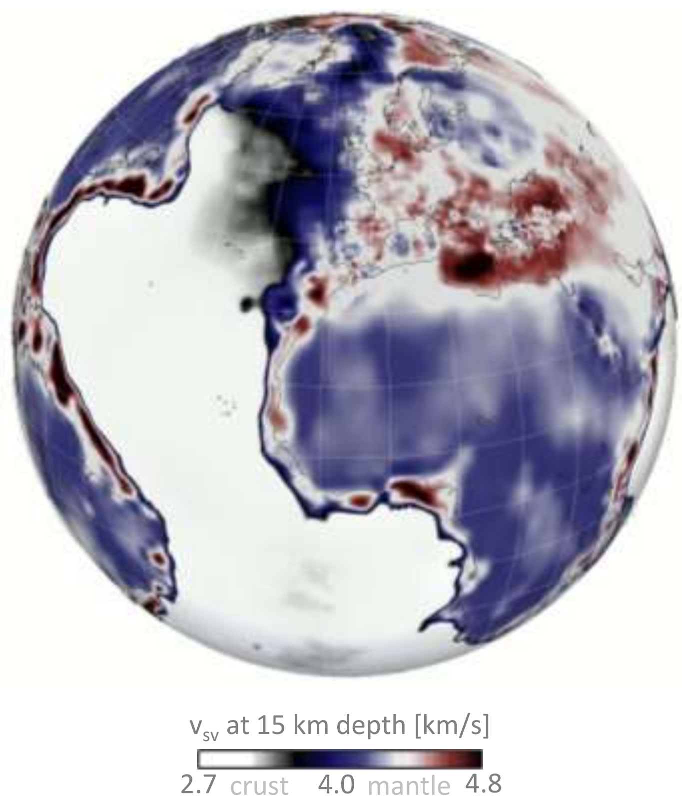
DEVELOPMENTS IN FULL-WAVEFORM INVERSION

Andreas Fichtner

Michael Afanasiev, Dirk-Philip van Herwaarden, Laura Cobden, Yesim Cubuk, Lion Krischer, Florian Rickers, Saulė Simutė, Jeannot Trampert, Tristan van Leeuwen, Antonio Villaseñor, *and many others* …



“Full-waveform inversion (FWI) has emerged as the *final and ultimate solution* to the Earth resolution and imaging objective.”

Announcement of the 2013 SEG workshop on FWI

ETH

“Full-waveform inversion (FWI) has emerged as the *final and ultimate solution* to the Earth resolution and imaging objective.”

Announcement of the 2013 SEG workshop on FWI

- We do not know the Earth very well …

  … and are still looking for *the* method to solve all our problems.

- FWI seems poorly understood outside a small group of people.

  Believe in miracles without seeing the limitations.

- Not generally understood that there are generally no ultimate solutions.

  All methods have range of applicability.

ETH

OUTLINE

1. Full-waveform inversion in a nutshell

- From ray tomography to full-waveform inversion
- A synthetic illustration of the main benefit

2. Real-world examples

- The Japanese islands: Recovering extremely low mantle velocities
- The Western Mediterranean: Crust/mantle resolution and uncertainty analysis

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1. Full-waveform inversion in a nutshell

- From ray tomography to full-waveform inversion
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2. Real-world examples

- The Japanese islands: Recovering extremely low mantle velocities
- The Western Mediterranean: Crust/mantle resolution and uncertainty analysis

3. Big challenges

- Are our computers big enough, or will they be in the near future?
- The data flood
- Our mode of operation

4. The Collaborative Seismic Earth Model

- Philosophy and technical implementation
- Generation 1

5. Discussion and Conclusions

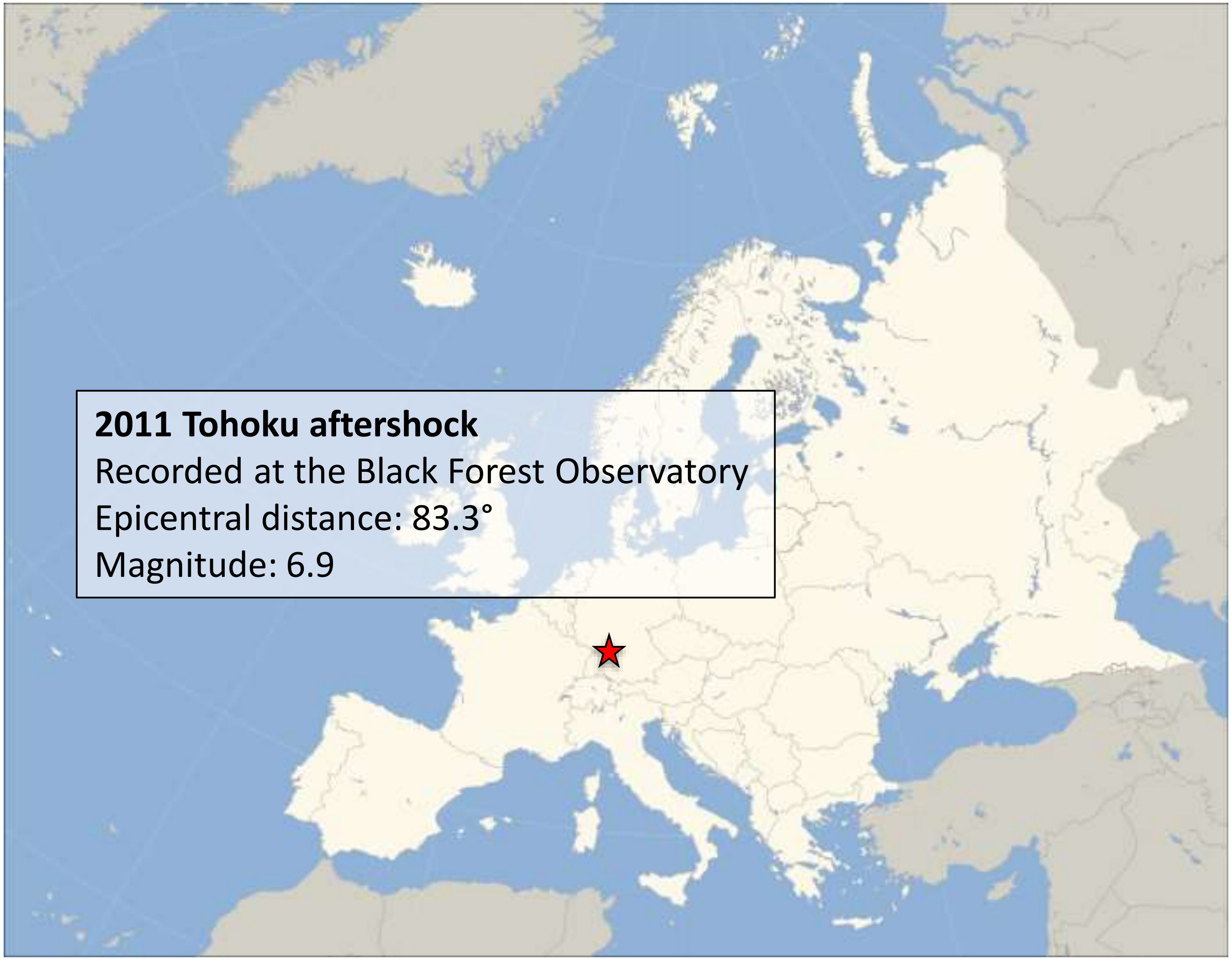
Full-waveform inversion in a nutshell

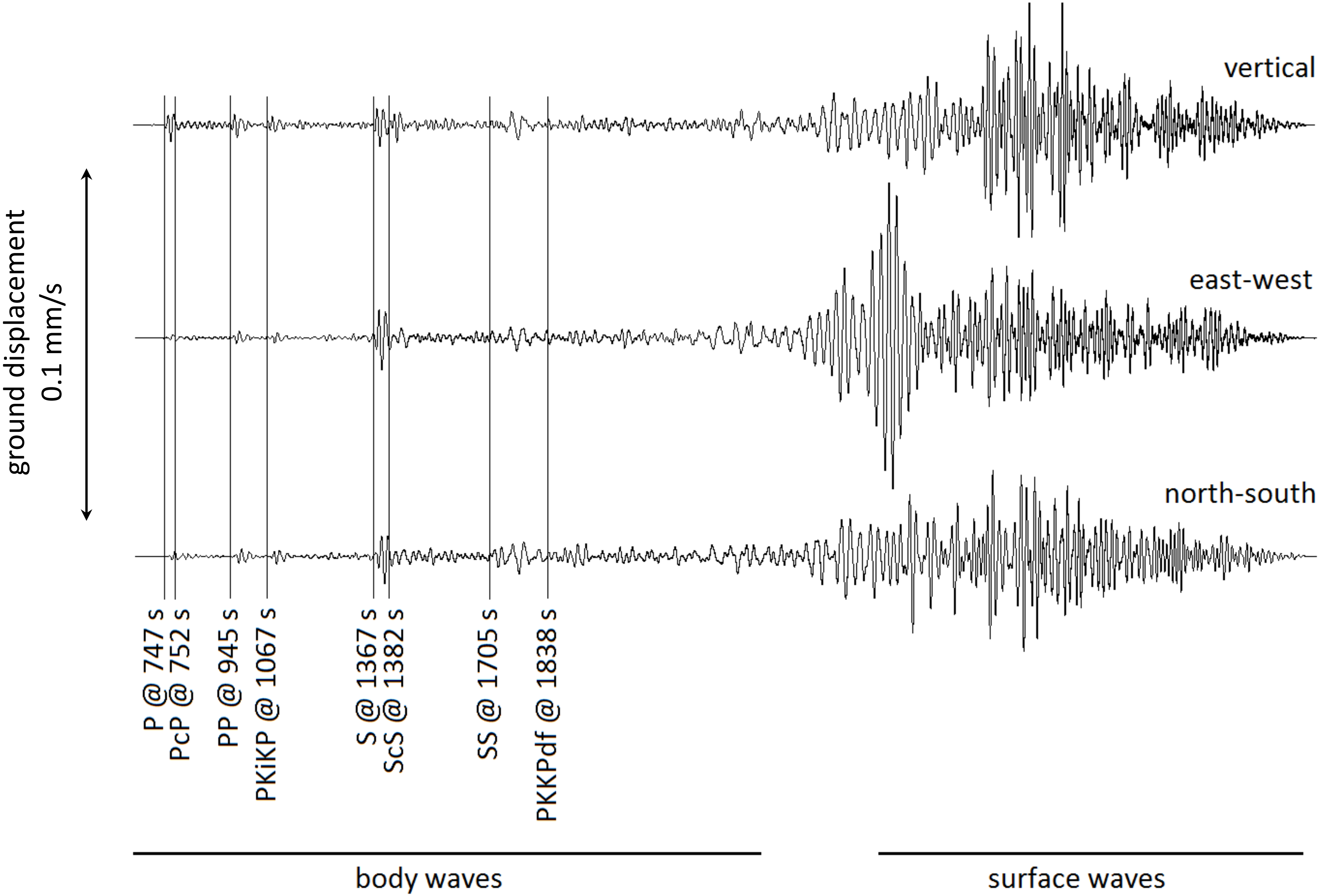
Exploiting complete waveforms for the benefit of improved resolution

Seismic Wave Propagation

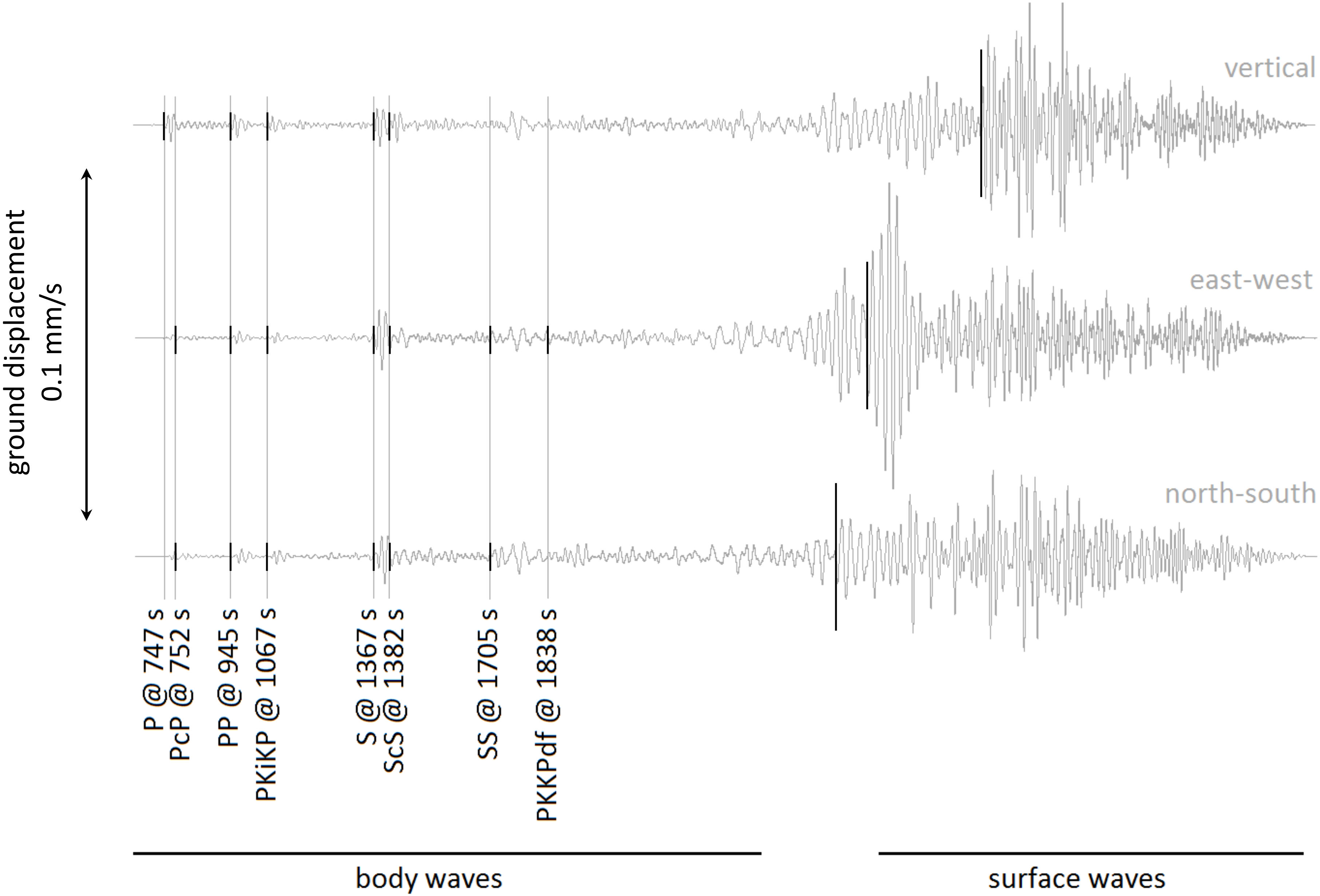
Numerical simulation [using Salvus; Afanasiev et al., 2018] of aTohoku aftershock [M 6.9]

SEISMOGRAMS

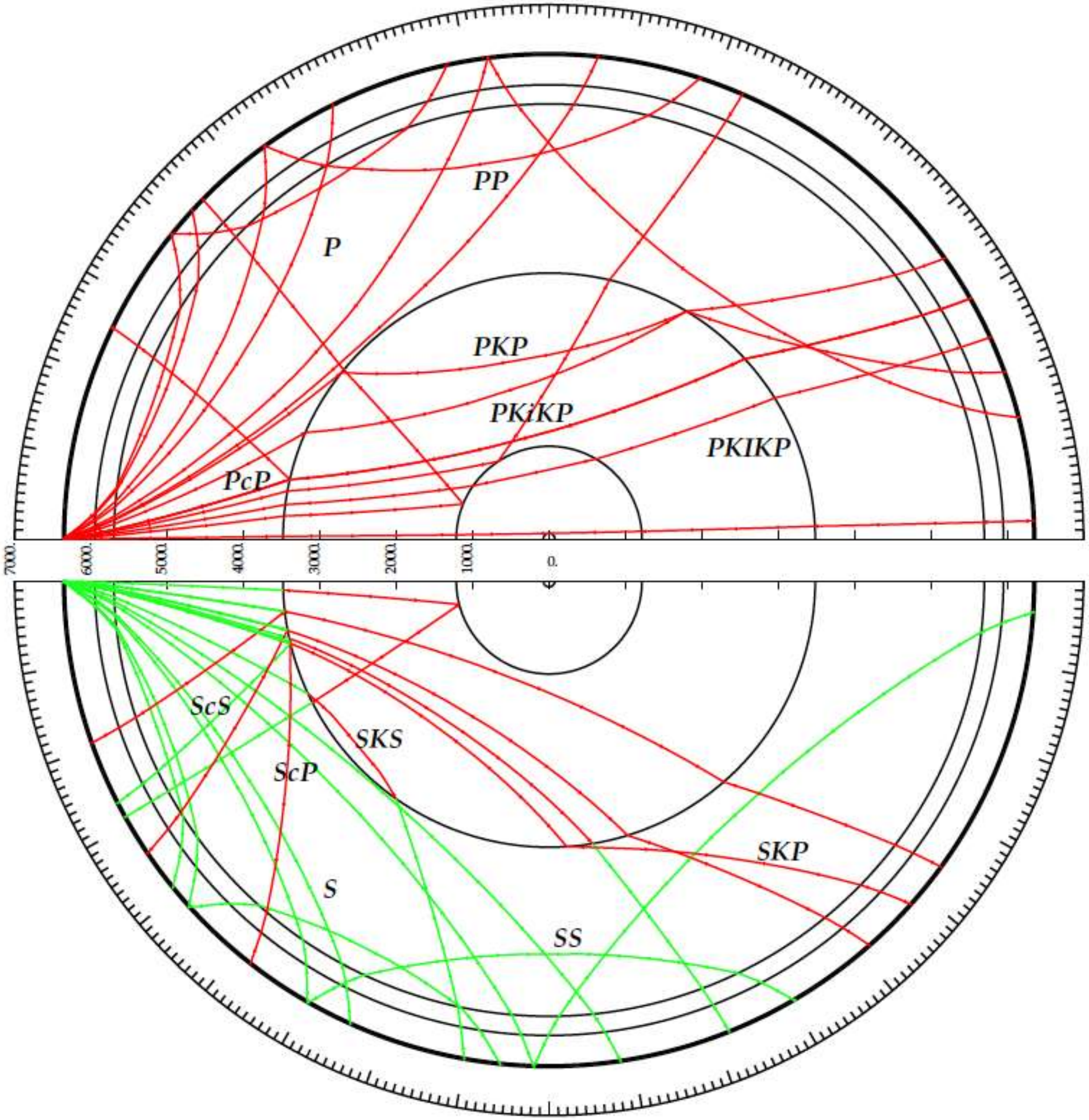



vertical
east-west
north-south
ground displacement
0.1 mm/s
P @ 747 s
PcP @ 752 s
PP @ 945 s
PKiKP @ 1067 s
S @ 1367 s
ScS @ 1382 s
SS @ 1705 s
PKKPdf @ 1838 s
body waves
surface waves

