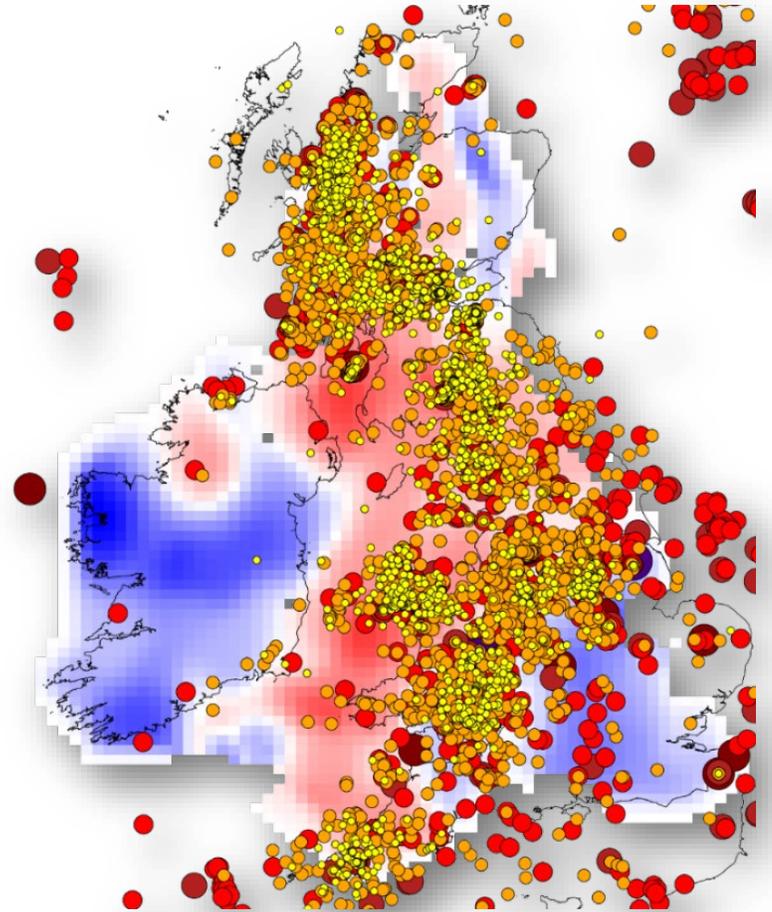


Seismic tomography, lithospheric strength and the spatial distribution of intraplate earthquakes

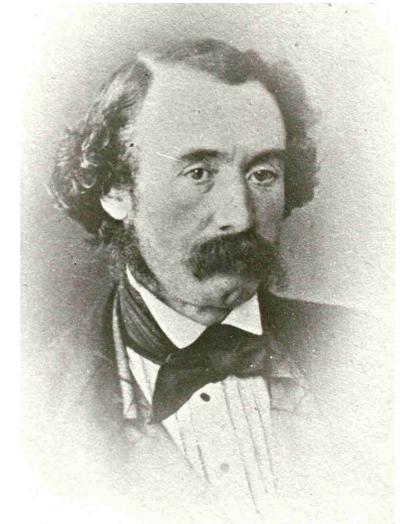
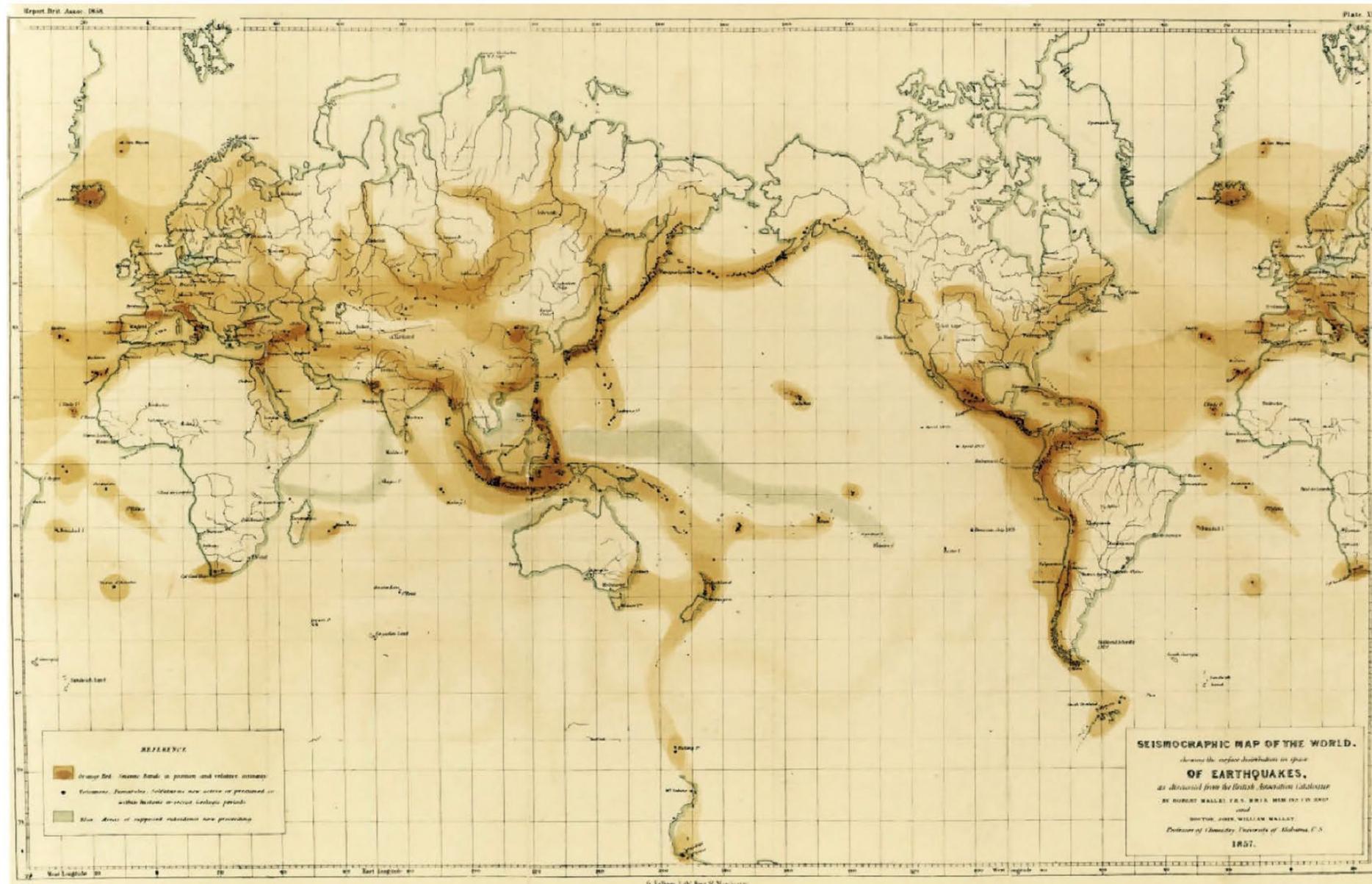
Sergei Lebedev¹, Raffaele Bonadio¹,
Tom Devenish Arzuza¹, Javier Fullea²

¹ University of Cambridge, UK

² Universidad Complutense de Madrid, Spain



Seismographic Map of the World (*Mallet & Mallet 1857*)

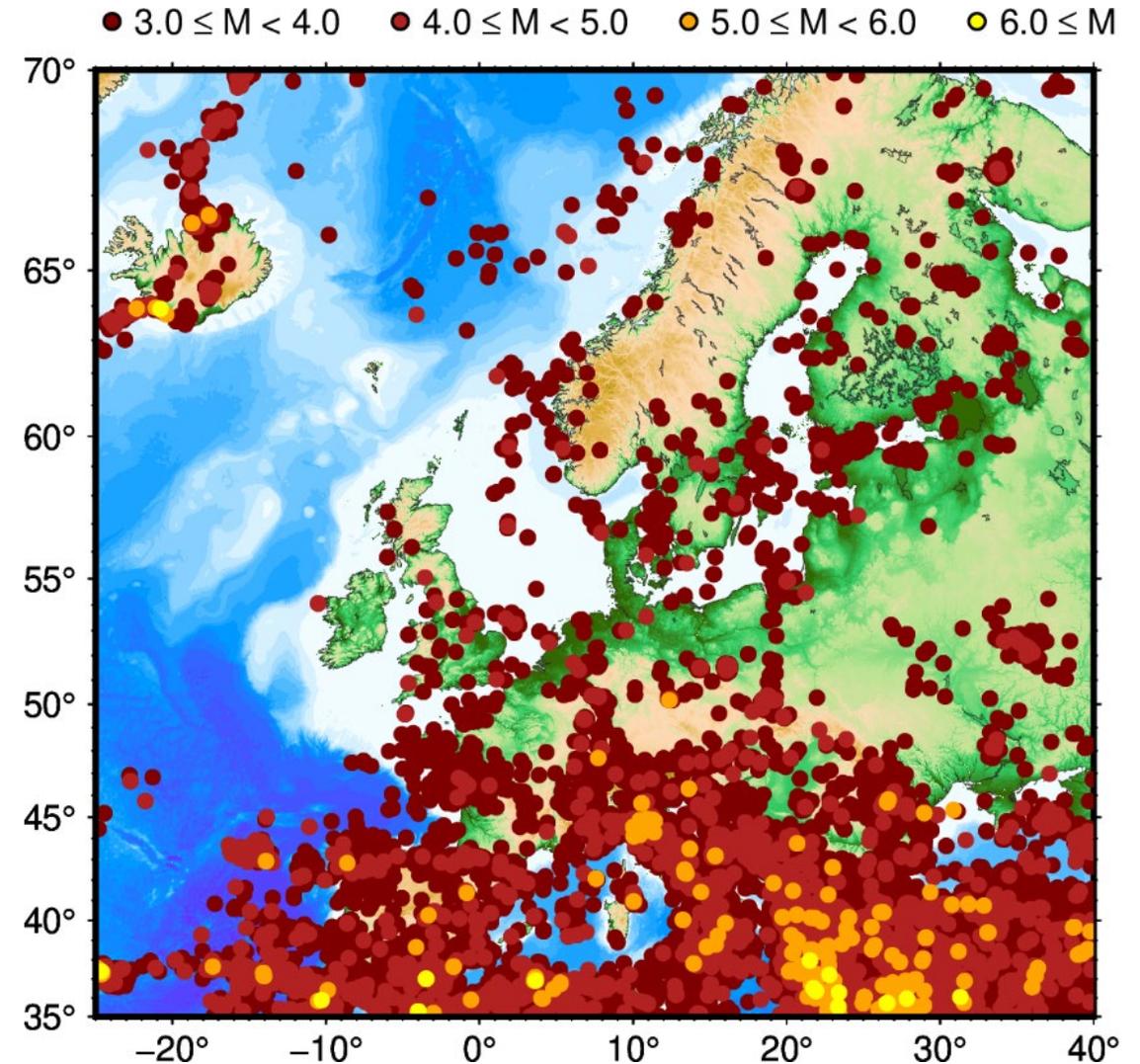


Robert Mallet

Pre-instrumental,
based on felt
reports of
earthquakes

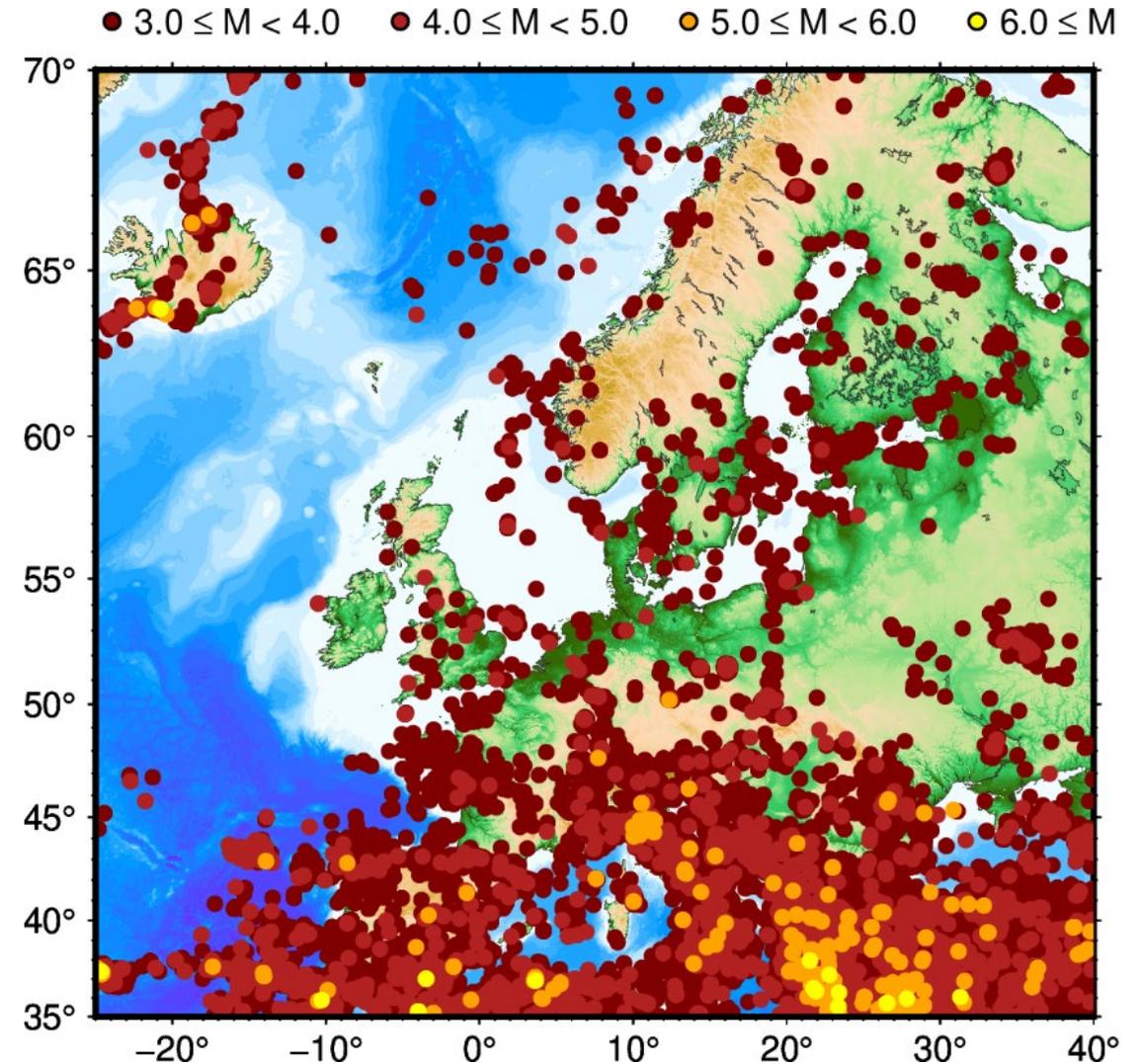
Intraplate seismicity

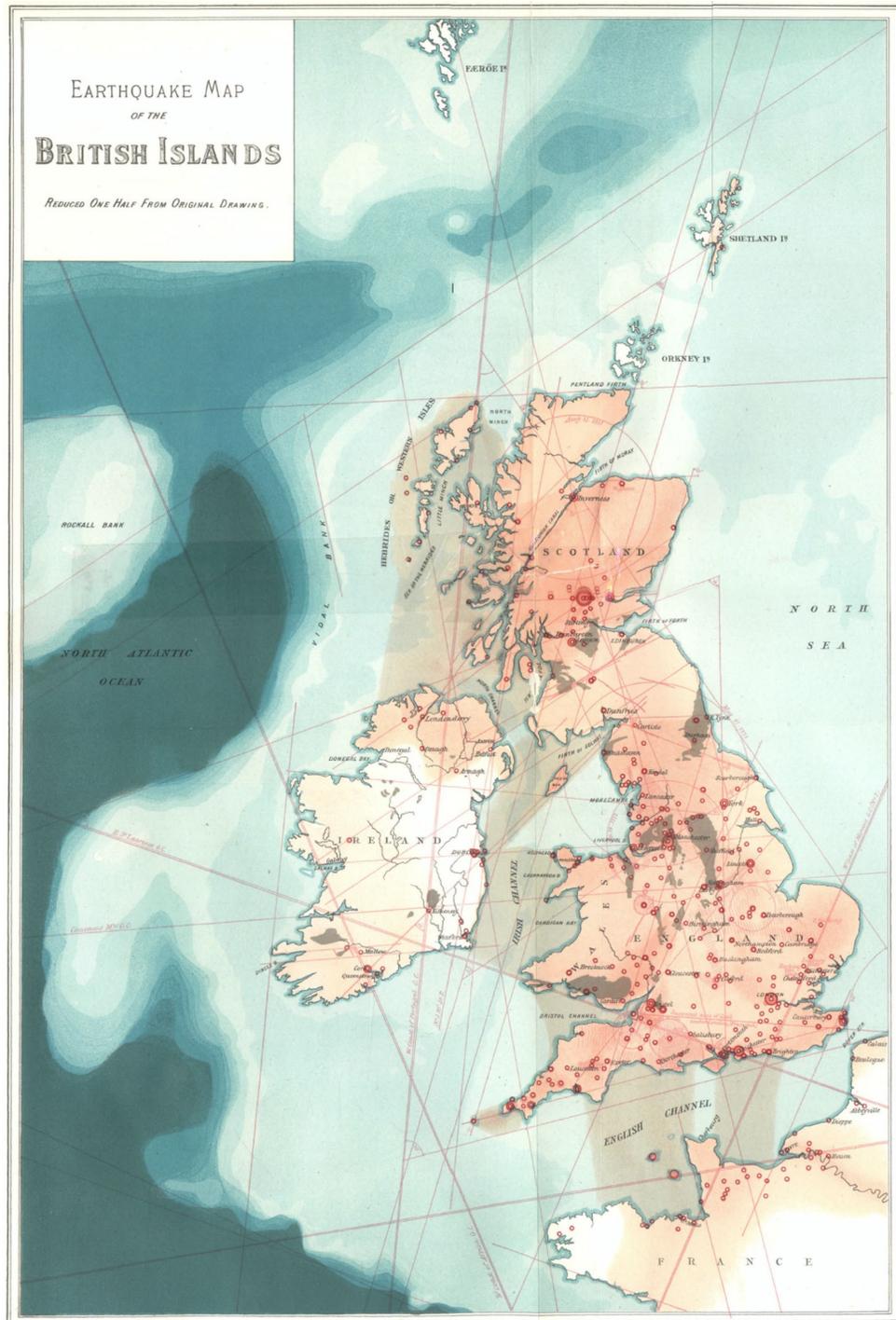
- Earthquakes in stable plate interiors
- Low but increasingly important, given the growing population density and infrastructure development
- **Distribution:** uneven, enigmatic
- Large earthquakes are rare but do happen
 - **New Madrid Seismic Zone**
three M7-8 earthquakes in 1811-1812
 - **2001 Gujarat earthquake**
M7.6, ~20,000 killed



Britain and Ireland

- Typical slowly deforming intraplate region, with strangely uneven earthquake distribution
- Away from plate boundaries (Pyrenees to the south, Alps to the SE, Mid-Atlantic Ridge to the NW)
- Dominant stress pattern – NW-SE compression
- Earthquake catalogues spanning many hundreds of years (yet, frustratingly incomplete)



