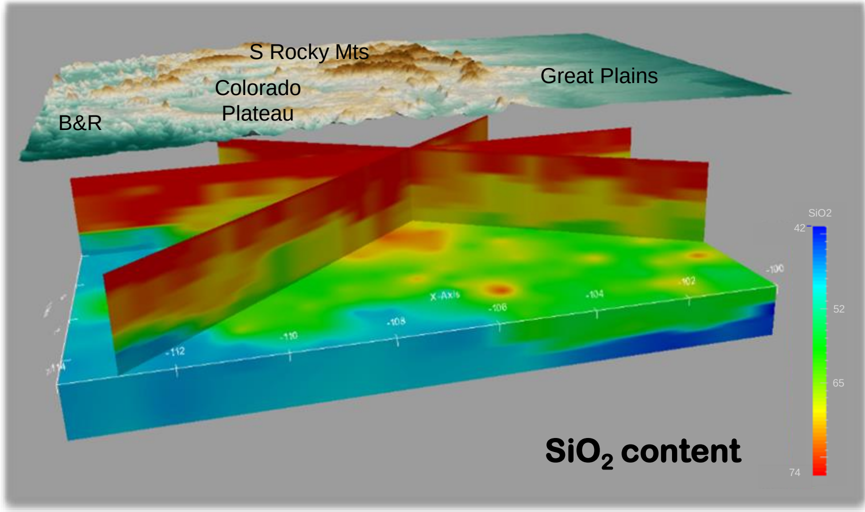
- *Surface Heat flow*
- *S and P body waves (tt)*
- *Rayleigh waves (disp. curves)*
- *Elevation*
- *P-wave RFs*
- *Gravity anomalies and gradients*
- *Geoid anomalies*

for the complete physical state of the lithosphere and sublithospheric upper mantle





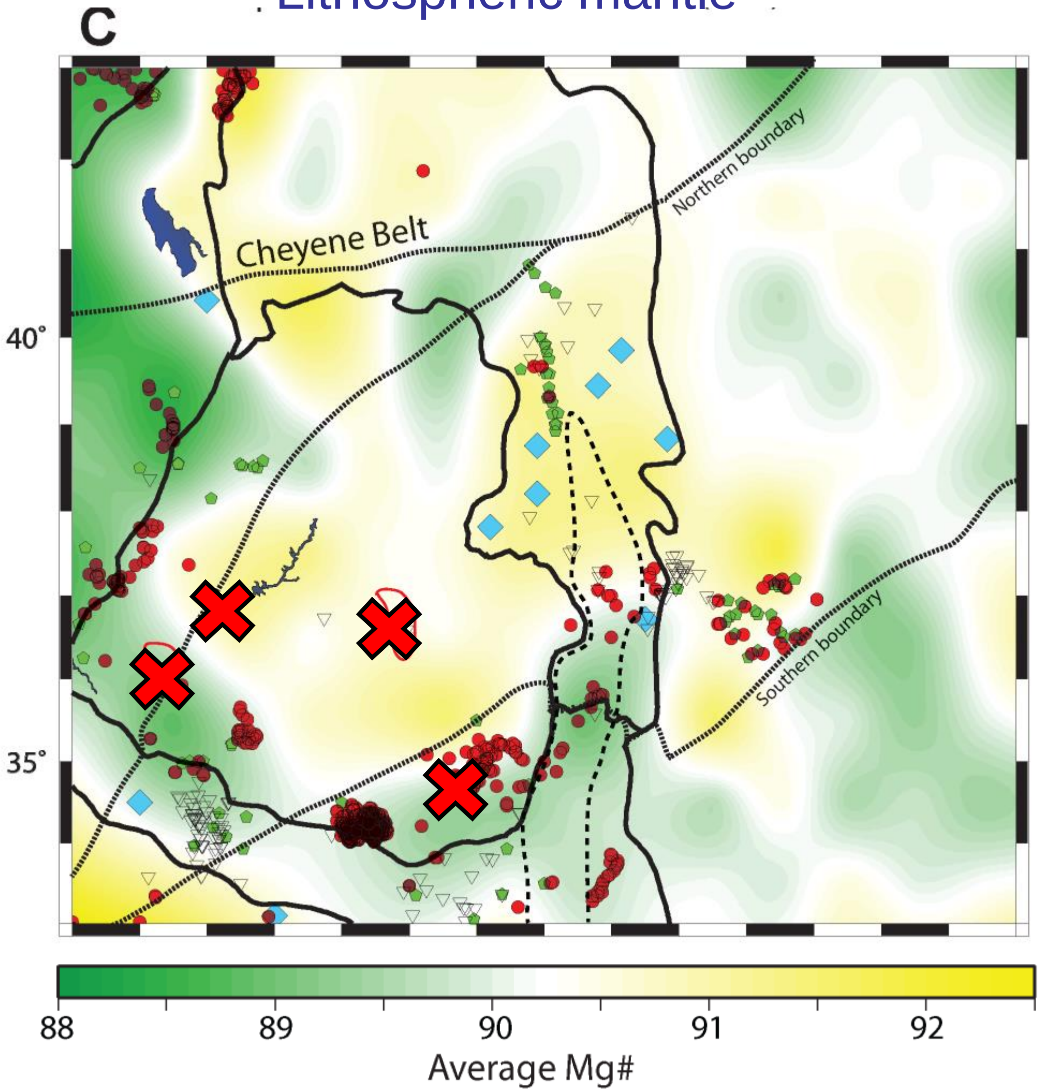


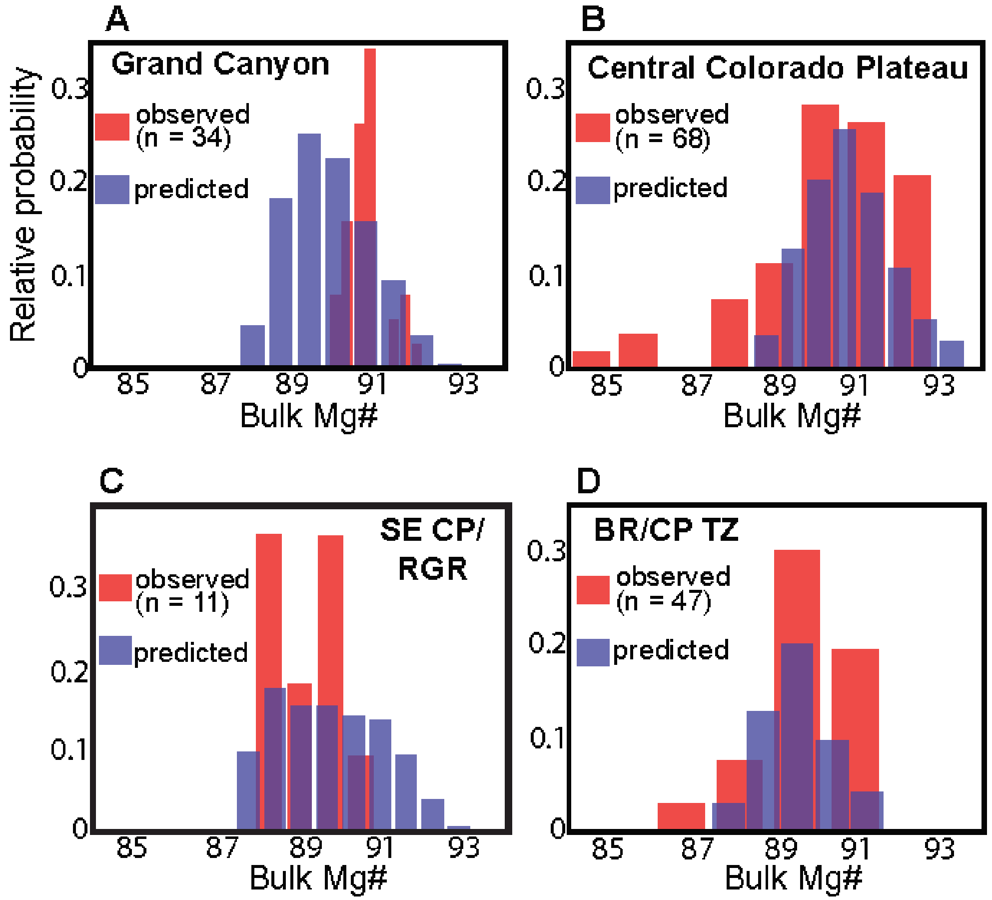


Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

3) Multi-observable Thermochemical Tomography (MTT) … … the Western-Central US

Lithospheric mantle

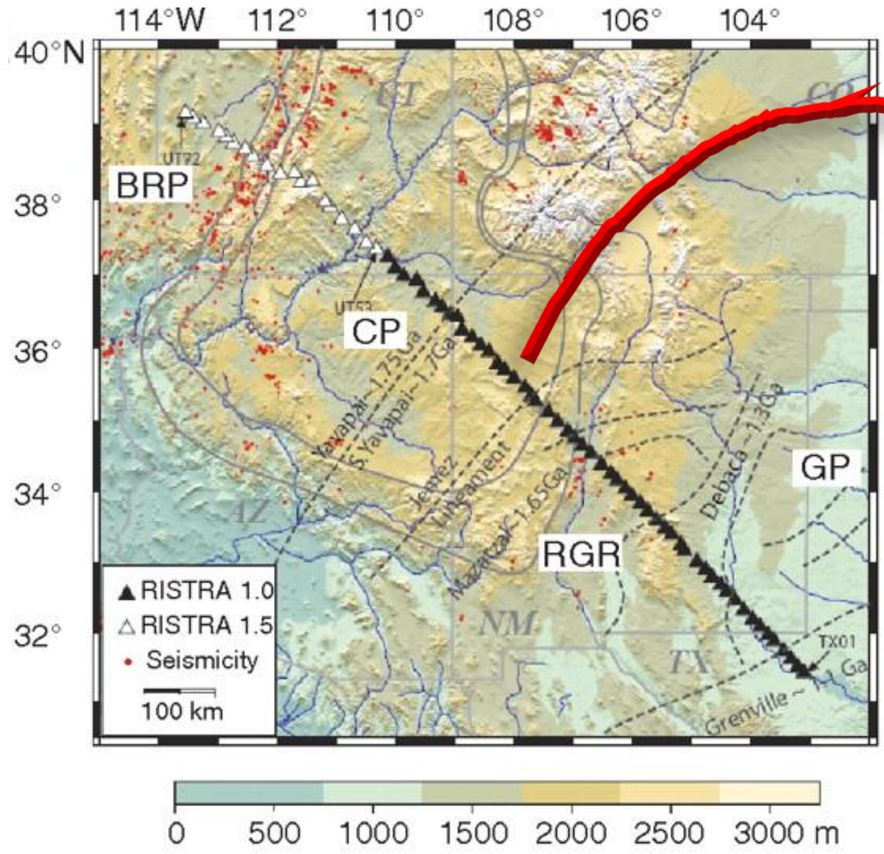


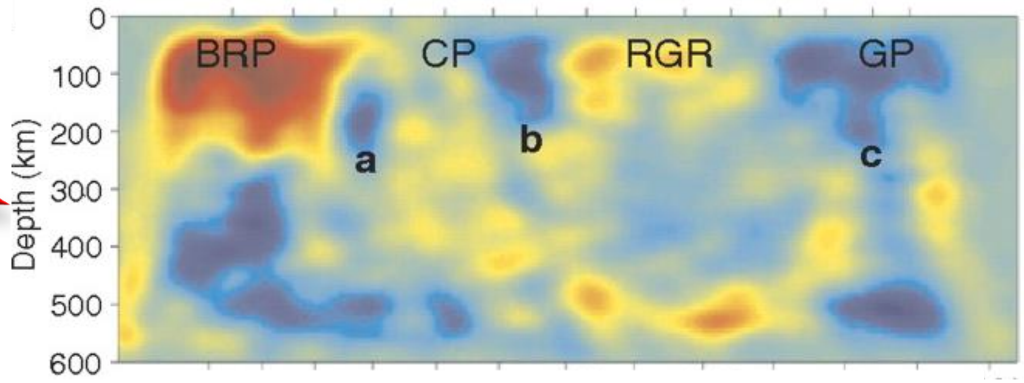


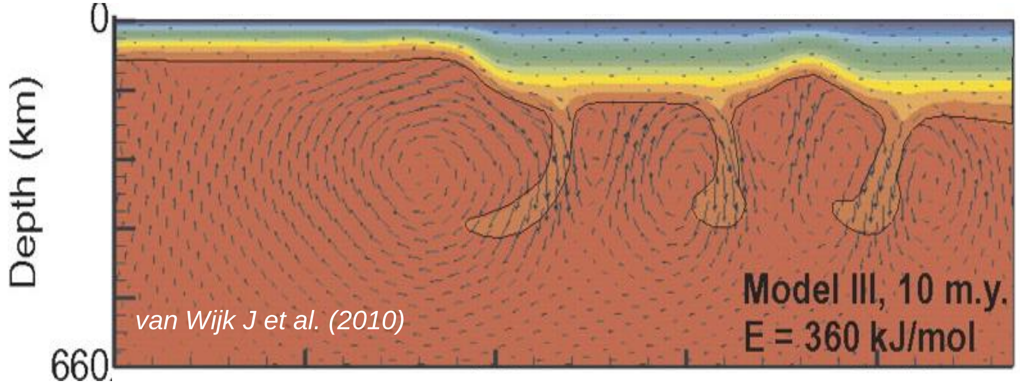
Afonso et al., JGR, 2016

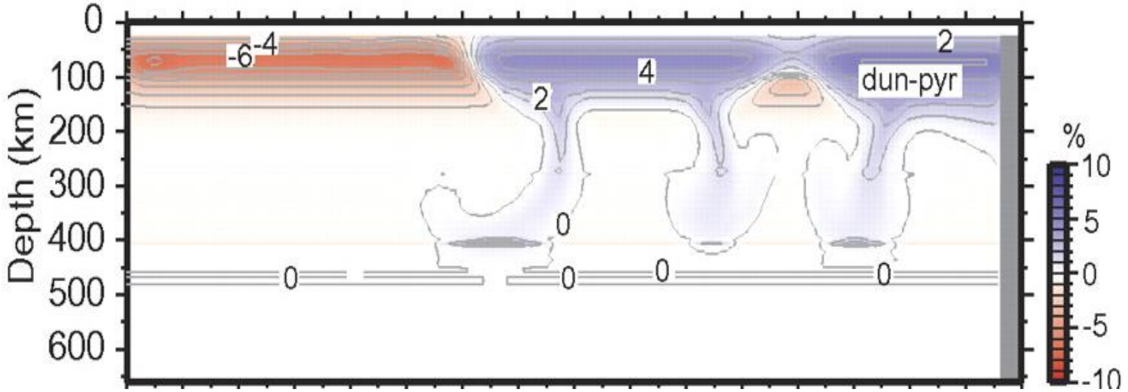
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