1: TRAVELTIME RAY TOMOGRAPHY

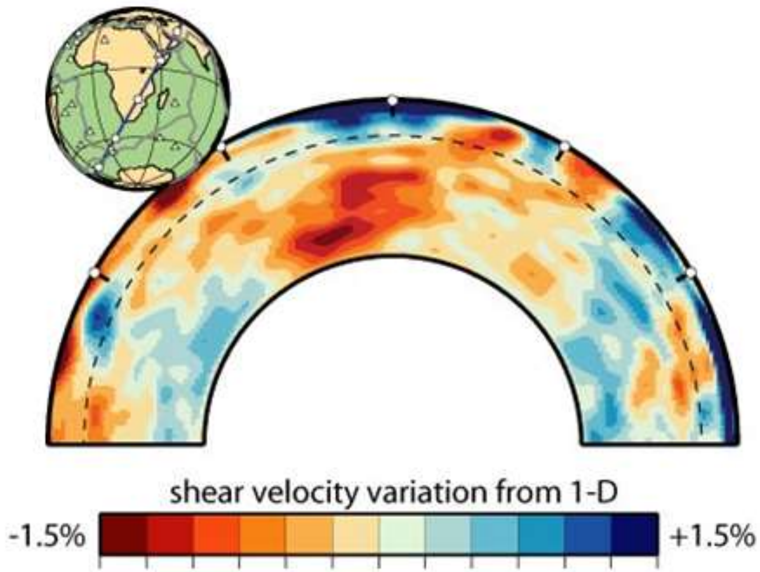


1: TRAVELTIME RAY TOMOGRAPHY

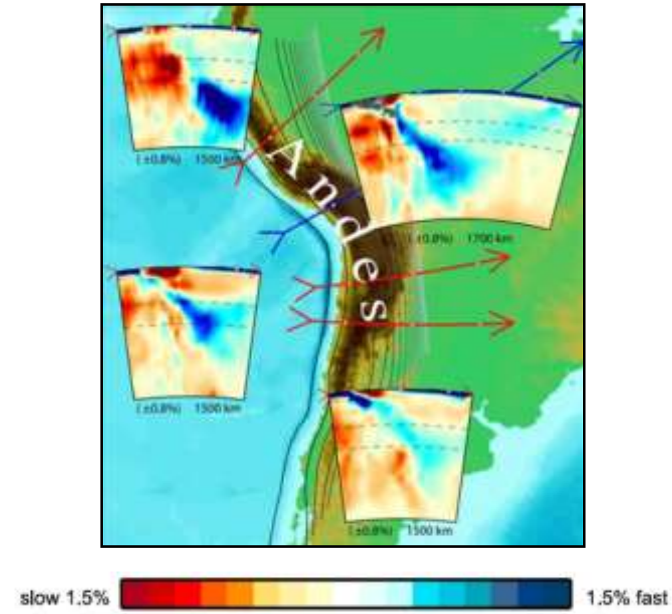


ak135 traveltime tables, Kennett et al., 2005

1: Traveltime Ray Tomography



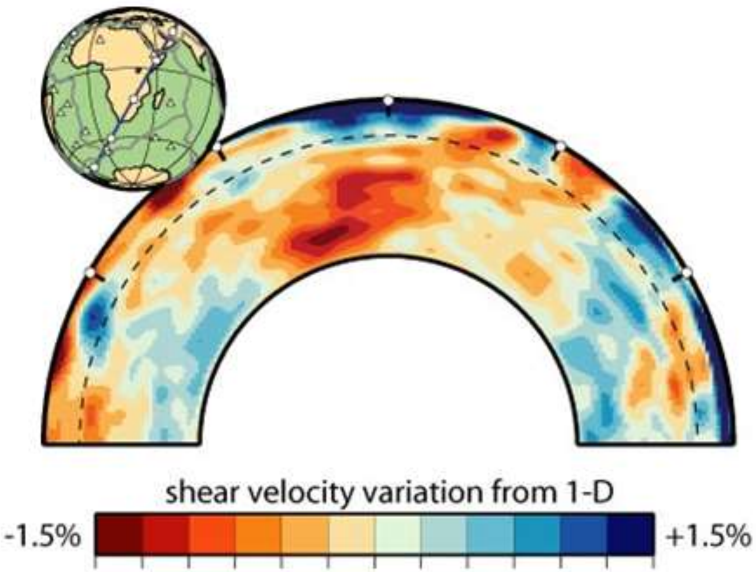
Ritsema et al., 2010



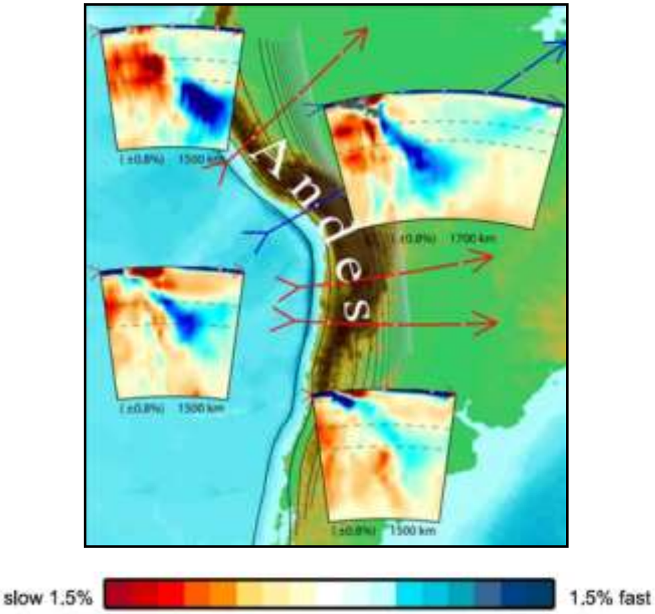
Obayashi et al., 1997

- The majority [by far] of all tomographies are traveltime ray tomographies.
- First applications: Aki et al. [1977], Dziewonski et al. [1977].
- Very well established.

1: TRAVELTIME RAY TOMOGRAPHY



Ritsema et al., 2010



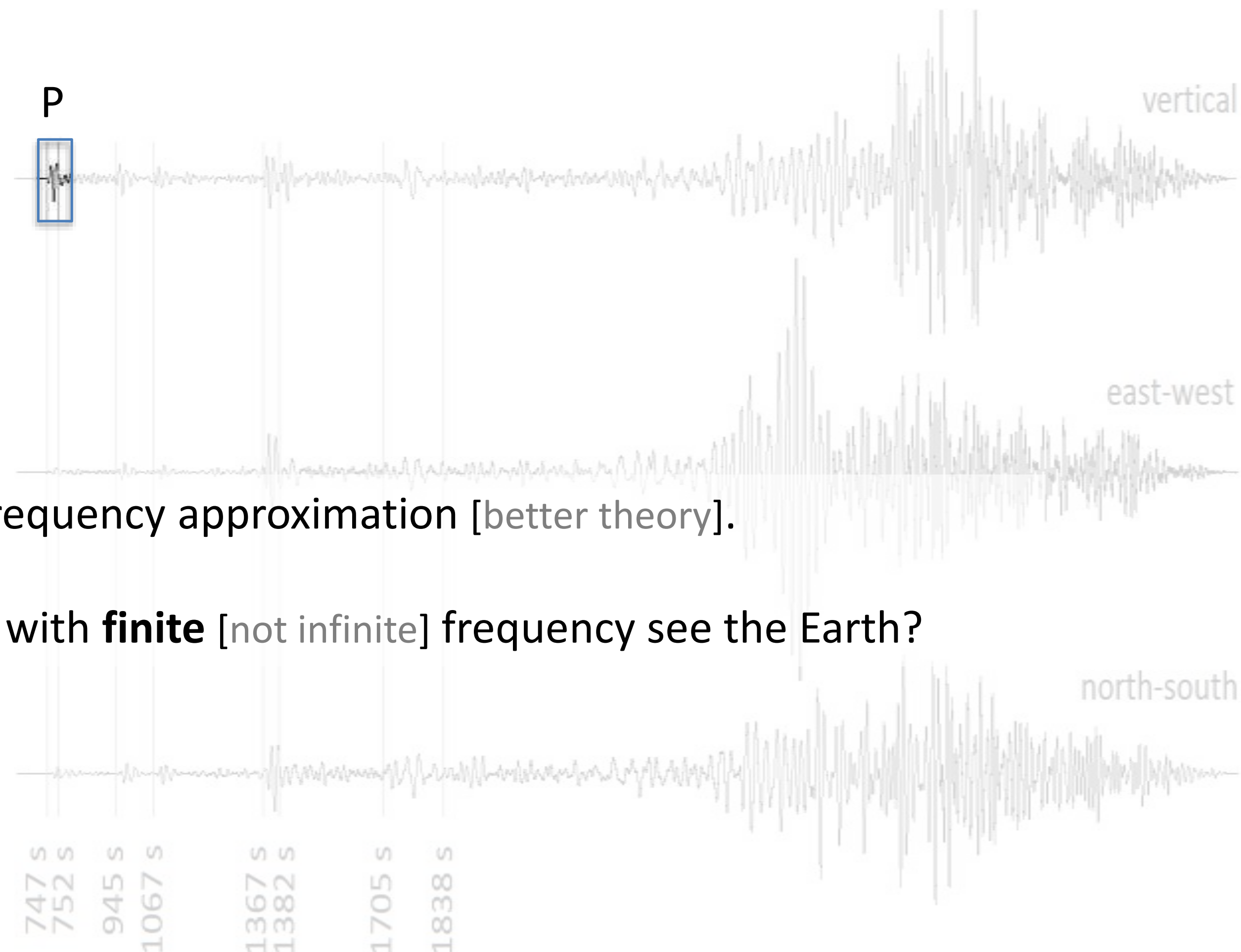
Obayashi et al., 1997

Pros

- Relatively simple theory.
- Computationally inexpensive.
- Possibility to incorporate a very large number of measurements.

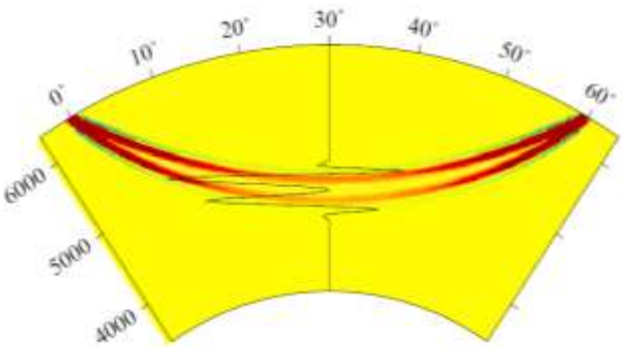
Cons

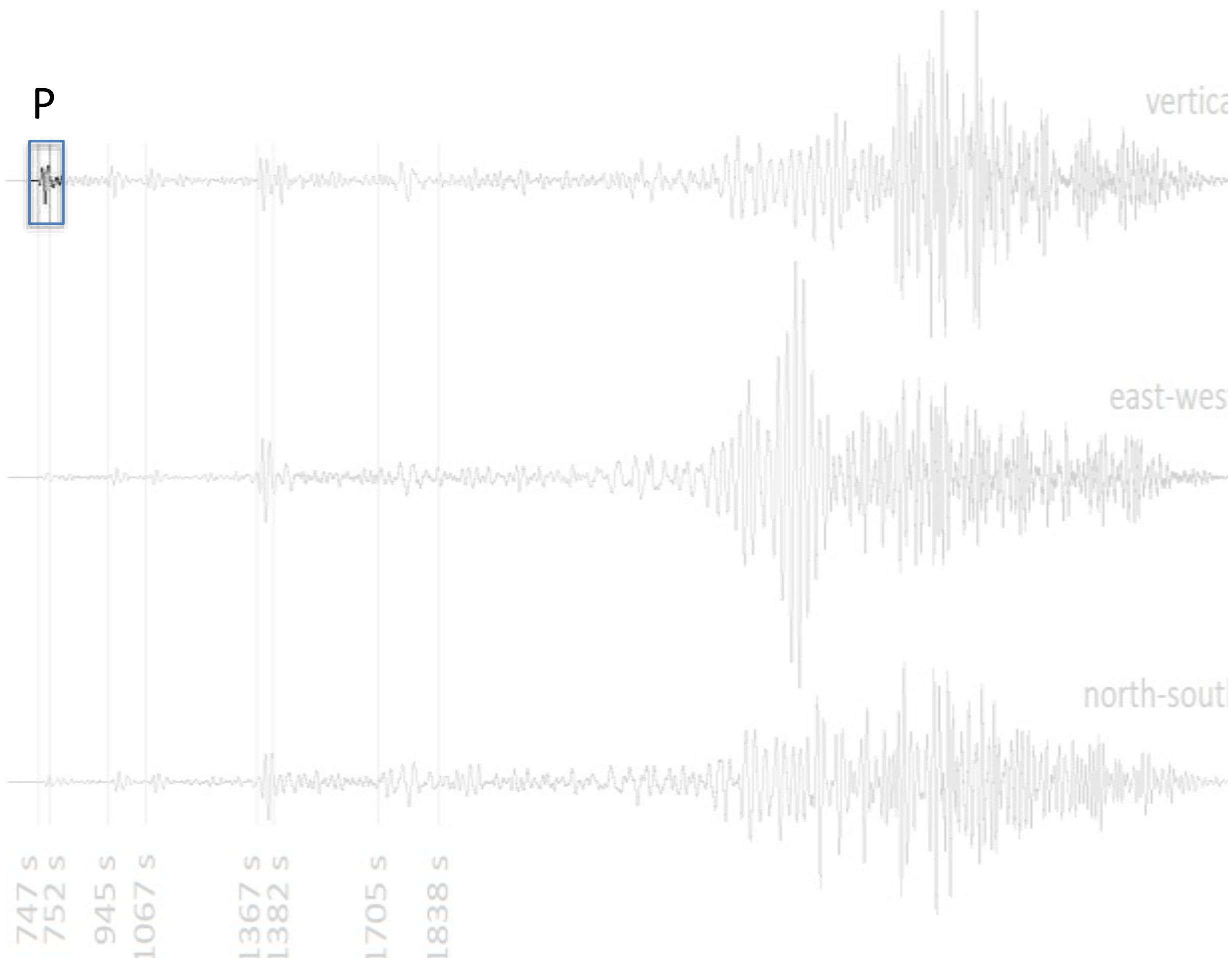
- Ray theory is an **infinite-frequency** approximation for **smooth** media.
- Any information contained in the waveform details is ignored.



- Drop infinite-frequency approximation [better theory].
- How do waves with **finite** [not infinite] frequency see the Earth?