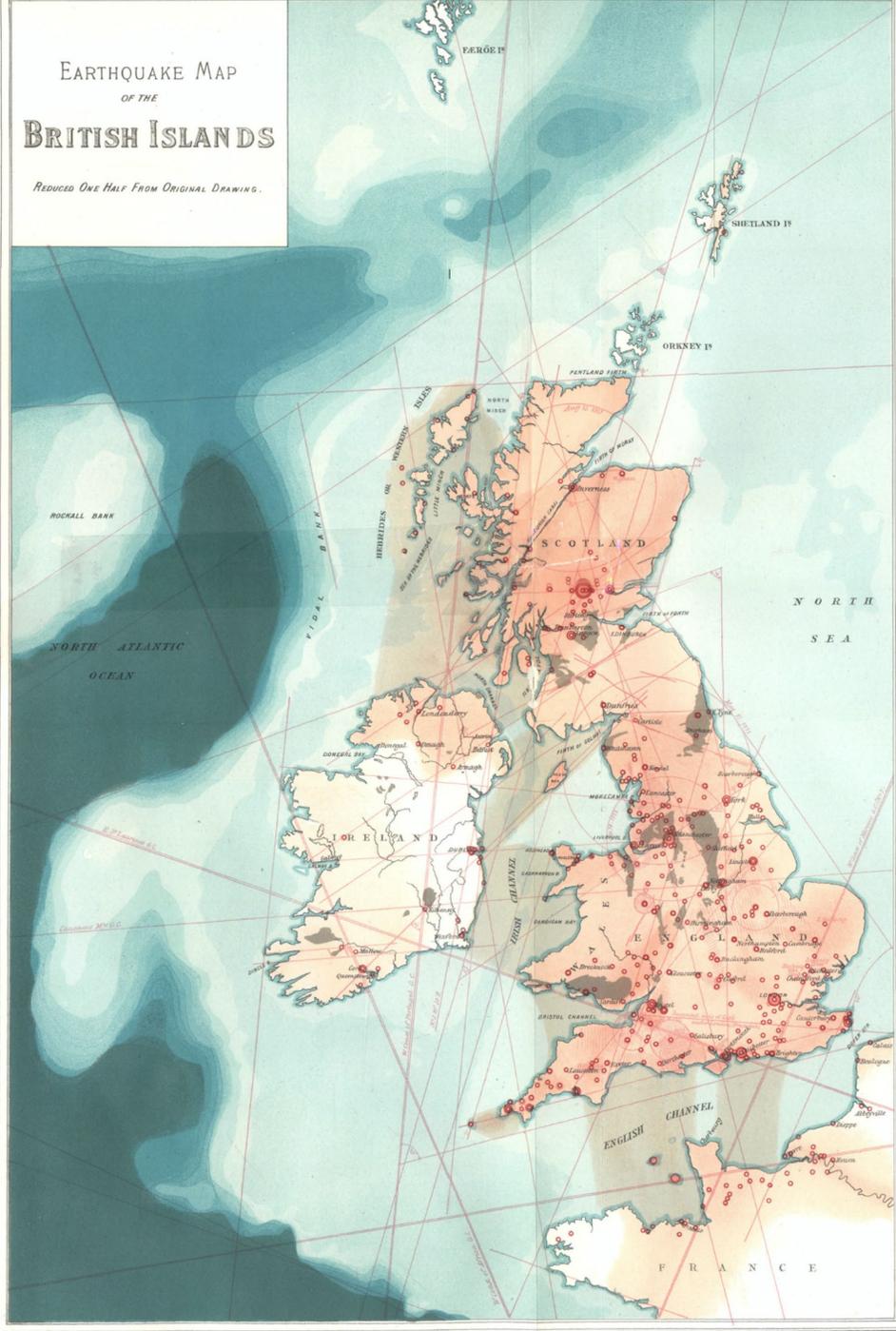


Joseph P. O'Reilly, 1884

Catalogue of the Earthquakes Having Occurred in Great Britain and Ireland during Historical Times; Arranged Relatively to Localities and Frequency of Occurrence, to Serve as a Basis for an Earthquake Map of the Three Kingdoms

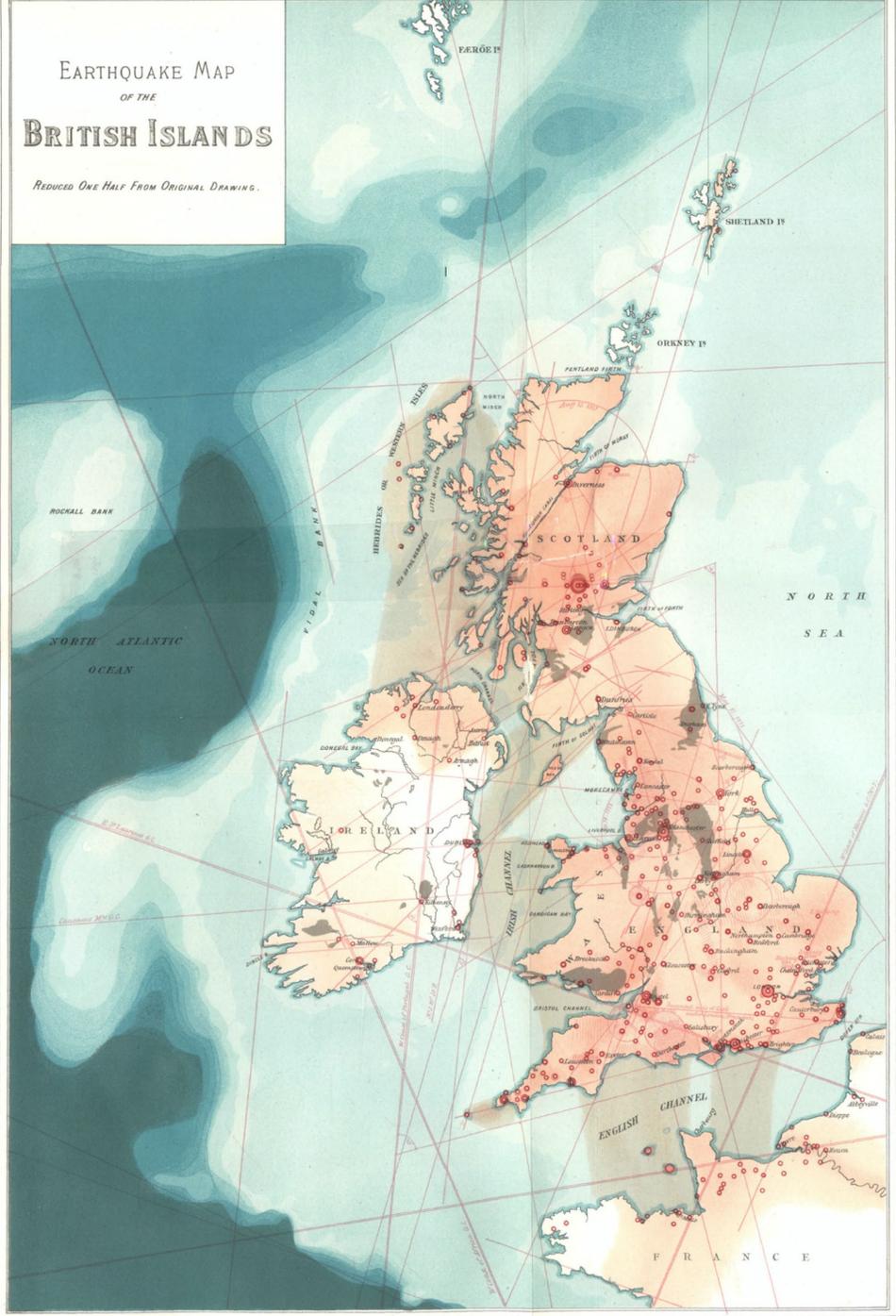
The Transactions of the Royal Irish Academy

- Historical earthquakes, 1426–1880
- The first map of seismicity of Britain and Ireland
- The first seismic hazard map



O'Reilly (1884):

An examination of the map shows at once that, so far as record indicates during historical time, Great Britain has been by far more subject to earthquake action than Ireland; and from this may be inferred the existence of barriers capable of preventing the extension of earthquake action from Great Britain to Ireland, as also the absence, beneath the surface of Ireland, of active foci capable of producing earthquakes in the present geological order of things.

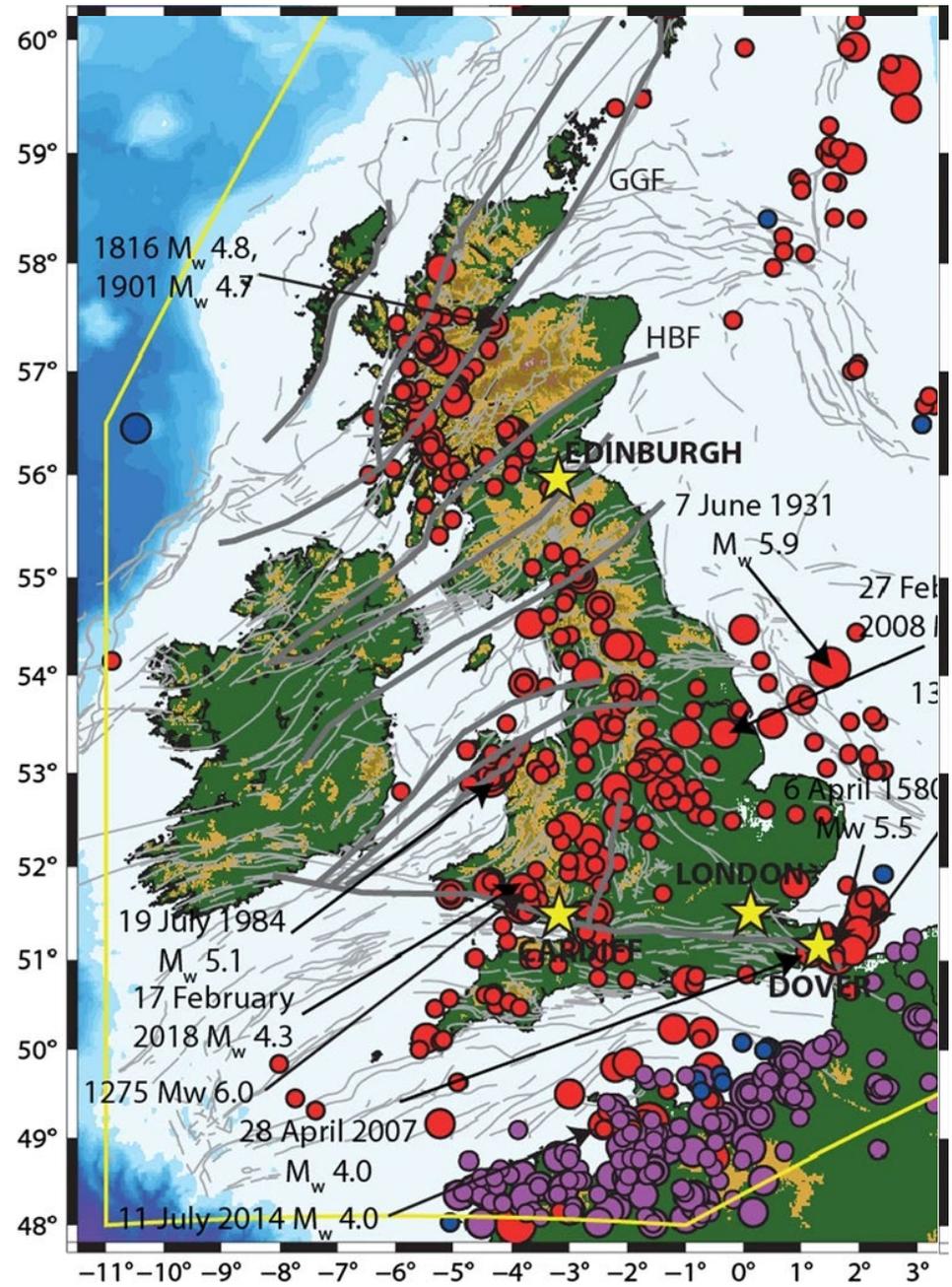


O'Reilly (1884):

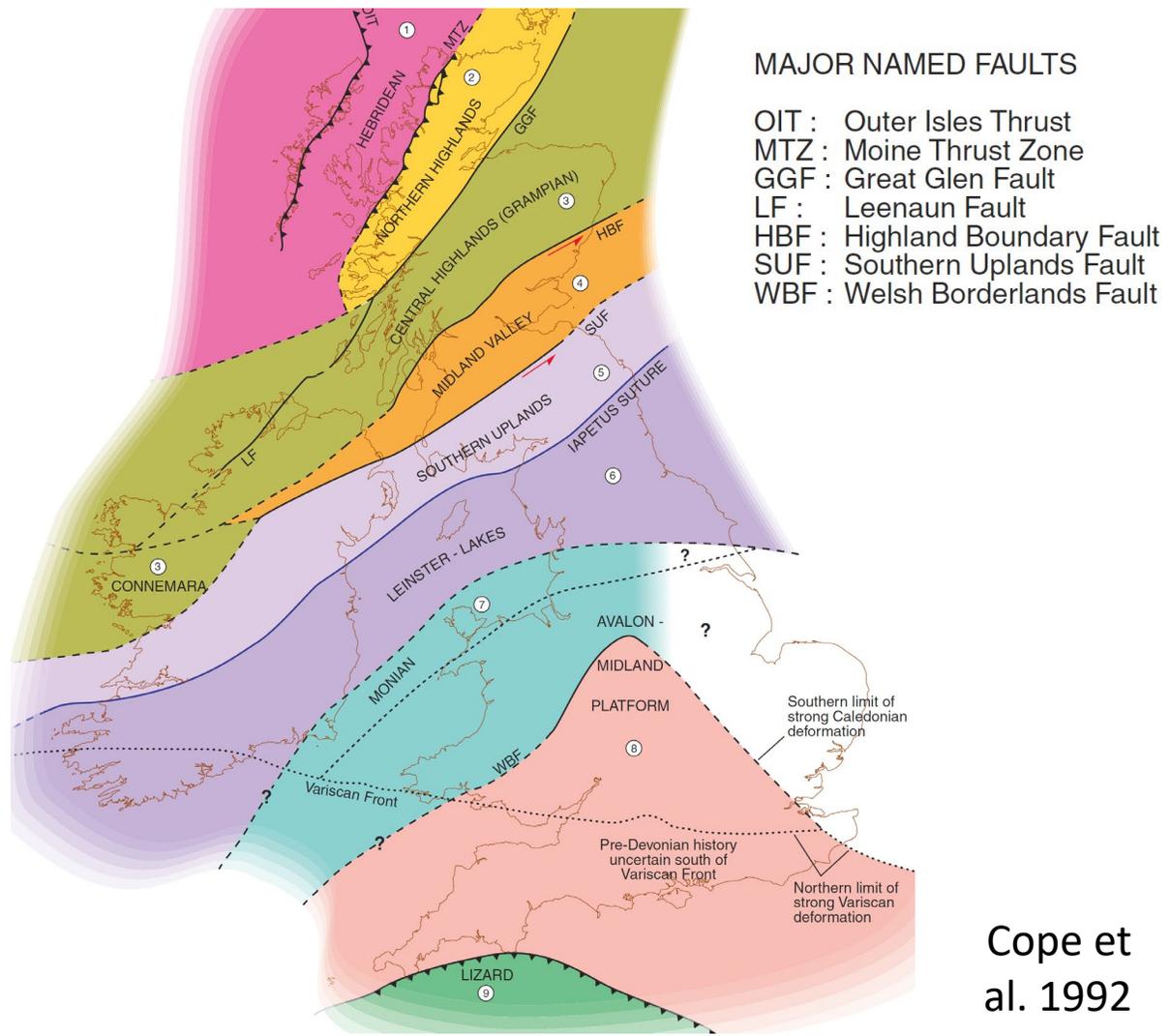
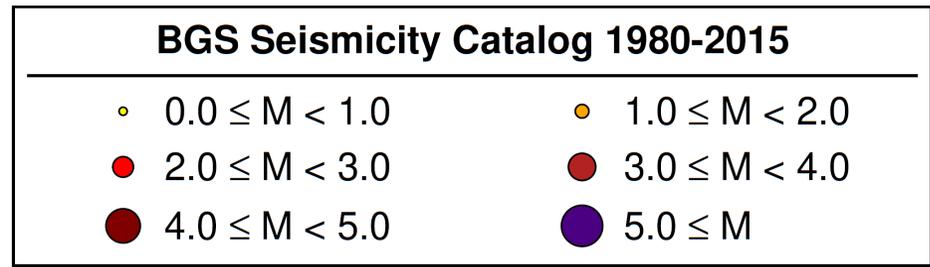
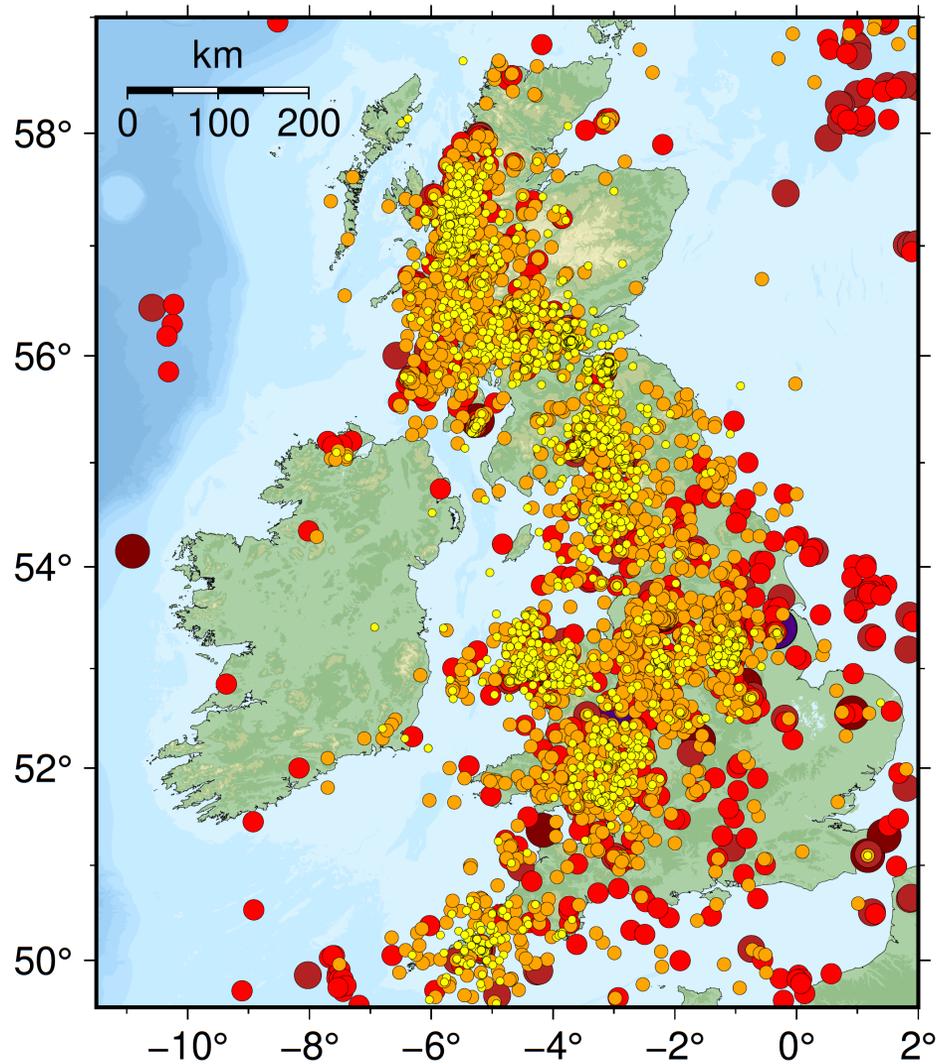
An examination of the map shows at once that, so far as record indicates during historical time, Great Britain has been by far more subject to earthquake action than Ireland; and from this may be inferred the existence of barriers capable of preventing the extension of earthquake action from Great Britain to Ireland, as also the absence, beneath the surface of Ireland, of active foci capable of producing earthquakes in the present geological order of things.