3) Multi-observable Thermochemical Tomography (MTT) … … the Western-Central US



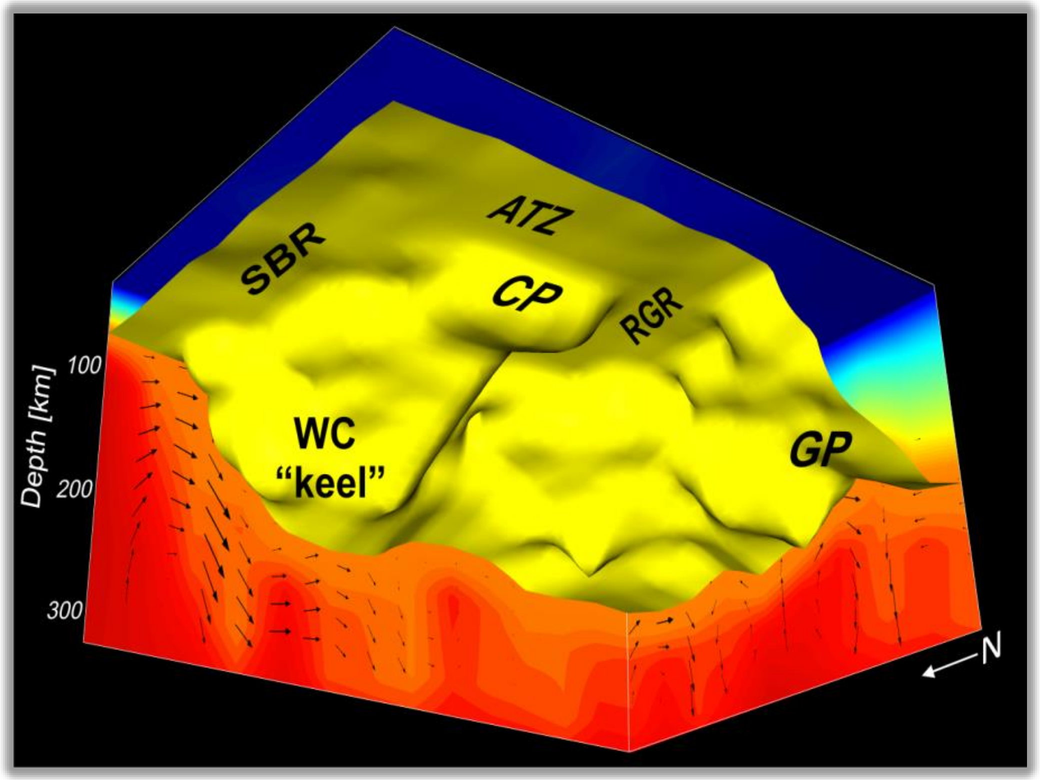




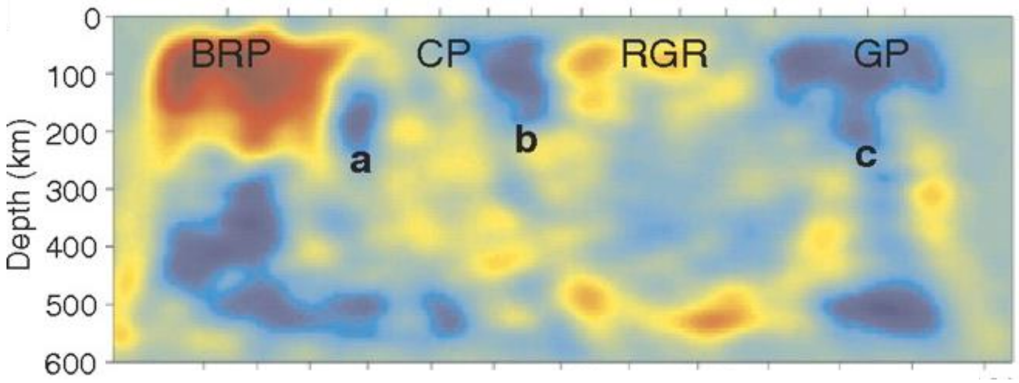


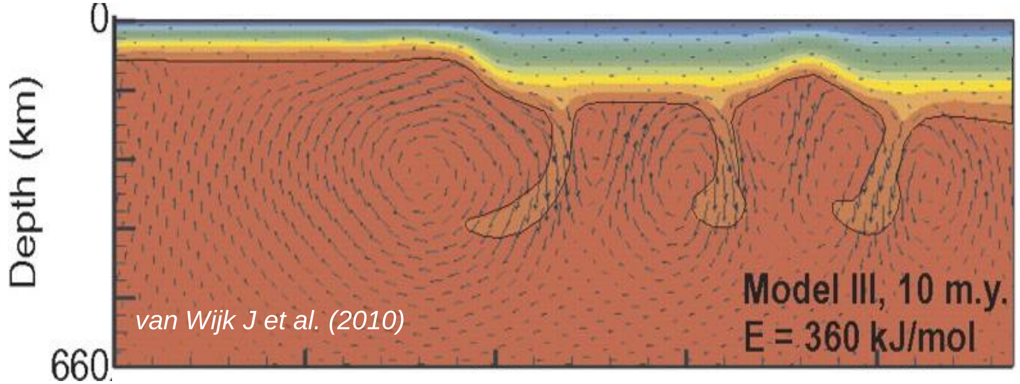
Traditional, yet cumbersome, approach

3) Multi-observable Thermochemical Tomography (MTT) … … the Western-Central US

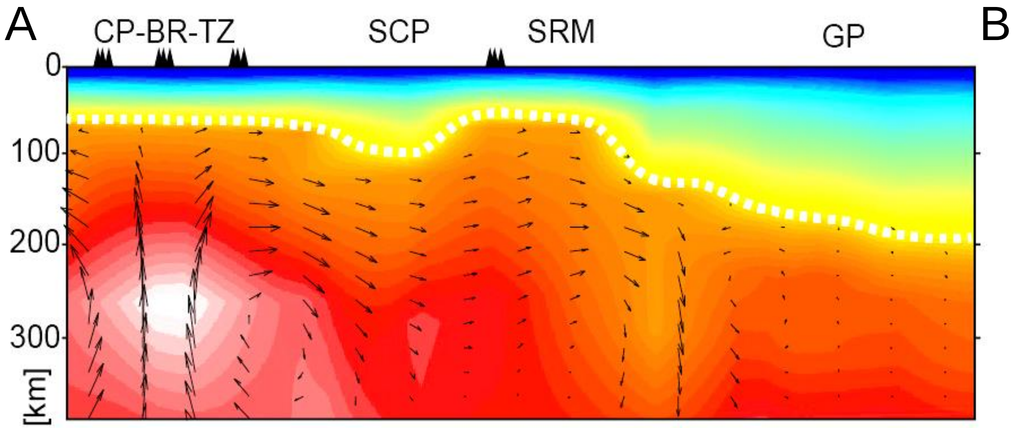


Afonso et al., JGR, 2016





van Wijk J et al. (2010)



This is not the result of a numerical simulation but the result of inverting the relevant data sets for the velocity field

4) There is no magic… … Reduced Order Techniques

JGR Solid Earth

RESEARCH ARTICLE

10.1029/2019JB018314

Fast Stokes Flow Simulations for Geophysical-Geodynamic Inverse Problems and Sensitivity Analyses Based On Reduced Order Modeling

O. Ortega-Gelabert[1], S. Zlotnik[1], J. C. Afonso[2,3], and P. Díez[1]

[1]Laboratori de Càlcul Numèric (LaCàN), Departament d'Enginyeria Civil i Ambiental, Universitat Politècnica de Catalunya, Barcelona, Spain, [2]Department of Earth and Planetary Sciences, Macquarie University, Sydney, Australia, [3]Centre for Earth Evolution and Dynamics, Department of Geosciences, University of Oslo, Oslo, Norway

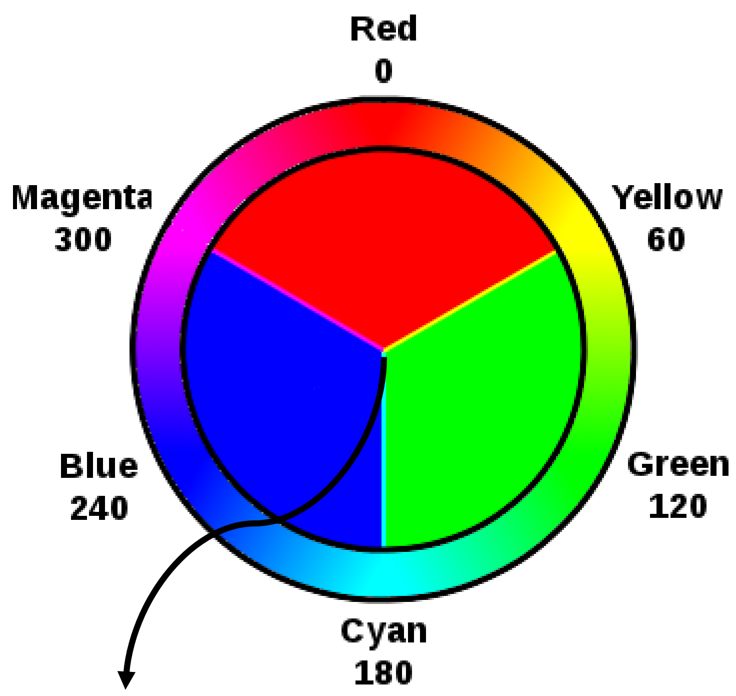
Key Points:
- An efficient method for producing ultrafast solutions of the 3-D Stokes problem for mantle convection is presented
- This method is particularly well suited for joint geodynamic-geophysical probabilistic inverse problems and studies of dynamic topography
- The method is suitable to tackle a range of probabilistic inverse problems where fast solutions for a complex forward problem are needed

Abstract Markov chain Monte Carlo (MCMC) methods have become standard in Bayesian inference and multi-observable inversions in almost every discipline of the Earth sciences. In the case of geodynamic and/or coupled geophysical-geodynamic inverse problems, however, the computational cost associated with the solution of large-scale 3-D Stokes forward problems has rendered probabilistic formulations

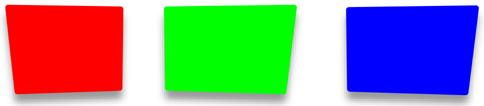
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

4) There is no magic… … Reduced Order Techniques

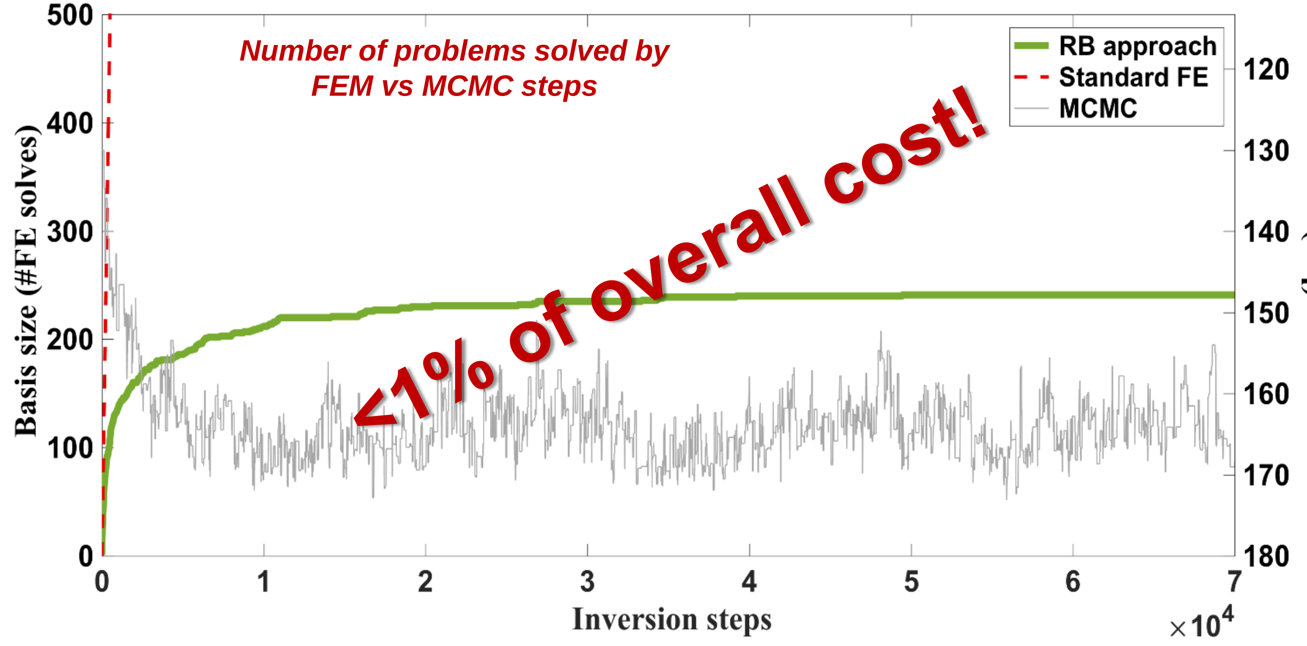
RBM made simple



Primary colours
=
basis



- If we want to obtain:
- Combine: = 0.4 + 0.7 + 1



Ortega-Galabert et al., JGR (2020)

4) There is no magic… … Reduced Order Techniques

I thought we could address a long-standing problem in geophysics… the inversion of 3D magnetotelluric data within a fully probabilistic formalism…

… enter Coti…

Geophysical Journal International

Issues ▾ More Content ▾ Subject ▾ Submit ▾ Purchase About ▾ All Geoph

Volume 223, Issue 3
December 2020
(In Progress)

Article Contents

A reduced order approach for probabilistic inversions of 3-D magnetotelluric data I: general formulation

M C Manassero ✉, J C Afonso, F Zyserman, S Zlotnik, I Fomin

Geophysical Journal International, Volume 223, Issue 3, December 2020, Pages 1837–1863, https://doi.org/10.1093/gji/ggaa415
Published: 01 September 2020 **Article history** ▾

PDF Split View Cite Permissions Share ▾

SUMMARY

Simulation-based probabilistic inversions of 3-D magnetotelluric (MT) data are arguably the best option to deal with the nonlinearity and non-uniqueness of the MT problem. However, the computational

4) There is no magic… … Reduced Order Techniques

Earth ArXiv

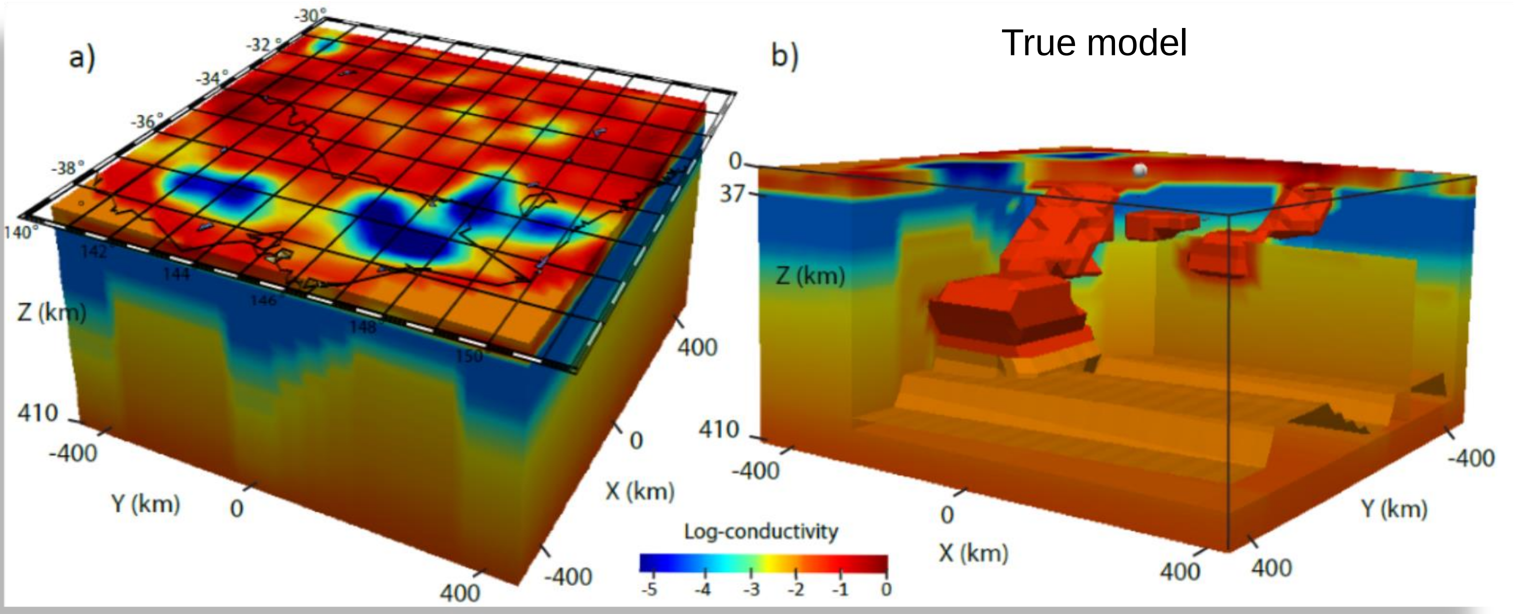
A Reduced Order Approach for Probabilistic Inversions of 3D Magnetotelluric Data II: Joint inversion of MT and Surface-Wave Data

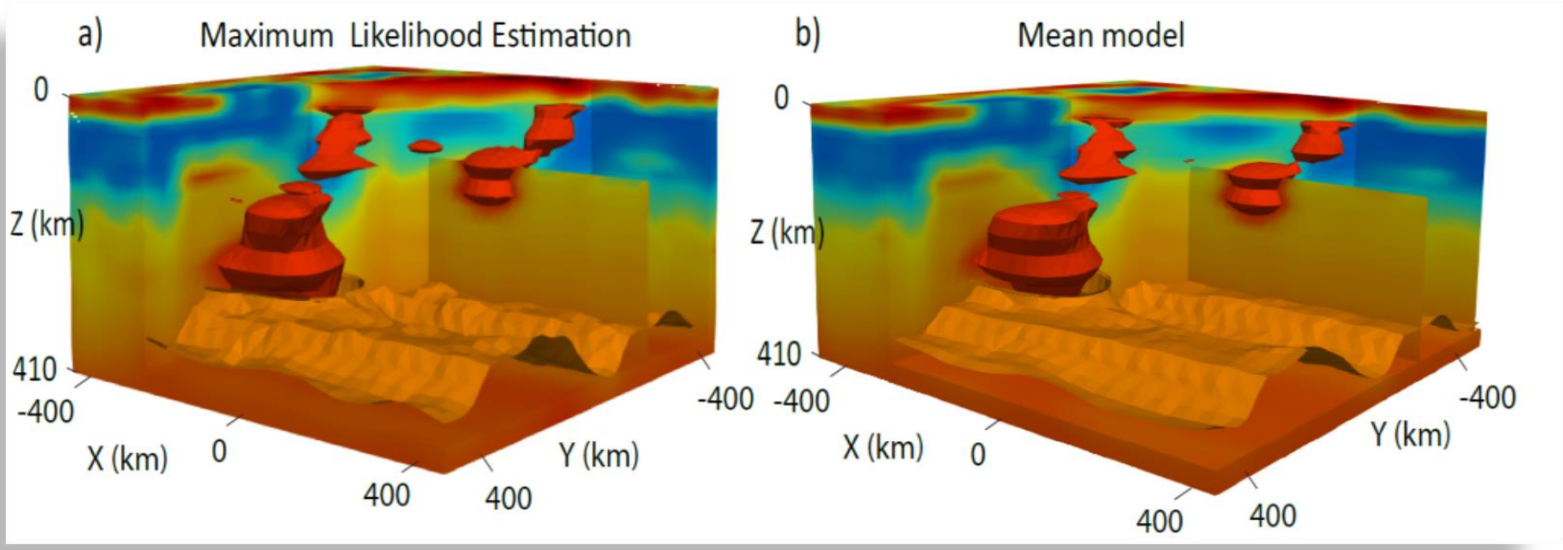
M.C. Manassero[1], J.C. Afonso[1,2], F. Zyserman[3], S. Zlotnik[4] and I. Fomin[1]

[1]Australian Research Council Centre of Excellence for Core to Crust Fluid Systems/GEMOC, Department of Earth and Environmental Sciences, Macquarie University, Sydney, Australia.
[2]Centre for Earth Evolution and Dynamics, Department of Geosciences, University of Oslo, Norway.
[3]CONICET, Facultad de Ciencias Astronómicas y Geofísicas, Universidad de La Plata, Argentina.
[4]Laboratori de Càlcul Numèric, Escola Tècnica Superior d'Enginyers de Camins, Canals i Ports, Universitat Politècnica de Catalunya, Barcelona, Spain.