Wave type: P wave
Parameter: P velocity
Period: 10 s

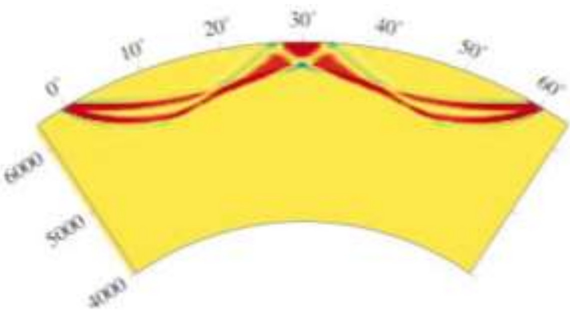


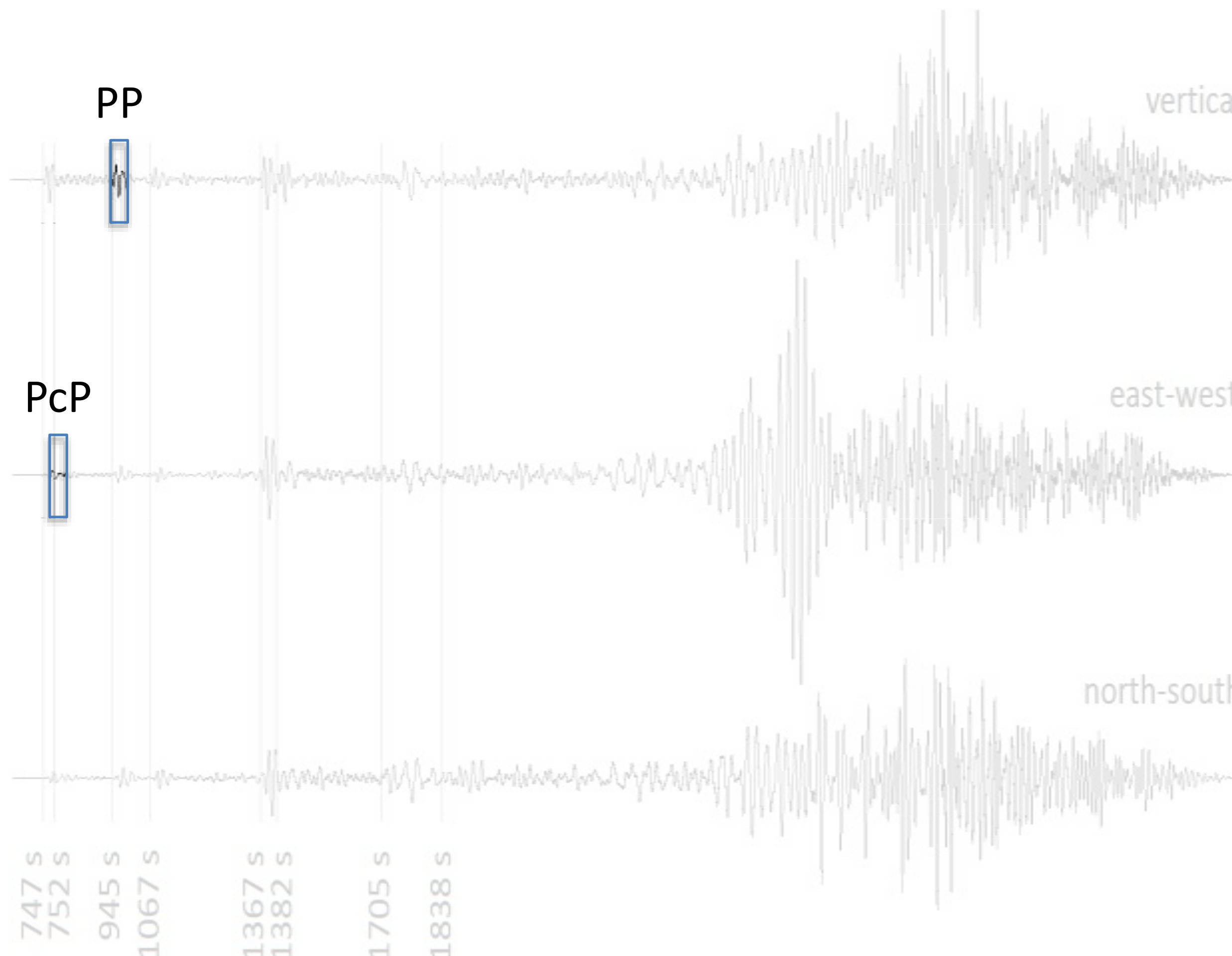


Hung et al. 2000

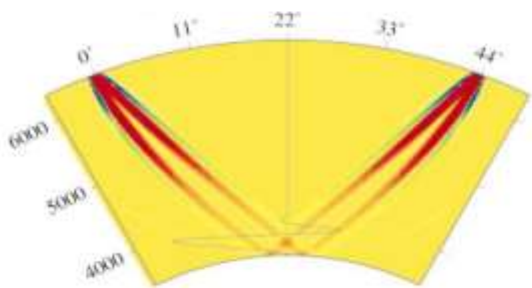
2: FINITE-FREQUENCY TOMOGRAPHY

Wave type: PP wave
Parameter: P velocity
Period: 20 s



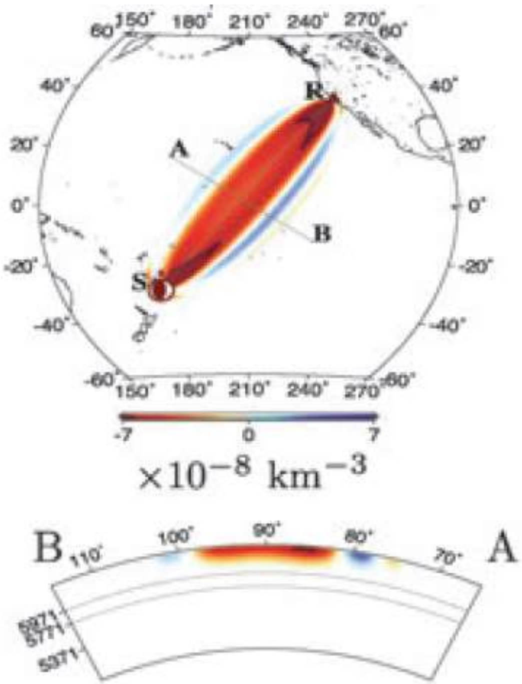


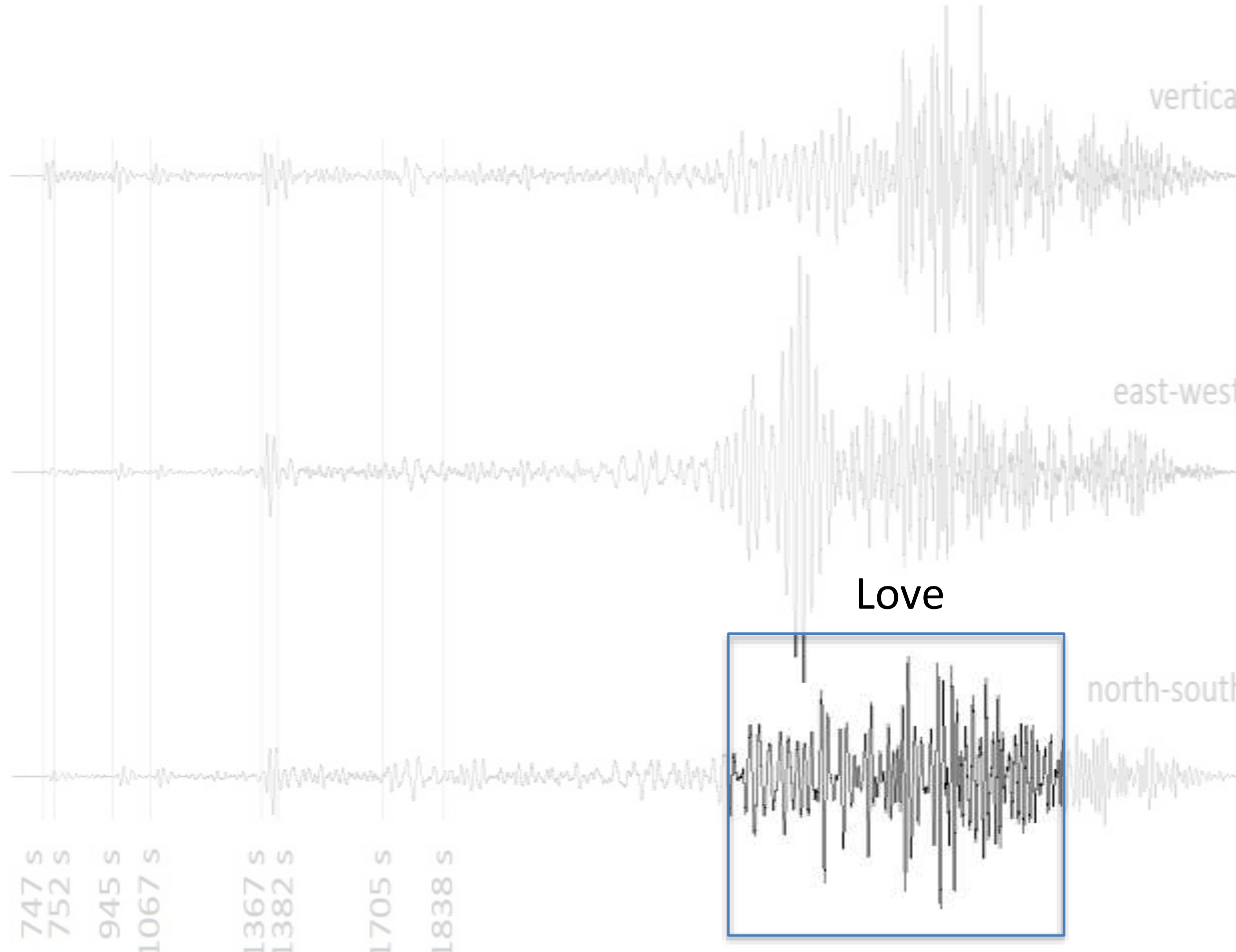
Wave type: PcP wave
Parameter: P velocity
Period: 20 s



Hung et al. 2000

Wave type: Single-mode Love wave
Parameter: S velocity
Period: 100 s





Zhou et al. 2004

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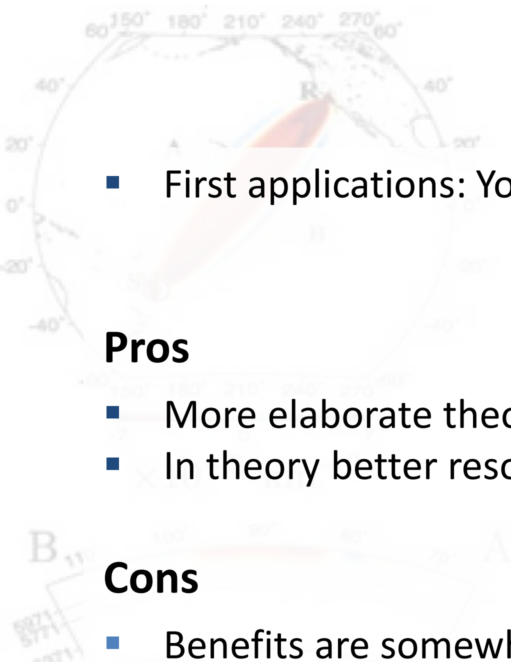
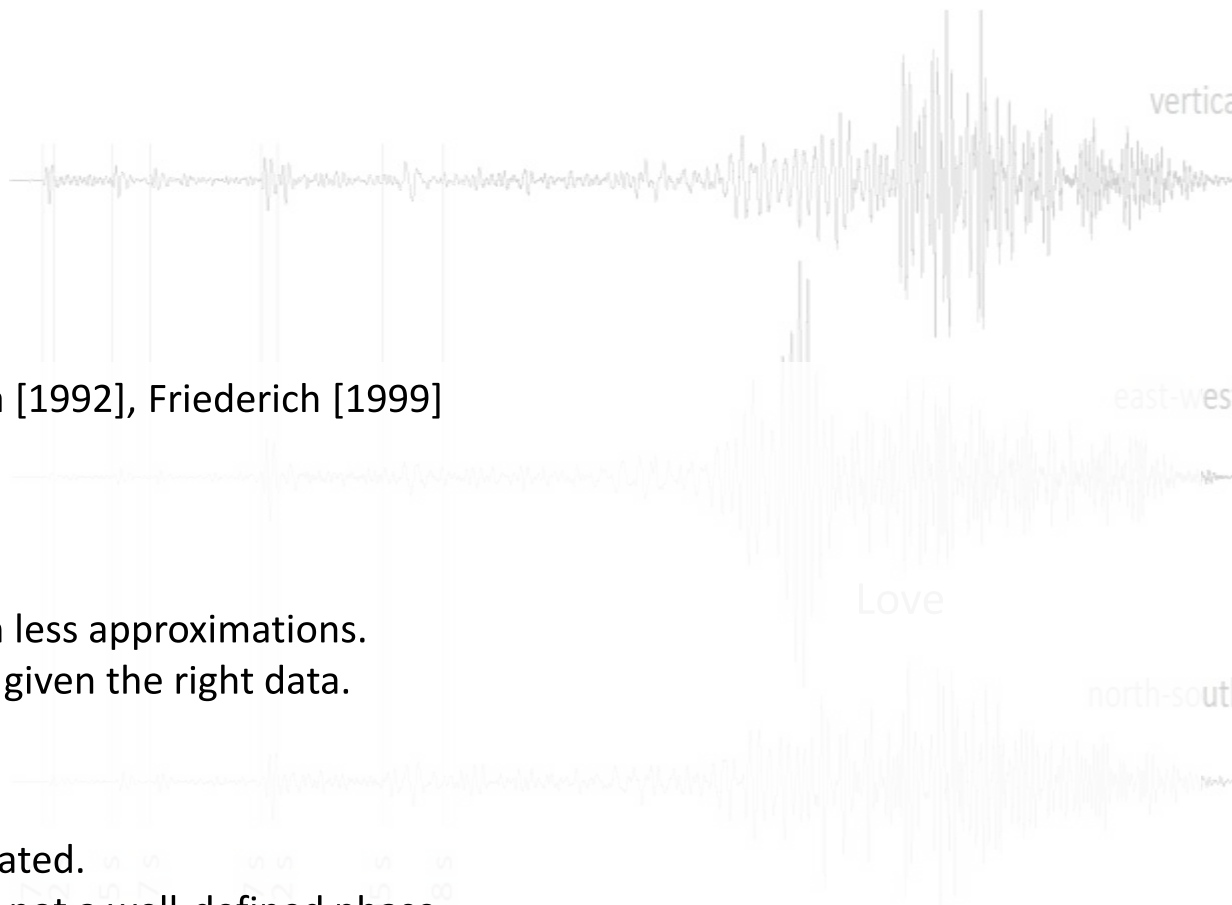




- First applications: Yomogida [1992], Friederich [1999]

Pros

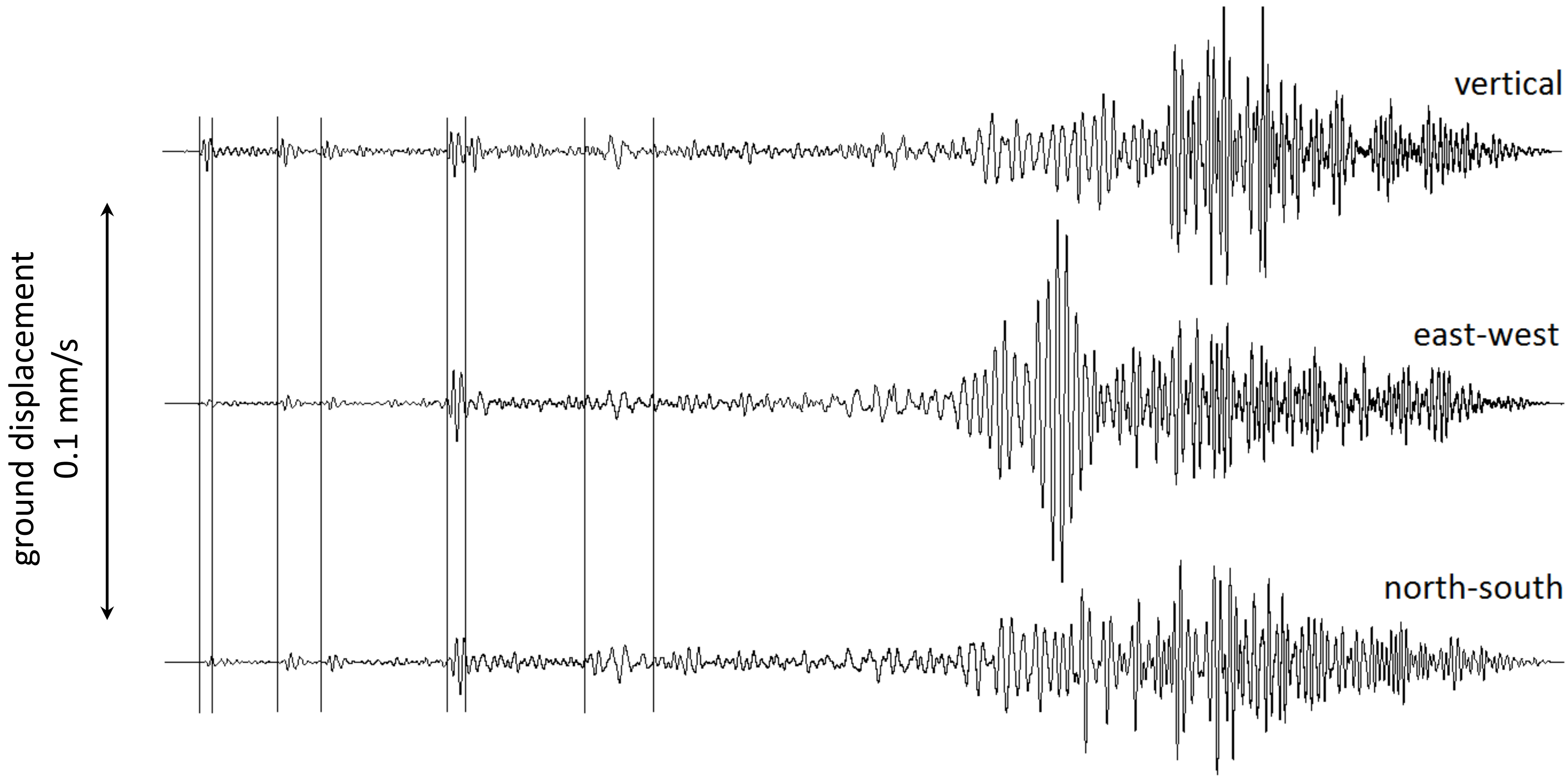
- More elaborate theory with less approximations.
- In theory better resolution, given the right data.