Two hypotheses. In modern terms:

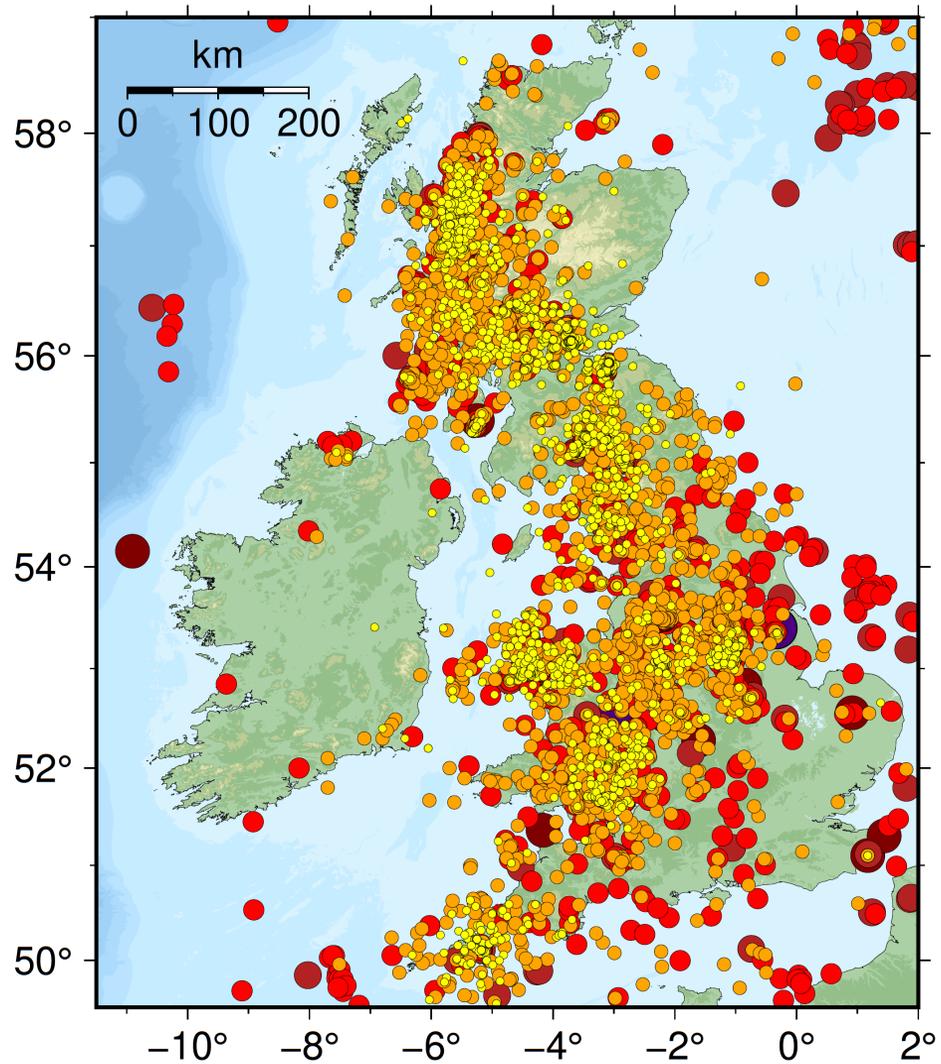
- Faults between Britain and Ireland that decouple their deformation
- Seismogenic faults are present beneath Britain but not beneath Ireland



Mosca et al., 2022



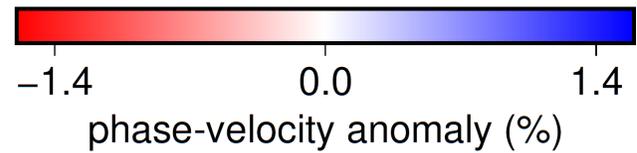
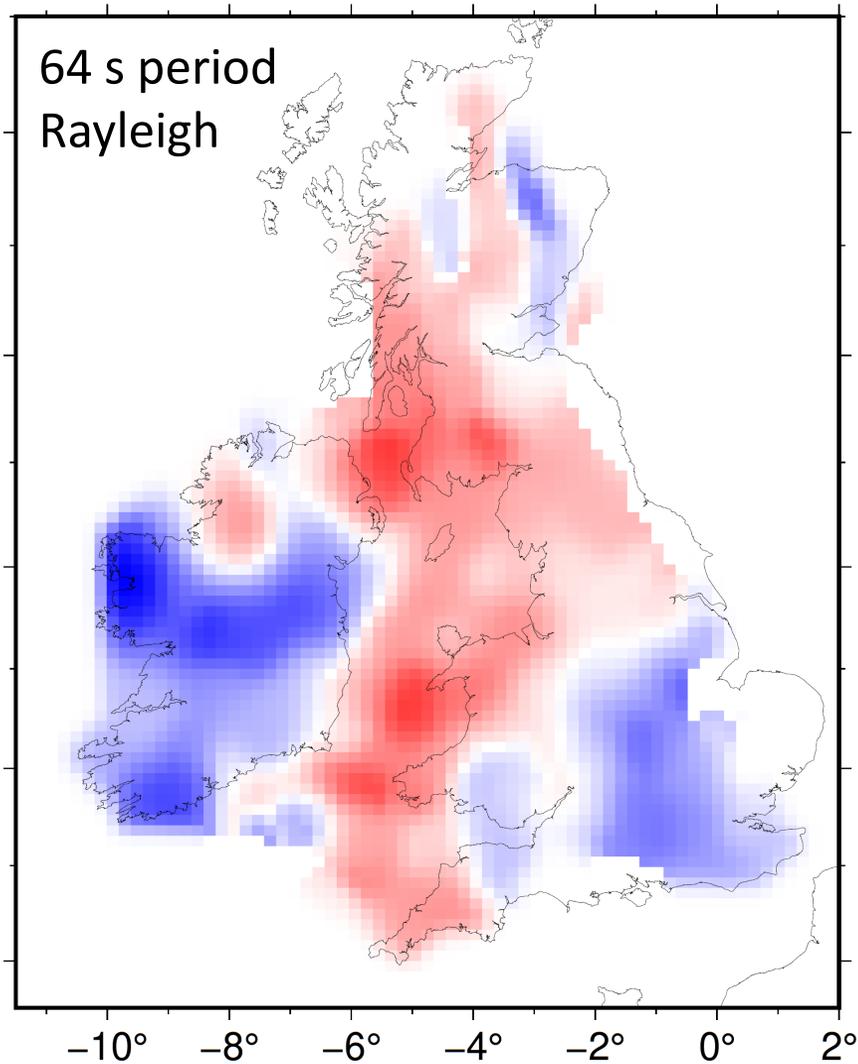
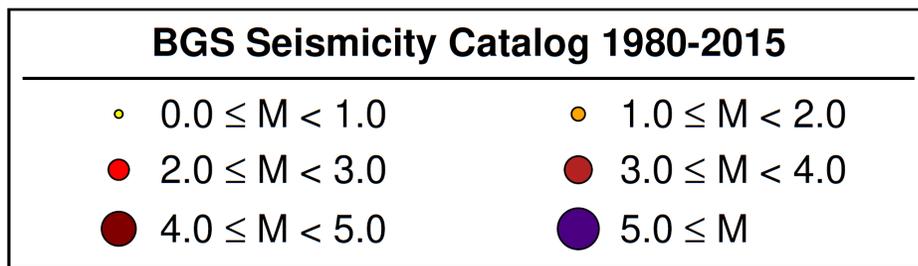
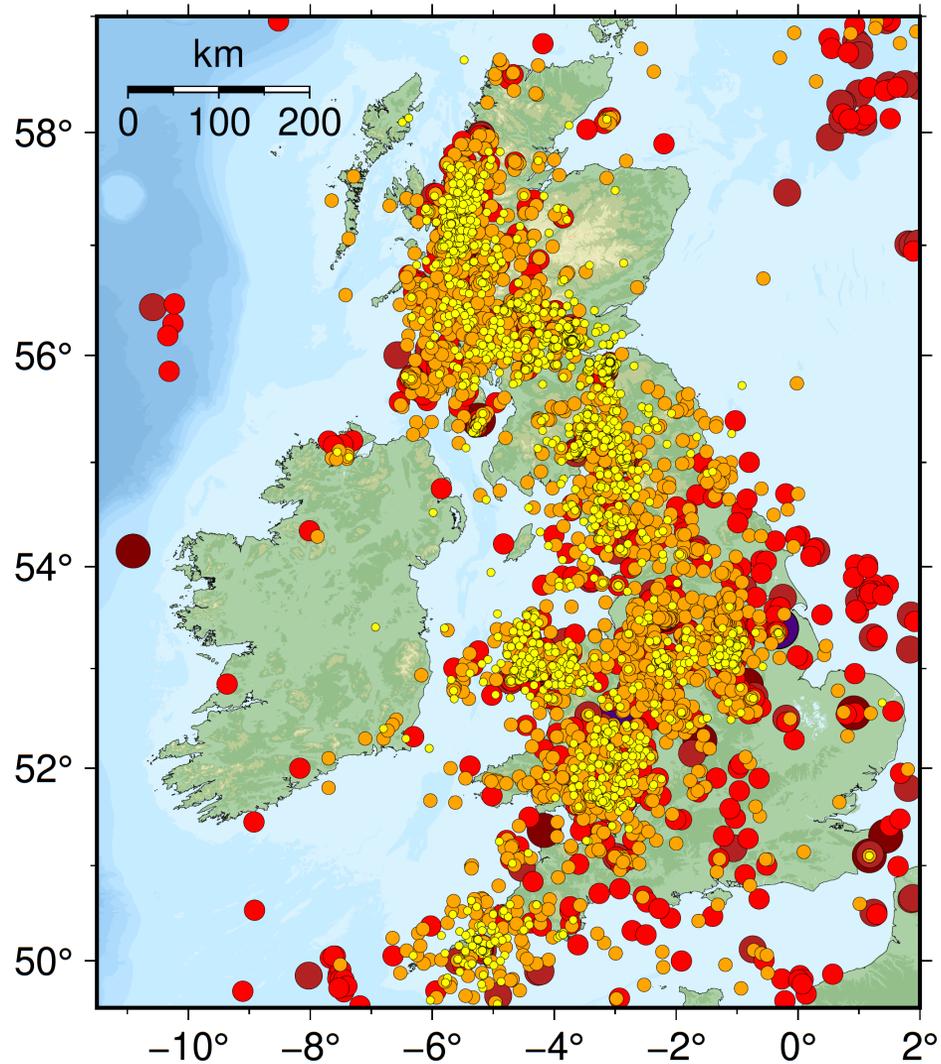
Tectonic units of Britain and Ireland



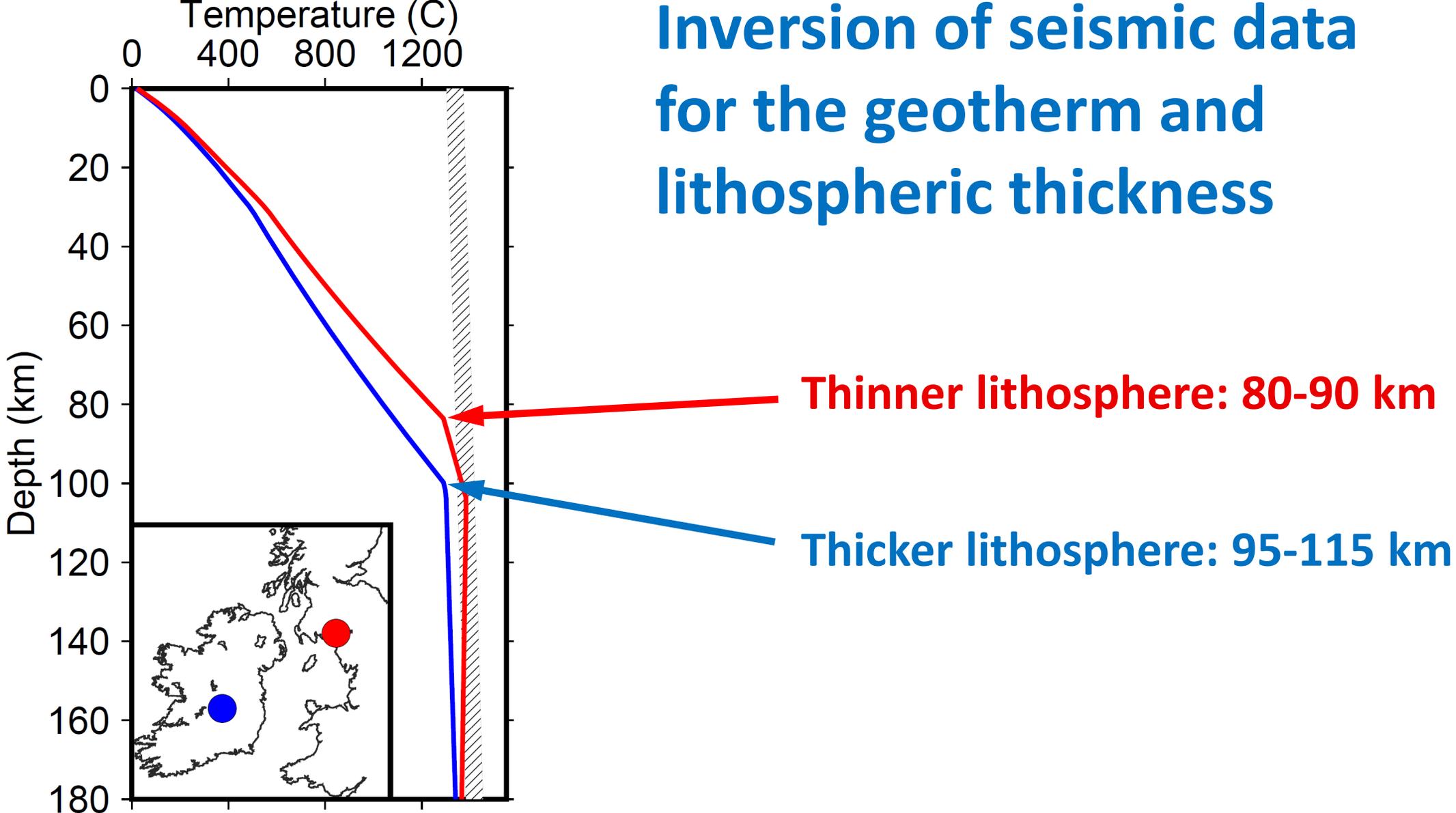
- *“The quest for an understanding of how the distribution of seismicity in the UK relates to geological structure has been a long and unfruitful one” – Musson, 2007*

BGS Seismicity Catalog 1980-2015





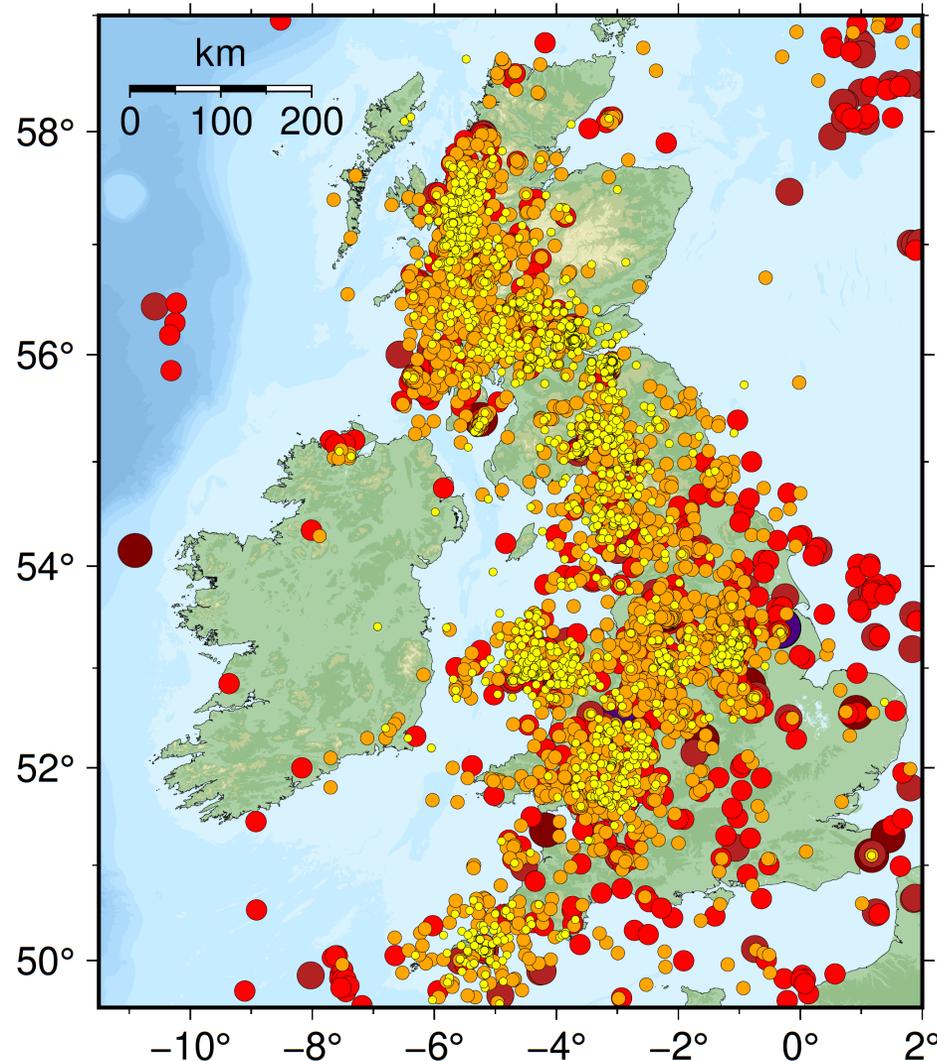
Inversion of seismic data for the geotherm and lithospheric thickness



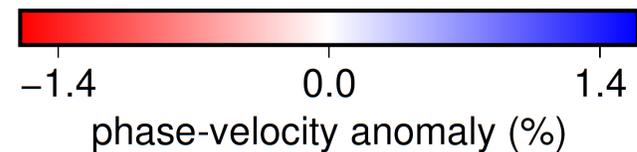
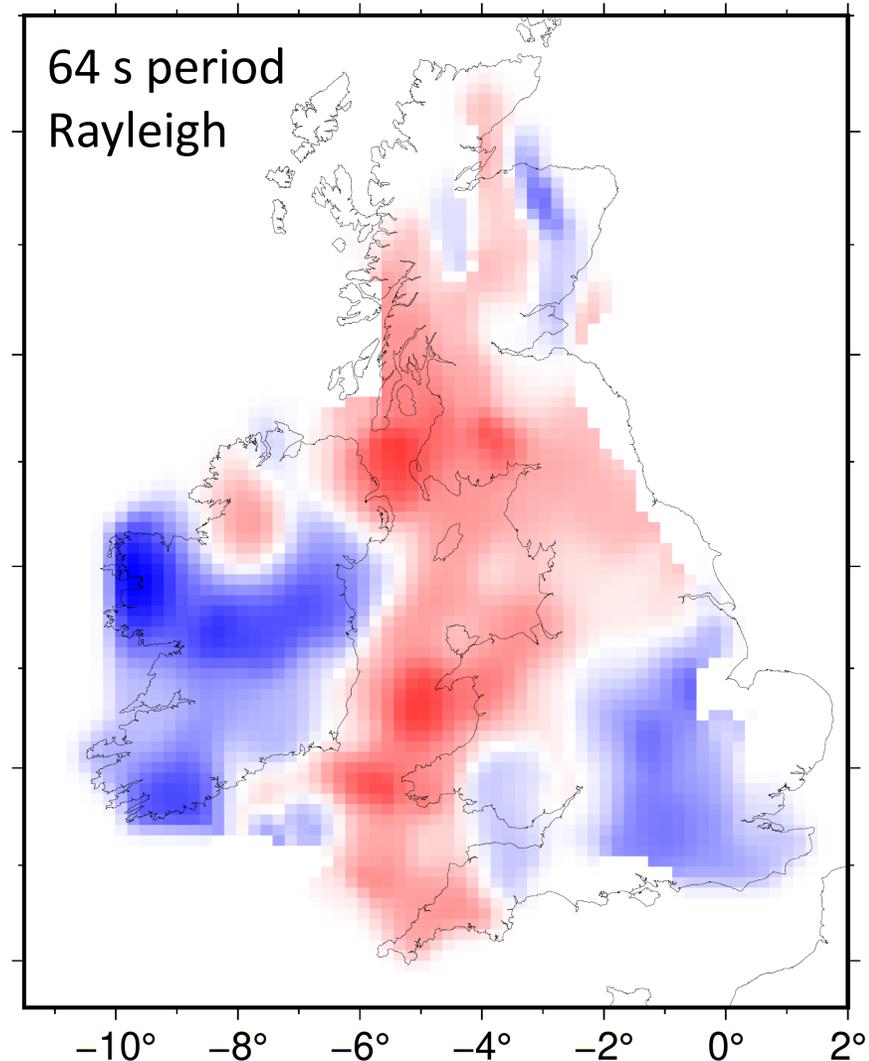
- Earthquake distribution is controlled not by crustal but by whole-plate structure

- Thickness, temperature, mechanical strength of the lithosphere

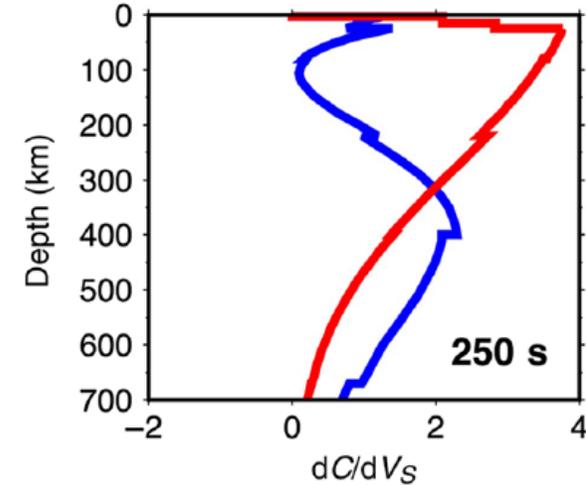
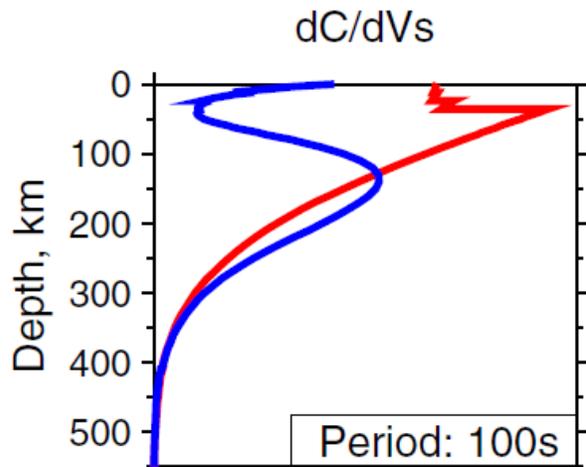
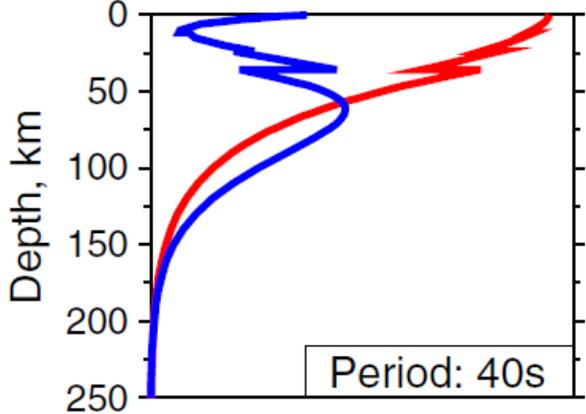
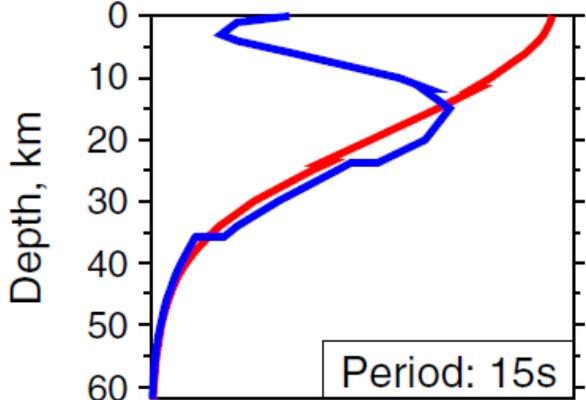
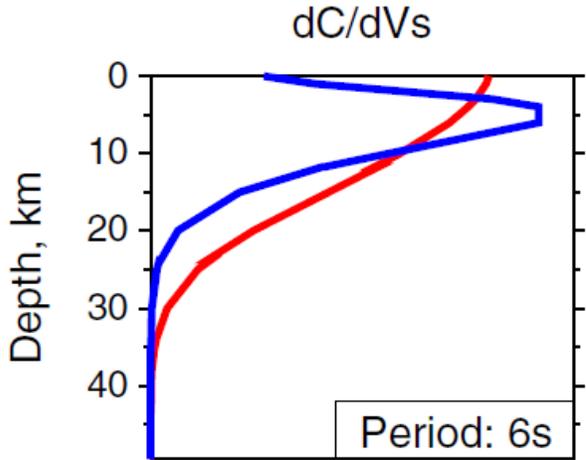
- How can we determine them?