Key Points:

- We present a novel strategy to invert 3D magnetotelluric (MT) data together with other data sets in a fully probabilistic manner.
- We apply our method and perform the first joint probabilistic inversions of 3D MT and surface-wave dispersion data for imaging the electrical conductivity distribution in the lithosphere.
- We demonstrate the capability and applicability of our approach to include 3D MT data into joint probabilistic inversions for the physical state of the interior of the Earth.

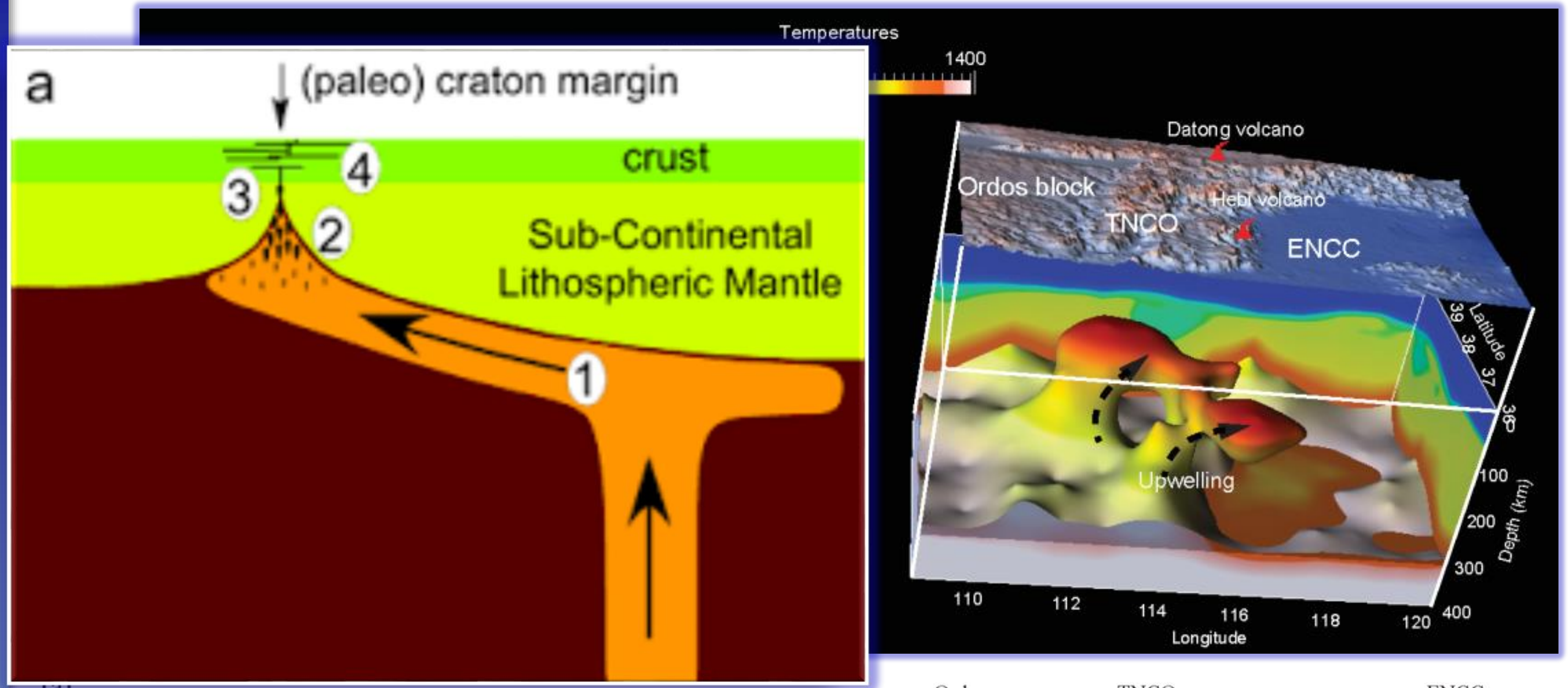




…but this is another story…

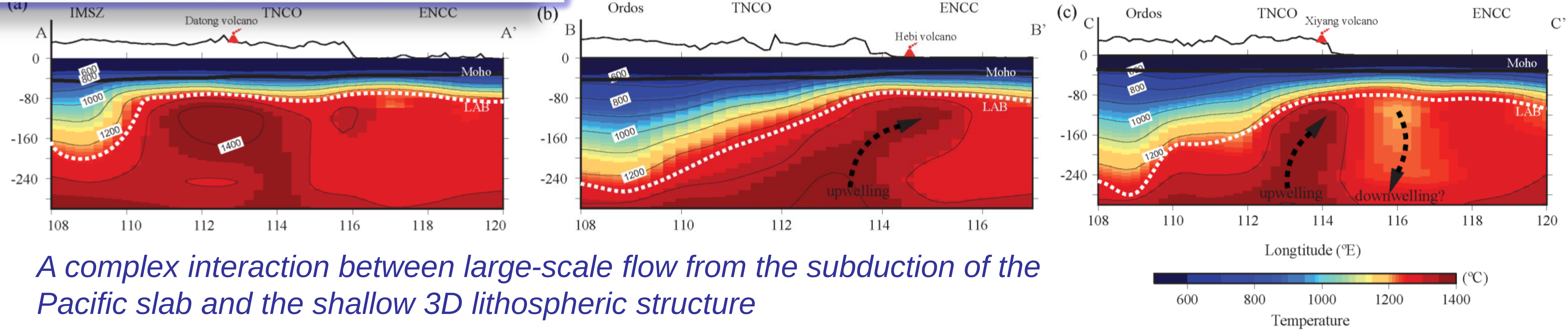
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

5) Some examples…



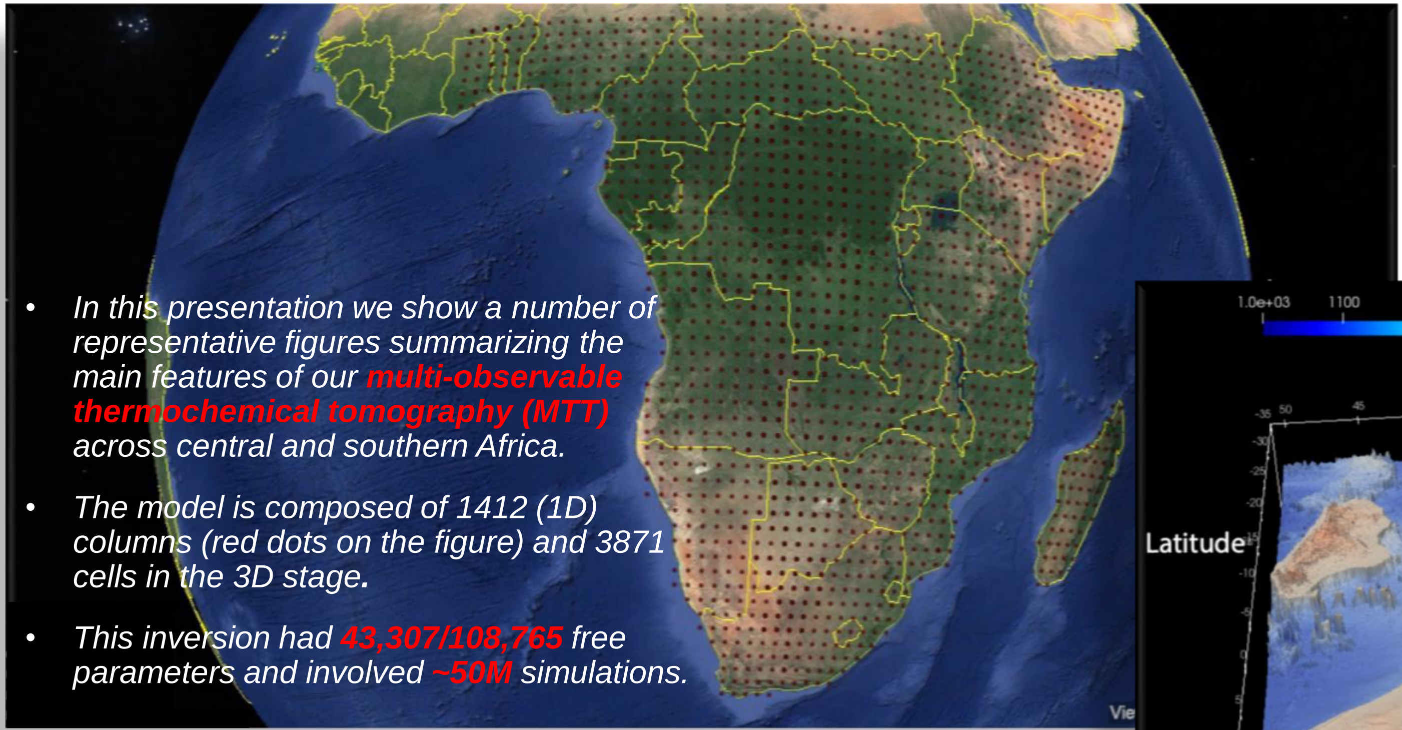
Thermochemical structure of the North China Craton: extent and causes of cratonic lithosphere modification

Guo, Z., Afonso, J.C. et al., GR, 2016



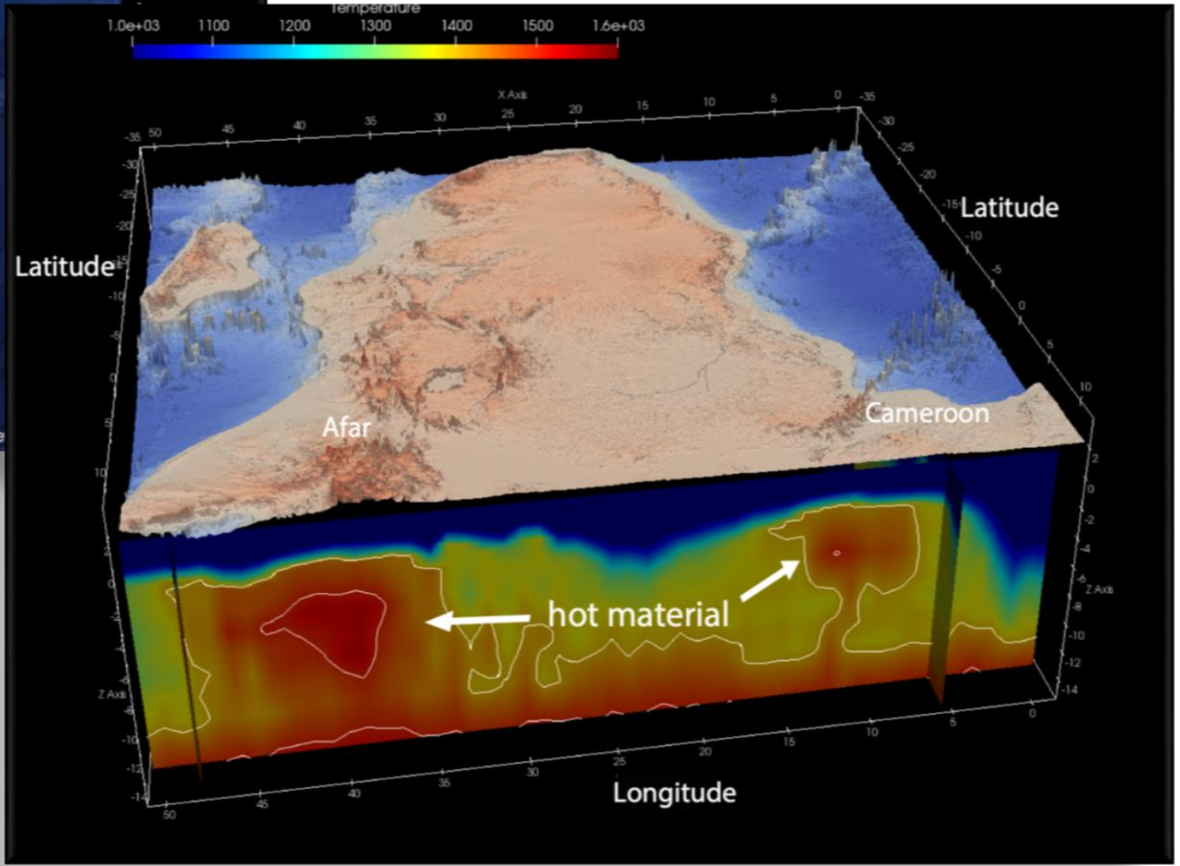
A complex interaction between large-scale flow from the subduction of the Pacific slab and the shallow 3D lithospheric structure

5) Some examples…



- *In this presentation we show a number of representative figures summarizing the main features of our* ***multi-observable thermochemical tomography (MTT)*** *across central and southern Africa.*
- *The model is composed of 1412 (1D) columns (red dots on the figure) and 3871 cells in the 3D stage.*
- *This inversion had* ***43,307/108,765*** *free parameters and involved* ***~50M*** *simulations.*

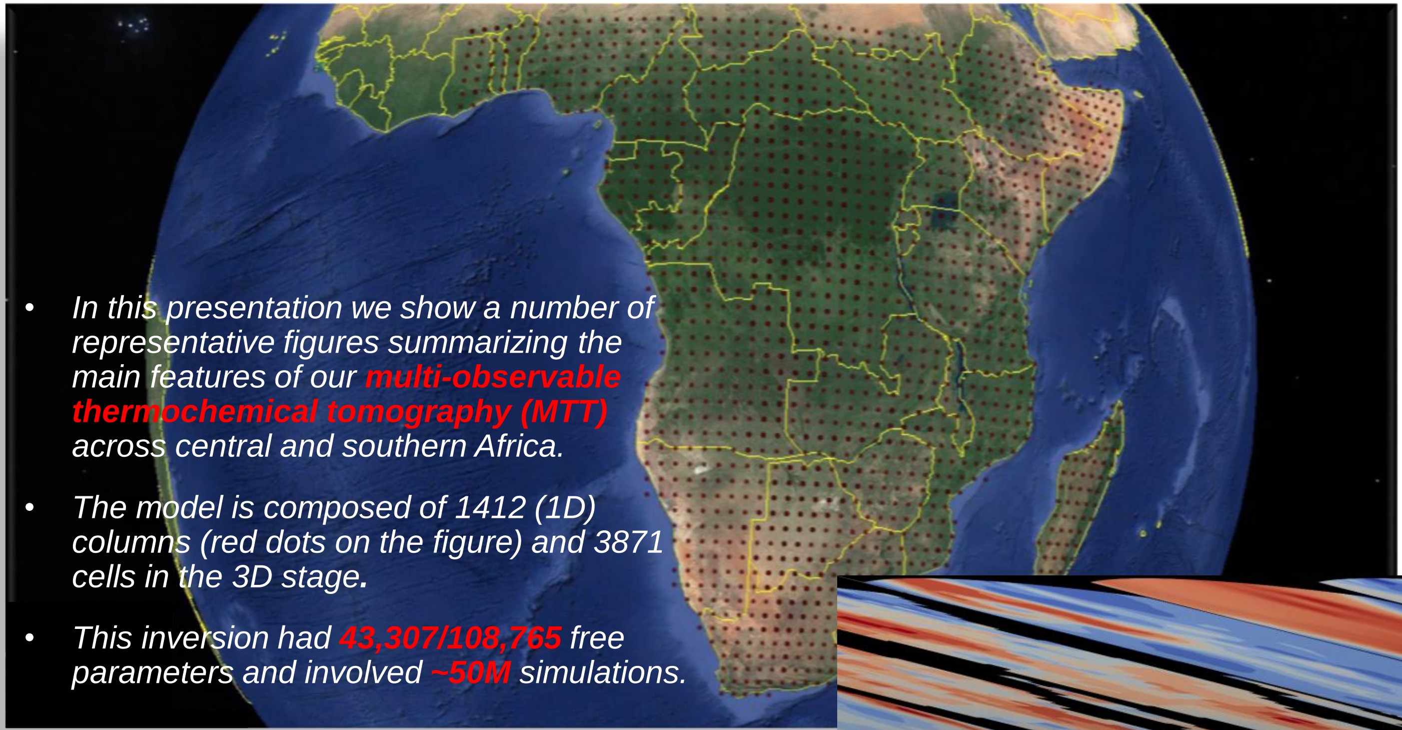
The approach has been successfully applied in a large number of tectonic scenarios