Cons

- Benefits are somewhat debated.
- Still ignores anything that is not a well-defined phase.
- Variants developed so far also require smooth media.

Zhou et al. 2004

3: Full-Waveform Inversion

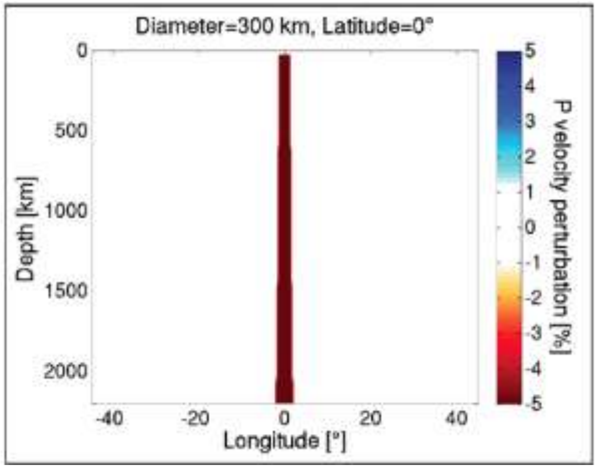


Solve the wave equation fully numerically for heterogeneous Earth [see Heiner Igel's talk].

- Avoid any significant modelling error [and related imaging artifacts].
- Use as much information as you can [every wiggle, if the noise permits to do so].

SYNTHETIC EXAMPLE

Input model – an idealised plume



Rickers et al., GJI 2012.

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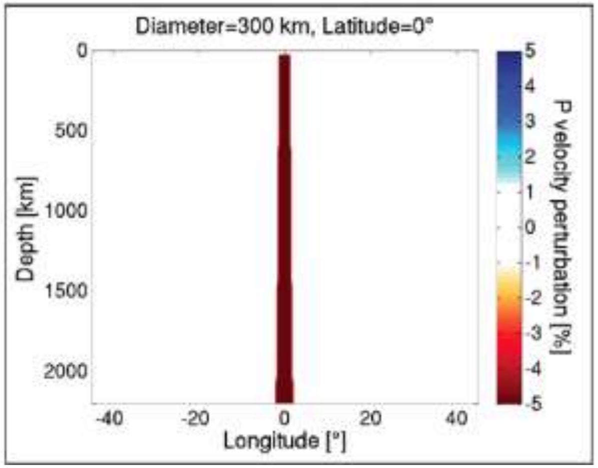
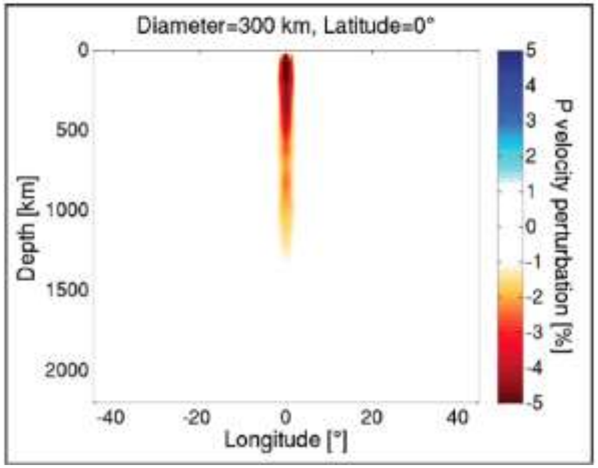


reconstructed model
using only P wave traveltimes



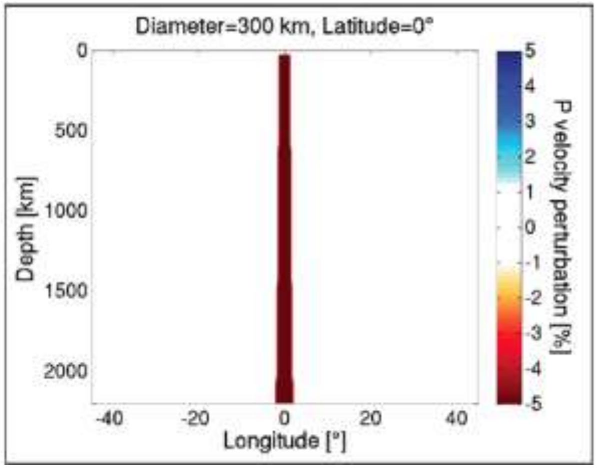
Wavefront healing: direct wave forgets about the plume.

Deep plumes cannot be resolved with traveltime tomography
[e.g. Treml 2006, Hwang 2011, Rickers 2012, Maguire et al. 2016].

Rickers et al., GJI 2012.

SYNTHETIC EXAMPLE

Input model – an idealised plume



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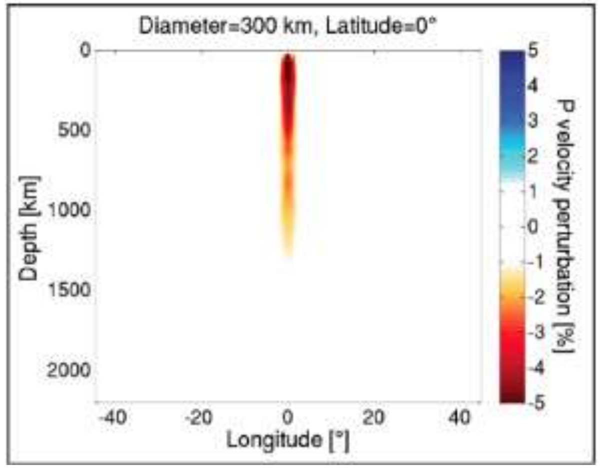
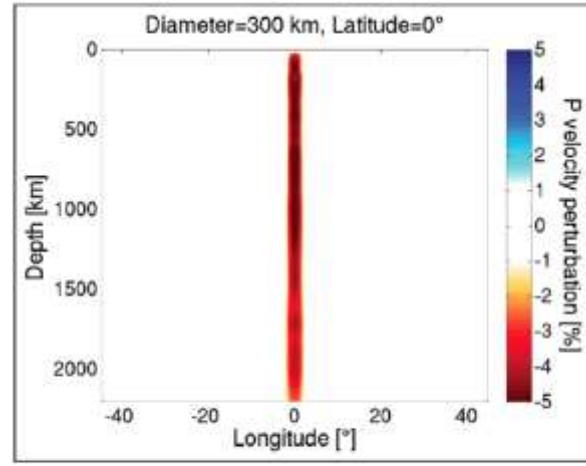


reconstructed model
complete seismograms

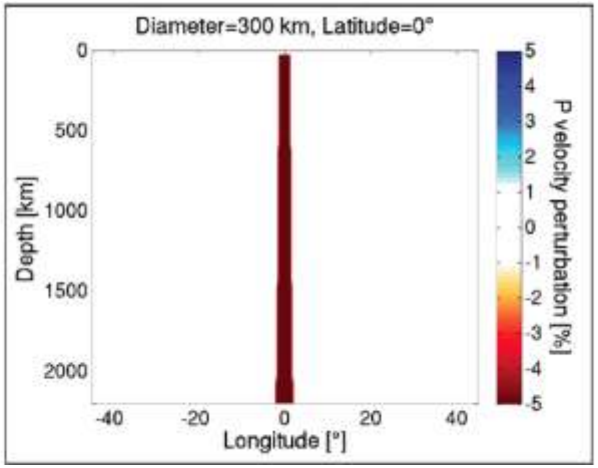


Rickers et al., GJI 2012.

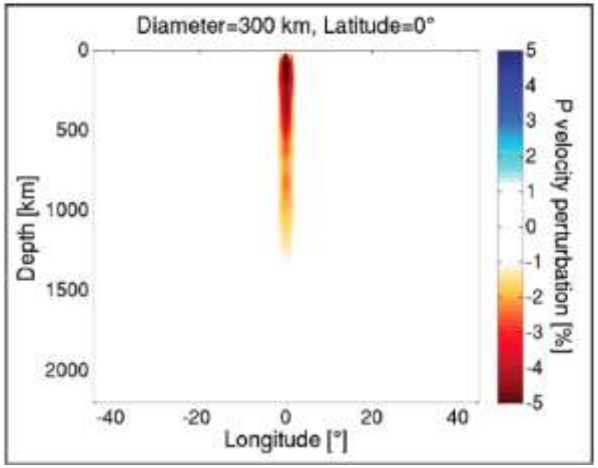
3: Full-Waveform Inversion

Synthetic Example

Input model – an idealised plume



reconstructed model
using only P wave traveltimes



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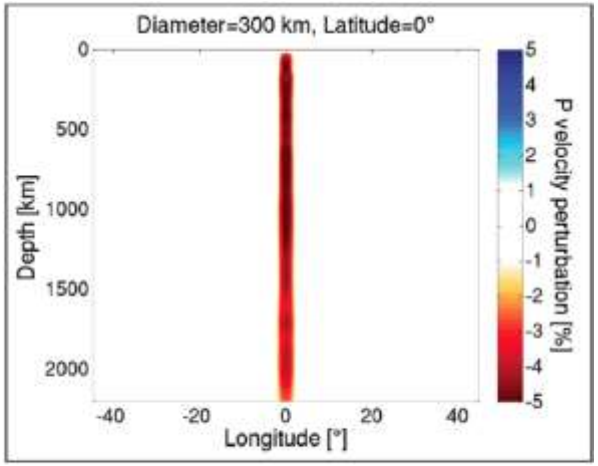

- First theoretical attempts: Bamberger, Chavent, Lailly [late 1970's]
- First applications in 2D: Crase, Igel, Tarantola [1990's]
- First applications in 3D: Chen, Tape, Fichtner [nearly 10 years ago]

3: Full-Waveform Inversion

Synthetic Example

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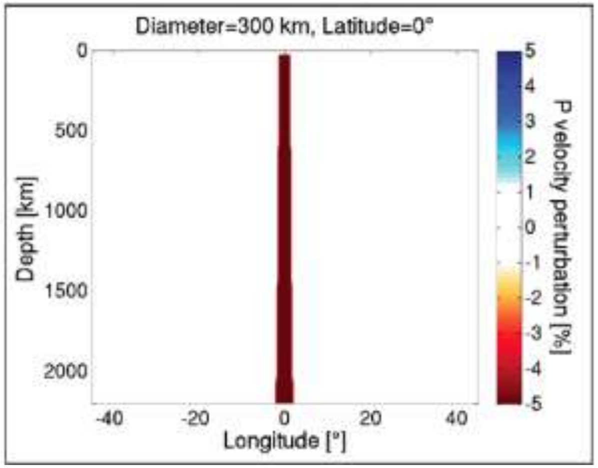

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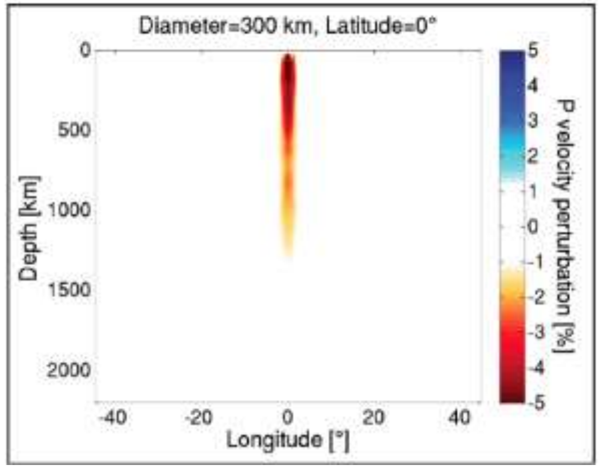

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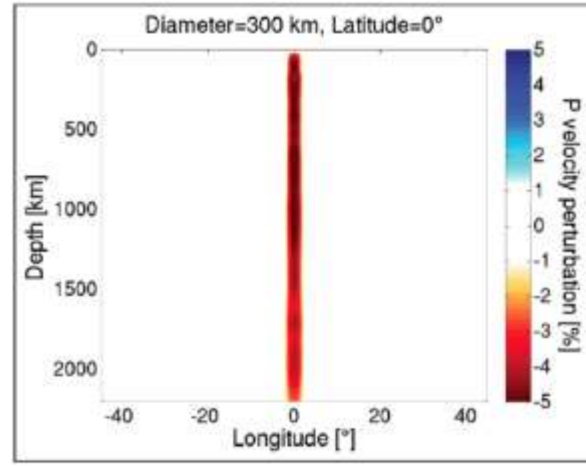


Pros

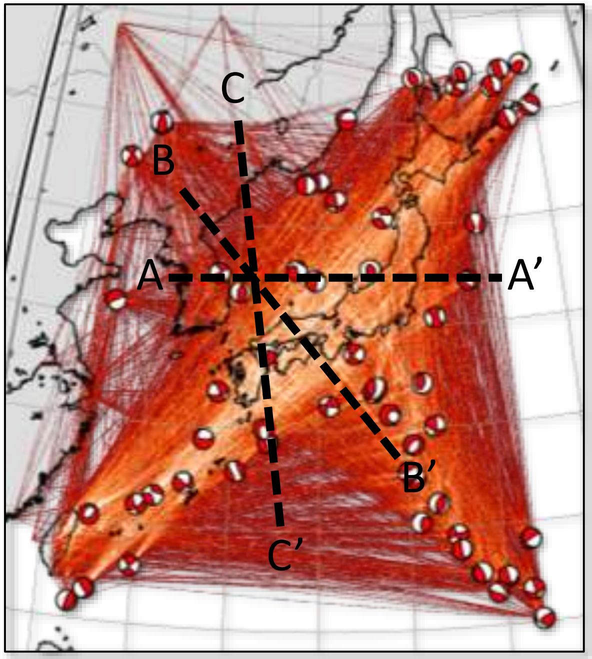
- Very few mathematical approximations. [Less approximation artefacts]
- Works for realistically heterogeneous Earth models. [Sharp velocity variations of >10 %]
- Exploitation of complete seismograms. [Naturally combine body and surface wave tomography. Improve resolution, given the right data.]

Cons

- Algorithmically complex.
- High computational requirements [due to fully numerical wave propagation].
- Use less earthquakes.

REAL-WORLD EXAMPLES

Amplitudes, crust/mantle resolution, and uncertainties

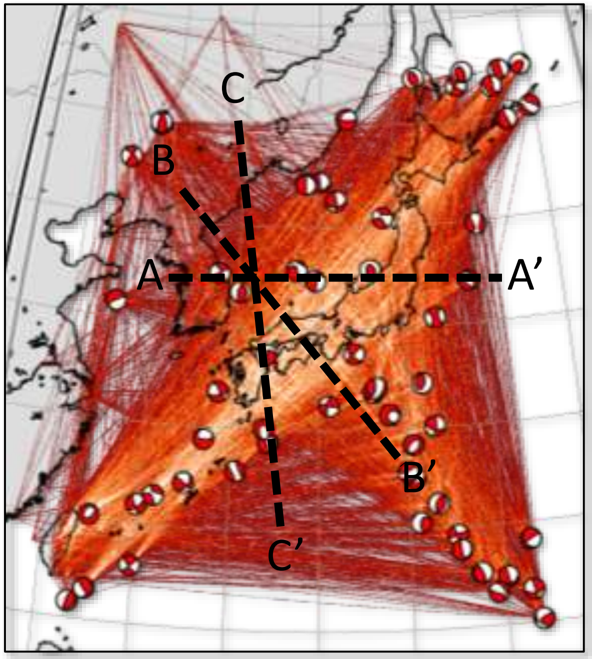


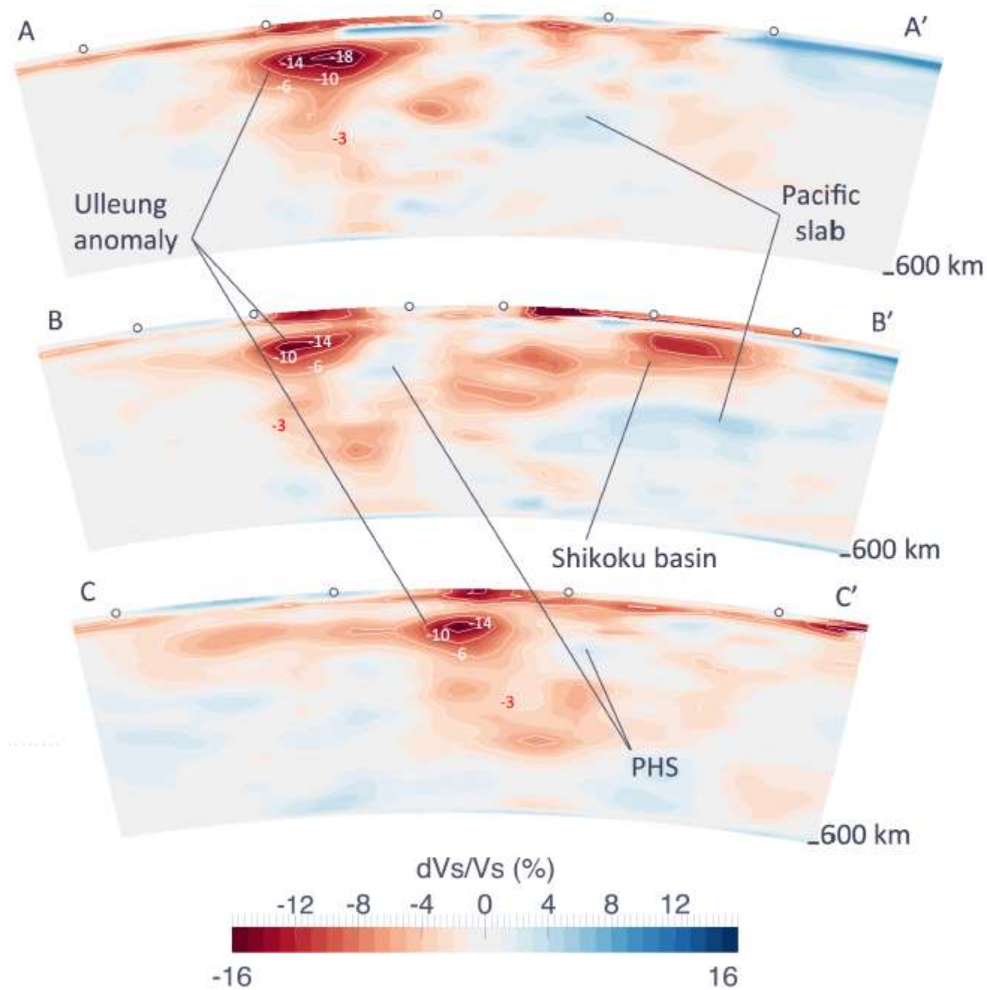
Data

- 58 earthquakes, >150 stations
- body waves, surface waves, ...
- periods: **15 – 150 s**