| BGS Seismicity Catalog 1980-2015 | |
|----------------------------------|----------------------|
| • $0.0 \leq M < 1.0$ | • $1.0 \leq M < 2.0$ |
| • $2.0 \leq M < 3.0$ | • $3.0 \leq M < 4.0$ |
| • $4.0 \leq M < 5.0$ | • $5.0 \leq M$ |

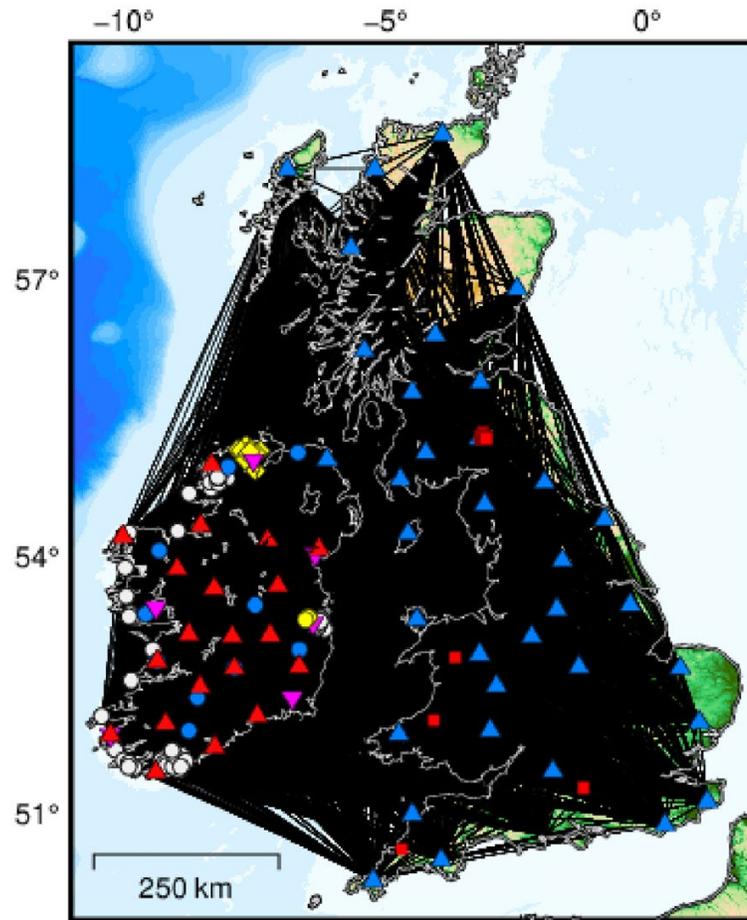


Depth sensitivity of surface waves

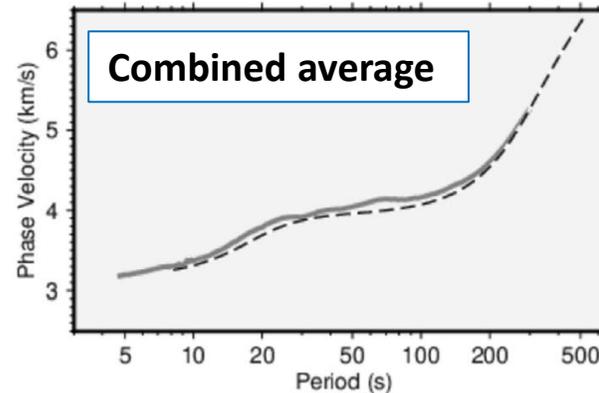
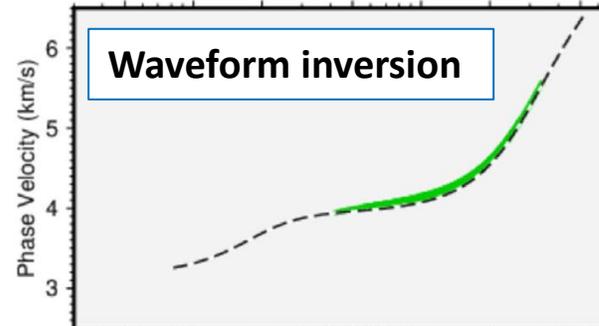
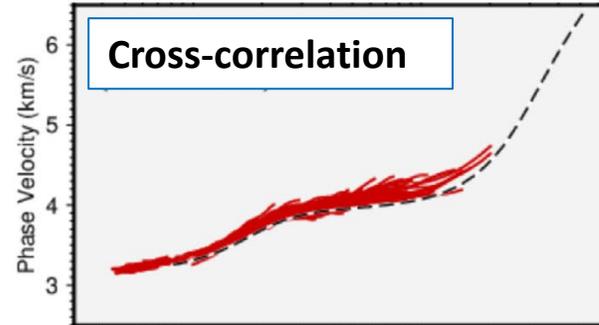


— : Rayleigh — : Love

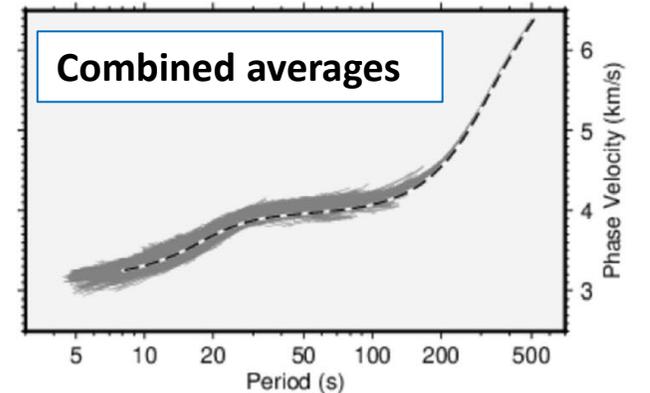
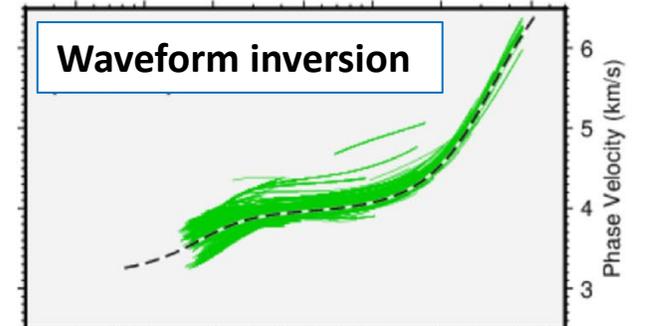
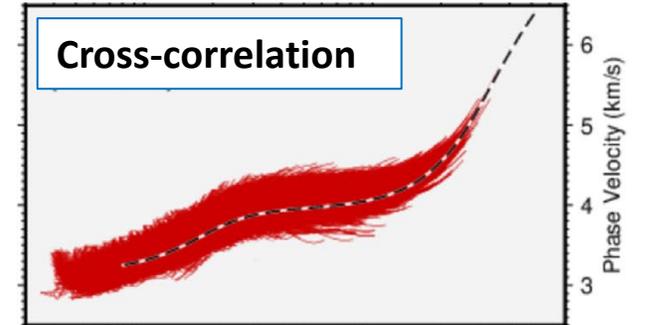
Broadband, interstation measurements of Rayleigh and Love phase velocities



One station pair

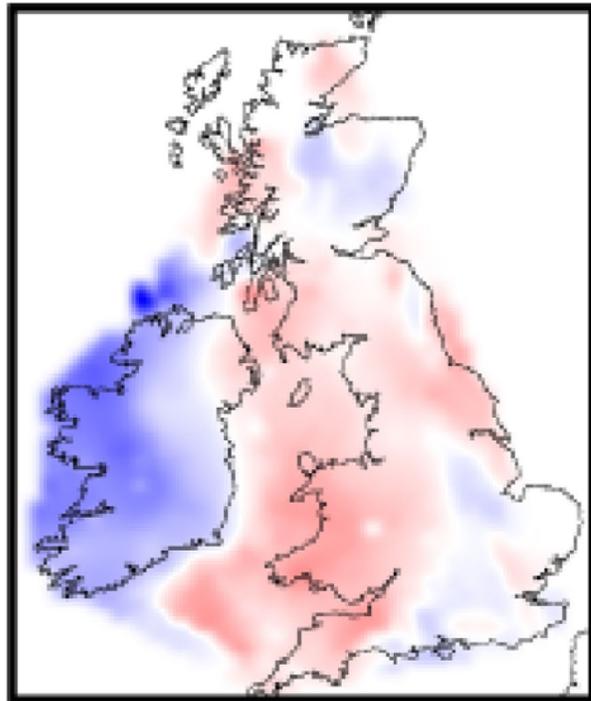


All station pairs



Surface-wave tomography

- Combine information from phase-velocity measurements by solving a large inverse problem at each period
- *Resolution*: we would like to have the most detailed map possible, but without the image being dominated by noise

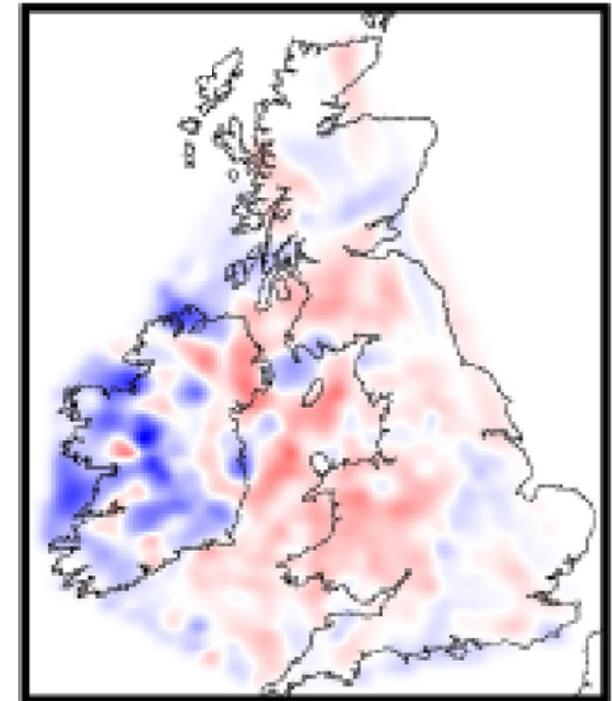


-1.9 0.0 1.9

Phase-velocity anomaly, %

resolution too low:

accurate image at its length scales, but regional detail is lost



-3 0 3

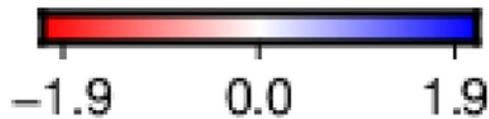
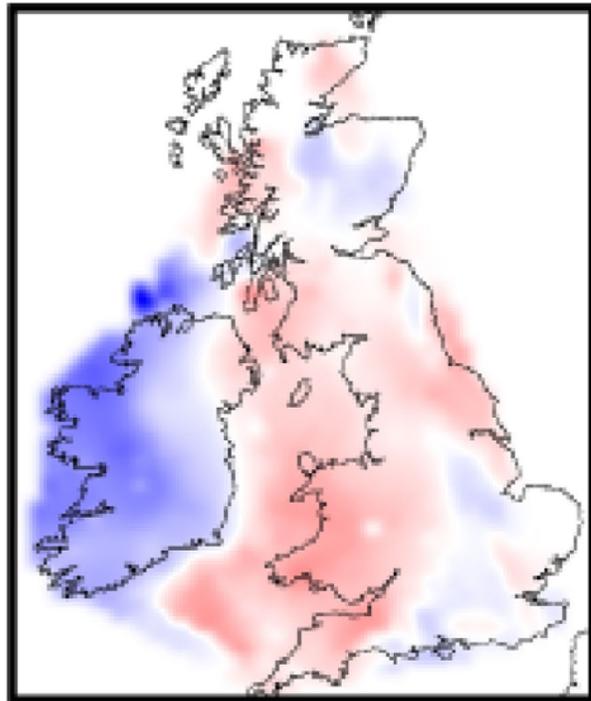
Phase-velocity anomaly, %

resolution too high:

a lot of detail, but the image is dominated by noise

40-s Rayleigh-wave maps

Bonadio et al., GJI 2021



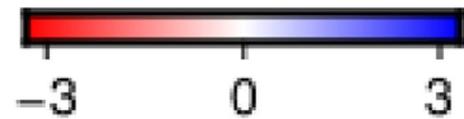
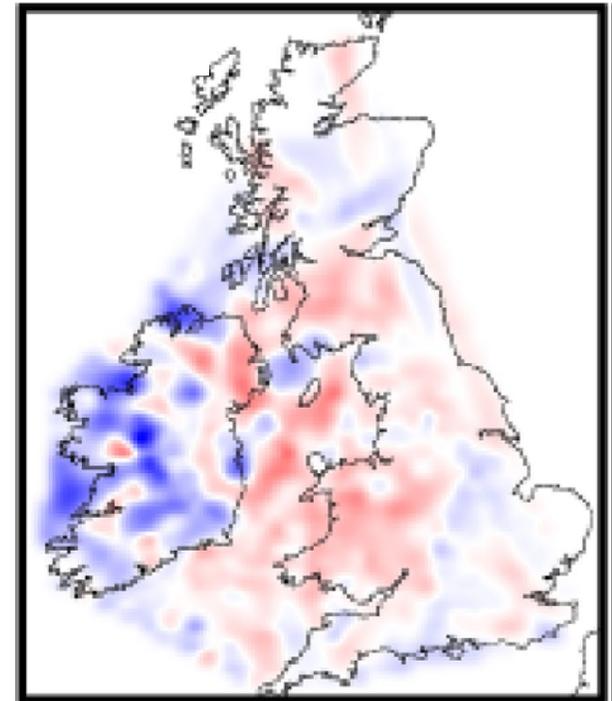
Phase-velocity anomaly, %

resolution too low:

accurate image at its length scales, but regional detail is lost

We would like
an **optimal**
resolution

40-s Rayleigh-wave maps



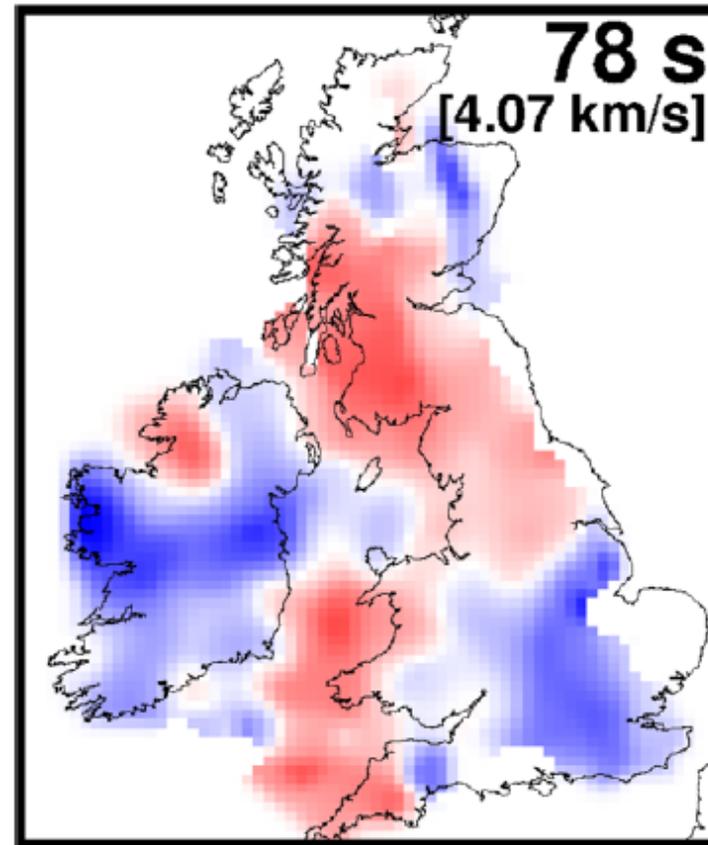
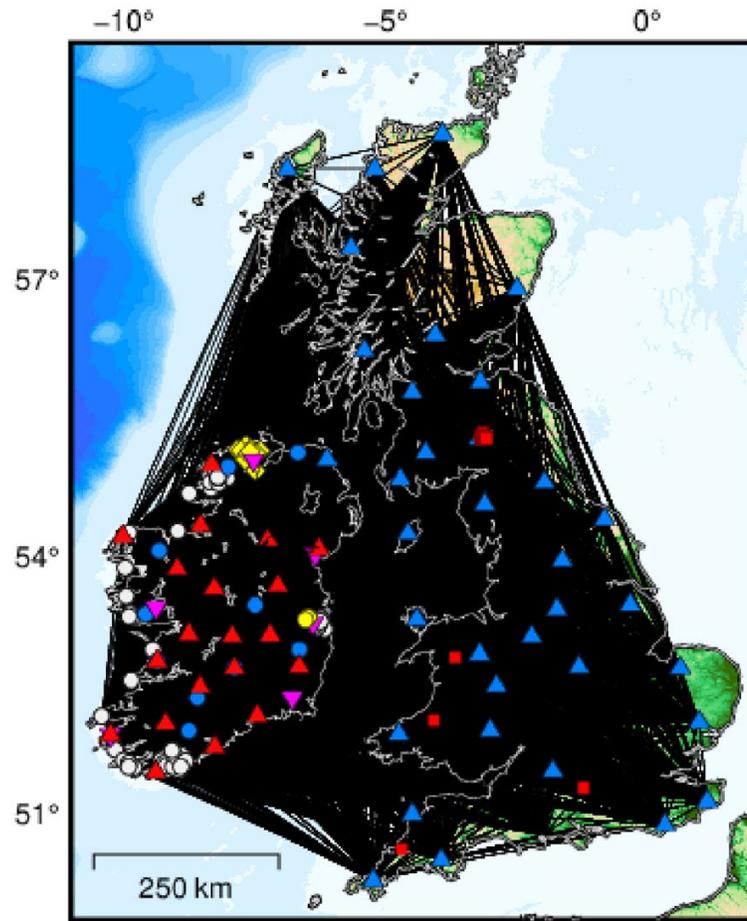
Phase-velocity anomaly, %

resolution too high:

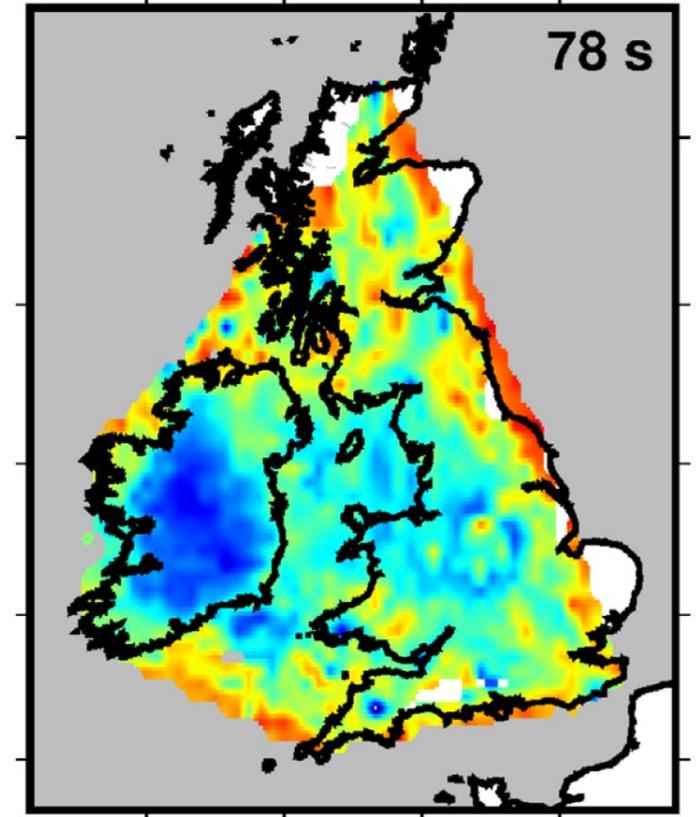
a lot of detail, but the image is dominated by noise