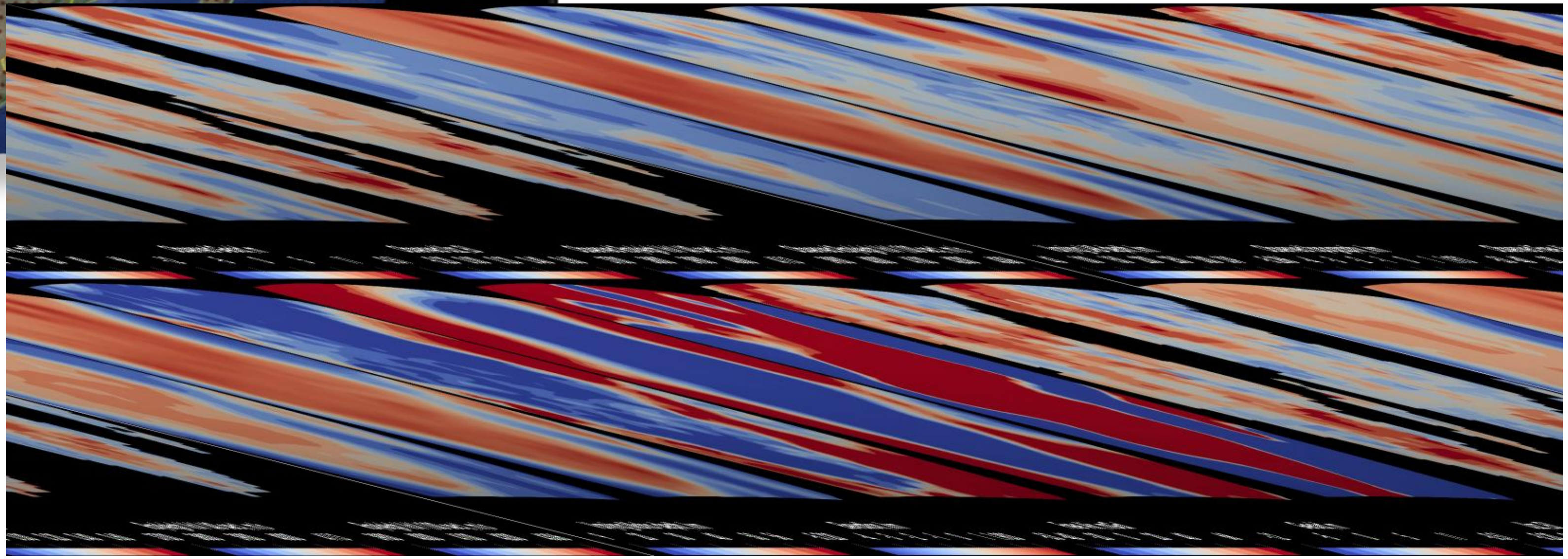
Central and Southern Africa (and Madagascar) within a collaborative project with DeBeers Inc.

5) Some examples…

The approach has been successfully applied in a large number of tectonic scenarios



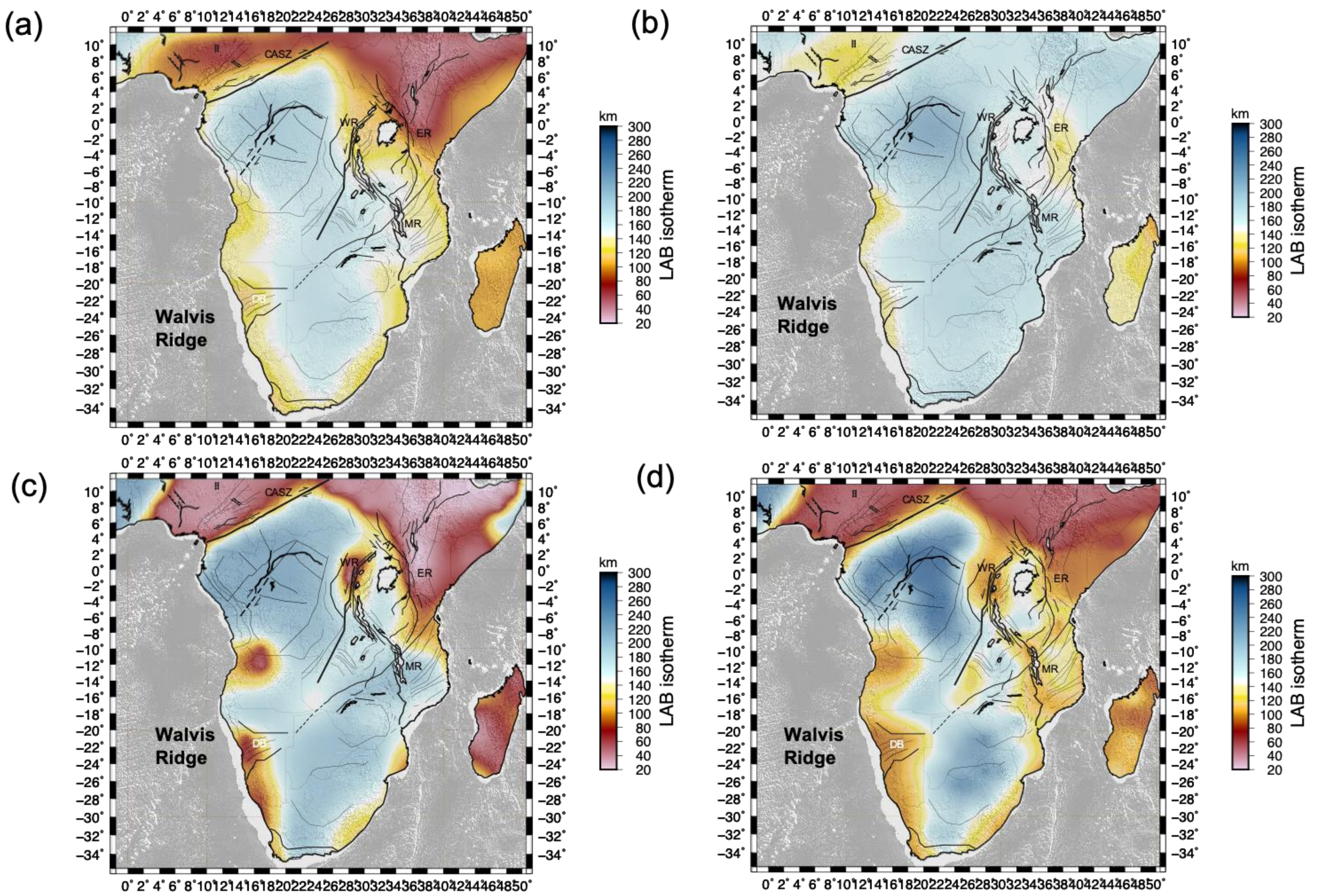
- *In this presentation we show a number of representative figures summarizing the main features of our **multi-observable thermochemical tomography (MTT)** across central and southern Africa.*
- *The model is composed of 1412 (1D) columns (red dots on the figure) and 3871 cells in the 3D stage.*
- *This inversion had 43,307/108,765 free parameters and involved ~50M simulations.*



Central and Southern Africa (and Madagascar) within a project financed by DeBeers Inc.

5) Some examples…

Most detailed lithospheric model to date, with the highest explicative power… reveals complex interactions between the lithosphere and the asthenosphere over time.



Comparison of lithospheric thickness:

(a) CAM 2016, Priestley et al. (2020), Geology

(b) Globig et al. (2016), G-3

(c) Steinberger (2016), GJI

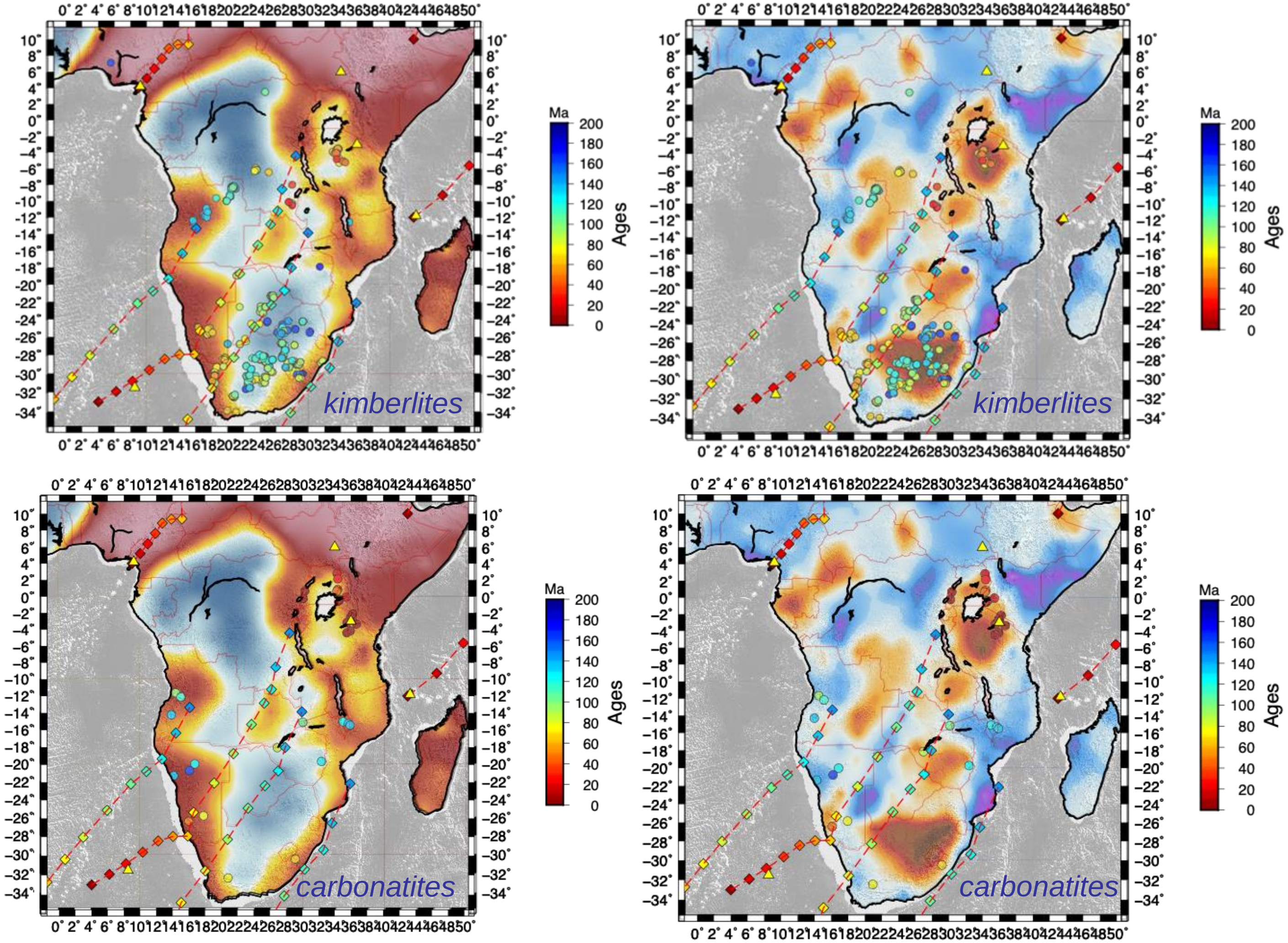
(d) MQ_MTT_2020, This study

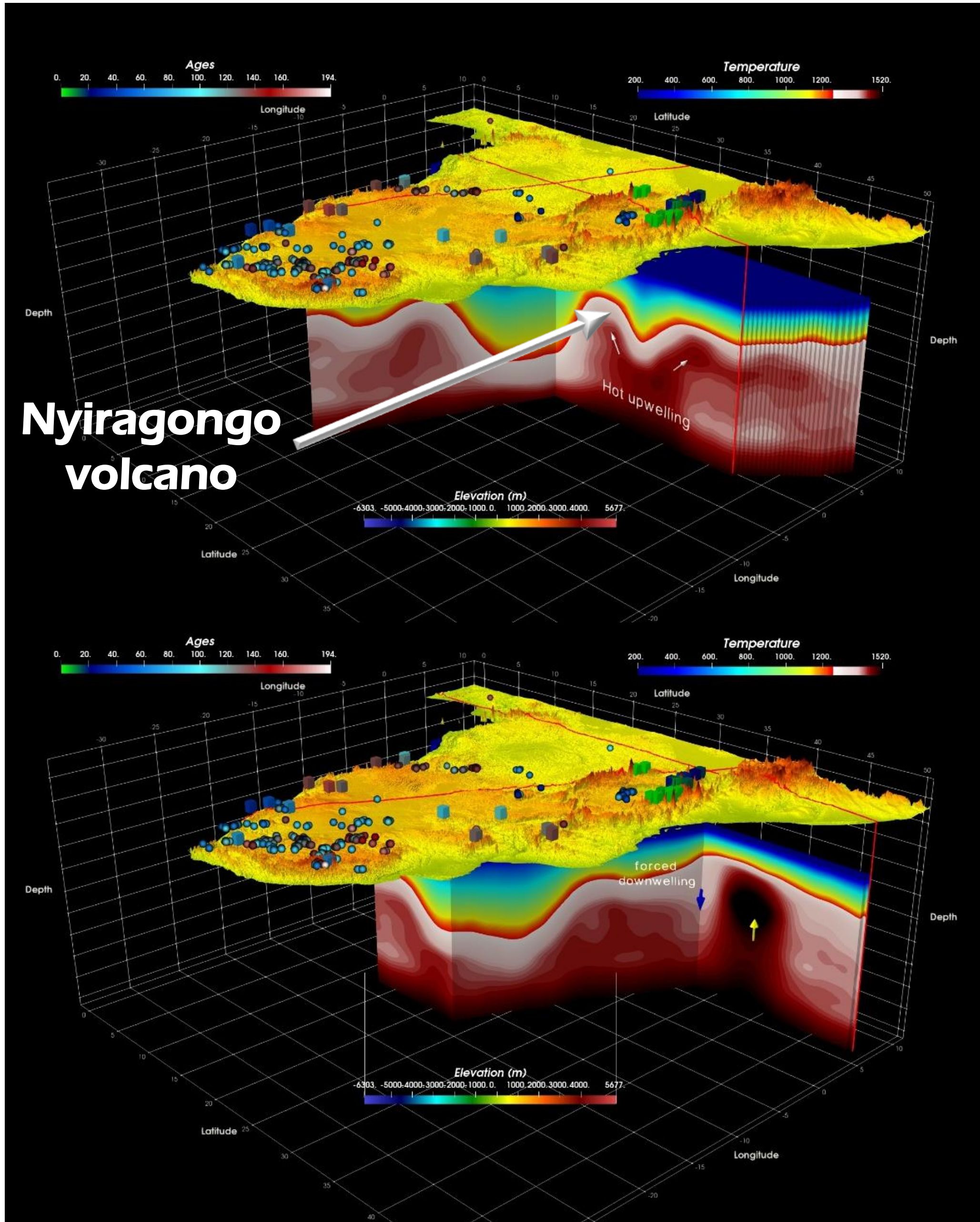
MG3 Macquarie's Geophysics and Geodynamics Group

Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

MACQUARIE University

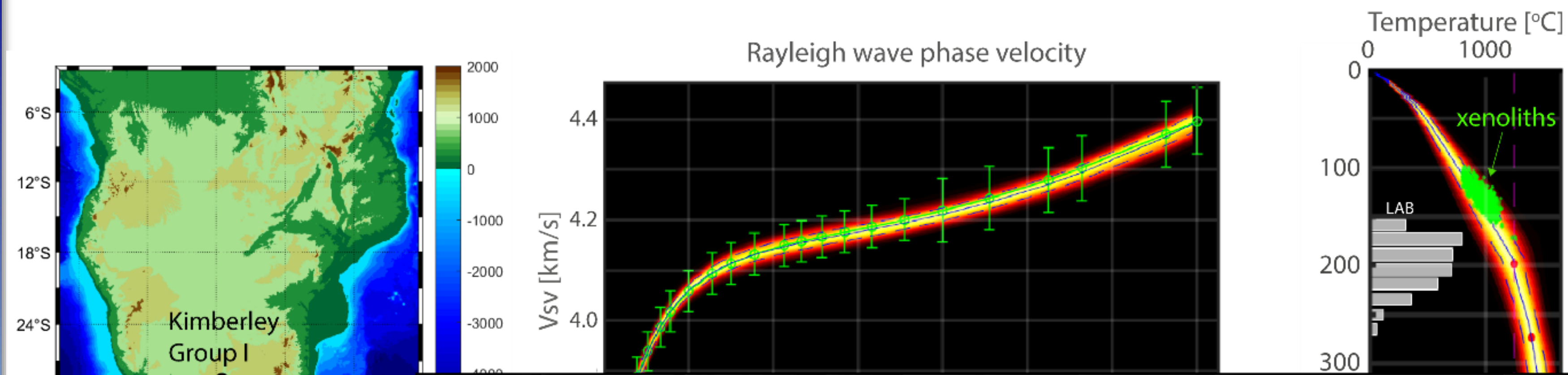
5) Some examples…

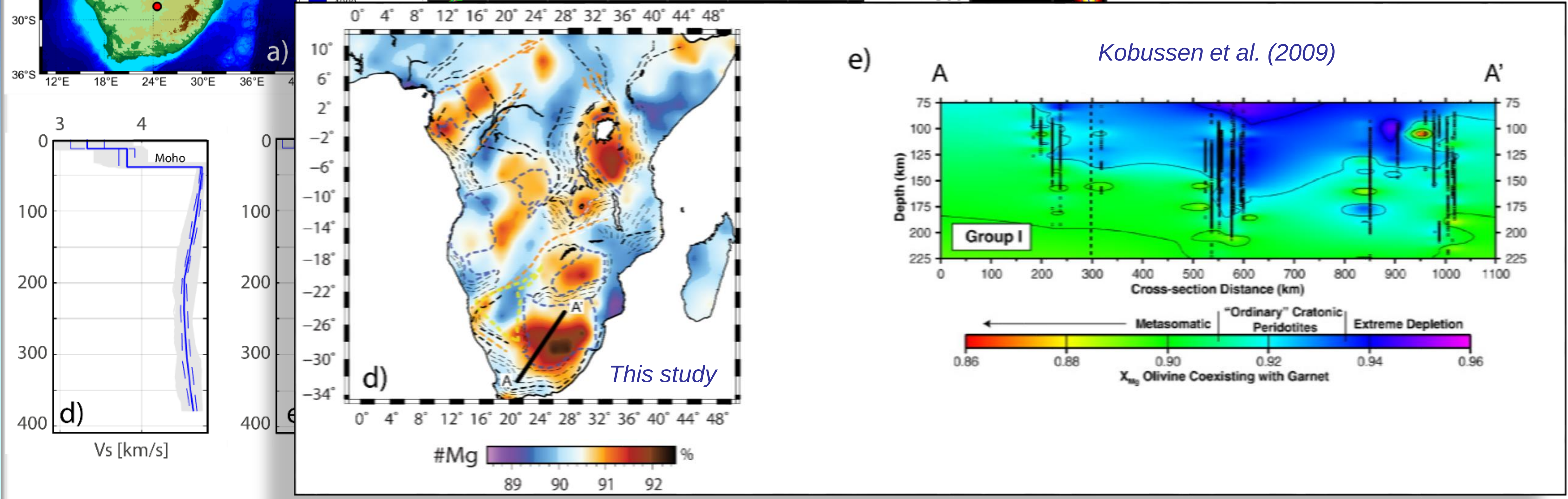




Most detailed lithospheric model to date… reveals complex interactions between the lithosphere and the asthenosphere over time.

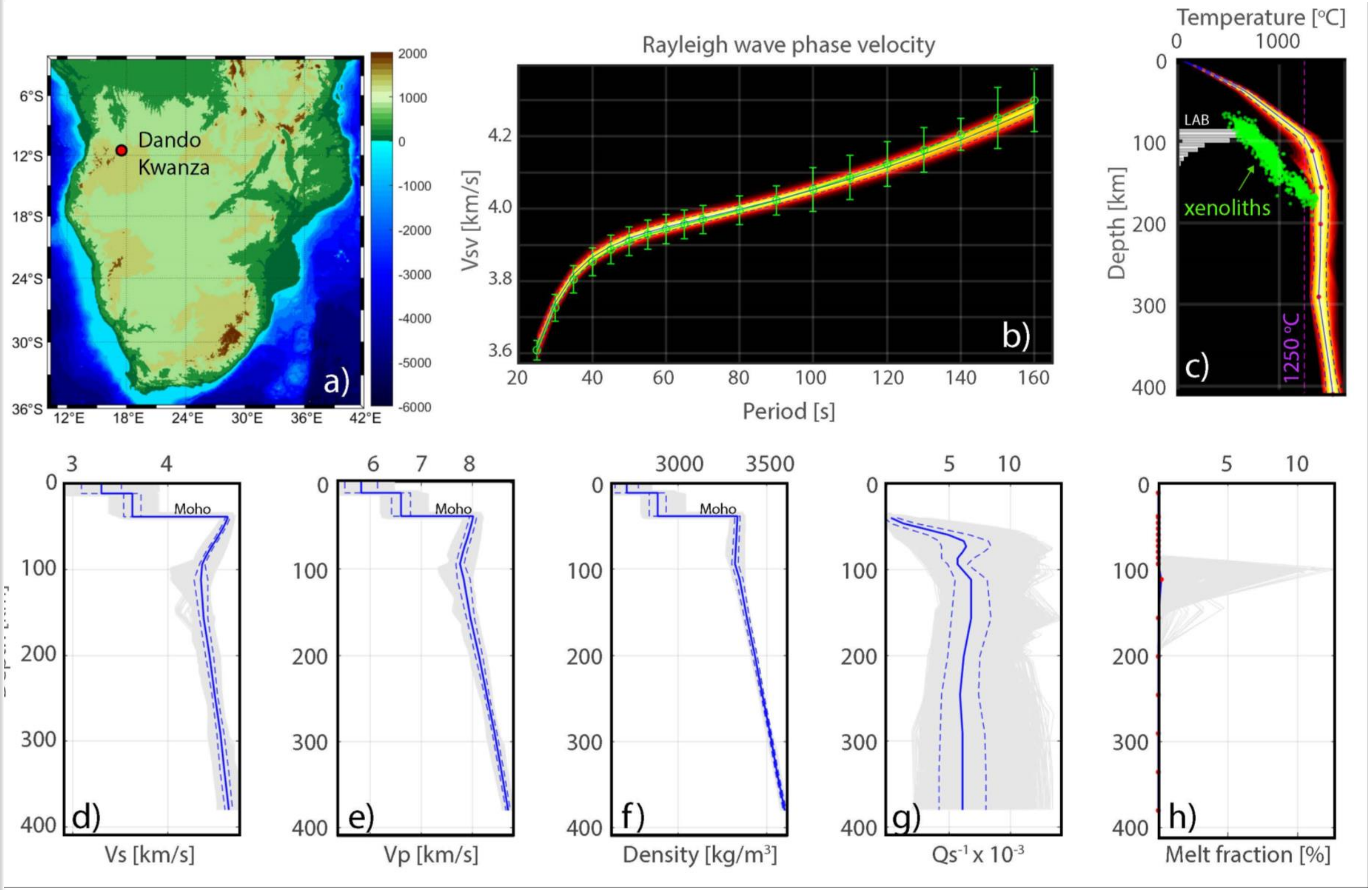
5) Some examples…





Kimberley Group 1: *~ 90 Ma old, overall compatible with present-day structure.*

5) Some examples…



Dando Kwanza kimberlites:
216-252 Ma old, incompatible with present-day structure… but look at the Nduluma cluster!

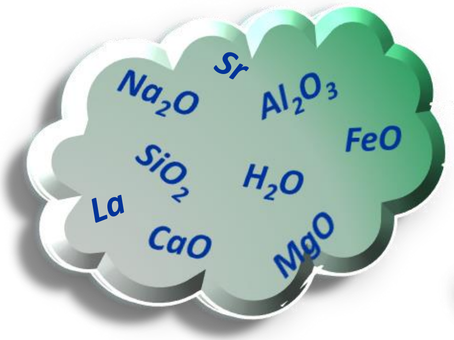
6) MPMCRT

1) We need to map the thermochemical structure of the lithosphere and upper mantle

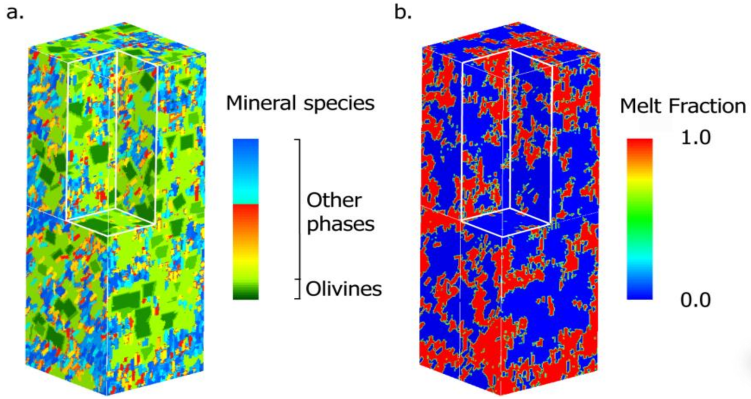
2) We need to be able to model processes of interest (e.g. melting, melt-rock interaction, etc) and their geophysical signatures

MPMCRT

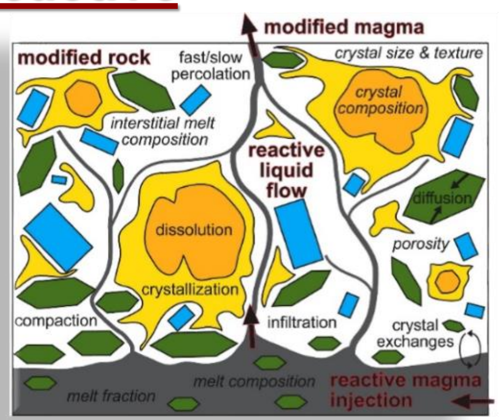
Multi-component



Multi-phase

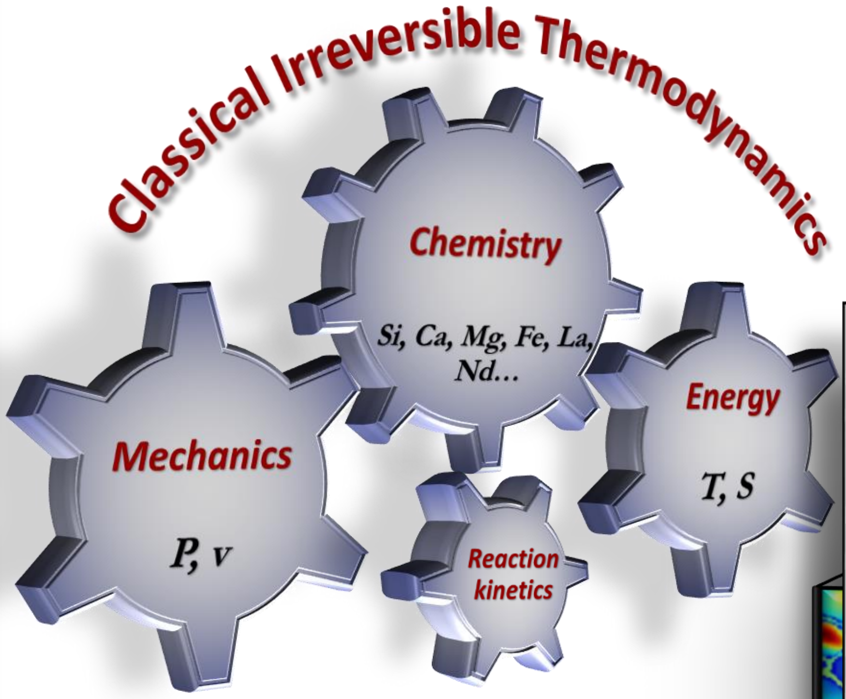


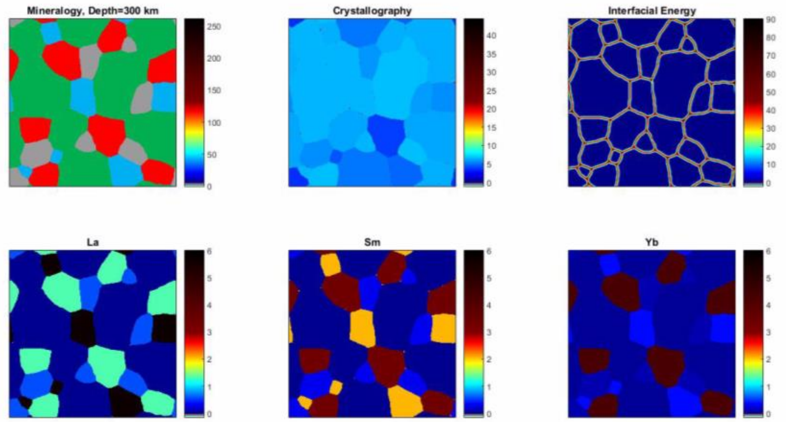
Reactive



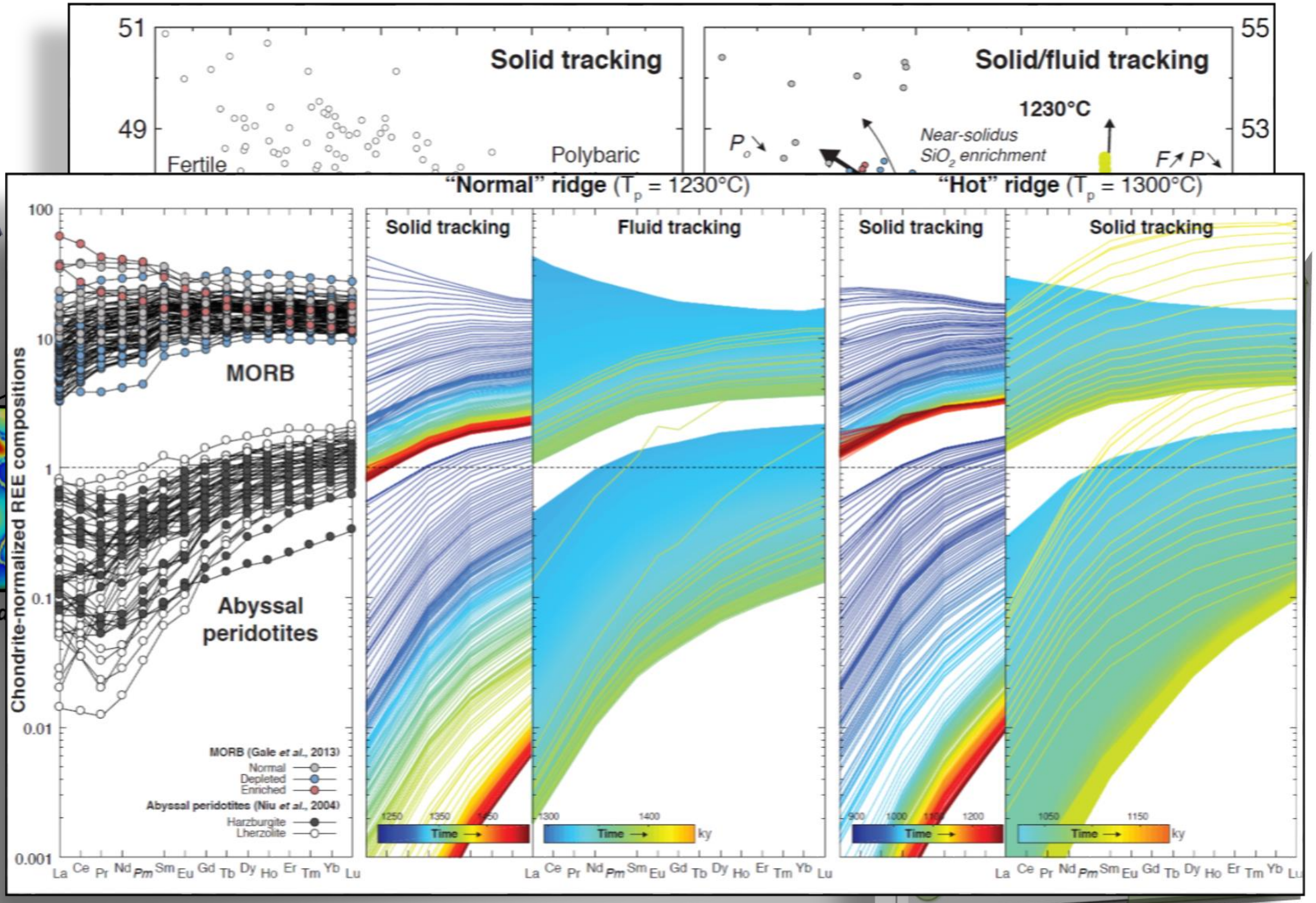
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