Simute et al., JGR 2016

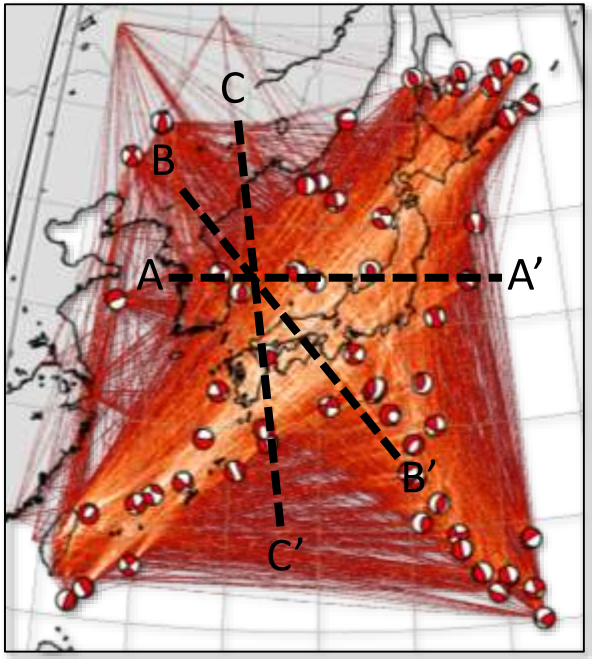
The Japanese Islands Region





Simute et al., JGR 2016

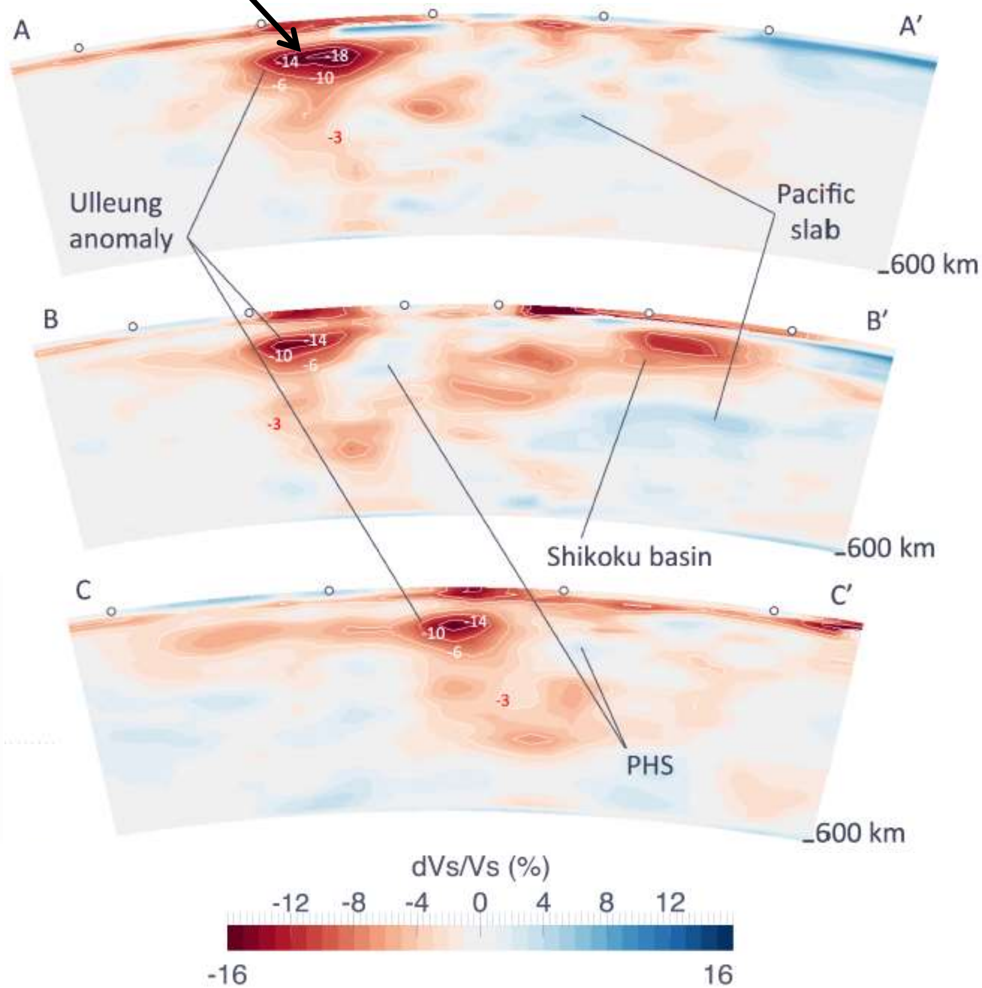
The Japanese Islands Region



$\delta \ln v_s$ = -19 %

[v_s = 3.55 km/s at 150 km depth]

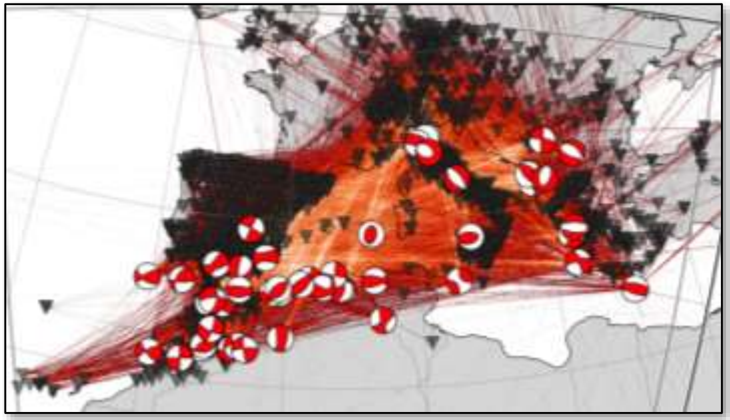
Ulleung Island



Earth is ‘slower’ than seen with ray tomography

[as predicted, e.g. Wielandt 1987, Igel & Gudmundsson 1996, Malcolm & Trampert 2011]

Simute et al., JGR 2016



surface wave ray coverage

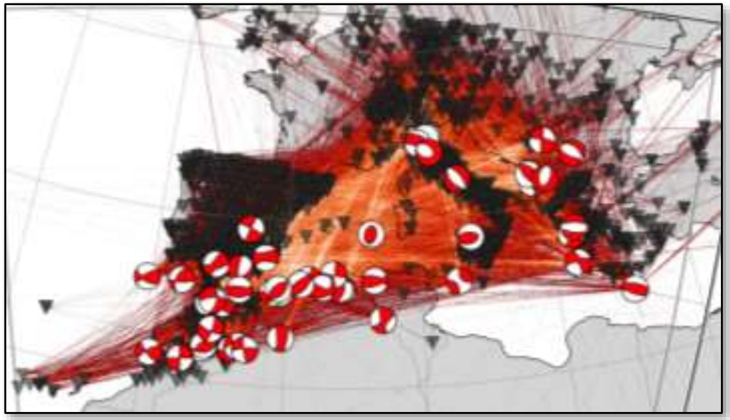
Data

- 52 earthquakes, >1000 stations
- body waves, surface waves, ...

- periods: **10 – 150 s**
- **6 – 90** propagation wavelengths

Fichtner & Villasenor, EPSL 2015

The Western Mediterranean



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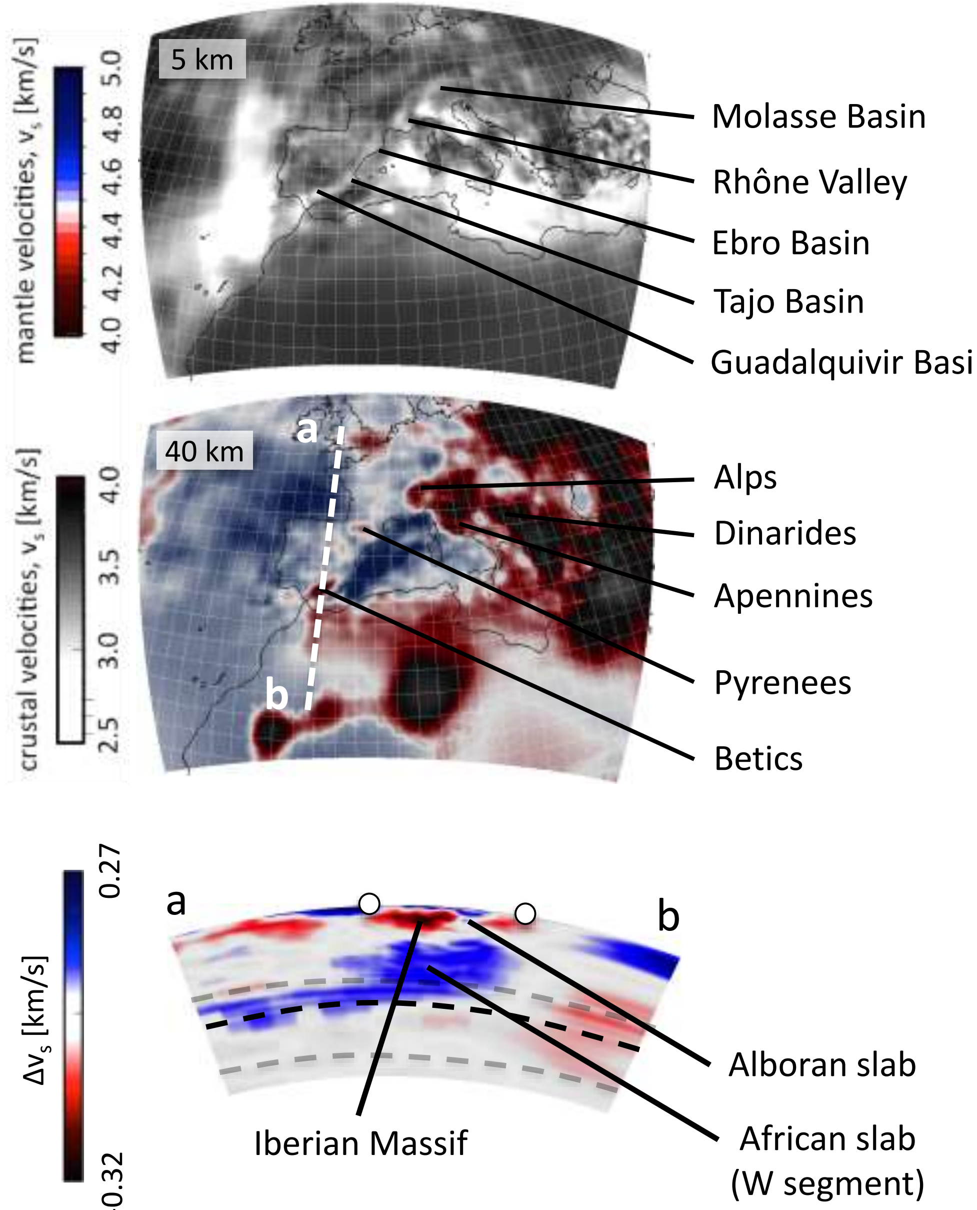


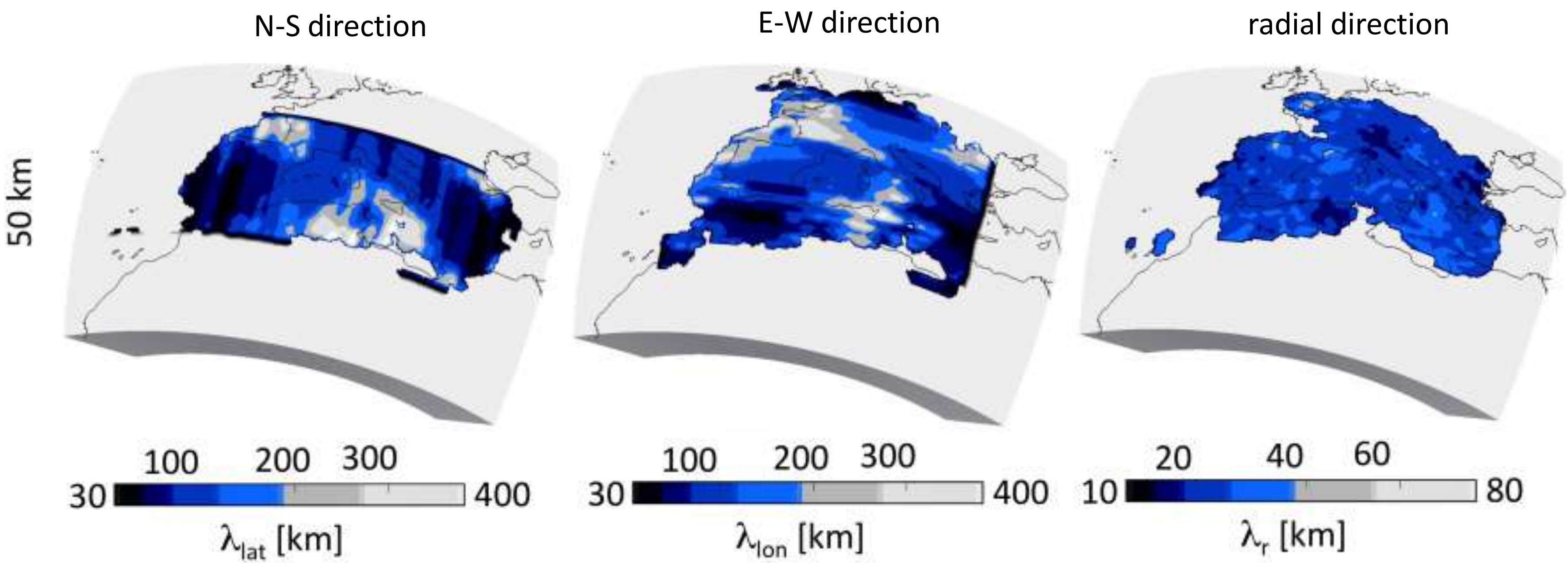
joint resolution of crust and mantle

['see' relation between deep-Earth processes and surface expressions]

Fichtner & Villasenor, EPSL 2015

Resolution analysis by random probing:

- Probing the resolution matrix with random test models [second-order adjoints]
- Direction- and position-dependent resolution lengths [point-spread function width]



efficient resolution analysis tools
[quantitative analysis instead of synthetic inverse crimes]

Fichtner & van Leeuwen, JGR 2015.

Intermediate take-home messages

- FWI on regional scales: It essentially works.
- Discovery of very low velocity regions. [Earth is more heterogeneous than we thought.]
  - Need to go beyond purely thermal interpretation of the model.
- Joint resolution of crustal and mantle structure
  - Direct view of relation between mantle structure and its surface imprint.
- Efficient resolution analysis tools are available.
  - Resolution is more heterogeneous than the Earth itself.

Challenges

Are Our Computers Big Enough, Or Will They Soon Be?

Compressional waves propagate through the whole Earth at

min. period: ≈ 1 s

Are Our Computers Big Enough, Or Will They Soon Be?

Compressional waves propagate through the whole Earth at

min. period: ≈ 1 s

Today

Global full-waveform inversion

min. period: ≈ 20 s

Today's computing power is at least 20^5 = **3.2 million** times too small!

Are Our Computers Big Enough, Or Will They Soon Be?

Compressional waves propagate through the whole Earth at	Today	in ≈ 50 years
	Global full-waveform inversion	Tomography based on fully numerical wave propagation
min. period: ≈ 1 s	**min. period: ≈ 20 s**	**min. period: ≈ 1 s**

Provided that:

Moore's law continues to hold.
We can handle computers that are 3.2 million times bigger.
We can write code to harness such resources.