Bonadio et al., GJI 2021

Optimal resolution tomography (solving the Backus-Gilbert problem with empirical model-error estimates)



-1.3 0.0 1.3
Phase-velocity anomaly (%)

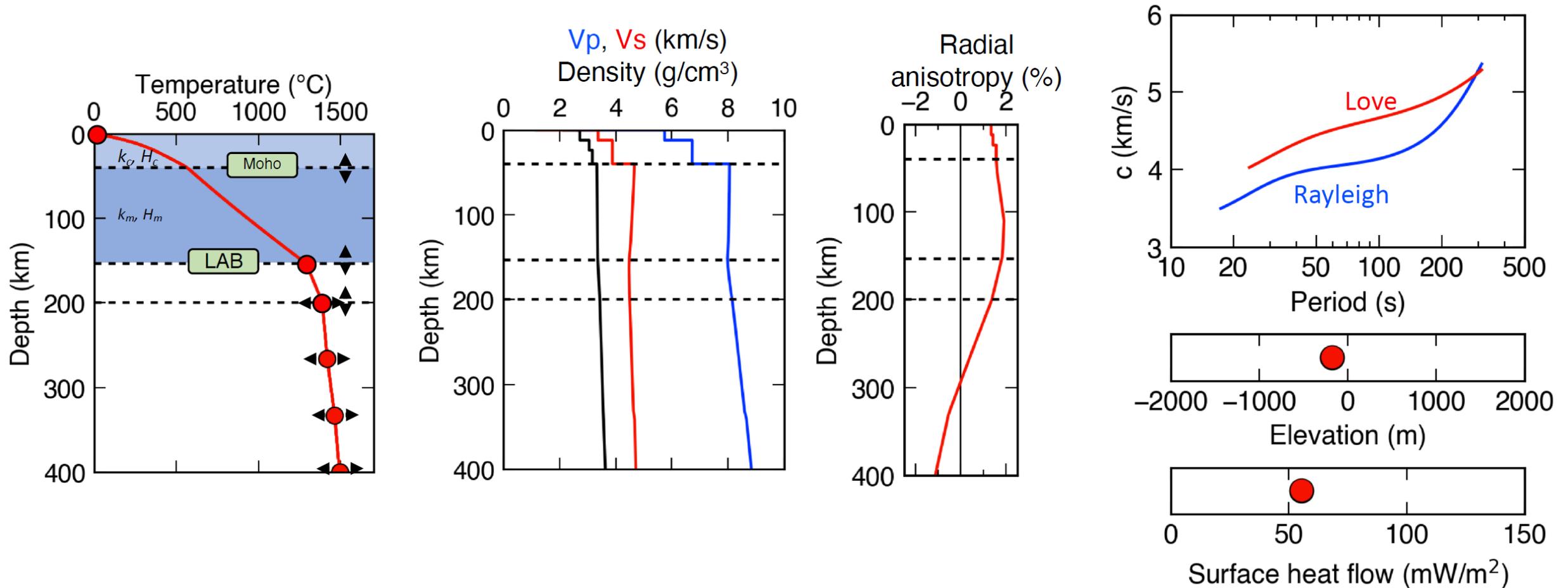


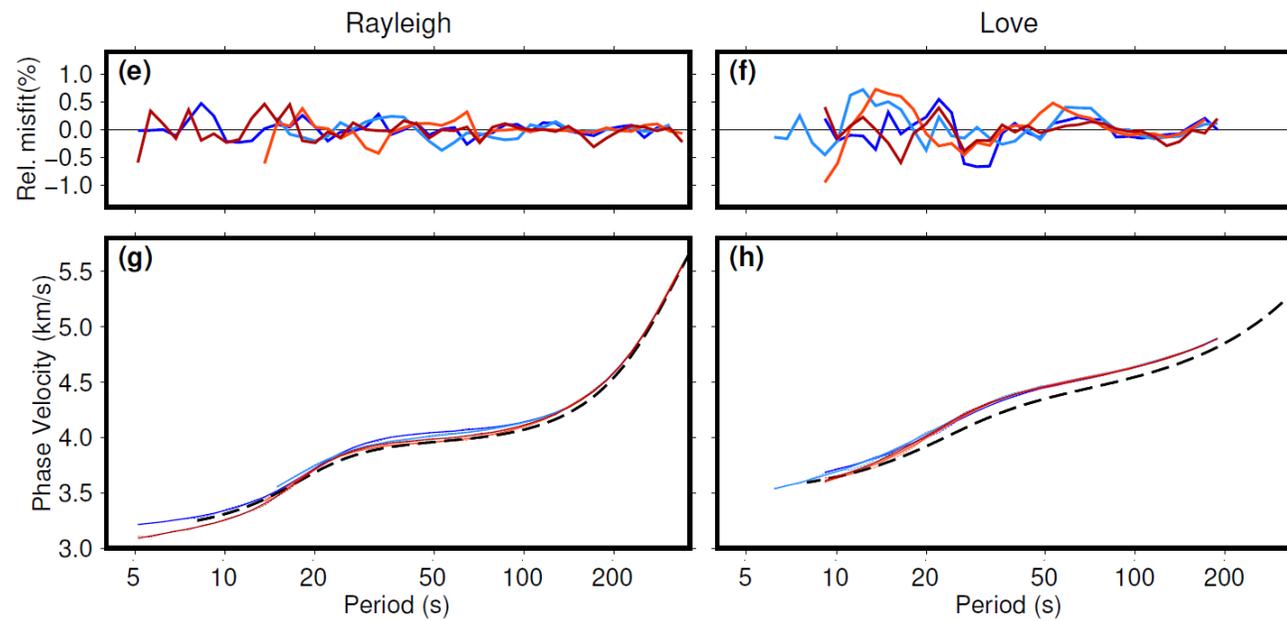
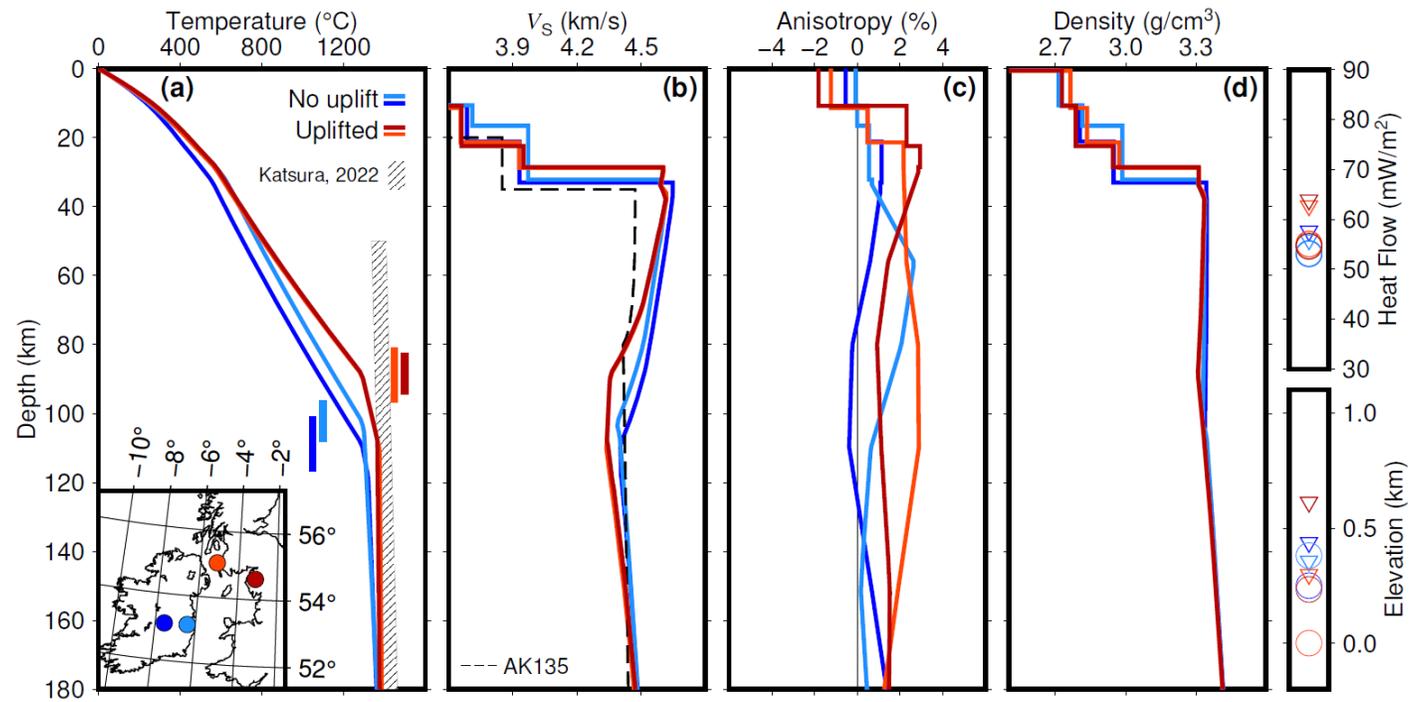
100 200 500
Resolving Length (km)

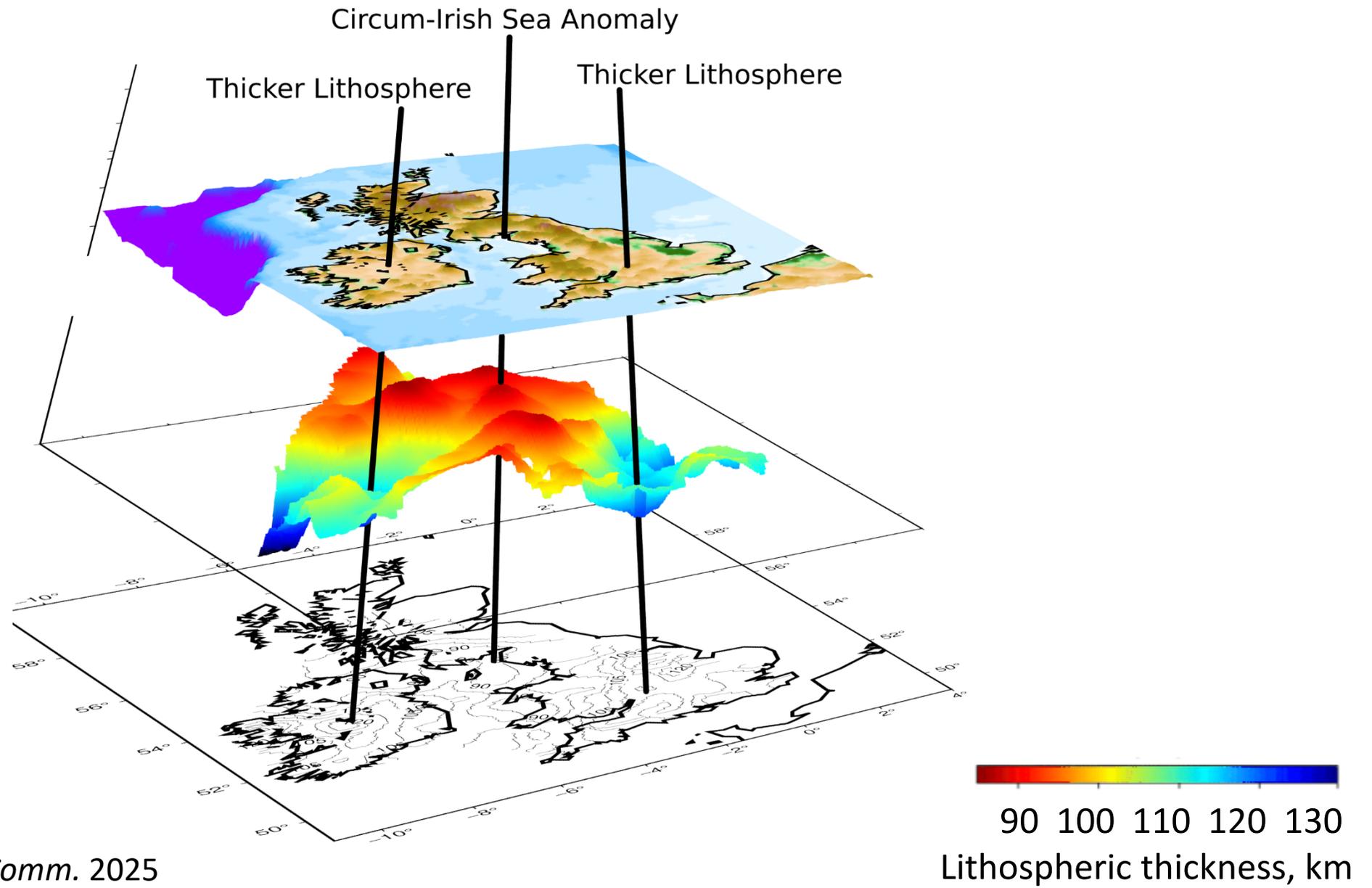
Seismic thermography of the lithosphere and asthenosphere: Thermodynamic inversion of surface-wave data

- A conventional workflow: invert for a 3D seismic velocity model and, then, convert that to temperature and lithospheric thickness. *Disadvantage:* errors and biases due to the non-uniqueness of the seismic-velocity models.
- *Thermodynamic inversion:* invert directly for temperature. Yields more accurate temperatures and seismic velocities.

Seismic thermography of the lithosphere and asthenosphere: Thermodynamic inversion of surface-wave data

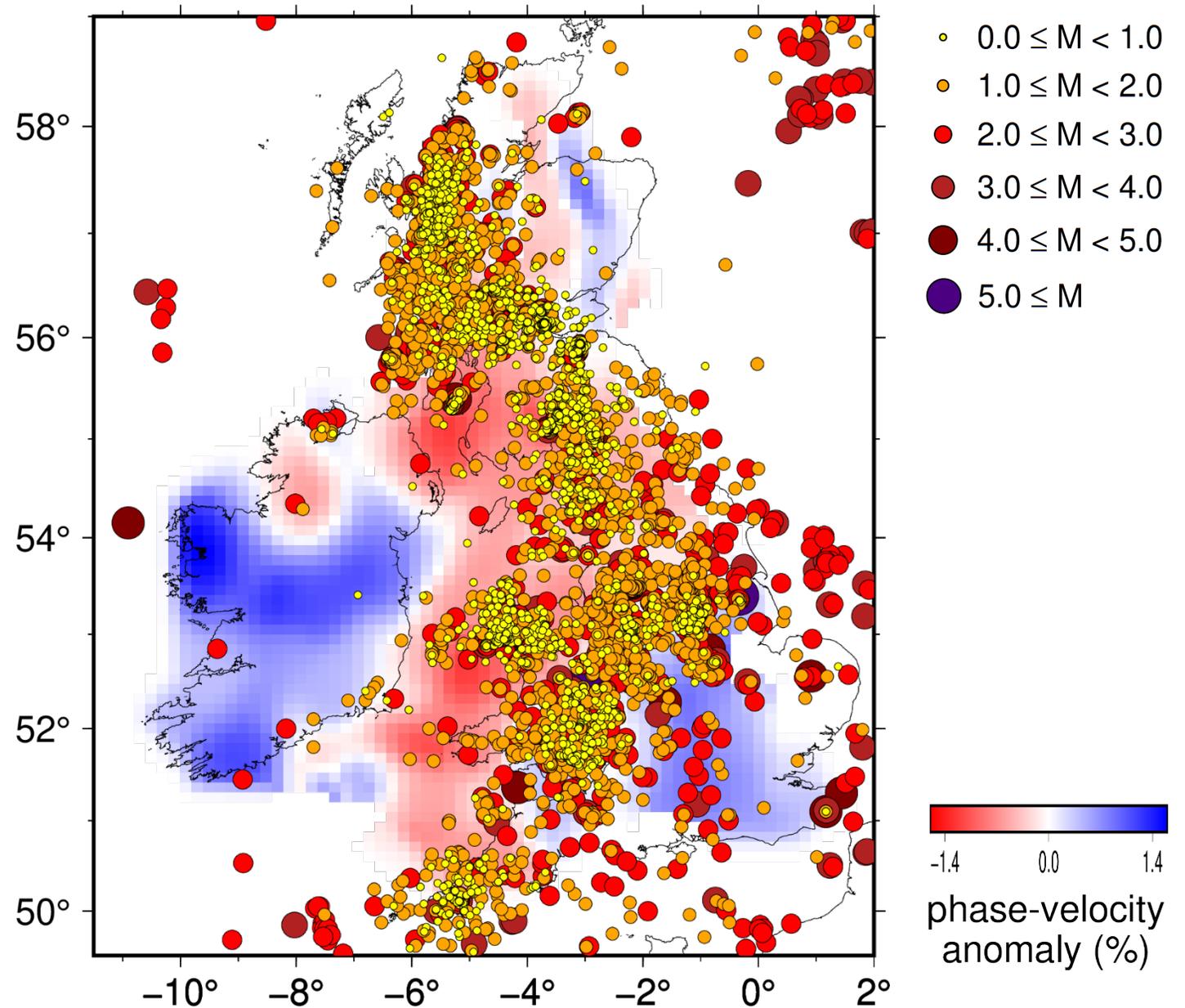






Lithosphere and seismicity

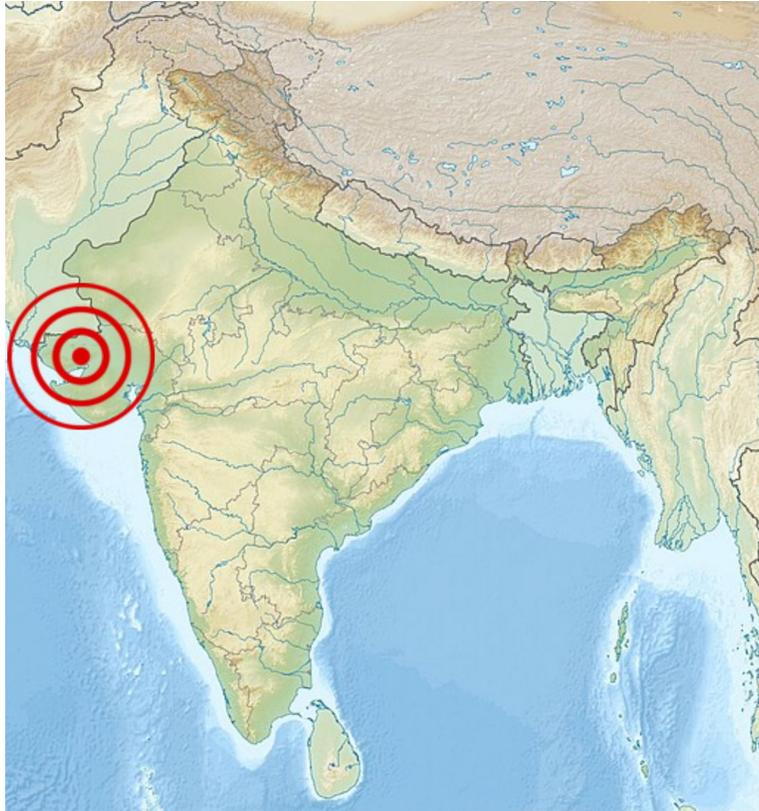
- Ireland has low seismicity because it has thick, cold, strong lithosphere
- Most Irish earthquakes are in the area of thin, warm lithosphere in the north
- Thick lithosphere and low seismicity in SE England and E Scotland
- **The mechanism behind the distribution of earthquakes: thinner, mechanically weaker lithosphere and thin-thick lithosphere contrasts localize deformation and seismicity**