MPMCRF



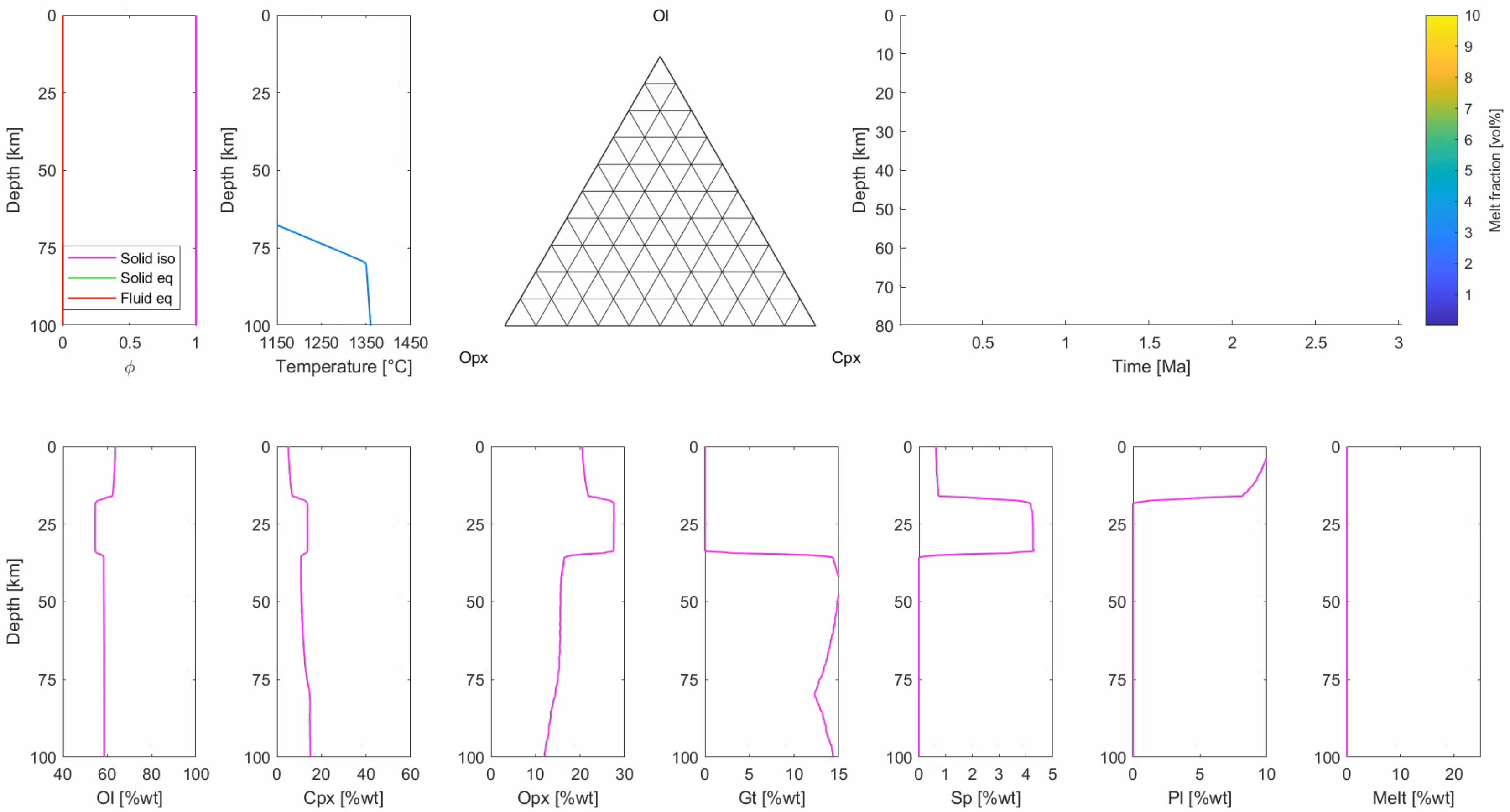


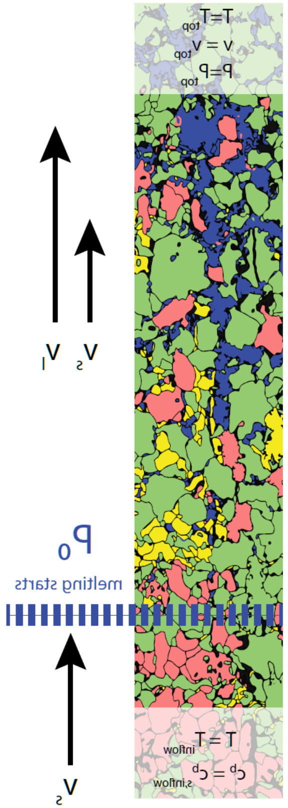
Oliveira, Afonso et al., (2017), GJI   Oliveira, Afonso et al., (2020), J. Petrol.



6) MPMCRT

Fluid-solid interaction… all around us: isentropic upwelling



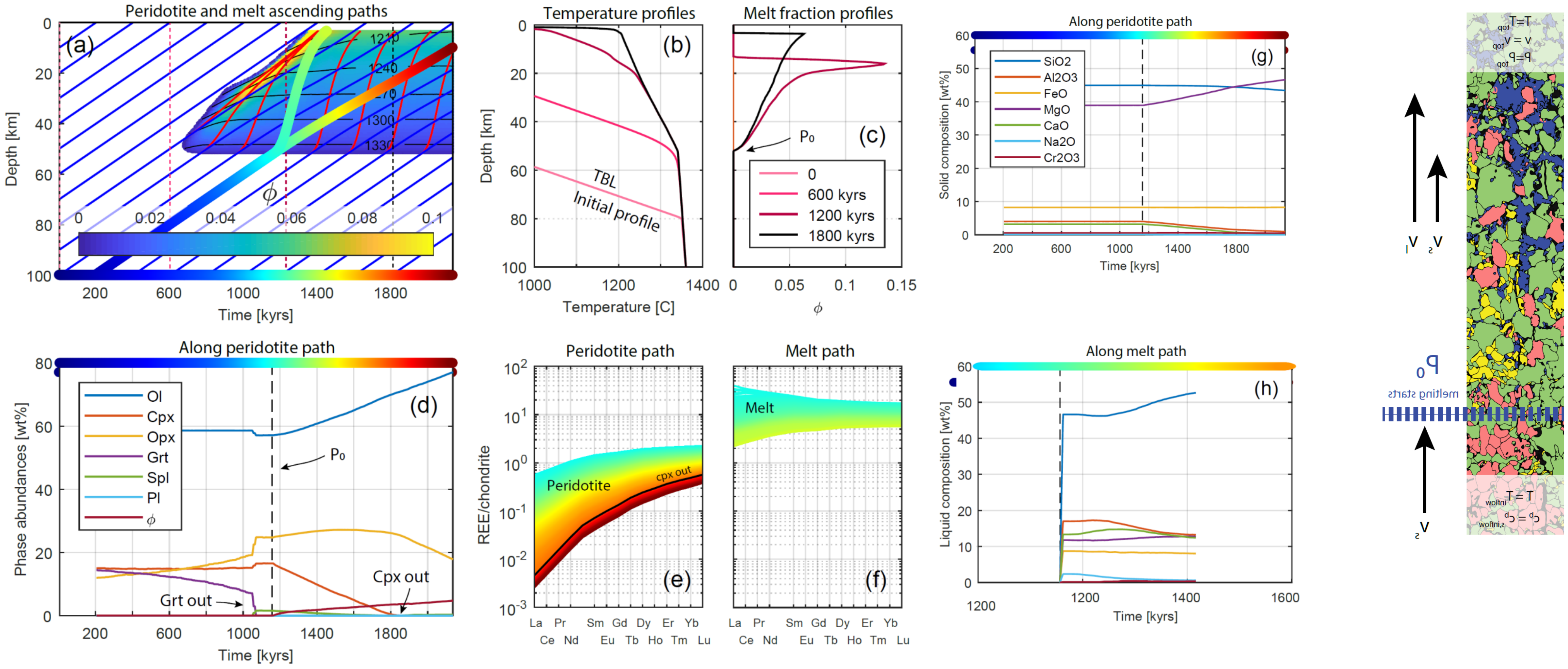


Heterogeneous sources. In this example we see the arrival of a pyroxenite

Oliveira, B., Afonso, J.C., Tilhac, R. (2020) J. Petrol.

6) MPMCRT

Fluid-solid interaction… all around us: isentropic upwelling



Oliveira, B., Afonso, J.C., Tilhac, R. (2020) J. Petrol.

6) MPMCRT … back to the Western/Central US

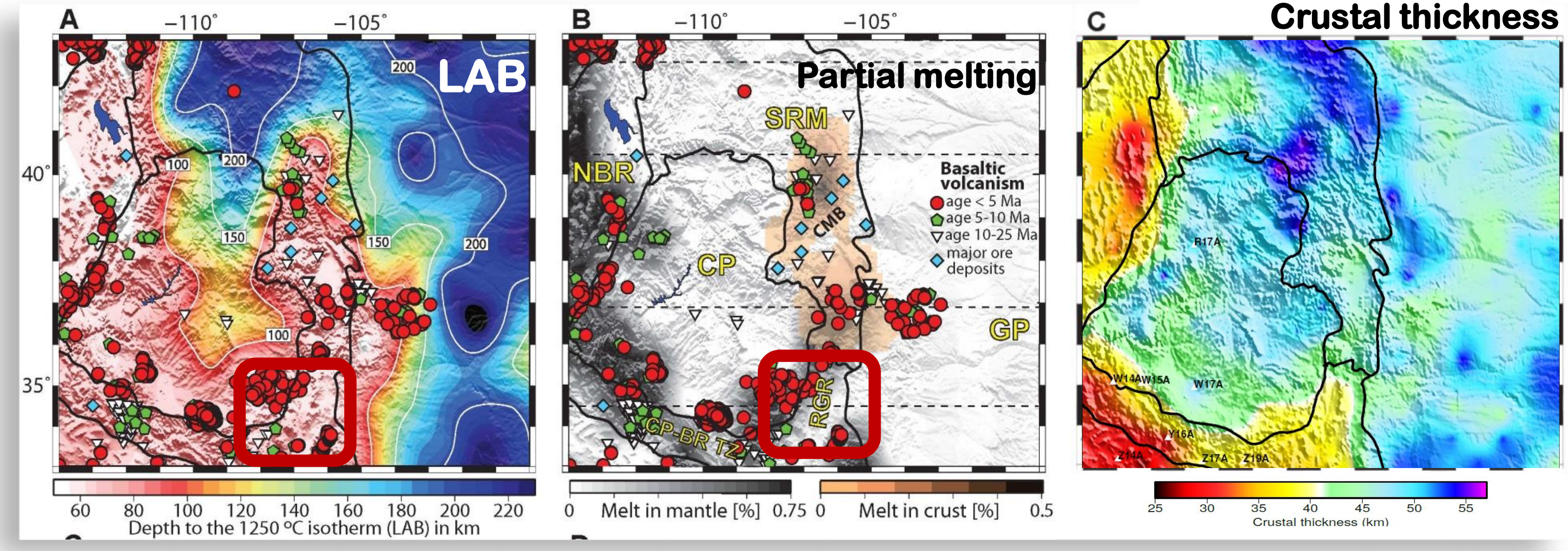
Afonso et al., JGR, 2016; Qashqai et al., Tectonics, 2018

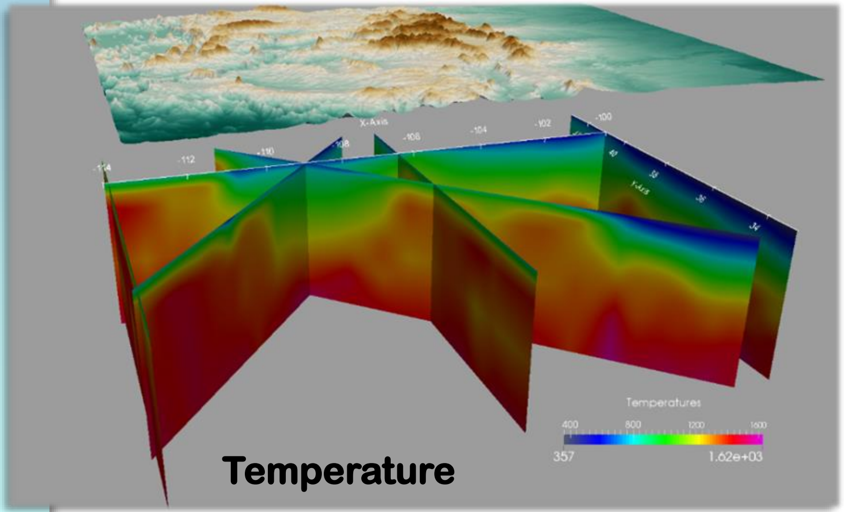
Multi-observable Thermochemical Thermochemical Tomography (MTT) of the Central/Western US

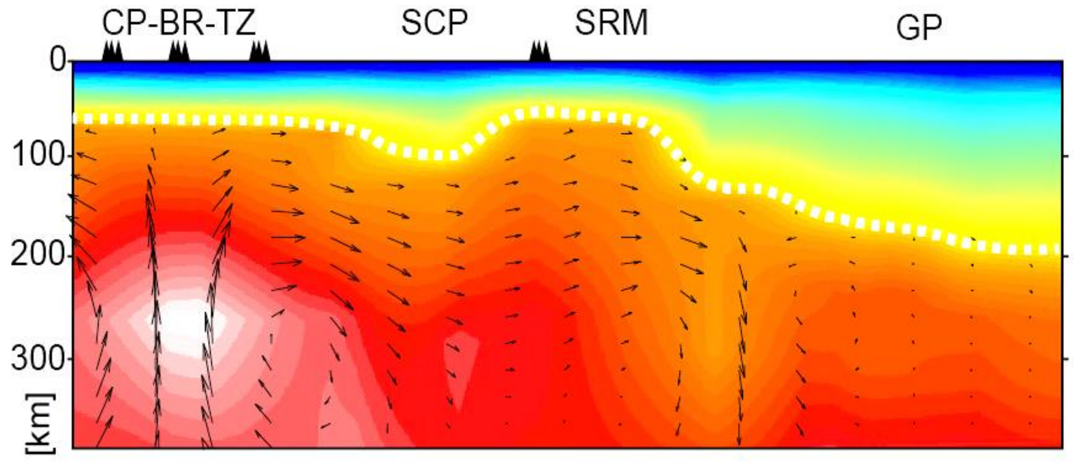
Eight datasets jointly inverted:

- *Surface Heat flow*
- *S and P body waves (tt)*
- *Rayleigh waves (disp. curves)*
- *Elevation*
- *P-wave RFs*
- *Gravity anomalies and gradients*
- *Geoid anomalies*

for the complete physical state of the lithosphere and sublithospheric upper mantle





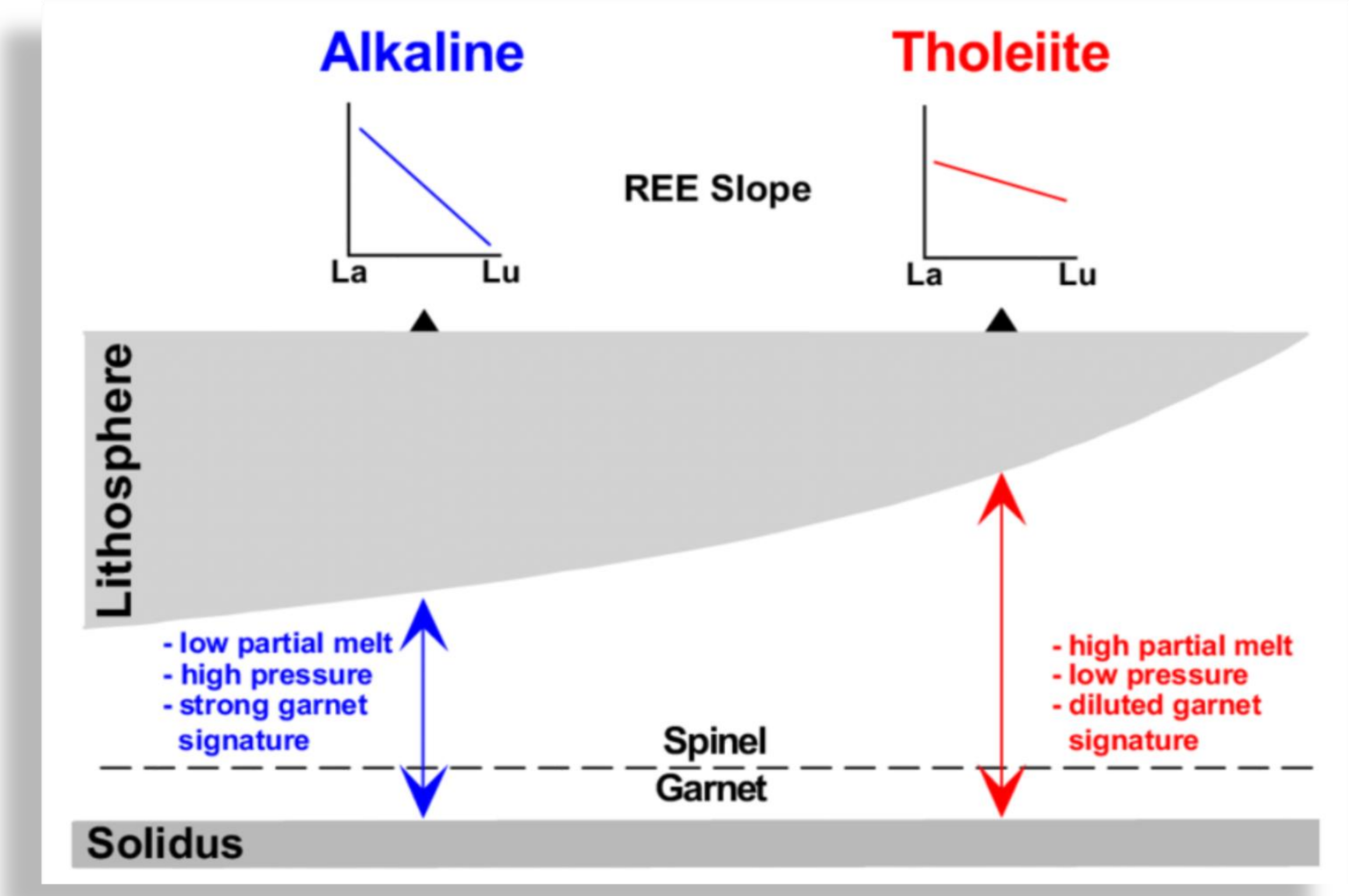


6) MPMCRT … back to the Western/Central US

Geochemical probabilistic inversion (trace and major elements!) for the physical state of the mantle beneath the RGR