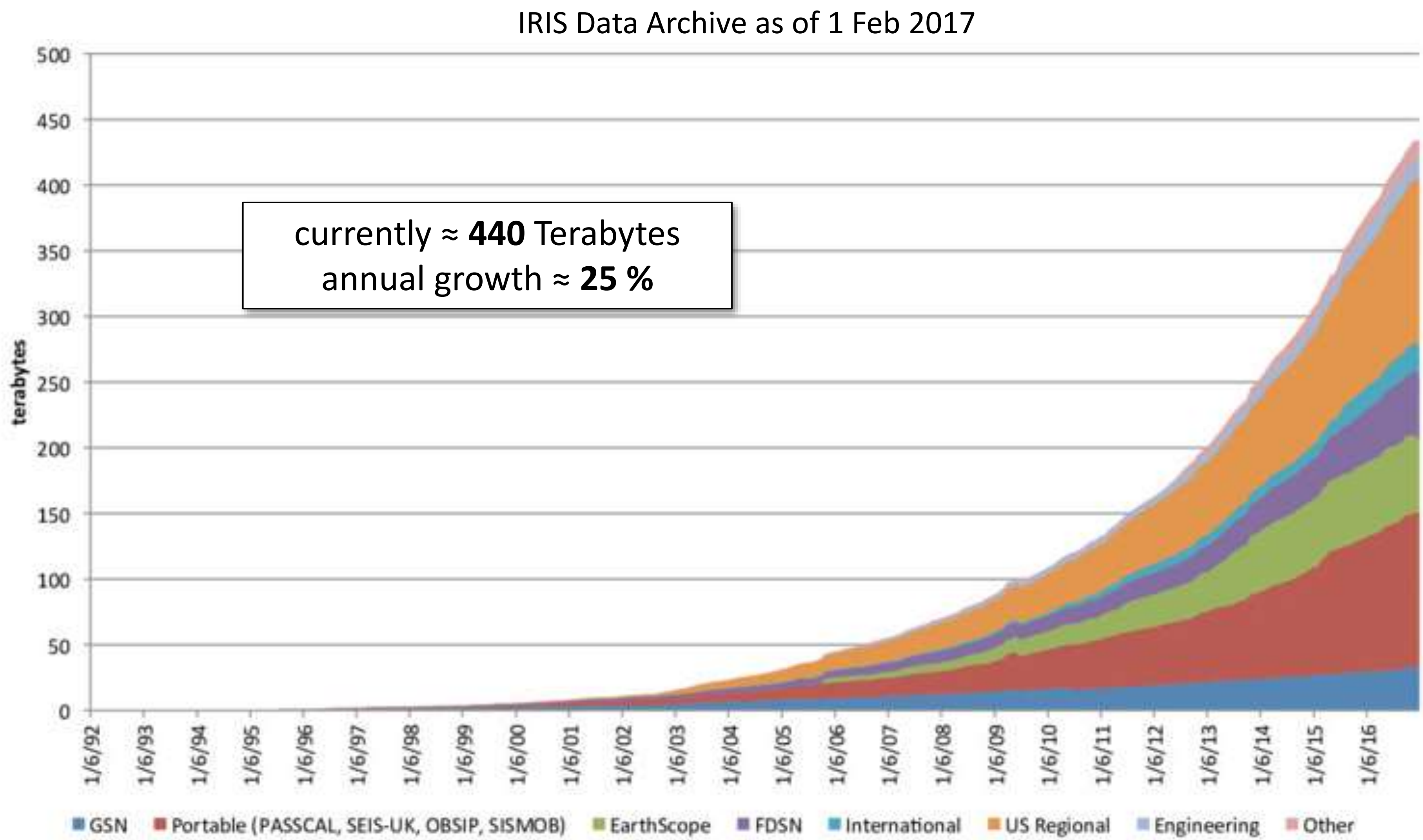
Are Our Computers Big Enough, Or Will They Soon Be?

Compressional waves propagate through the whole Earth at **min. period: ≈ 1 s**	Today Global full-waveform inversion **min. period: ≈ 20 s**	in ≈ 50 years Tomography based on fully numerical wave propagation **min. period: ≈ 1 s**

Provided that:

Moore's law continues to hold.
We can handle computers that are 3.2 million times bigger.
We can write code to harness such resources.

Computer power alone will not solve the problem.


IRIS Data Archive as of 1 Feb 2017
currently ≈ 440 Terabytes
annual growth ≈ 25 %
terabytes
500
450
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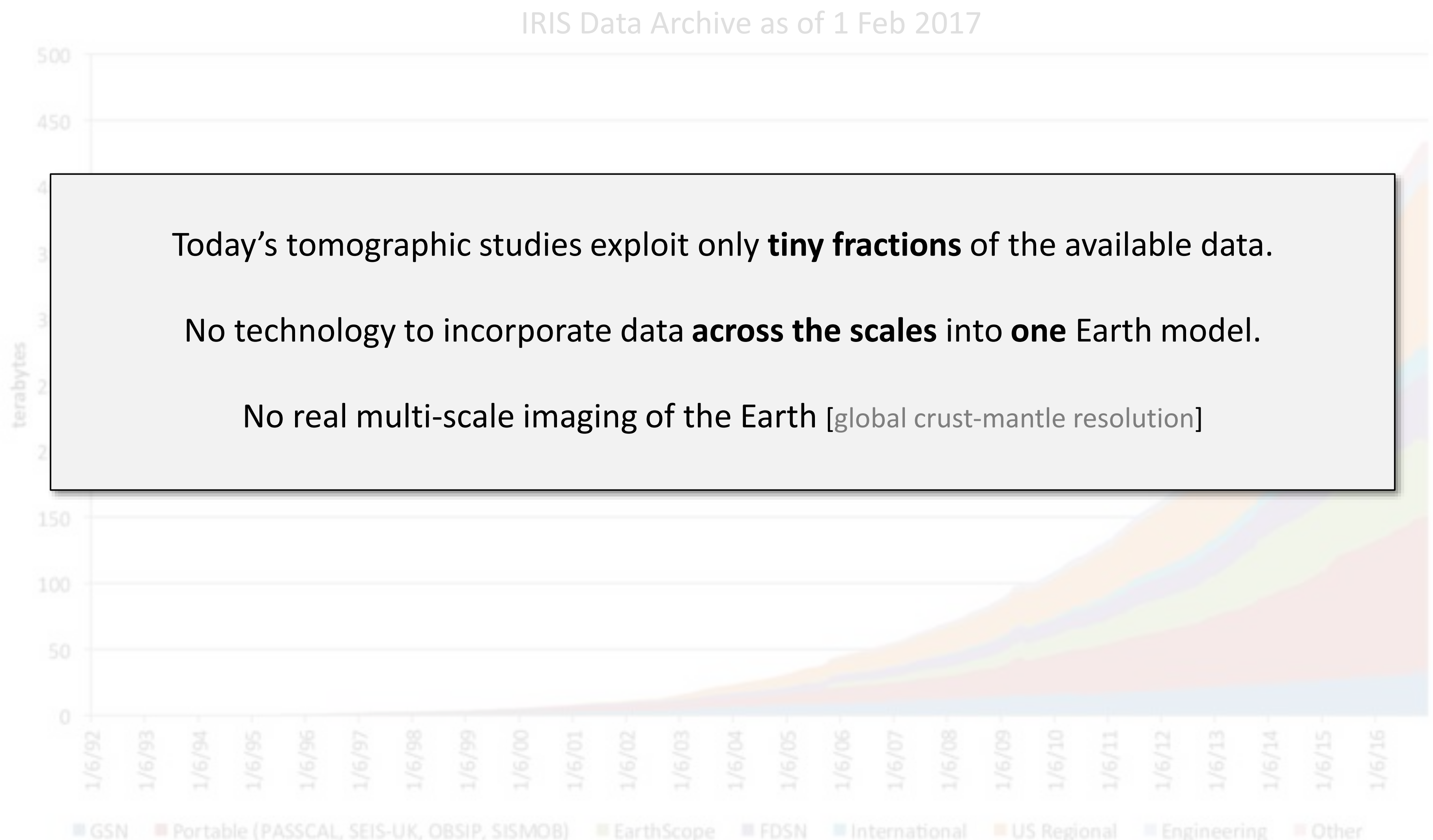
1/6/12
1/6/13
1/6/14
1/6/15
1/6/16
GSN
Portable (PASSCAL, SEIS-UK, OBSIP, SISMOB)
EarthScope
FDSN
International
US Regional
Engineering
Other

THE DATA FLOOD

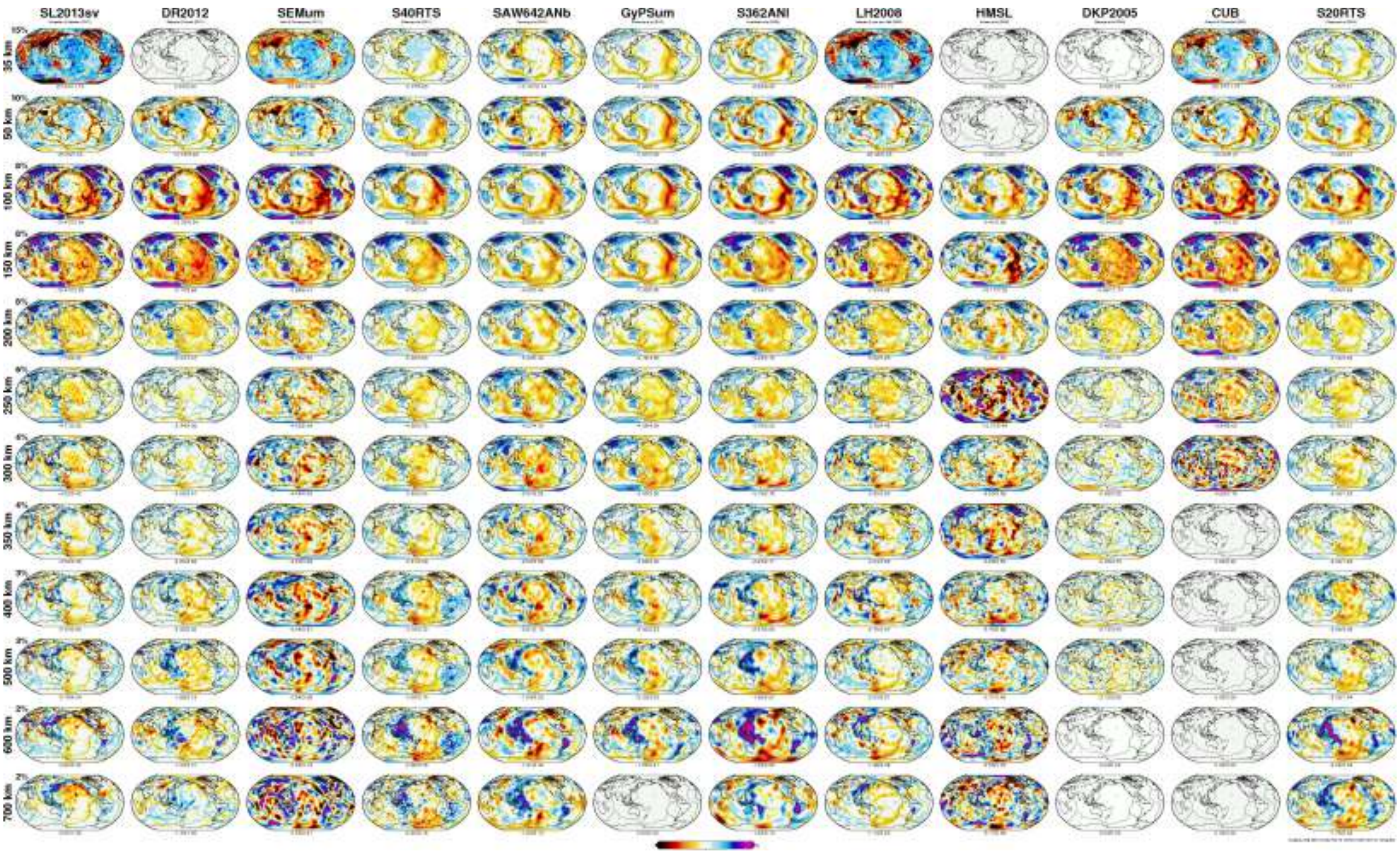


Today’s tomographic studies exploit only **tiny fractions** of the available data.

No technology to incorporate data **across the scales** into **one** Earth model.

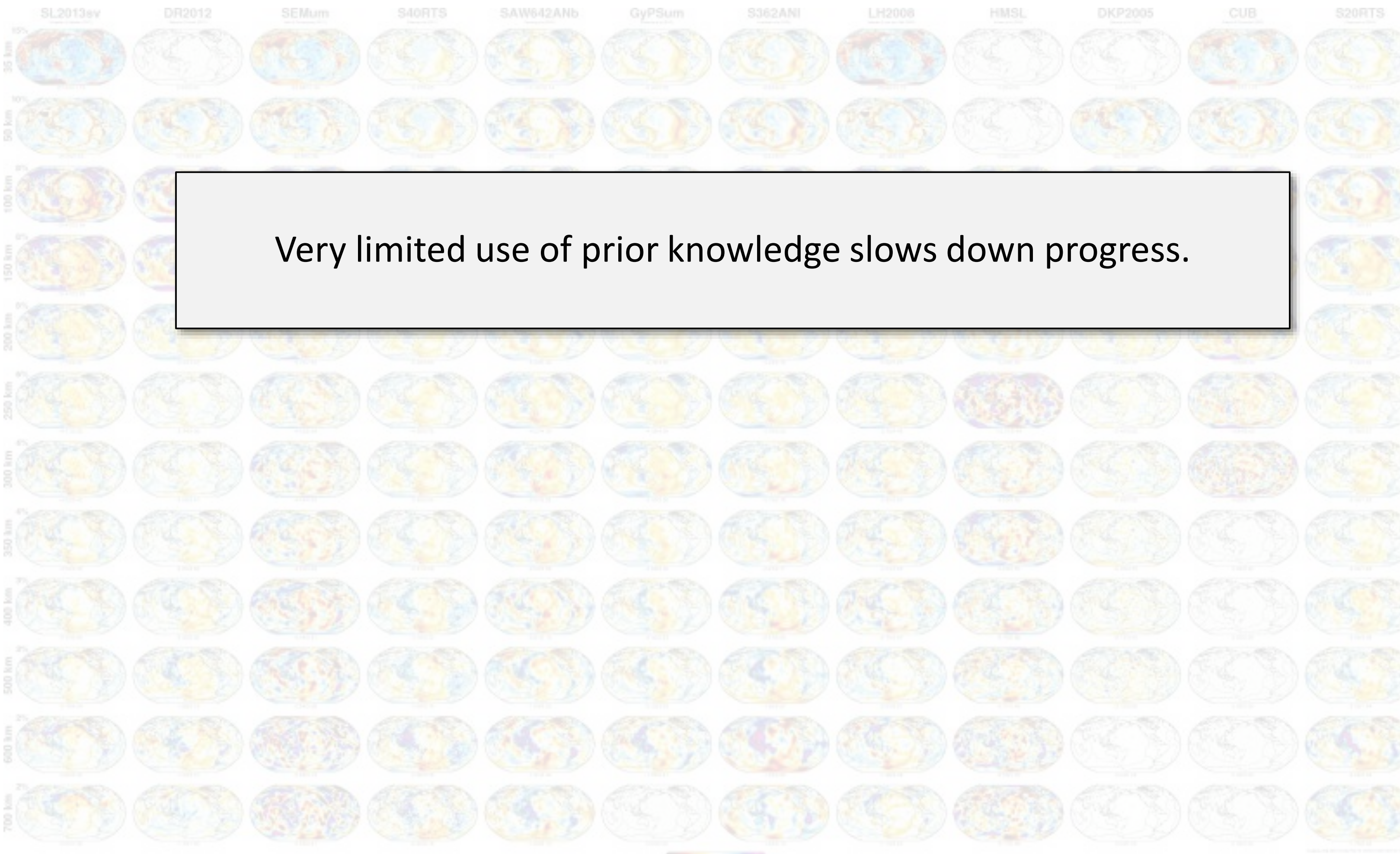
No real multi-scale imaging of the Earth [global crust-mantle resolution]

Comparison of 12 recent tomographic images of the same object [compiled by Andrew Schaeffer]



OUR MODE OF OPERATION

Comparison of 12 recent tomographic images of the same object [compiled by Andrew Schaeffer]



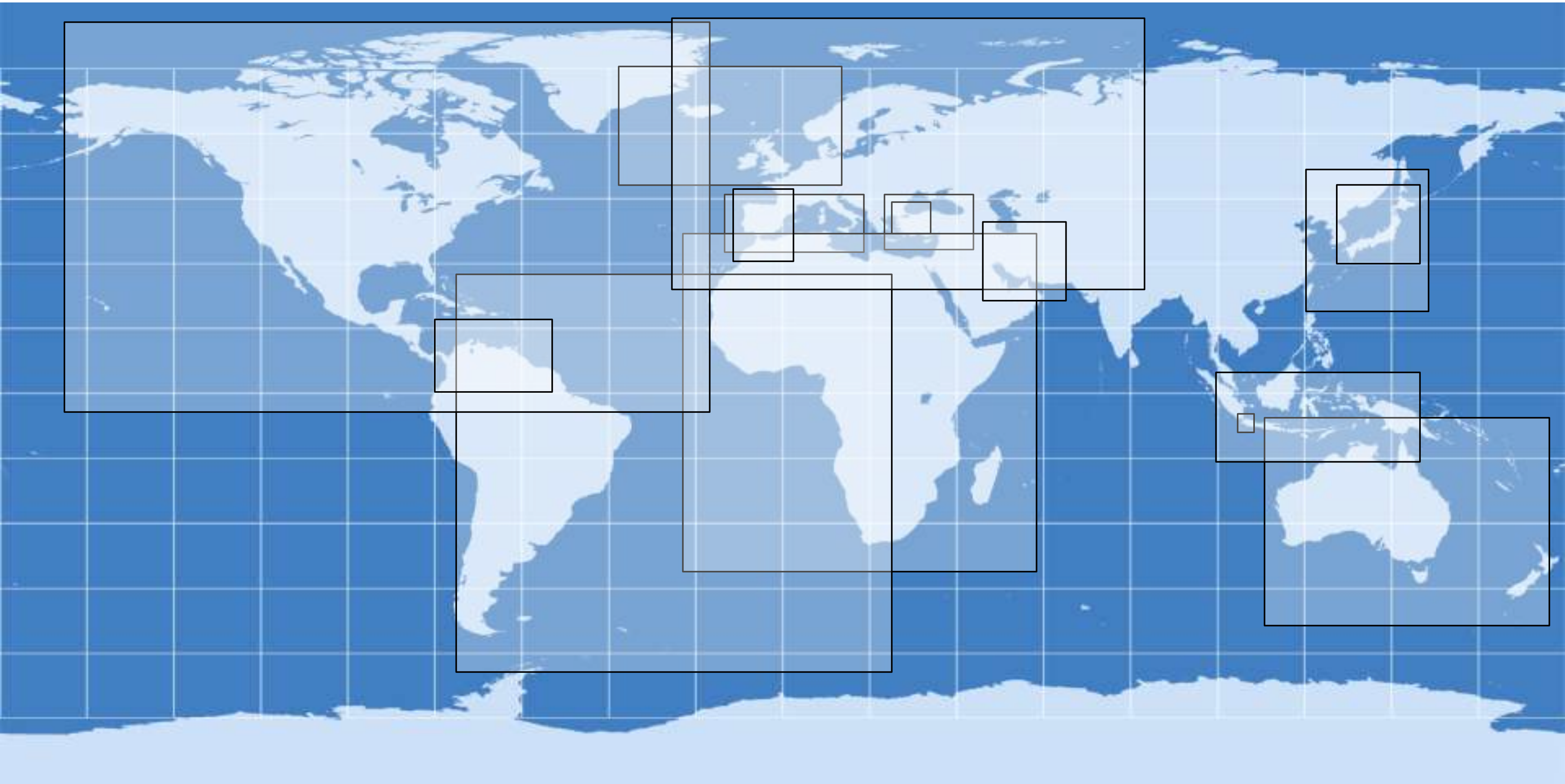
Very limited use of prior knowledge slows down progress.