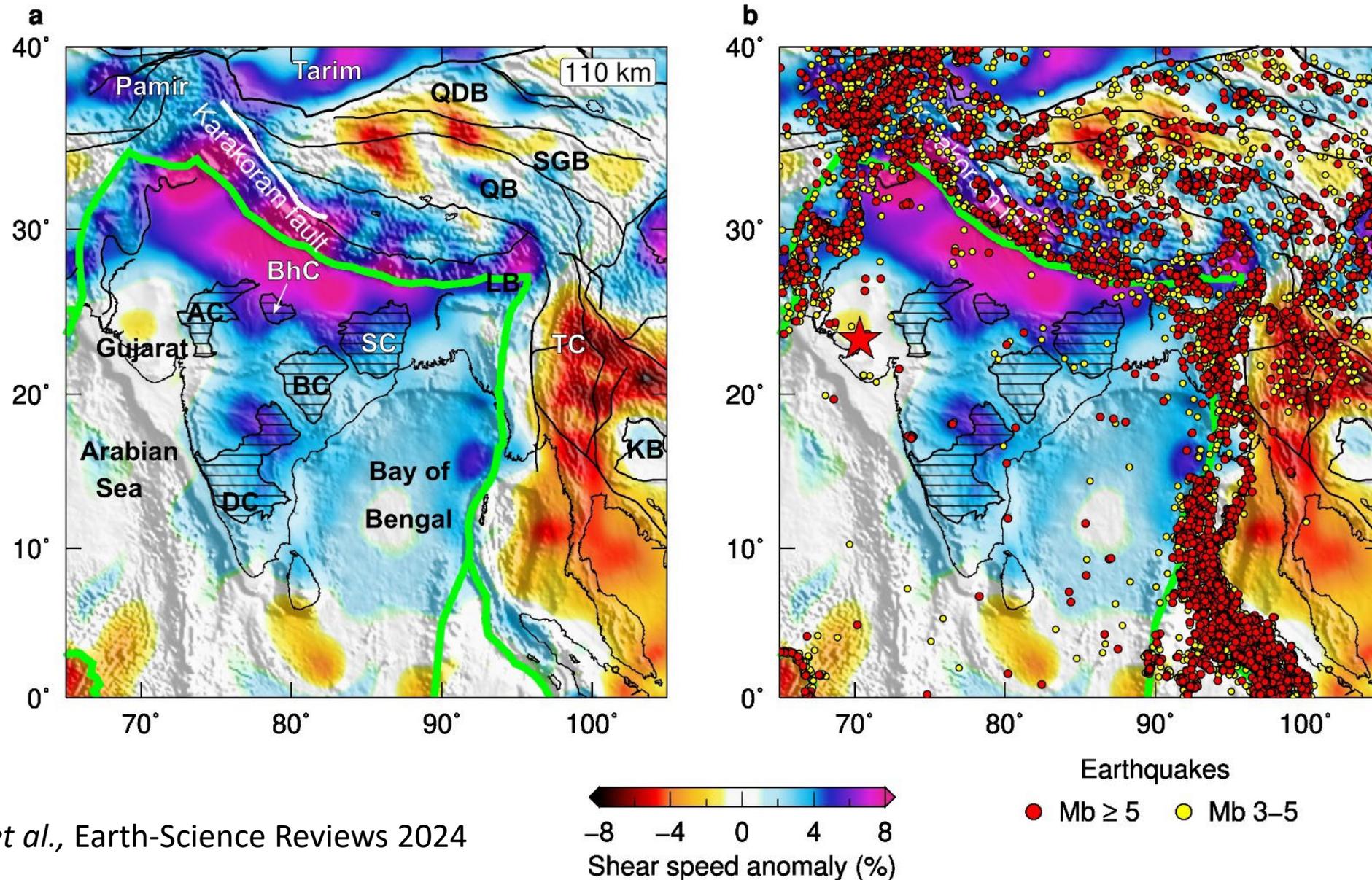
Lebedev et al., 2023

2001 Gujarat earthquake, India

M7.6, ~20,000 killed



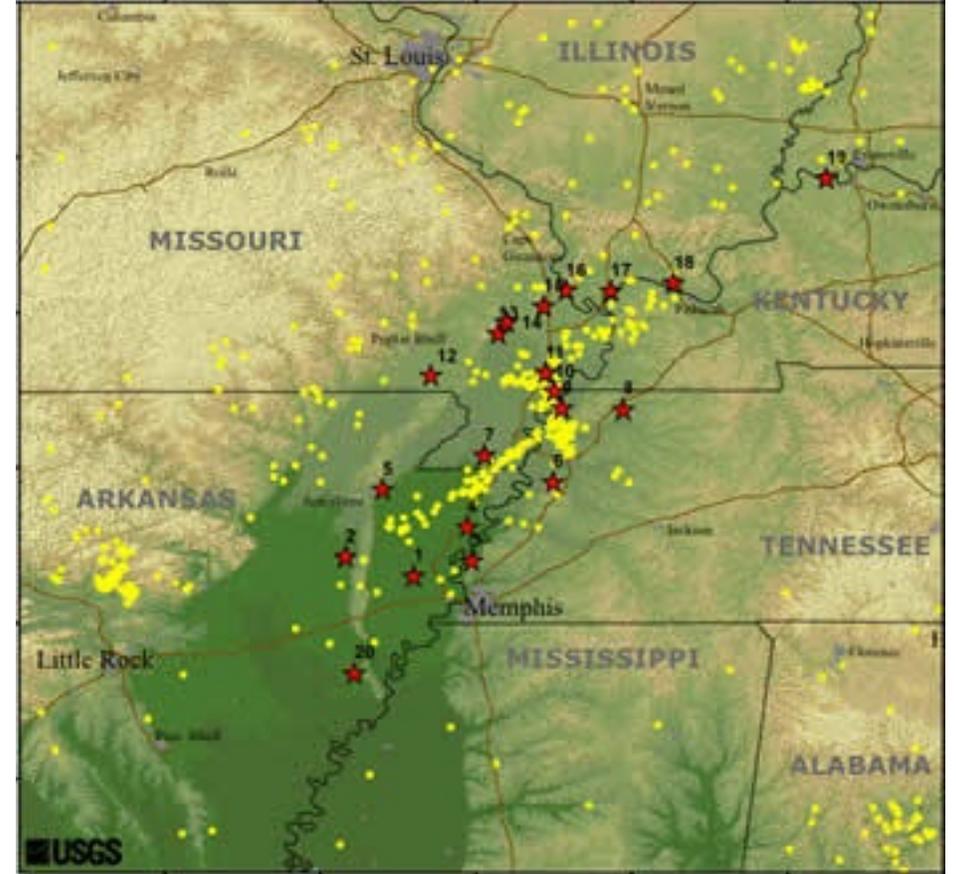
The 2001 Gujarat earthquake: where the lithosphere is relatively thin



Dou et al., Earth-Science Reviews 2024

New Madrid Seismic Zone

Three M7-8 earthquakes in 1811-1812

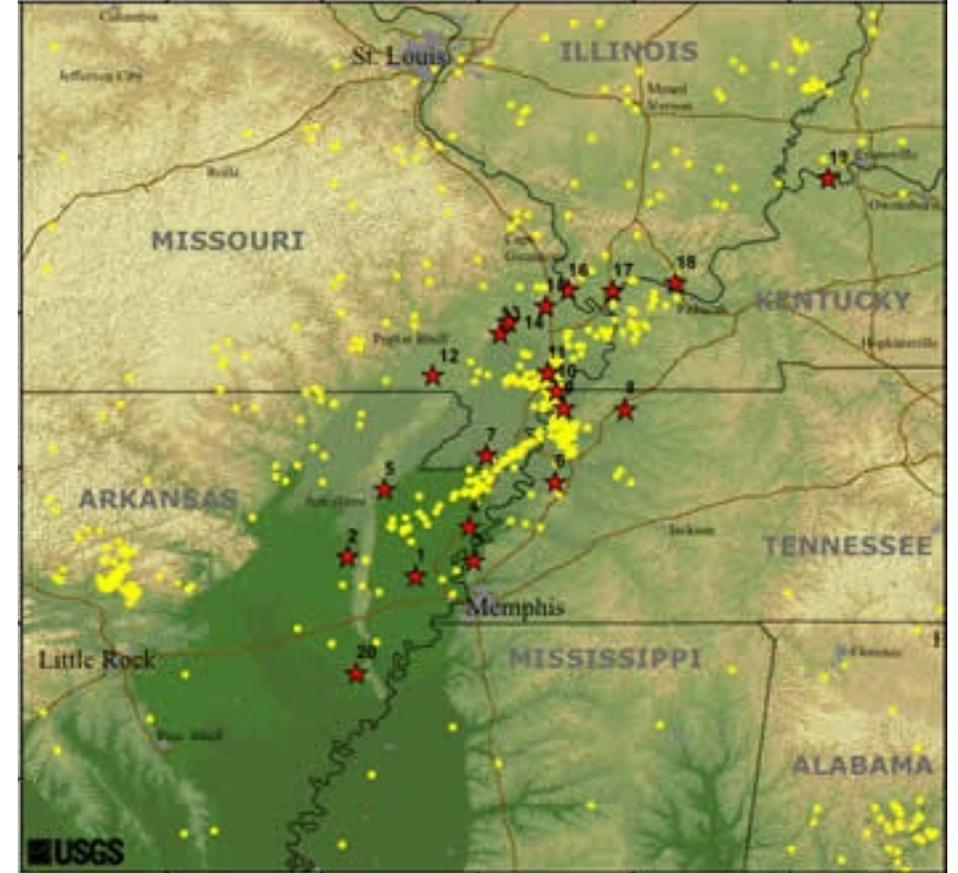
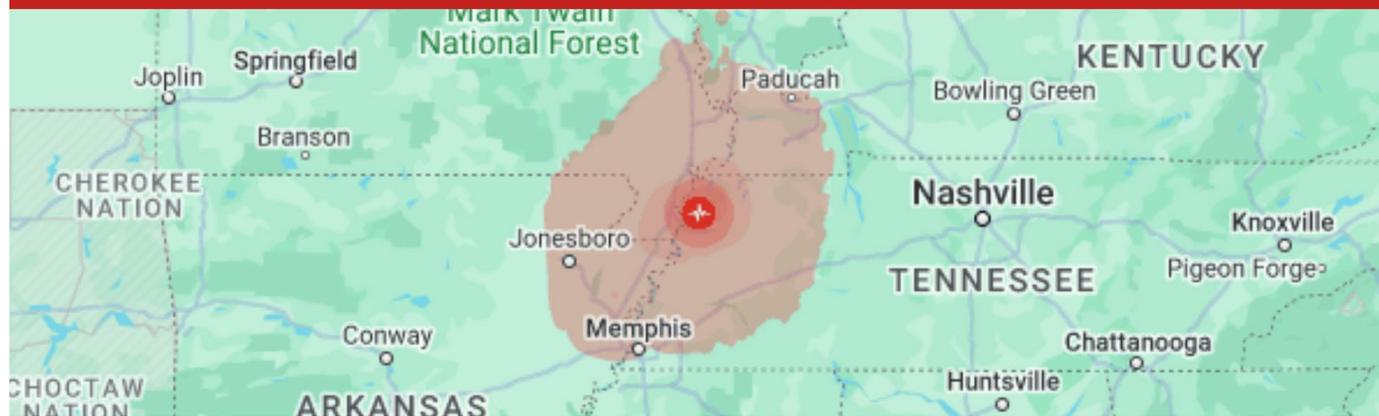


New Madrid Seismic Zone

Three M7-8 earthquakes in 1811-1812

Magnitude 3.8 earthquake

16 km from Caruthersville, MO, USA · 16 May, 09:19



Wion / Trending / Scientists Warn 86,000 People Could Die In Devastating Earthquake In Little-Known US Seismic Zone

Scientists warn 86,000 people could die in devastating earthquake in little-known US seismic zone



Edited By [Anamica Singh](#)

Published: Sep 09, 2025, 07:32 IST | Updated: Sep 09, 2025, 08:14 IST



New Madrid Seismic Zone is due an earthquake of magnitude 7 that can cause devastation even on the East Coast. **Photograph:** (Wikimedia Commons)

ADVERTISEMENT

ADVERTISEMENT



NEWS | Aug. 6, 2025

Arkansas National Guard Bolsters Disaster Response Plan

By 1st Lt. Melody Daniel, Arkansas National Guard

NORTH LITTLE ROCK, Ark. - The Arkansas National Guard is working closely with its state and federal partners to intensify preparations for a high-magnitude earthquake from the New Madrid Seismic Zone, which spans from Illinois to northeast Arkansas.



NATIONAL GUARD

ALWAYS READY ALWAYS THERE

Home

News ▾

Features ▾

About the Guard ▾

Leadership ▾

Resources ▾

Contact Us

Home : News : Article View



NEWS | Aug. 6, 2025

Arkansas National Guard Bolsters Disaster Response Plan

By 1st Lt. Melody Daniel, Arkansas National Guard

NORTH LITTLE ROCK, Ark. - The Arkansas National Guard is working closely with its state and federal partners to intensify preparations for a high-magnitude earthquake from the New Madrid Seismic Zone, which spans from Illinois to northeast Arkansas.



Daily business news and economic stories

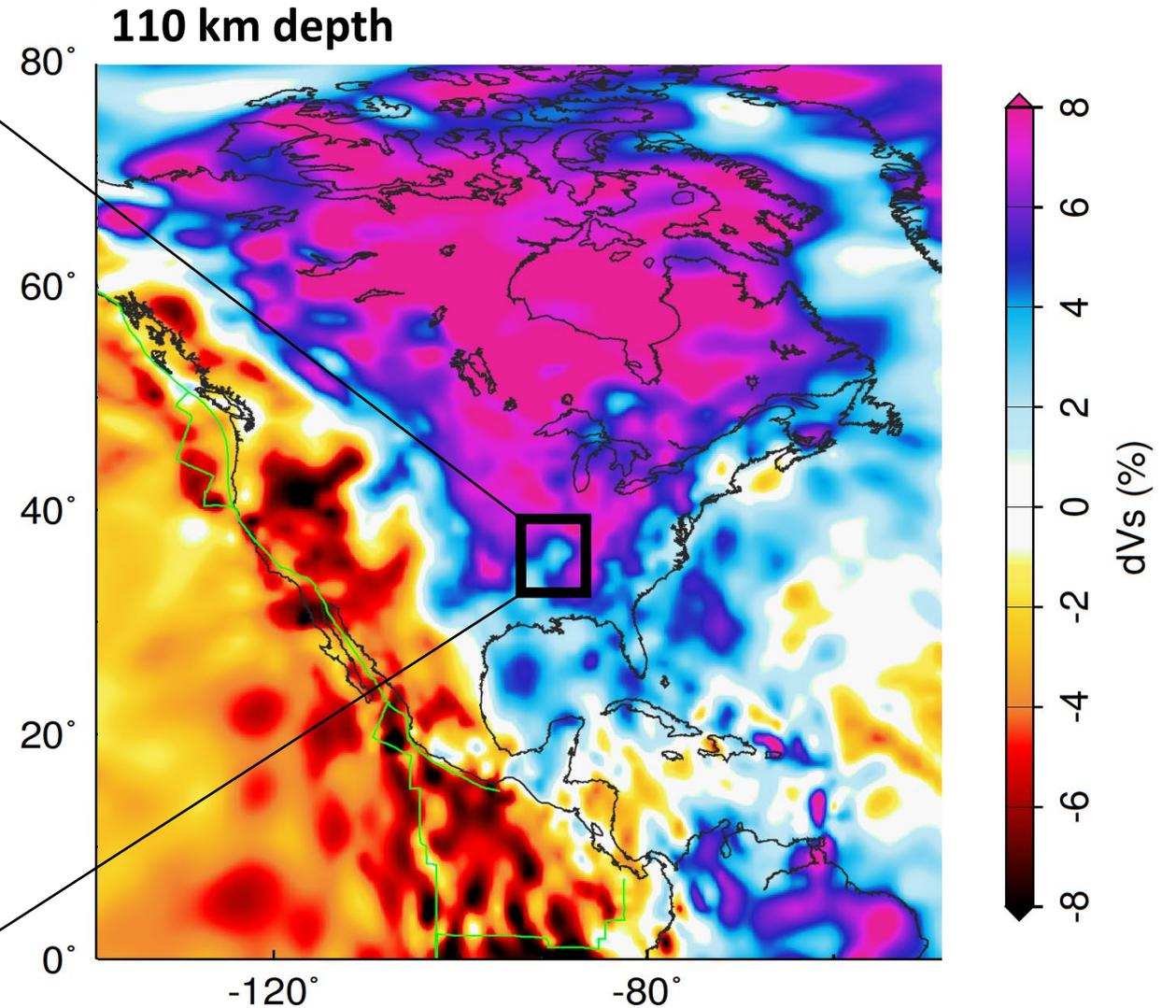
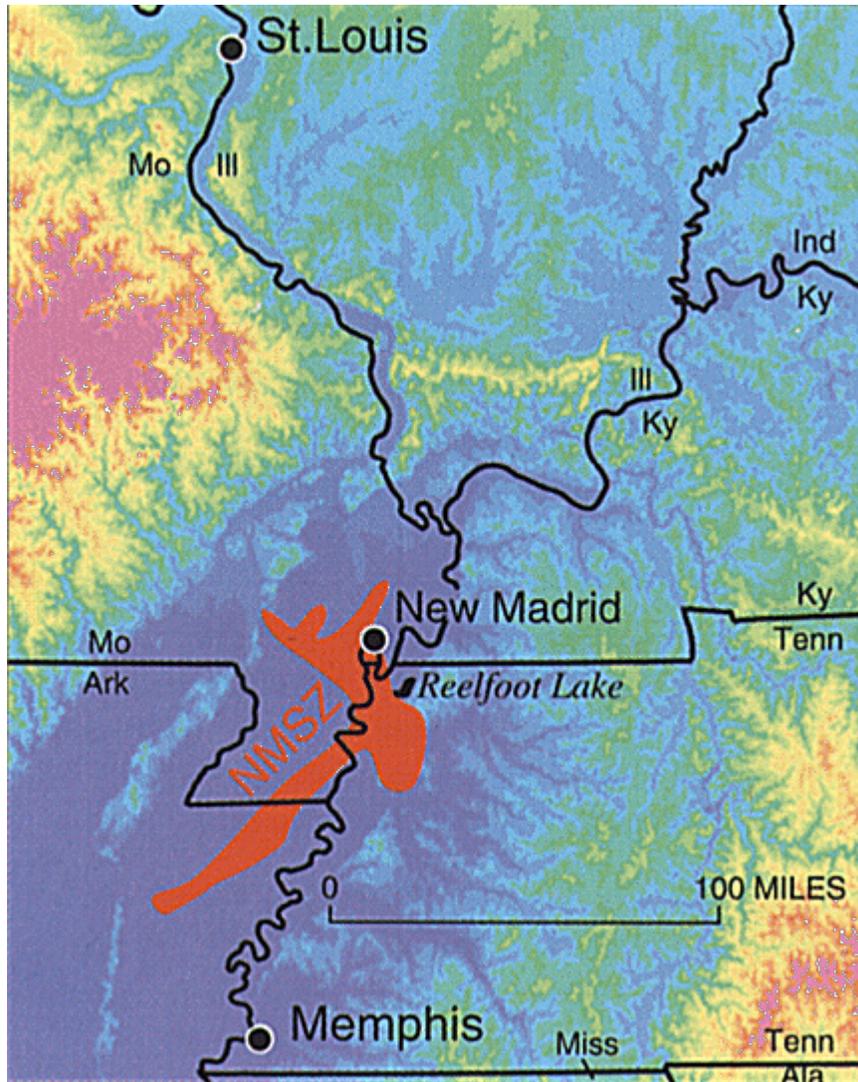
OCT 24, 2025

Why are earthquake insurance premiums skyrocketing in the middle of the country?