47 samples (basalts) screened for peridotitic, primitive melts and corrected for Ol and Cpx fractionation

The idea in a nutshell…



Courtesy of D. Dockman

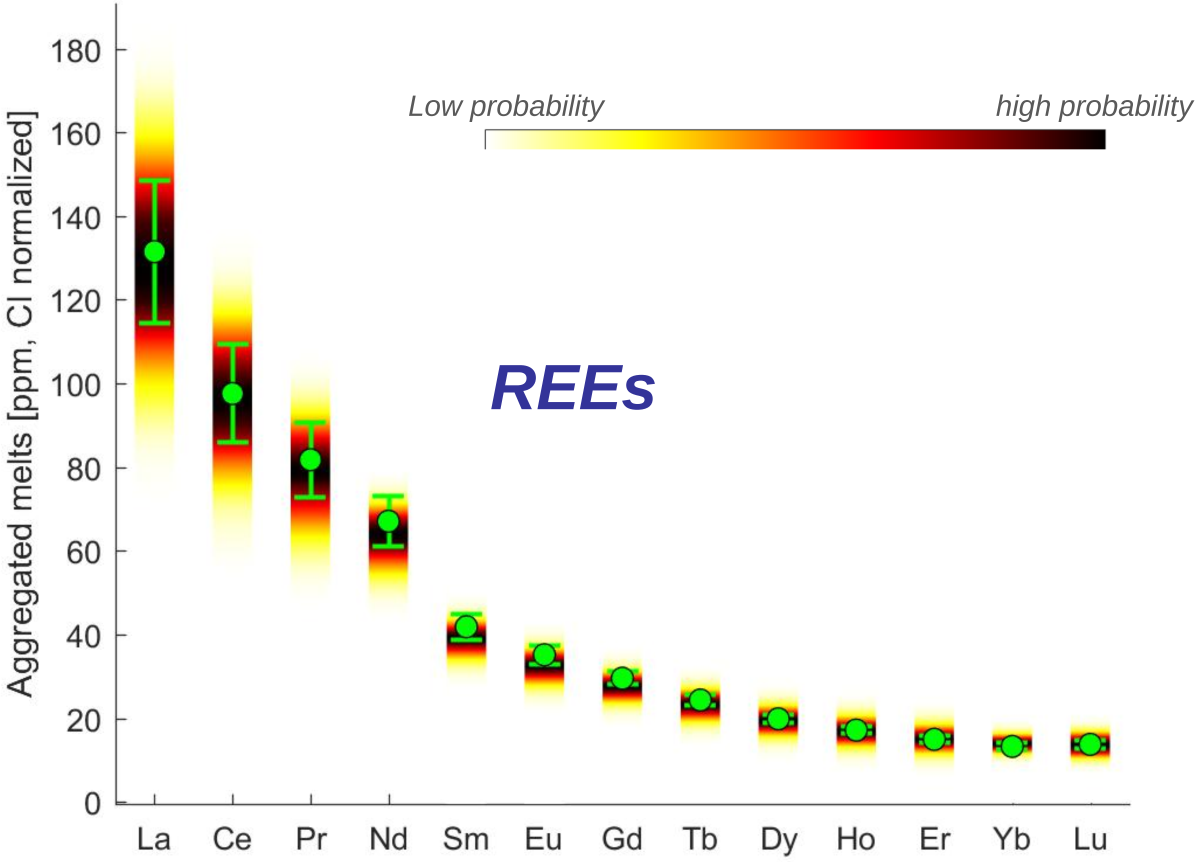
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

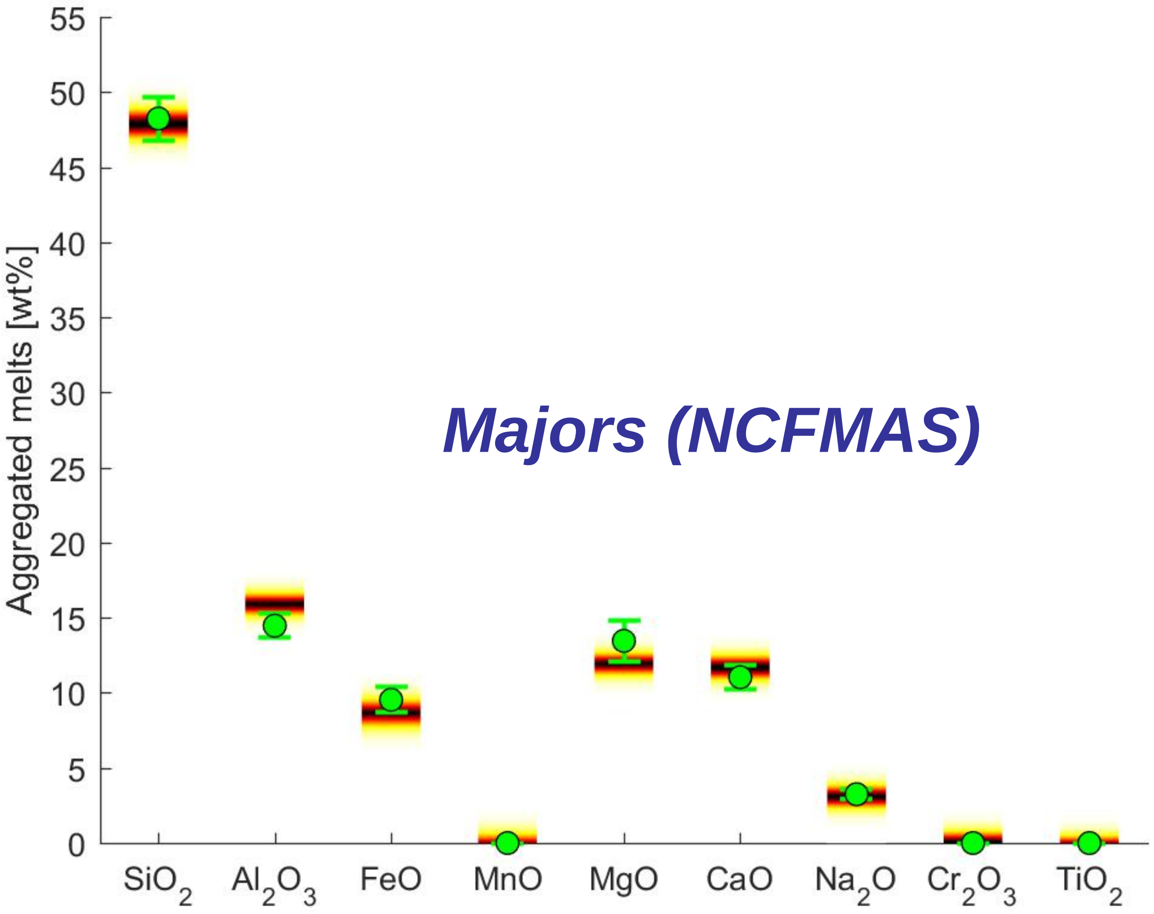
6) MPMCRT … back to the Western/Central US

Geochemical probabilistic inversion (trace and major elements!) for the physical state of the mantle beneath the RGR

Data fits

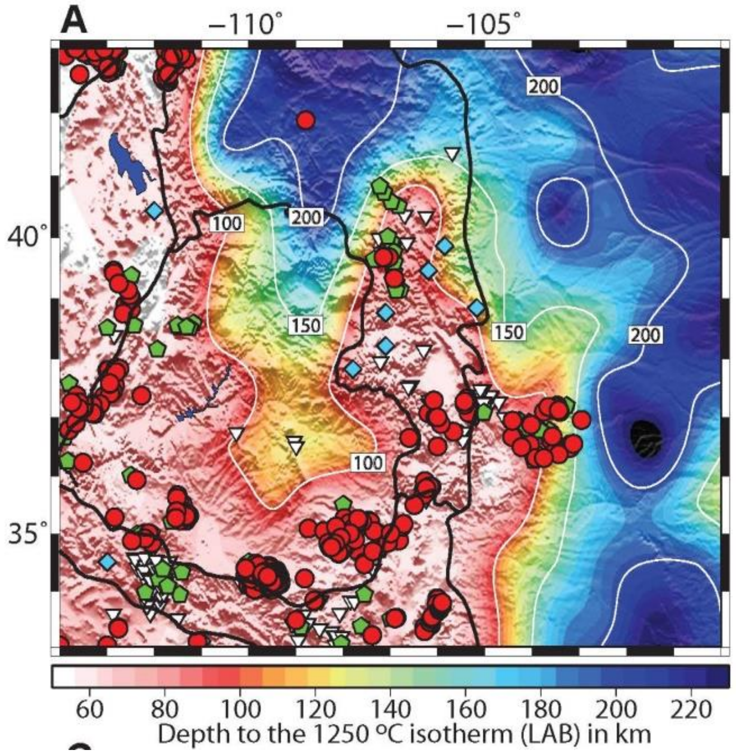
Oliveira, B., Afonso, J.C., Klocking, M. (in review)



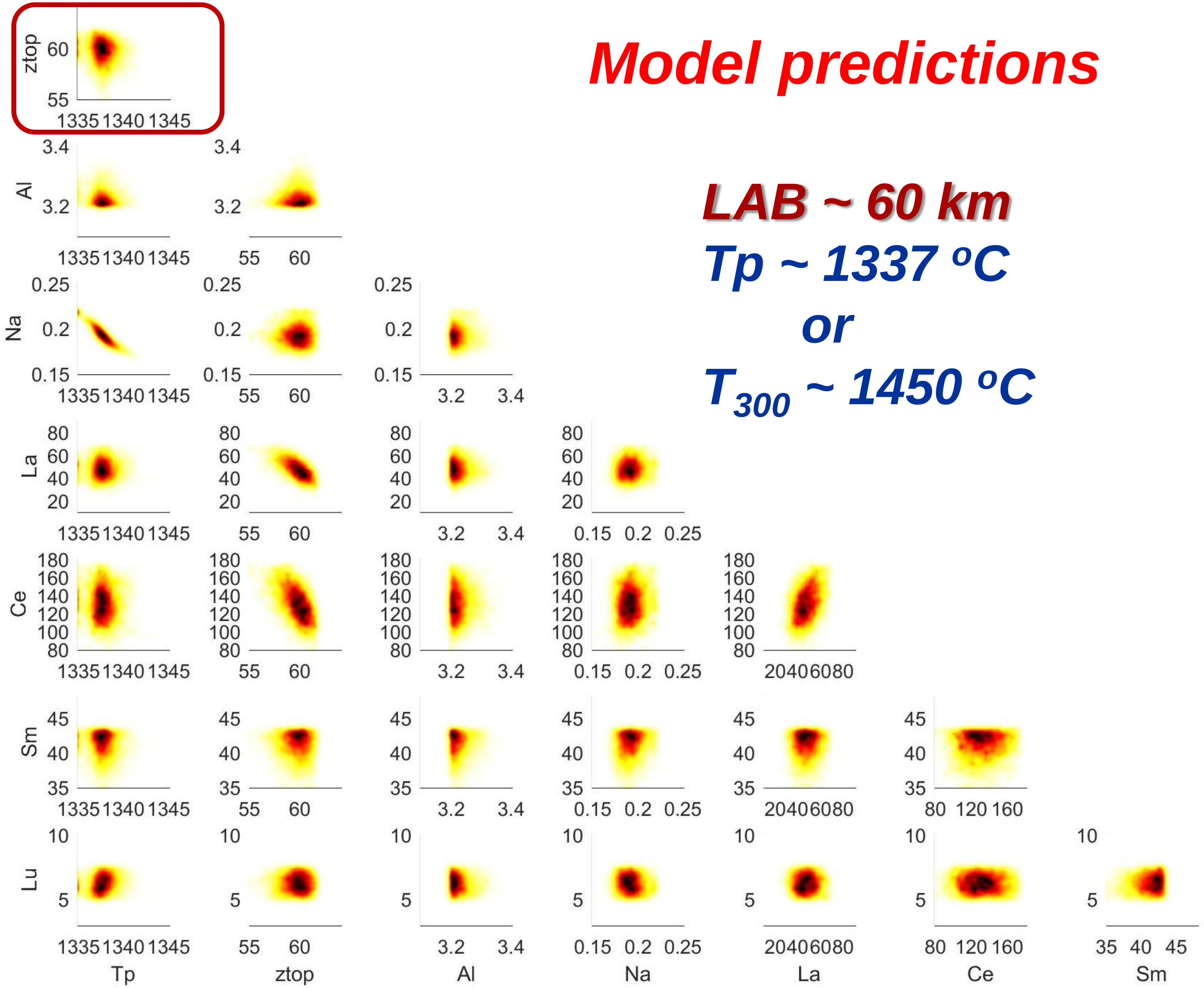


6) MPMCRT … back to the Western/Central US

Geochemical probabilistic inversion (trace and major elements!) for the physical state of the mantle beneath the RGR



Oliveira, B., Afonso, J.C., Klocking, M. (in review)