The Collaborative Seismic Earth Model

General Concept

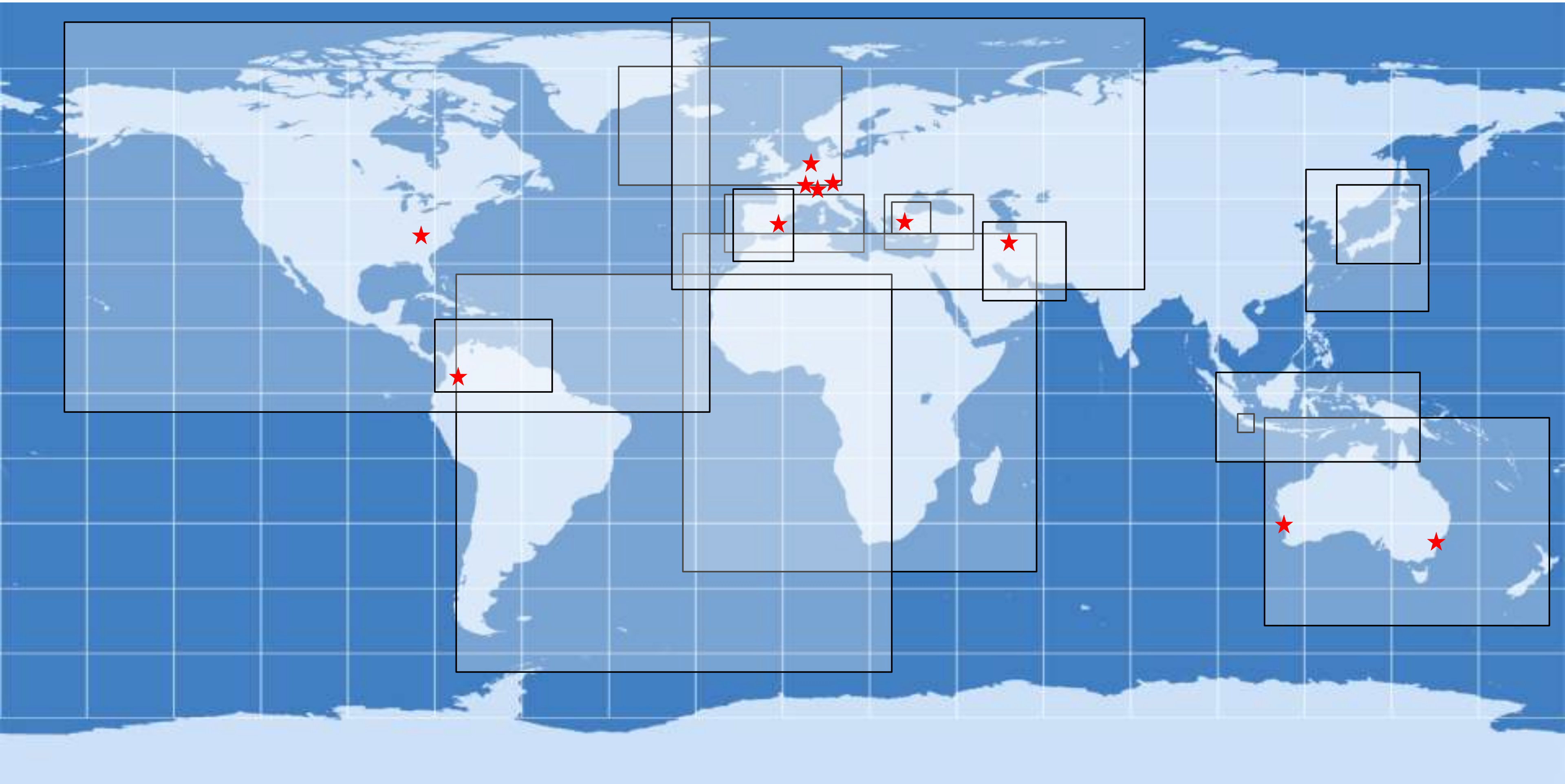
- Evolutionary multi-scale model.
- Successive regional refinements [e.g. when new data become available].
- Contributed by different researchers.
- Consistent with each other and with global Earth structure.
- Community-driven “divide and conquer”.

Overview of current subregions



Afanasiev et al., *Geophys. J. Int.*, 2016.

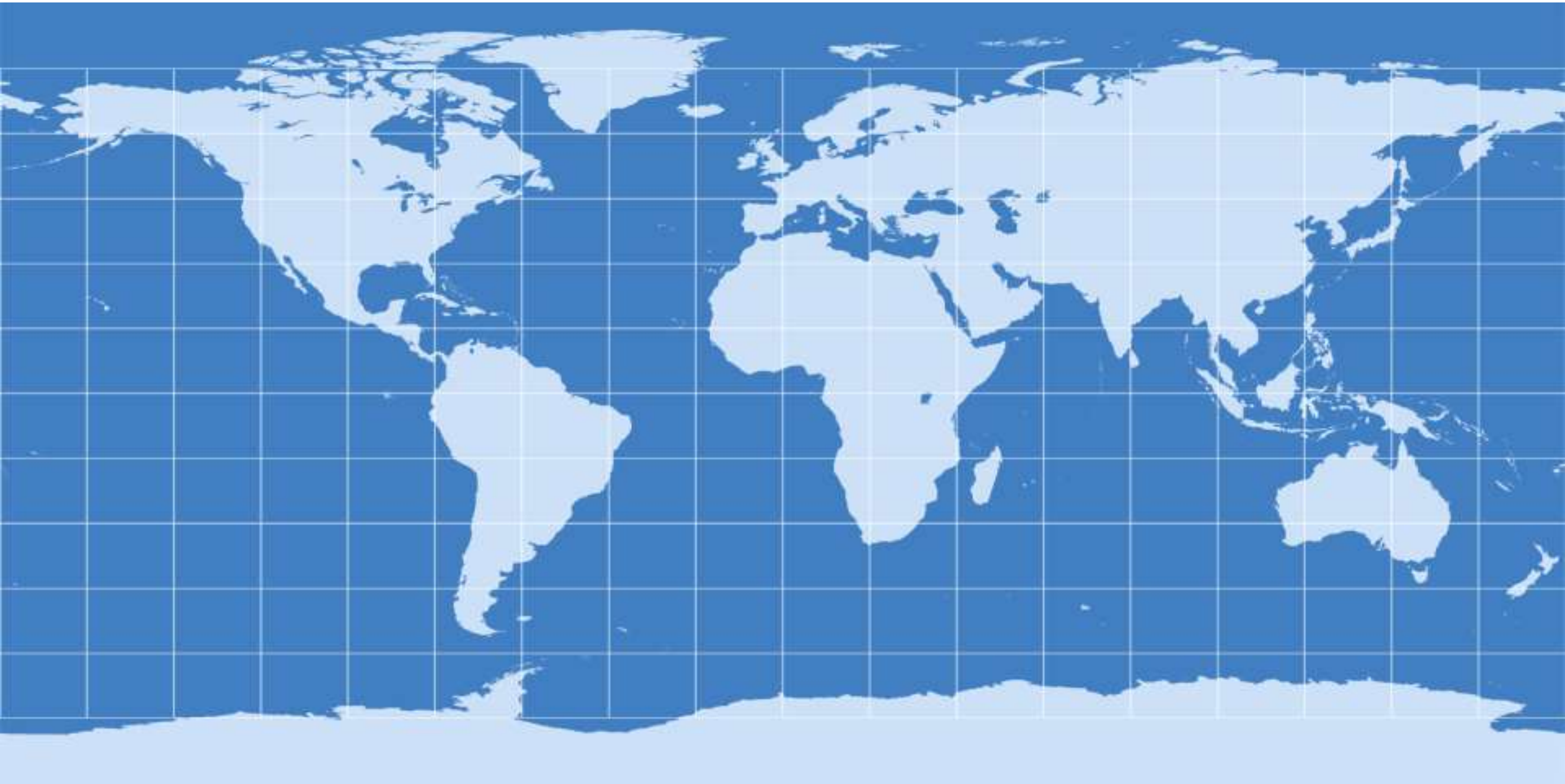
Overview of current subregions



★ collaborators

Afanasiev et al., *Geophys. J. Int.*, 2016.

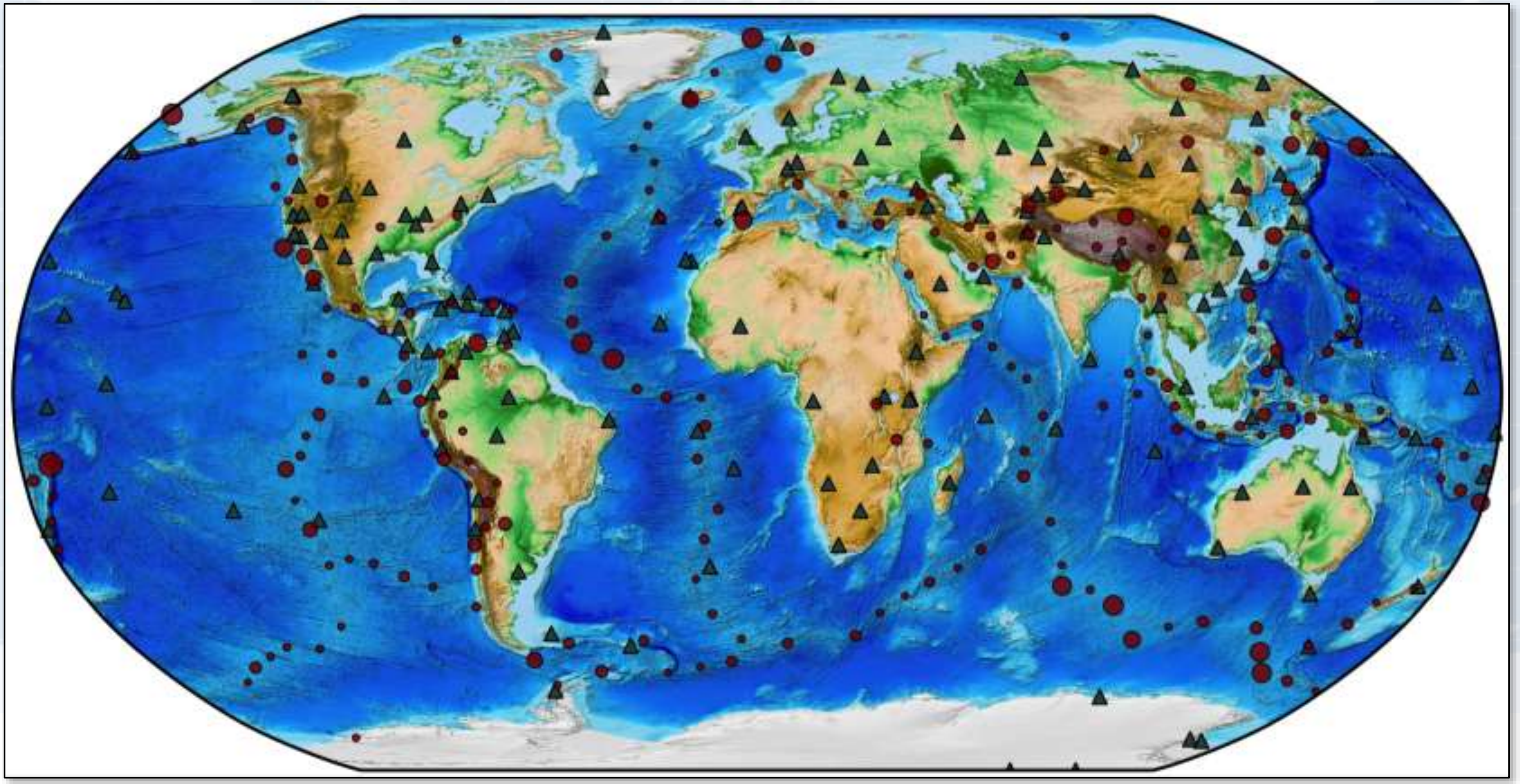
The global subregion



Afanasiev et al., *Geophys. J. Int.*, 2016.