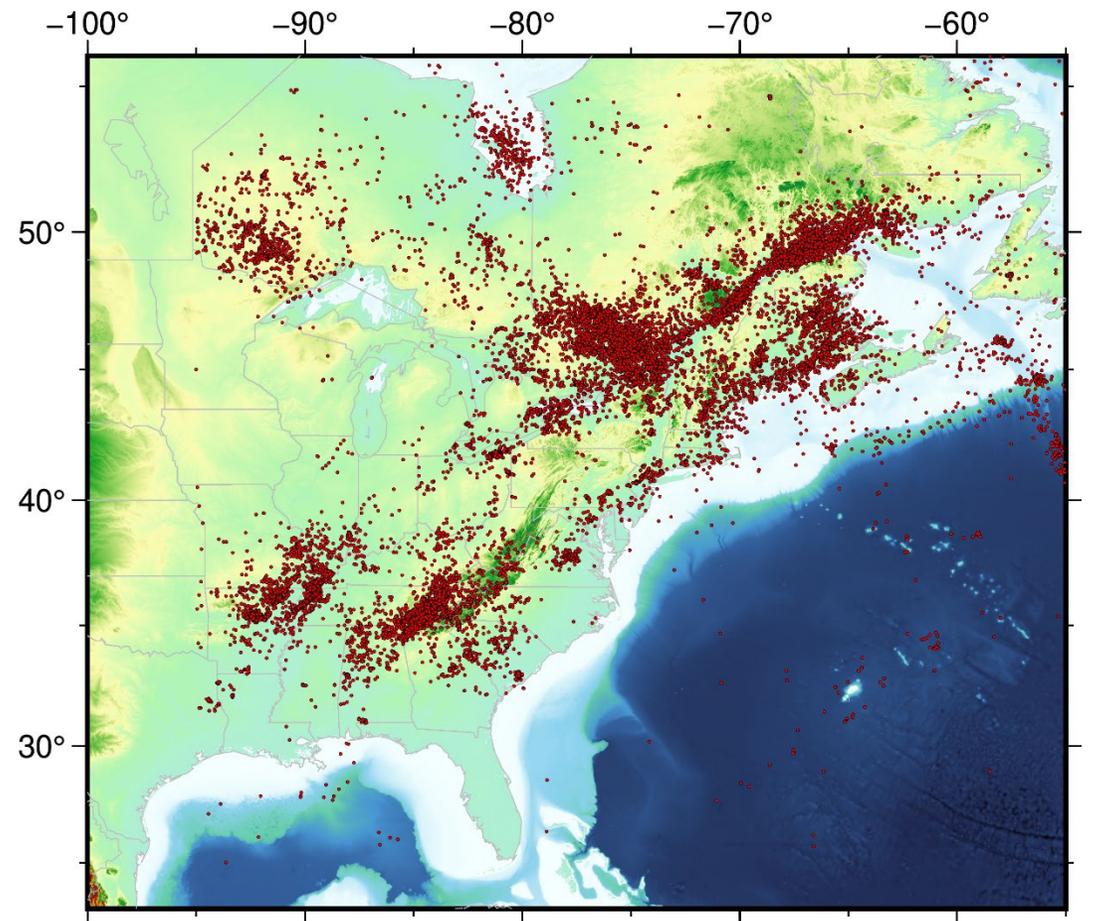
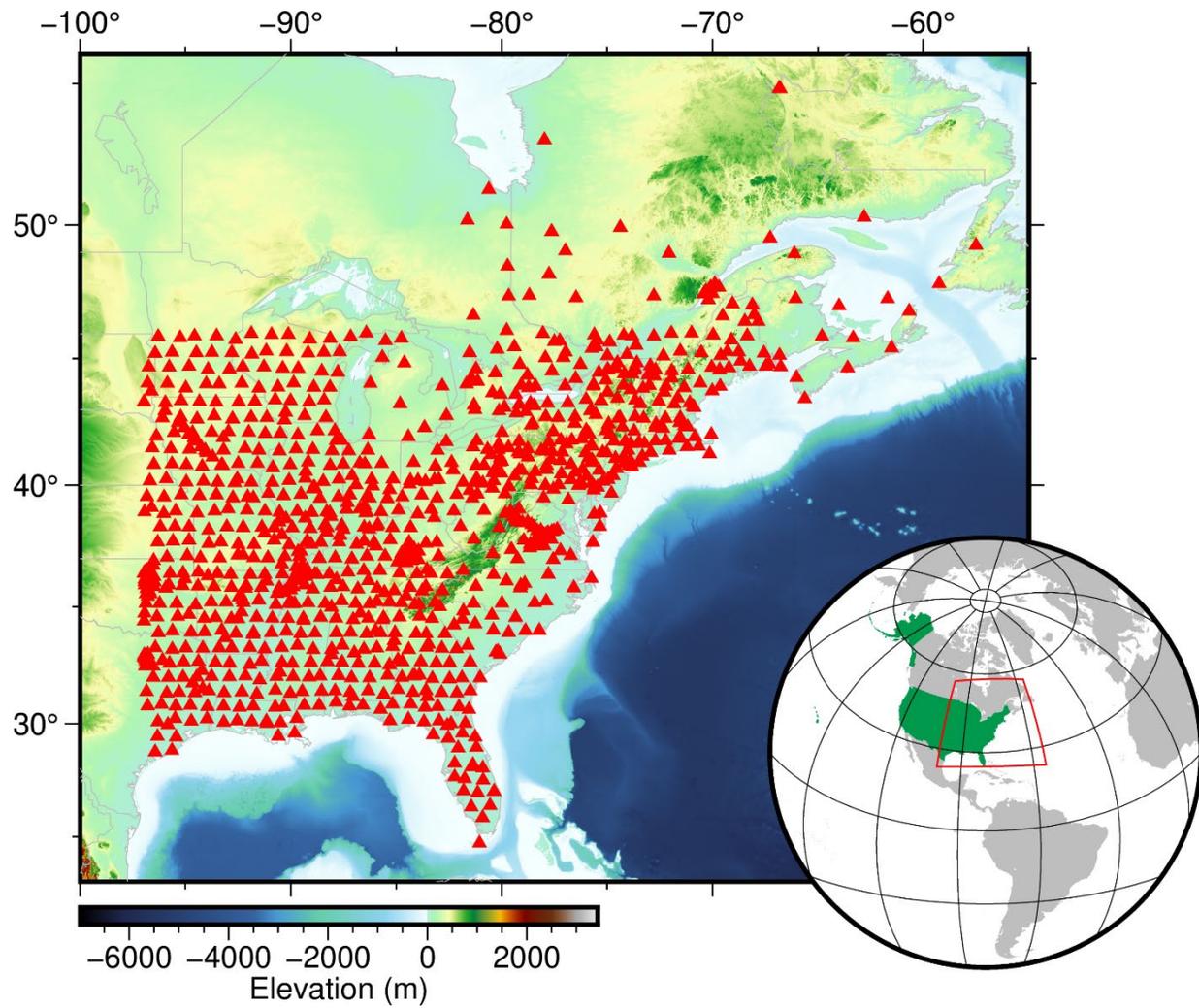
Insurance costs for some Missouri residents have skyrocketed since 2000, and coverage has shrunk to just 10% of homes.

[Housing](#) | by Harshawn Ratanpal

The New Madrid Seismic Zone is where the lithosphere is relatively thin



Celli et al. 2021

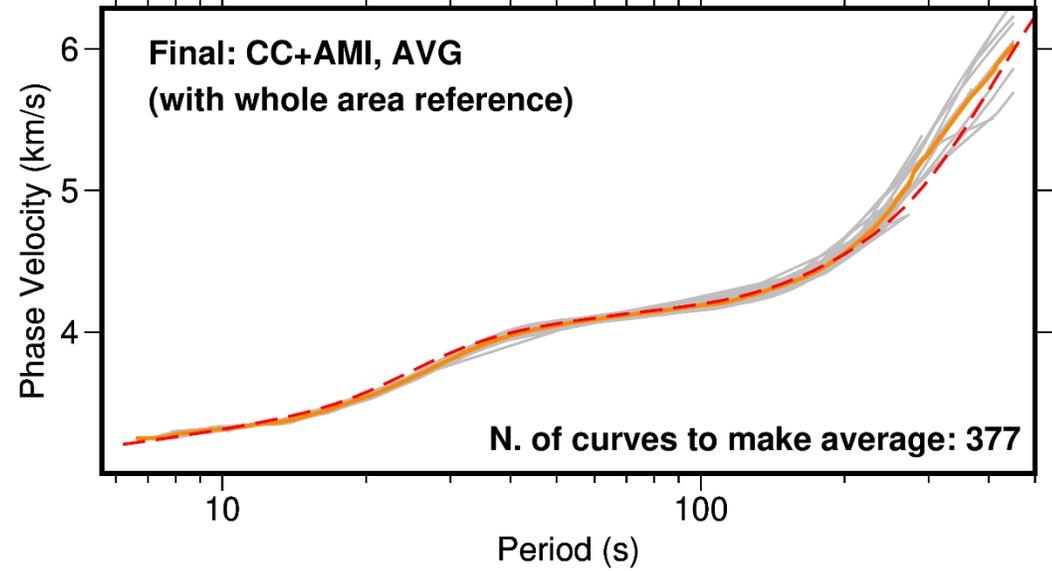
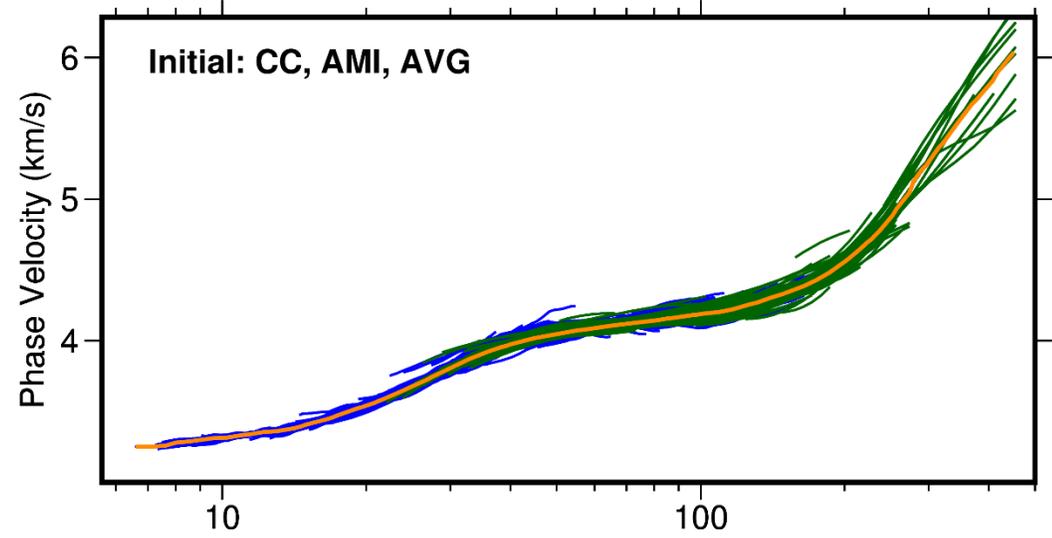
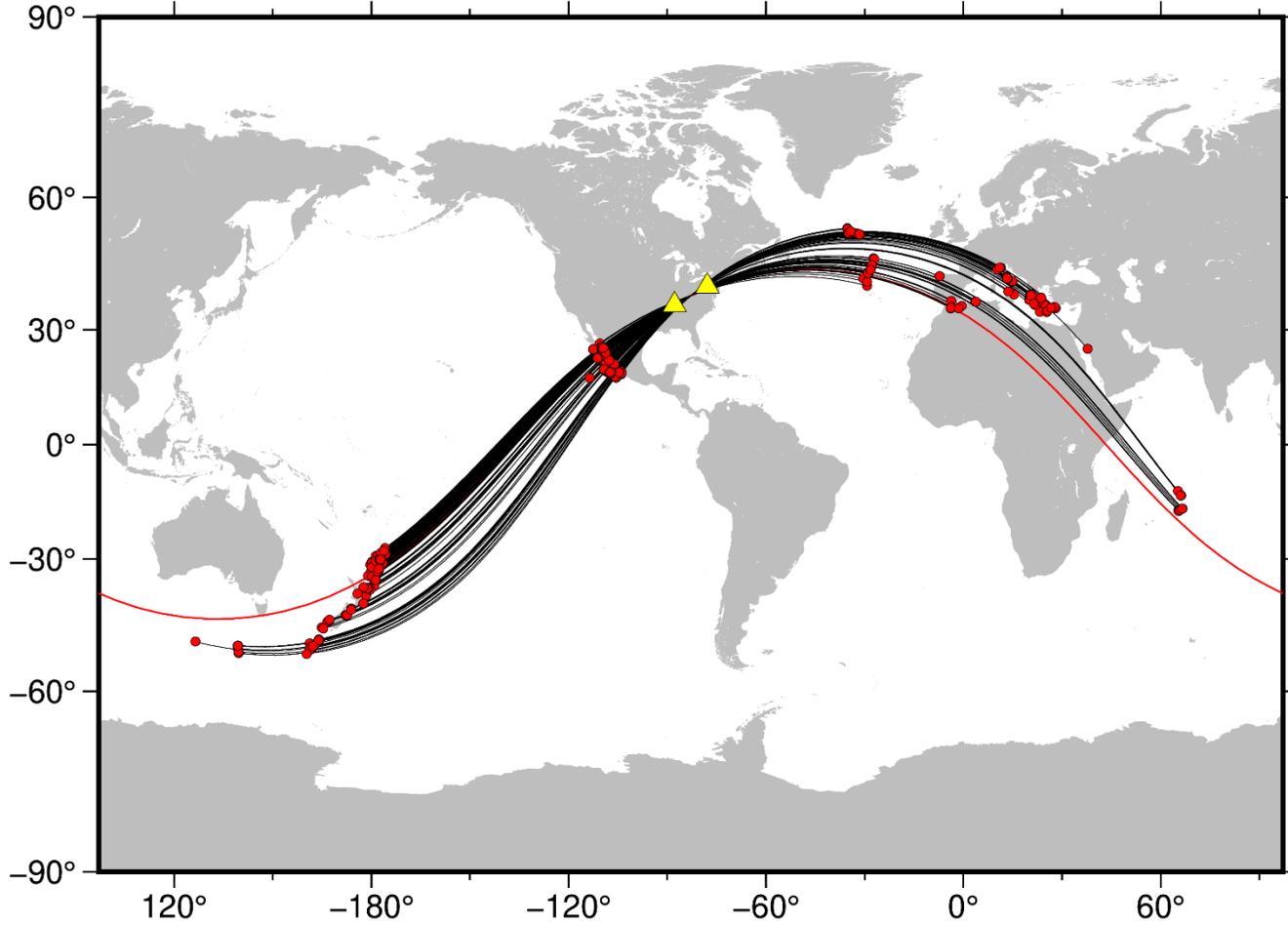