Model predictions

LAB ~ 60 km

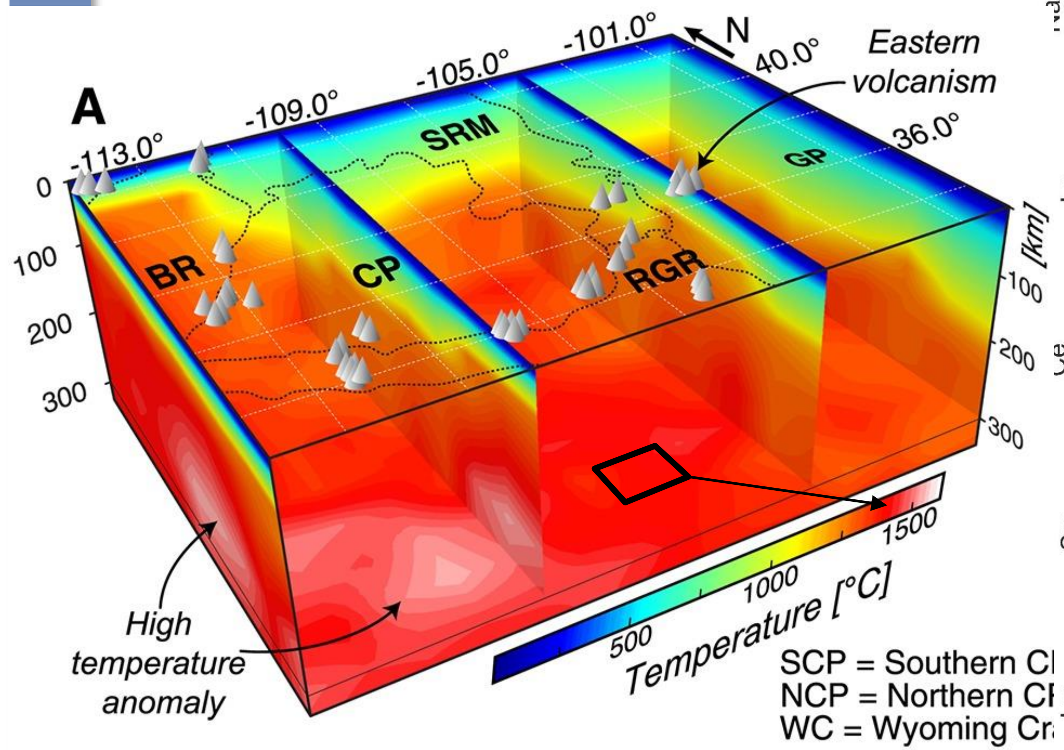
Tp ~ 1337 °C

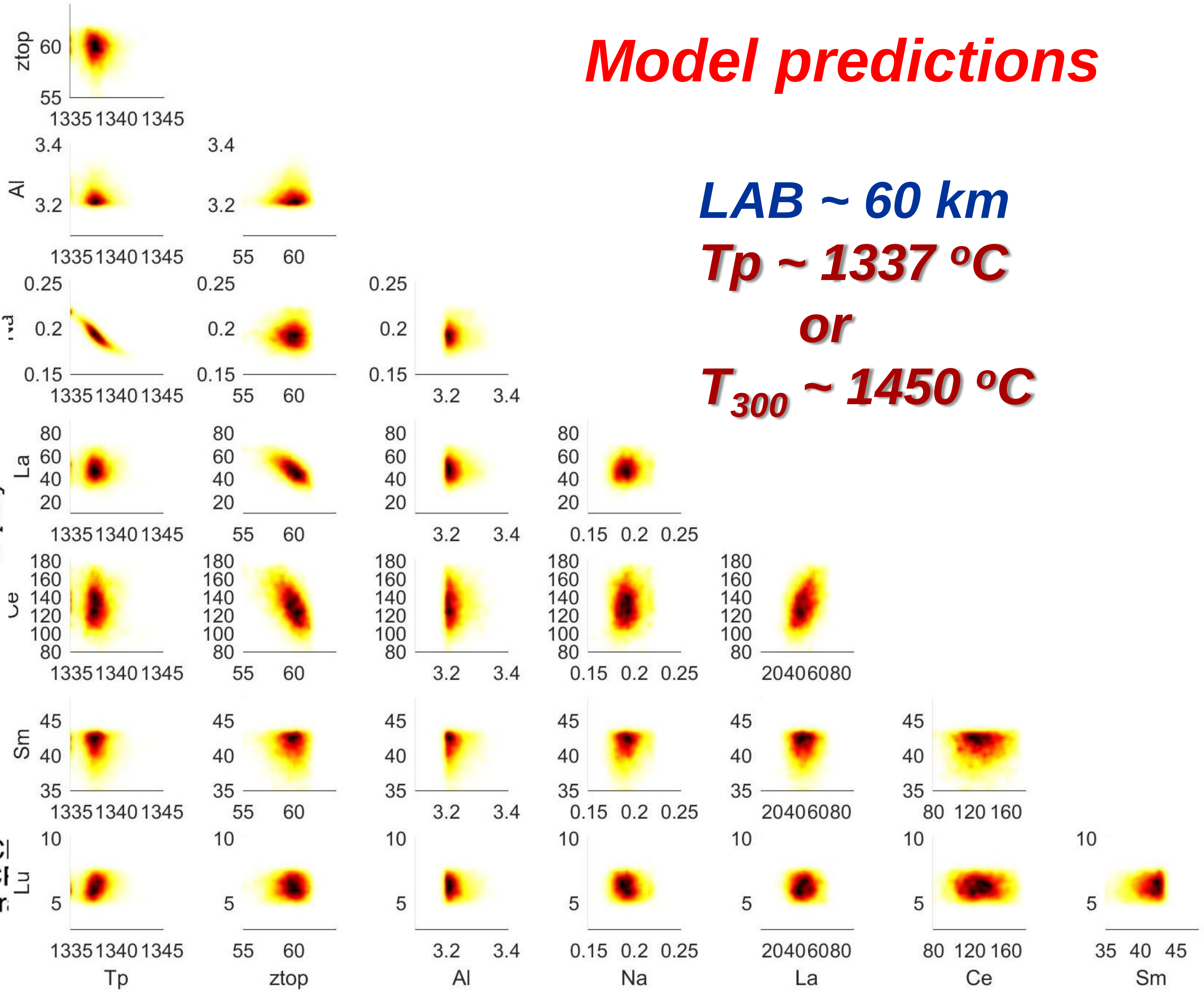
or

T_{300} ~ 1450 °C

6) MPMCRT … back to the Western/Central US

Geochemical probabilistic inversion (trace and major elements!) for the physical state of the mantle beneath the RGR





Model predictions

LAB ~ 60 km

Tp ~ 1337 ºC

or

T_{300} ~ 1450 ºC

Oliveira, B., Afonso, J.C., Klocking, M. (in review)

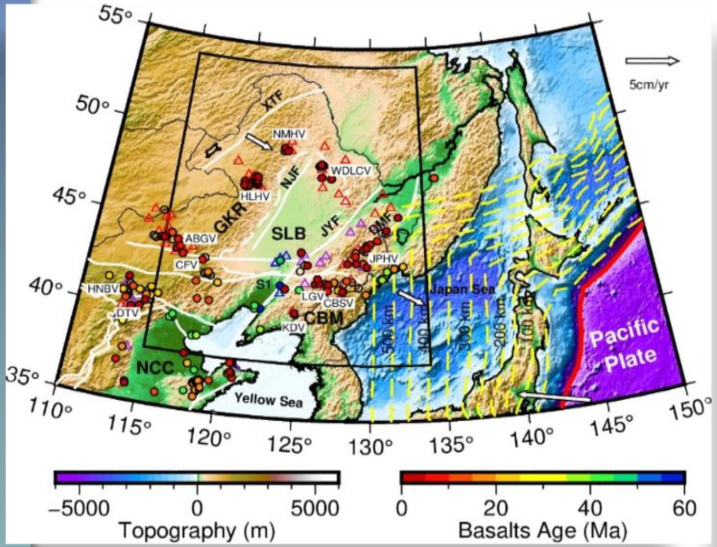
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

7) True Geochemical-Geophysical probabilistic joint inversions

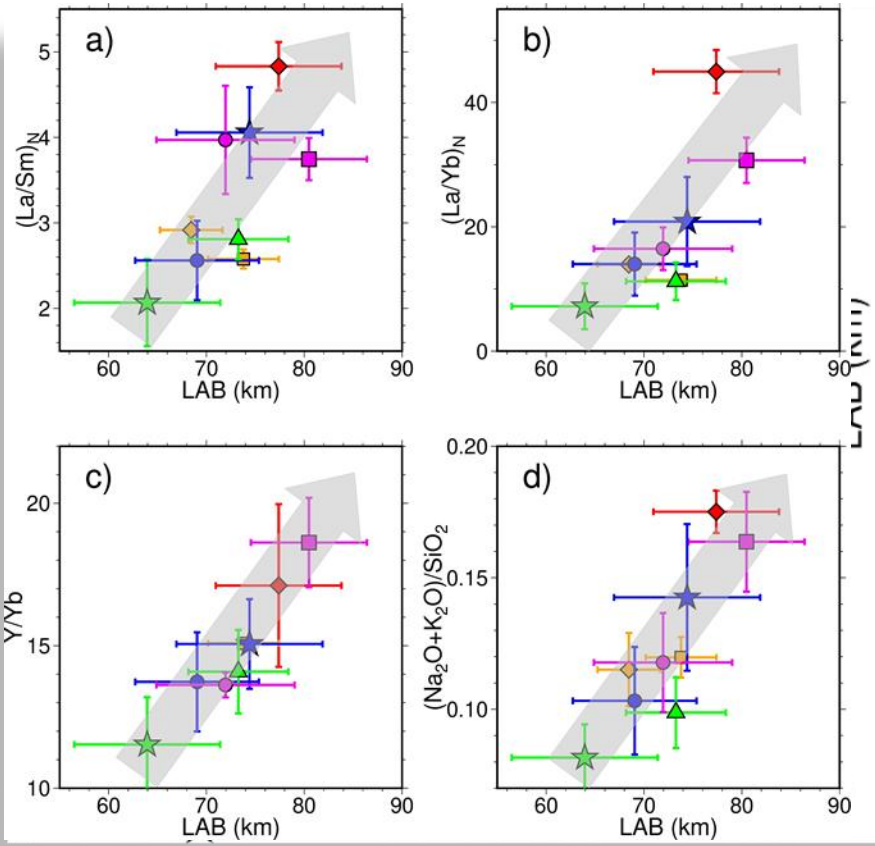
*** True geochemical-geophysical joint inversions for characterizing the physical state of the mantle in regions with recent or active volcanism**

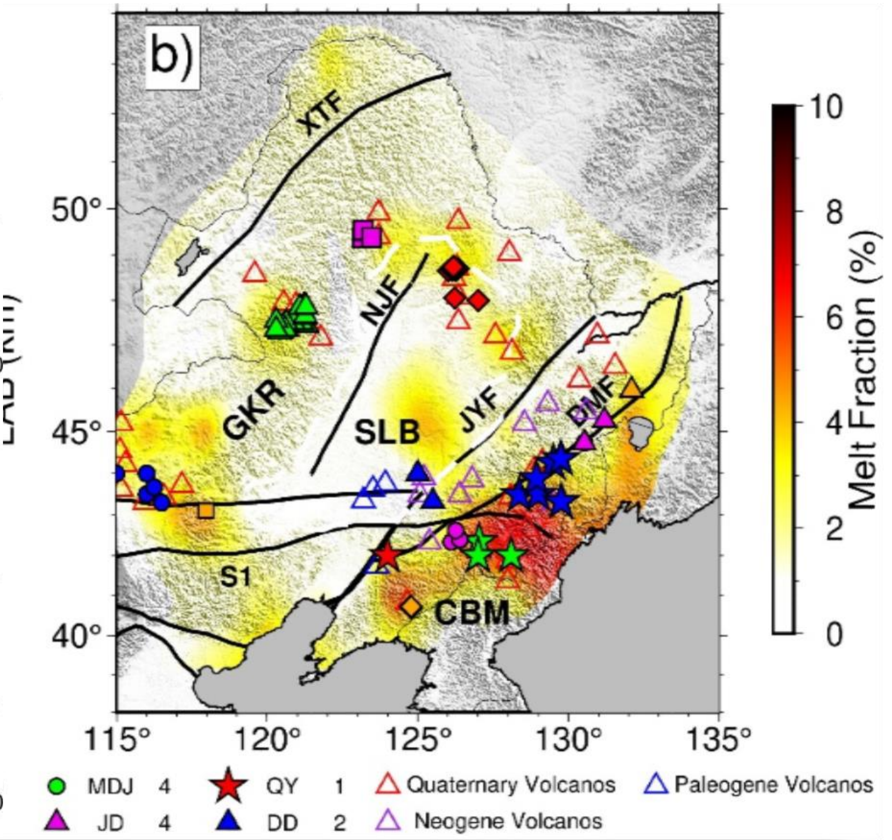
*** It brings the time dimension (4D) into play… e.g. variations in the LAB with time.**

An example in NE China



Courtesy of Anqi Zhang





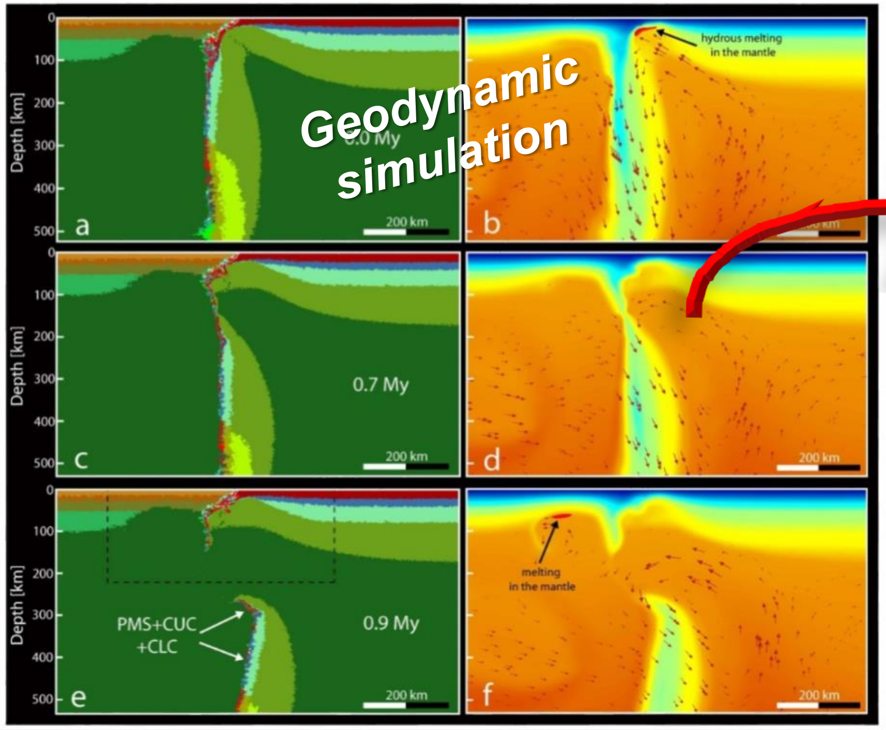
Multi-data and multi-scale probabilistic inversion for imaging the physical and chemical state of the Earth's interior

MG3 Macquarie's Geophysics and Geodynamics Group

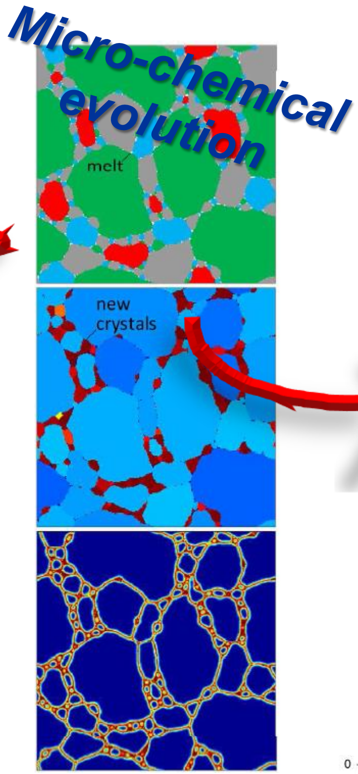
MACQUARIE University

8) The exciting future

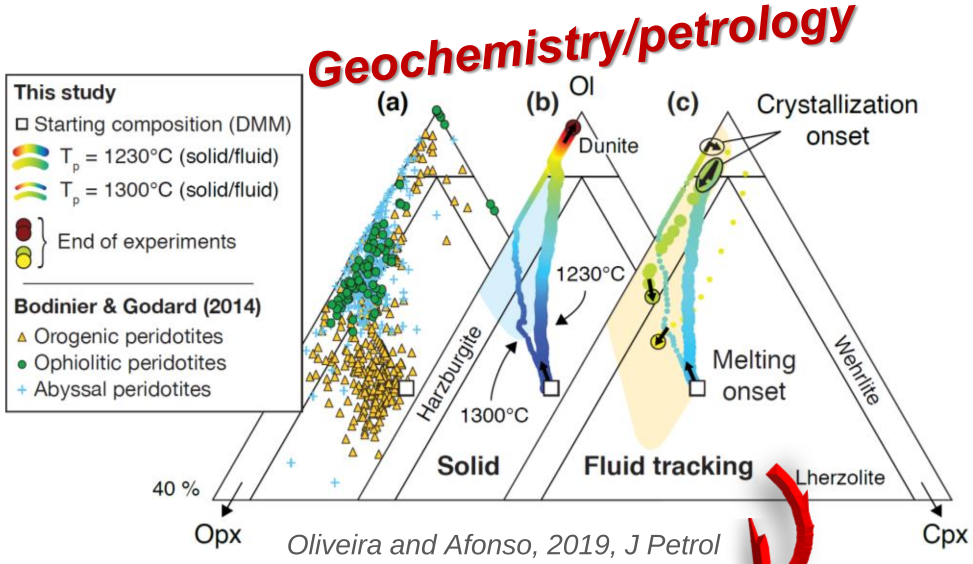
The formal combination of inverse geophysical theory with multi-phase multi-component reactive flow simulations constrained by non-equilibrium thermodynamics and micro-structural evolution…



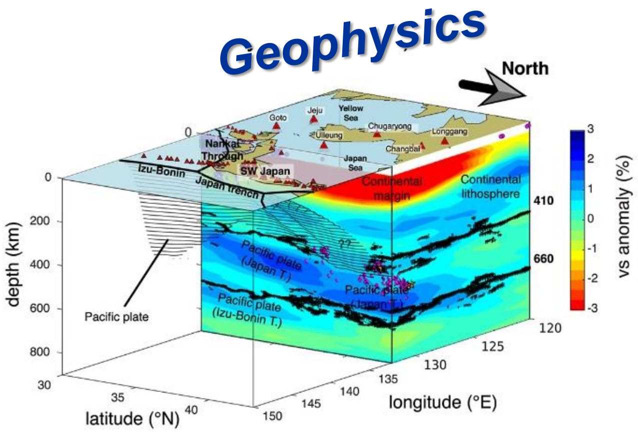
Afonso and Zlotnik, 2011

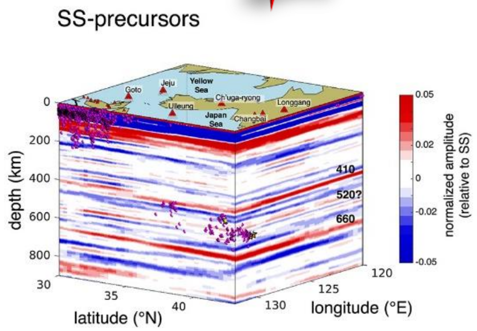


Grose and Afonso; 2019, J. Petrol.



Oliveira and Afonso, 2019, J Petrol





Tauzin, Kim and Afonso, 2018, JGR

Bridging the gaps…

9) Conclusions

- ***Simulation-based or physics-based inversions for the physical state of the Earth's interior are a reality and are here to stay…***

- *Closing gaps between geophysics and geochemistry … which literally means working for geochemists*

- *Then, we may as well model geochemical processes… and related them to geophysics/geodynamics*

- *Multi-scale, disequilibrium processes/feedbacks are our main interest*

Thank you!!!!!