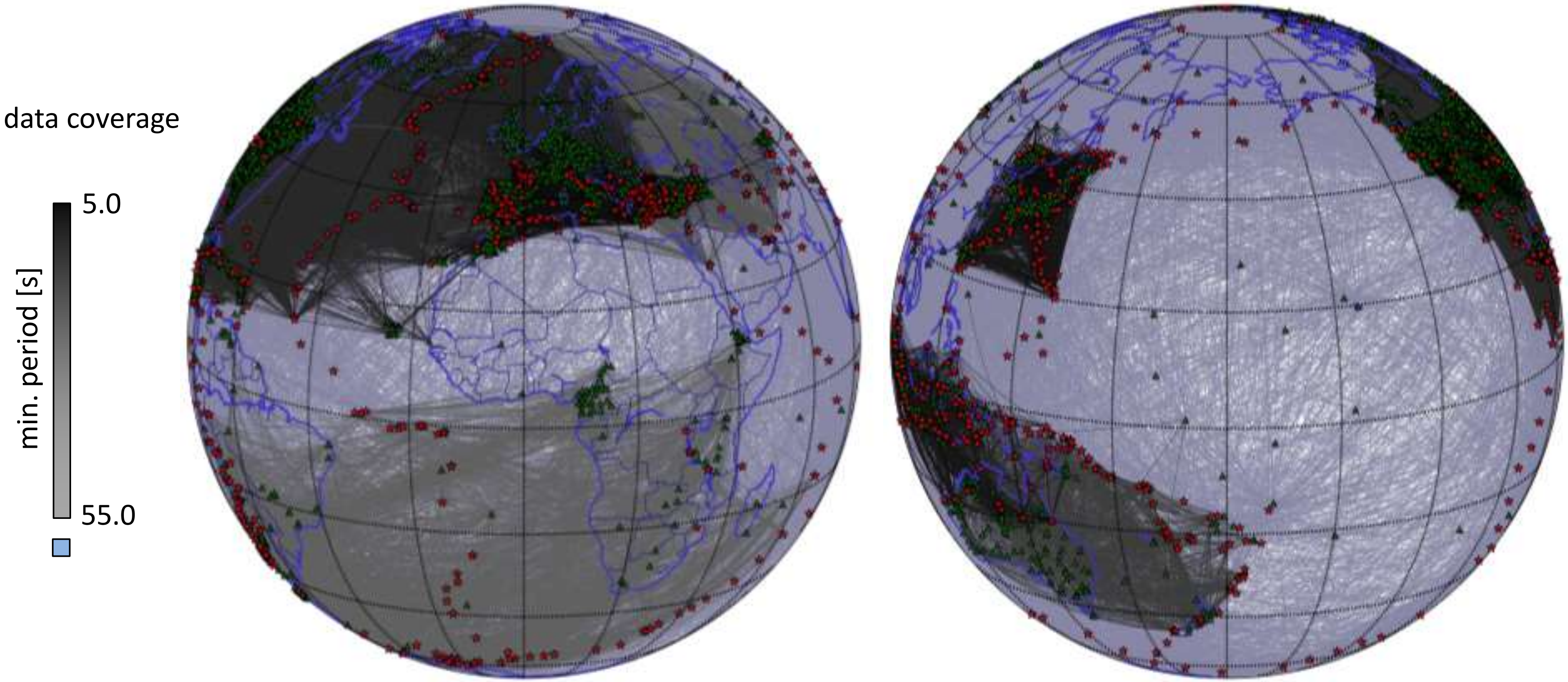
The global subregion

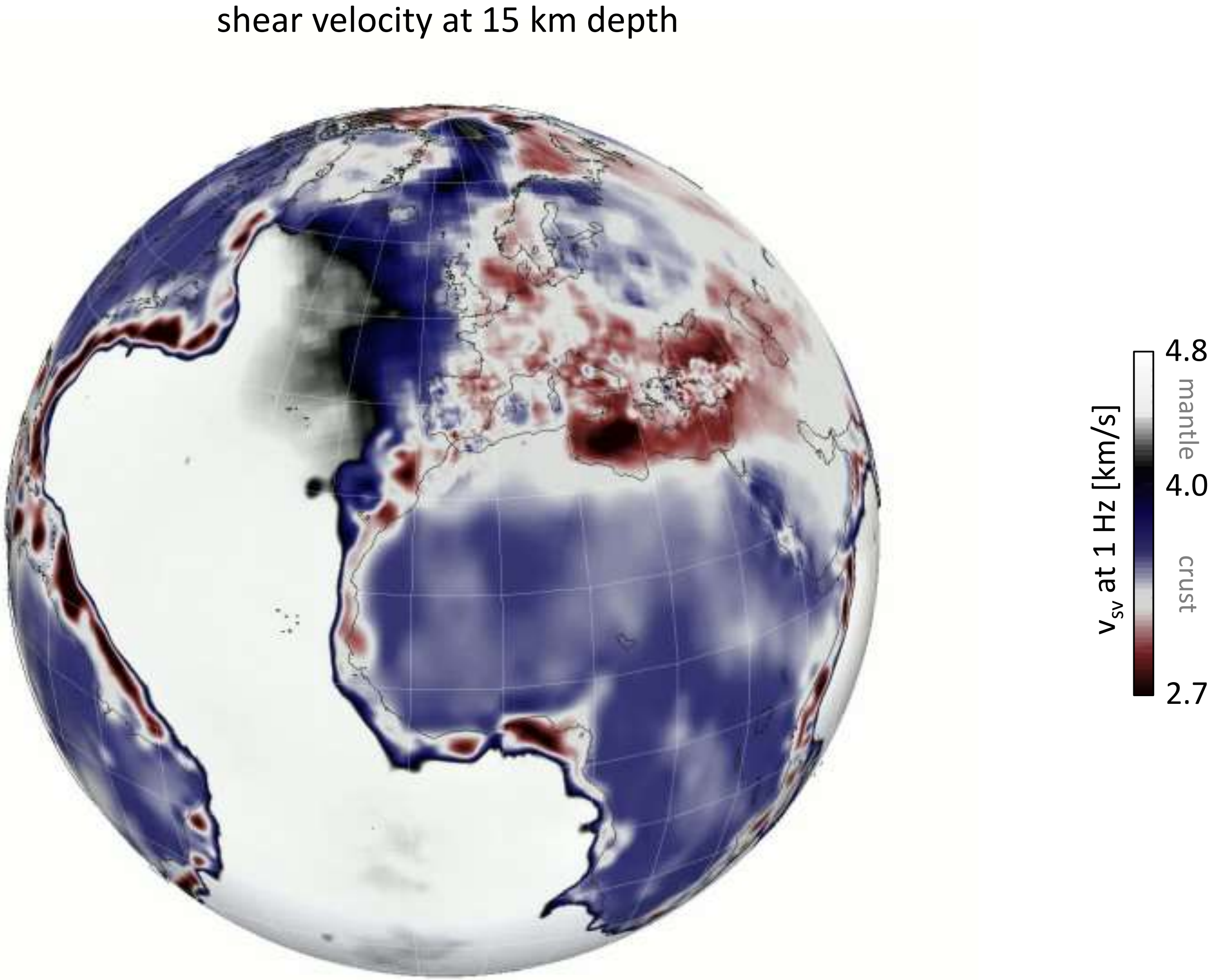
- Ensure consistency of regional updates with global dataset.



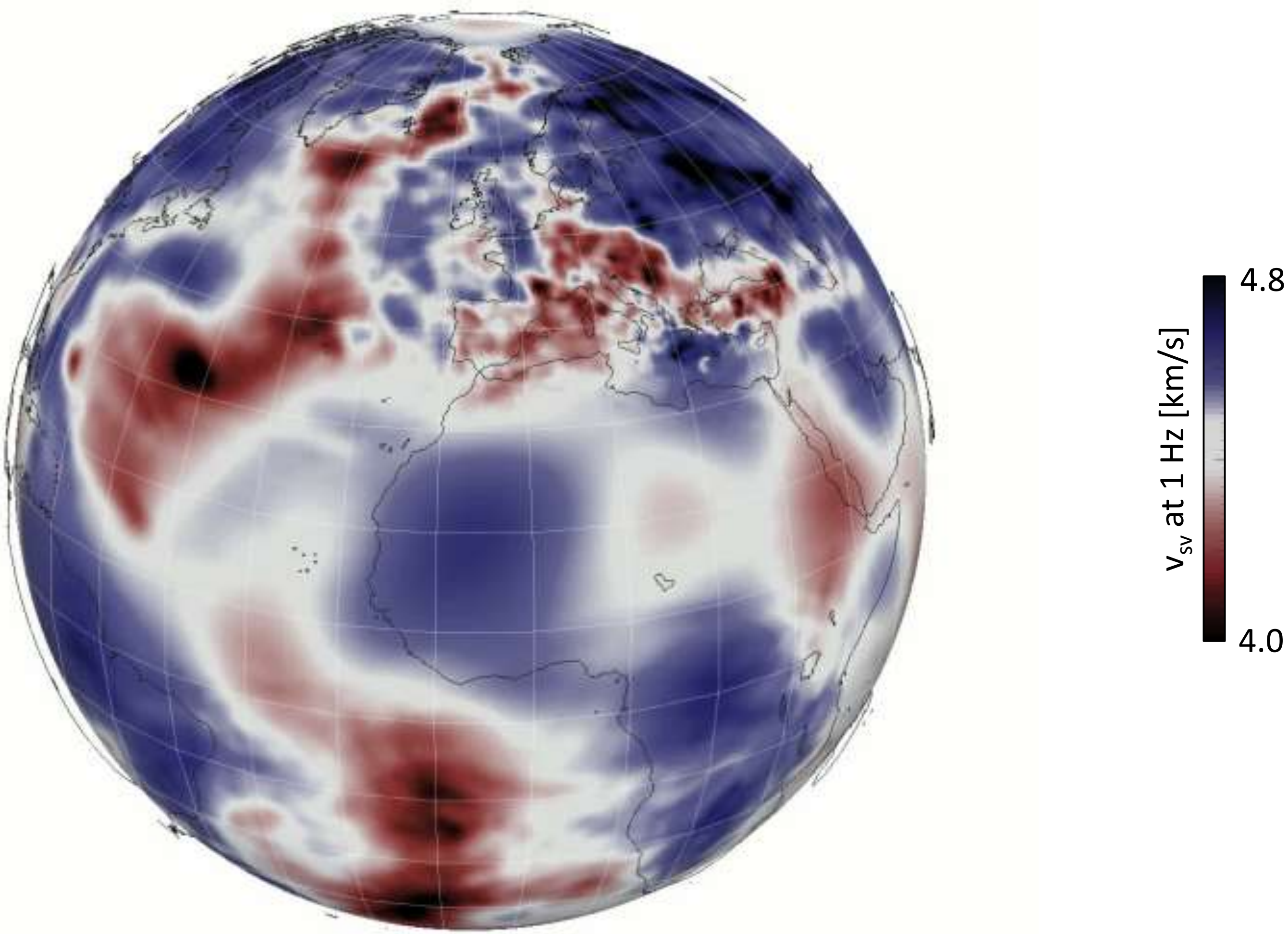
Afanasiev et al., *Geophys. J. Int.*, 2016.

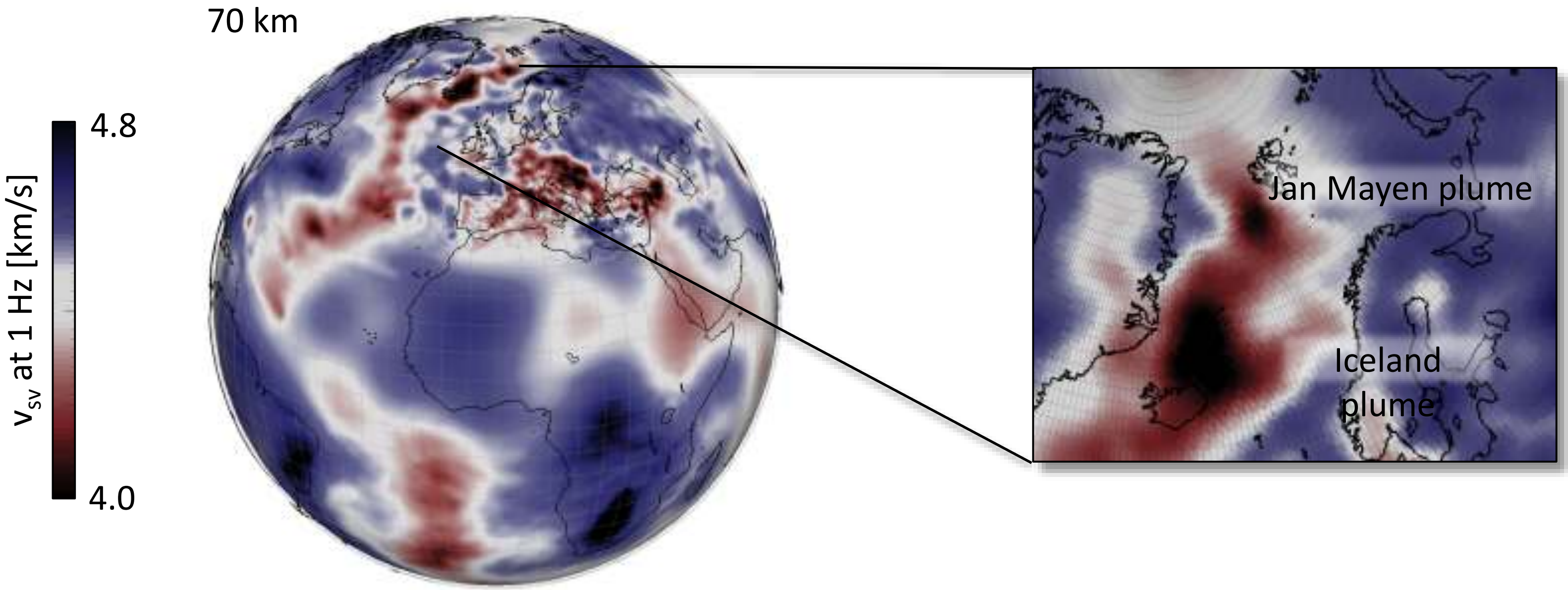
CURRENT DATA COVERAGE




shear velocity at 15 km depth
4.8
mantle
4.0
crust
2.7
v_{sv} at 1 Hz [km/s]

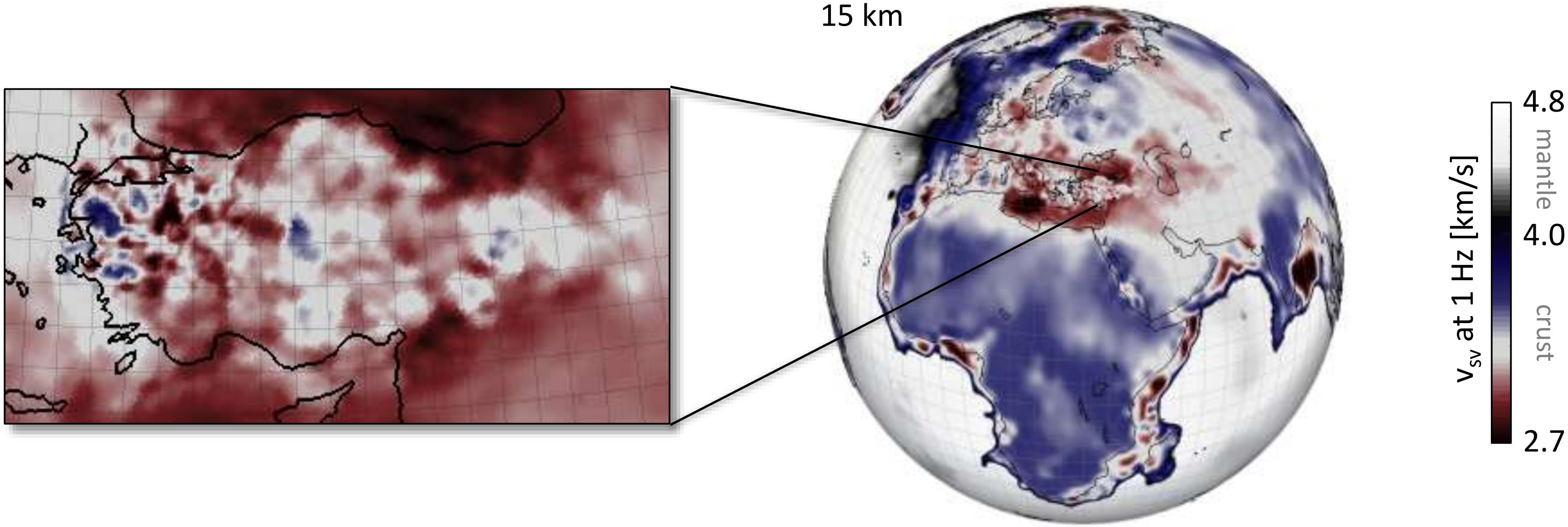
shear velocity at 100 km depth





Understanding the Earth's dynamics and evolution

- Hot convective upwellings from 100's – 1000's km depth.
- Key to understand: volcanism, heat budget and evolution of the Earth.

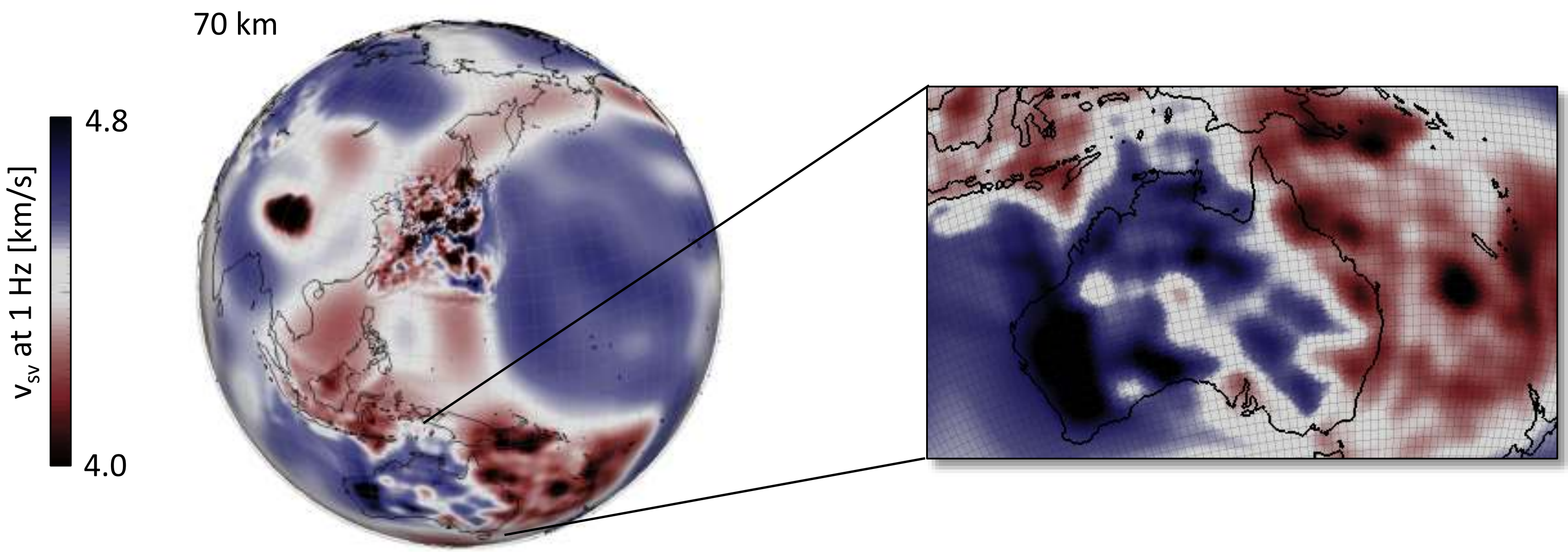


Towards earthquake ground motion prediction

- Anticipate ground motion caused by a given earthquake.
- ➢ Inform engineers, building codes, ...

Near-real-time earthquake characterisation

- Better Earth model → better information on earthquake properties.
- Key to improve tsunami early warning systems.
- Joint project with *Australian National University* and *Geoscience Australia*.



FWI: Range of optimal applicability

- High-quality data. [You trust all the wiggles that you exploit.]
- Strongly heterogeneous medium. [Δv around 10 % or more, ocean-continent boundary]

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- Discovery of smaller and stronger heterogeneities.
- Interpretation requires incorporation of compositional effects [anomalies too big for being purely thermal].
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- Powerful random probing techniques make uncertainties accessible.
- Quantitative resolution analysis. **Go beyond the chequerboard!**

Discussion & Conclusions

Big challenges [not necessarily limited to FWI]:

- Computer power will remain insufficient for a long time [good, if you like using your brain].
- Data flood requires man power that an individual group does not have.
- Individualism and insufficient use of prior knowledge.
- Remaining problem: Change the community's mode of operation.

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- Vision of a community-driven, evolutionary, global multi-scale model.
- Continued and consistent refinements on all scales.
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Thanks for your attention!