Devenish Arzuza et al., *work in progress*

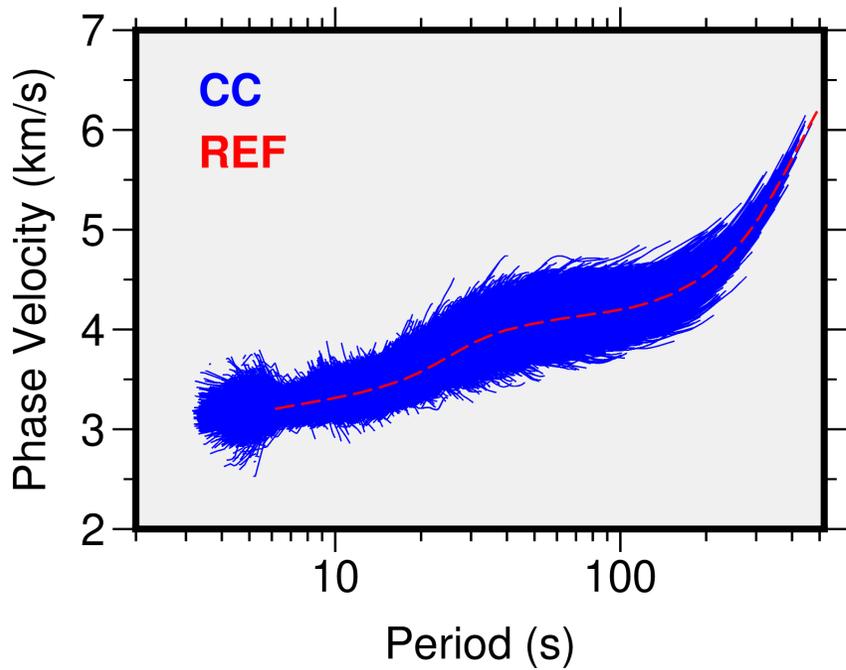
IU.SSPA_IU.WVT

Interstation distance:
1000.12 km

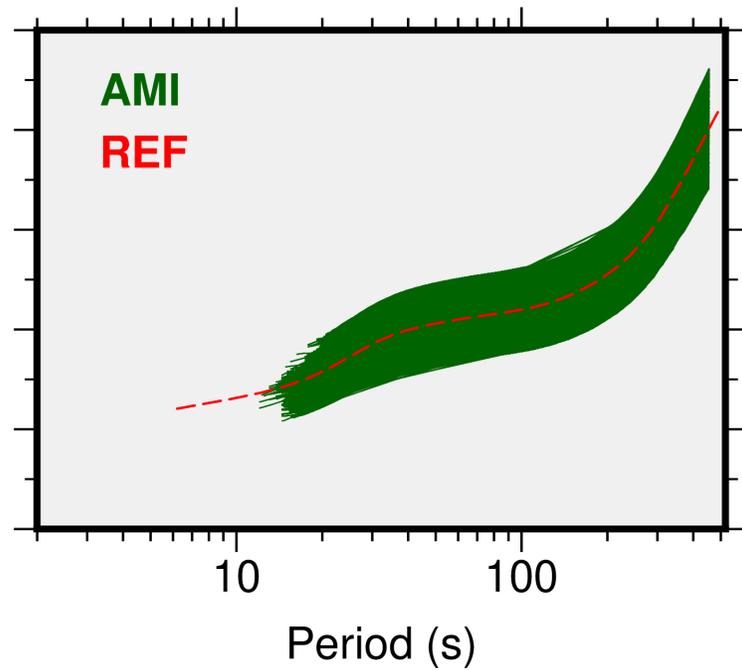
Number of events:
356



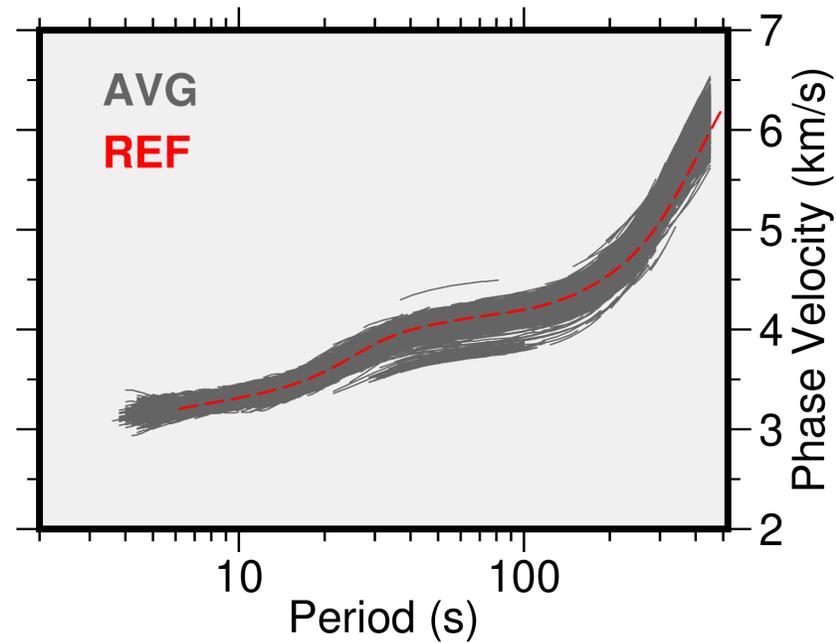
Cross-correlation

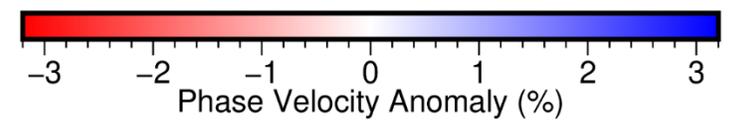
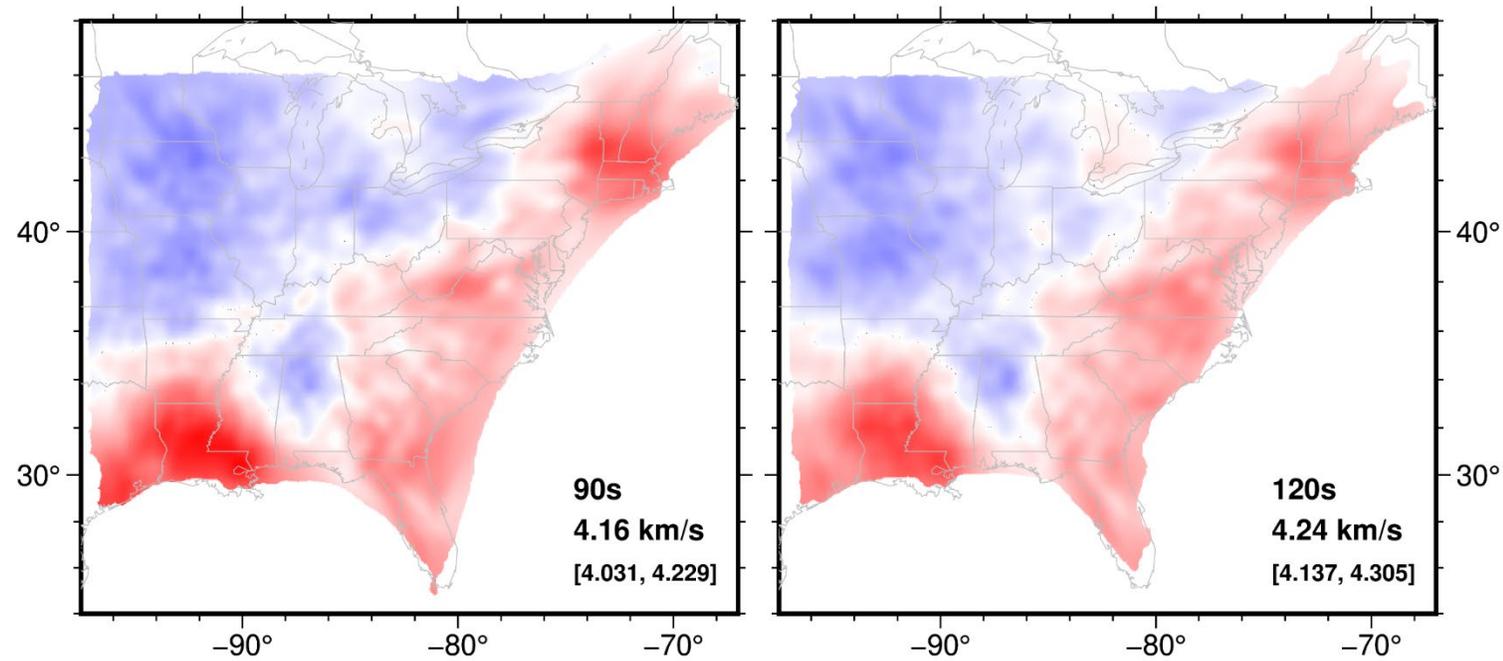
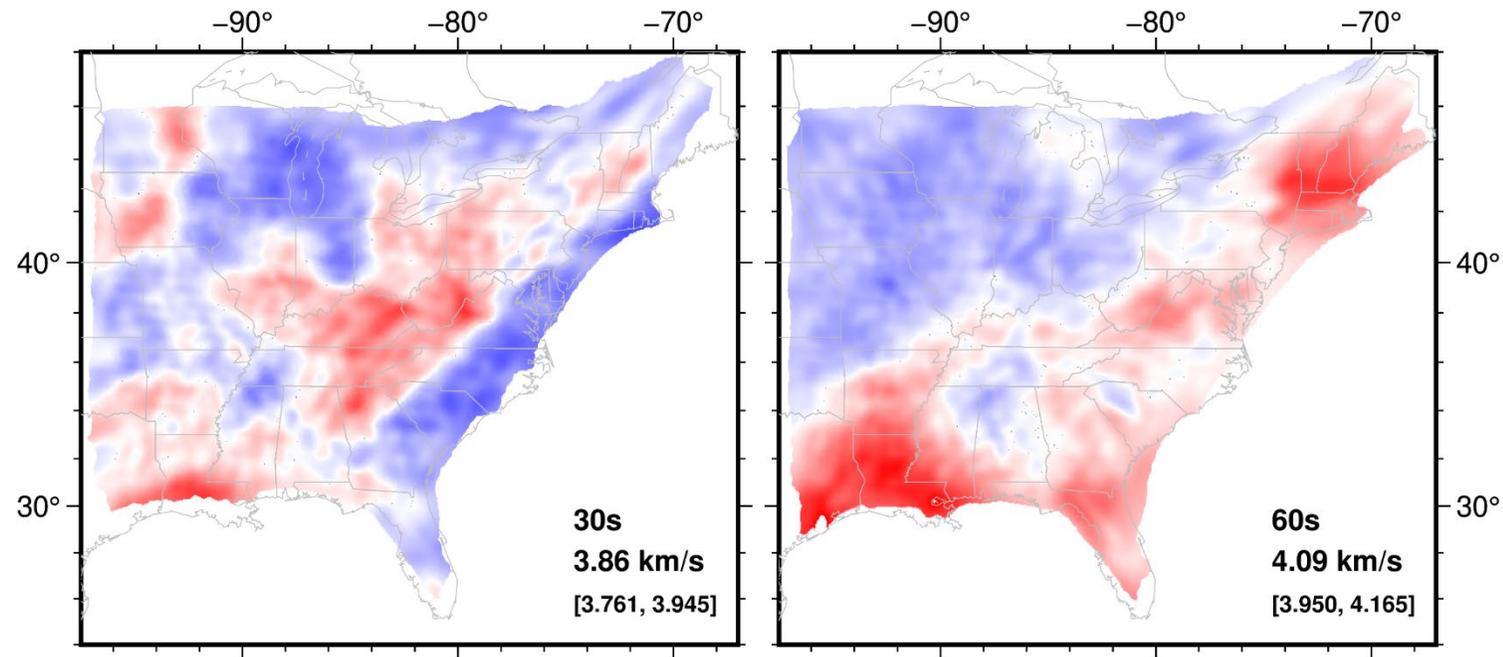


Waveform inversion

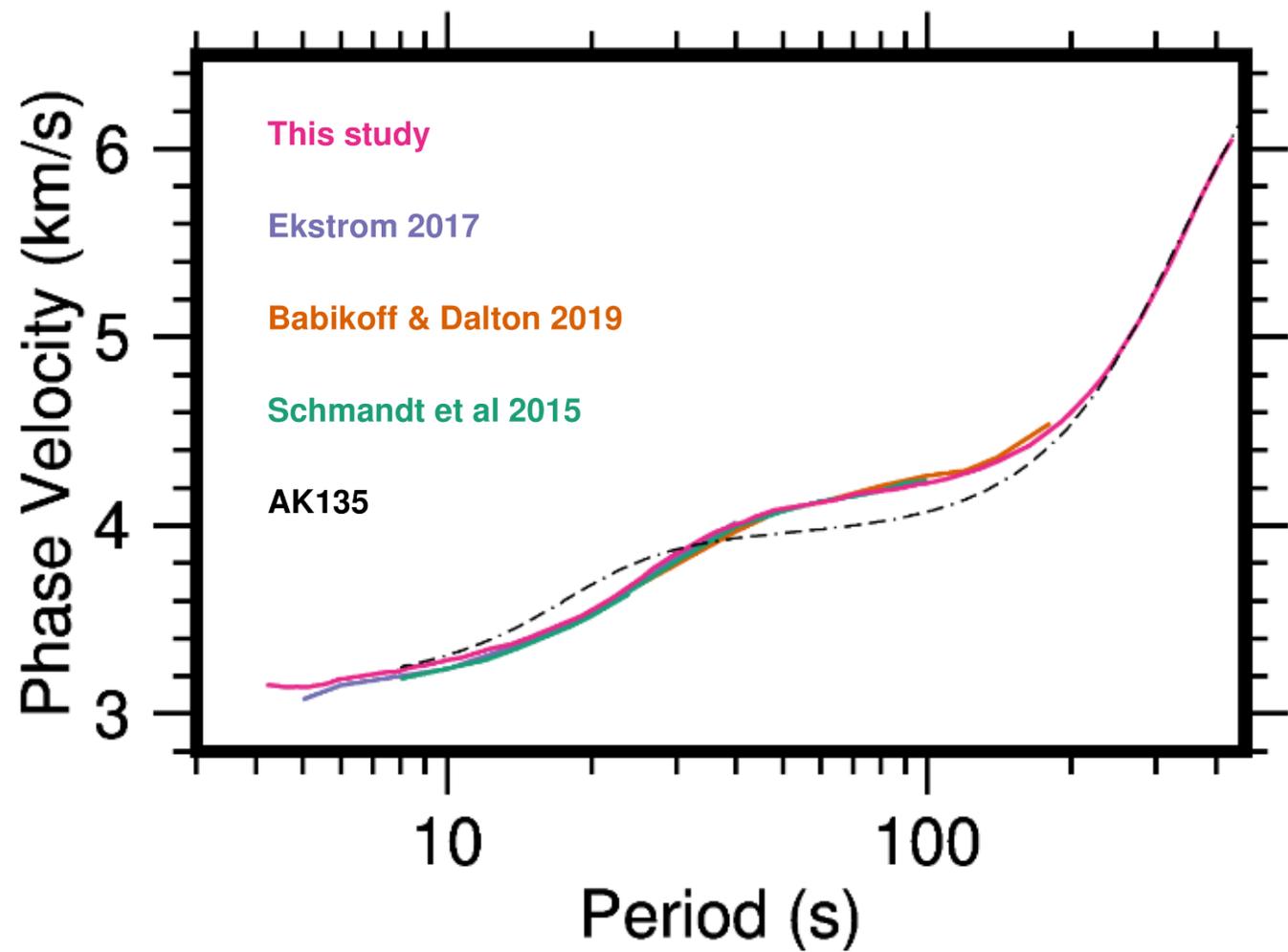
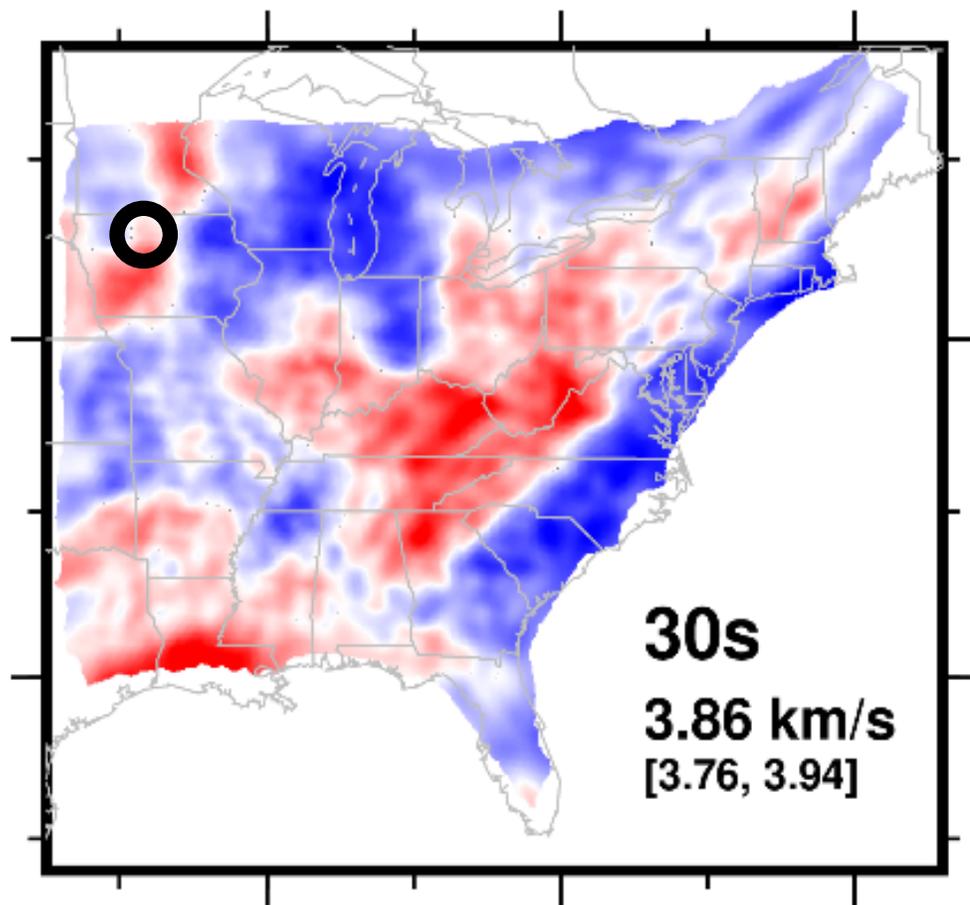


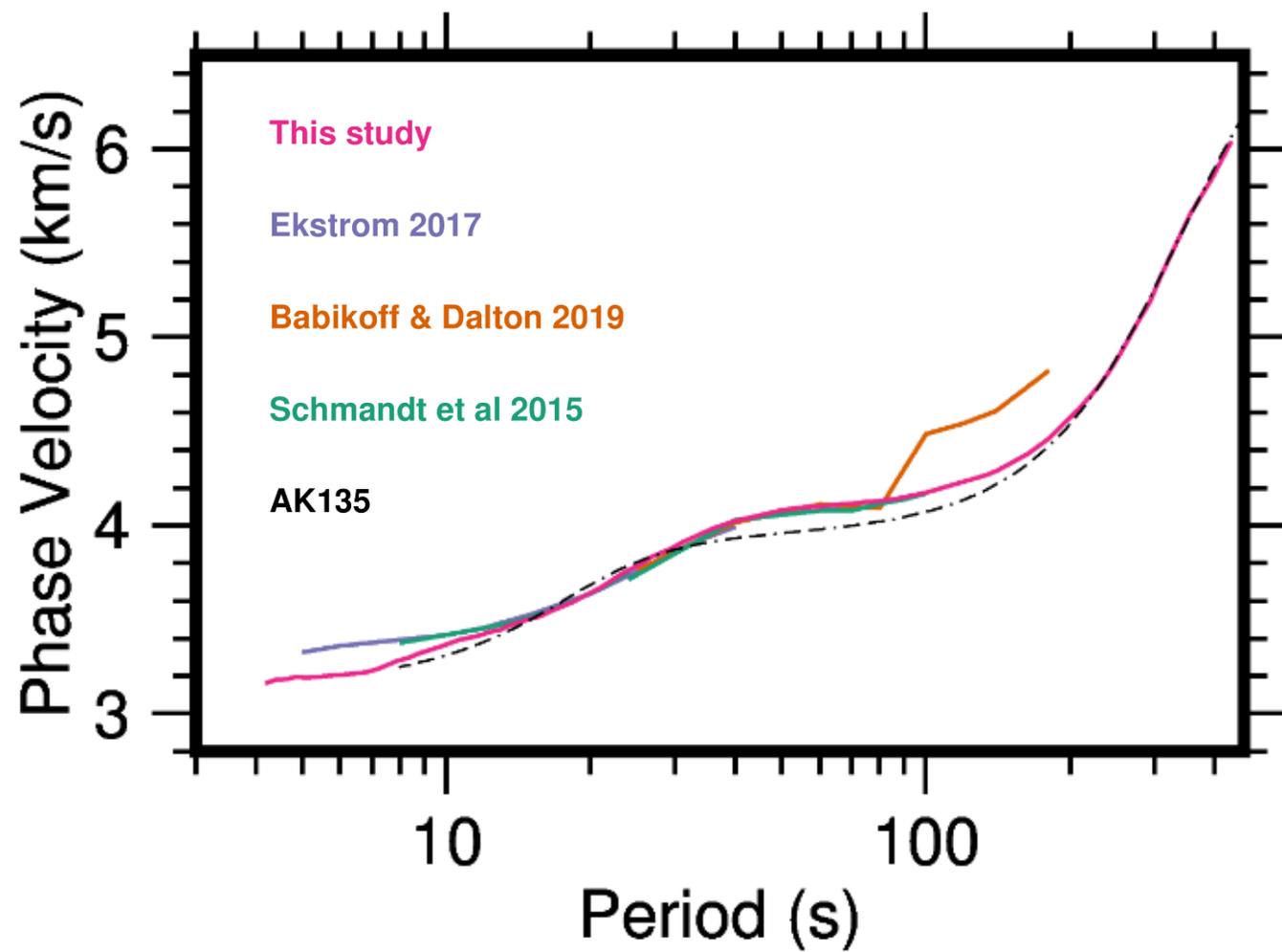
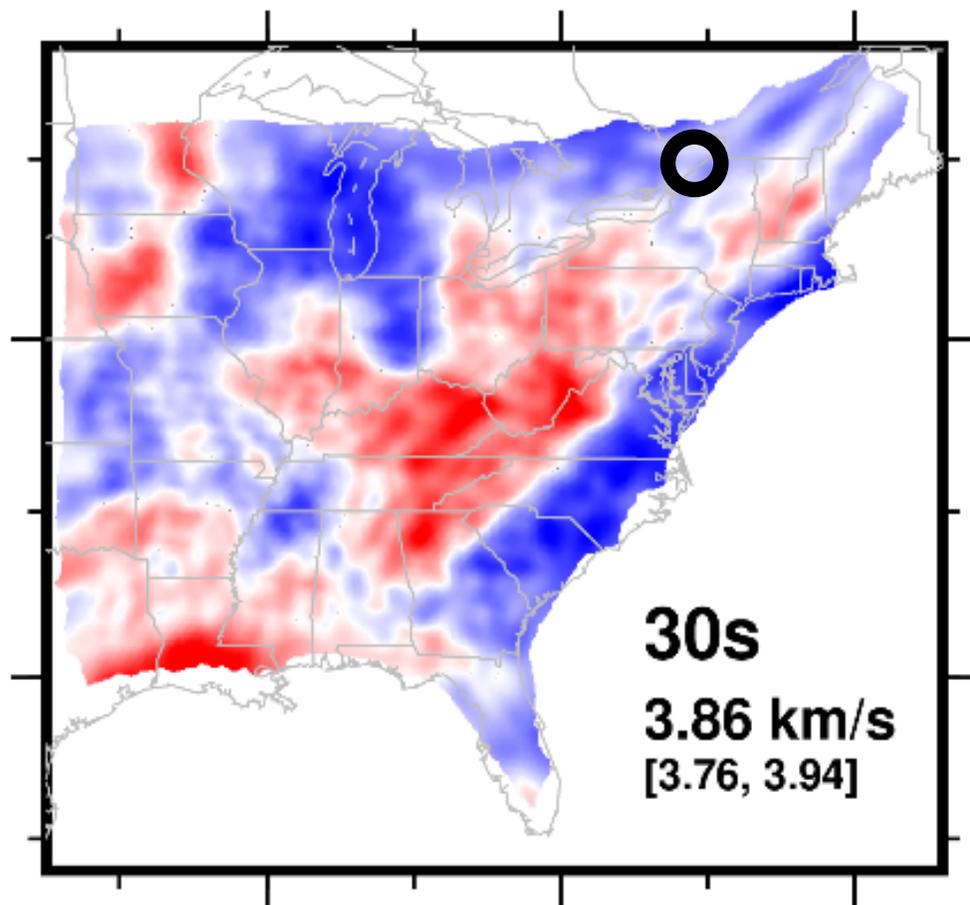
Combined averages

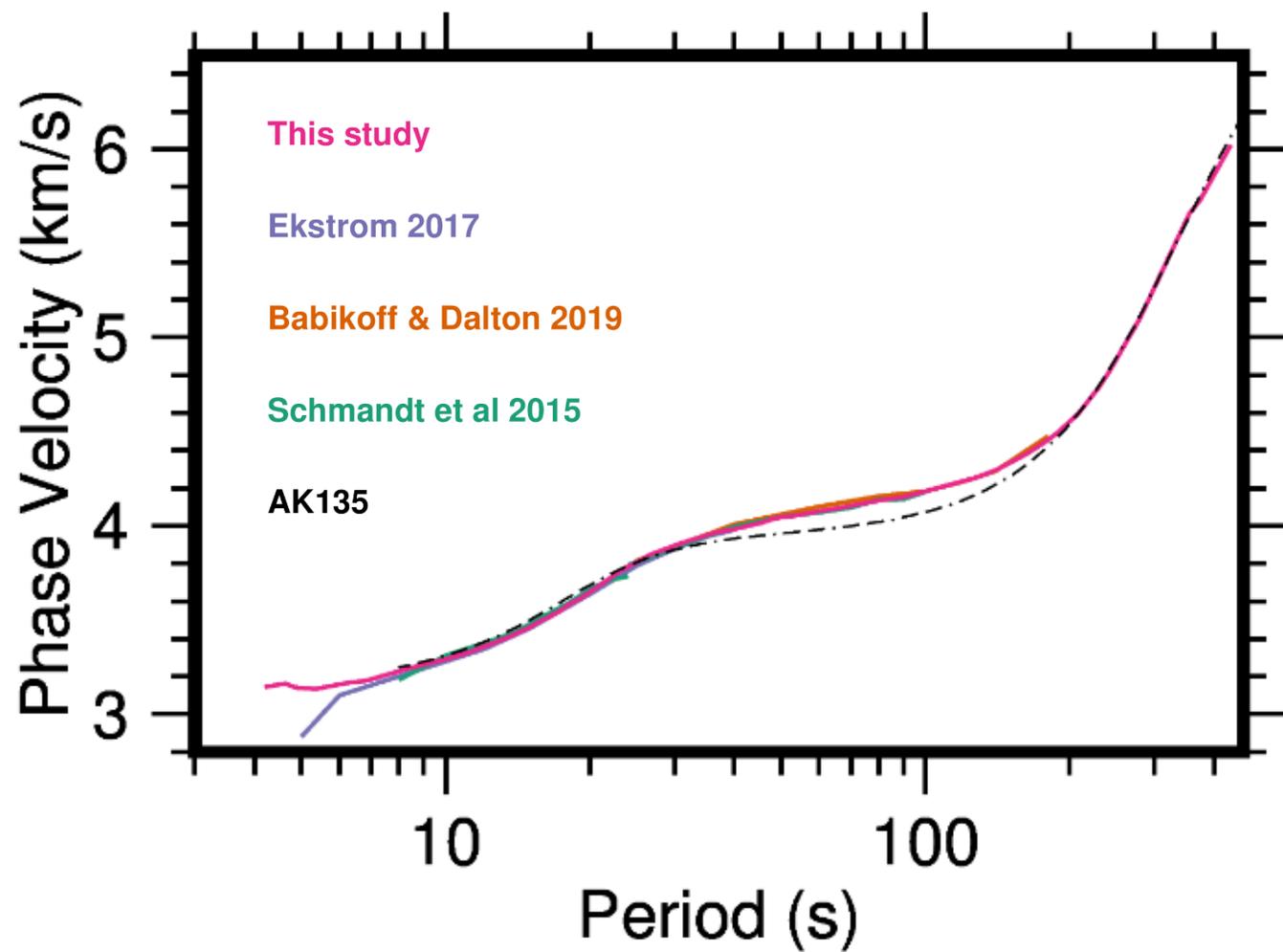
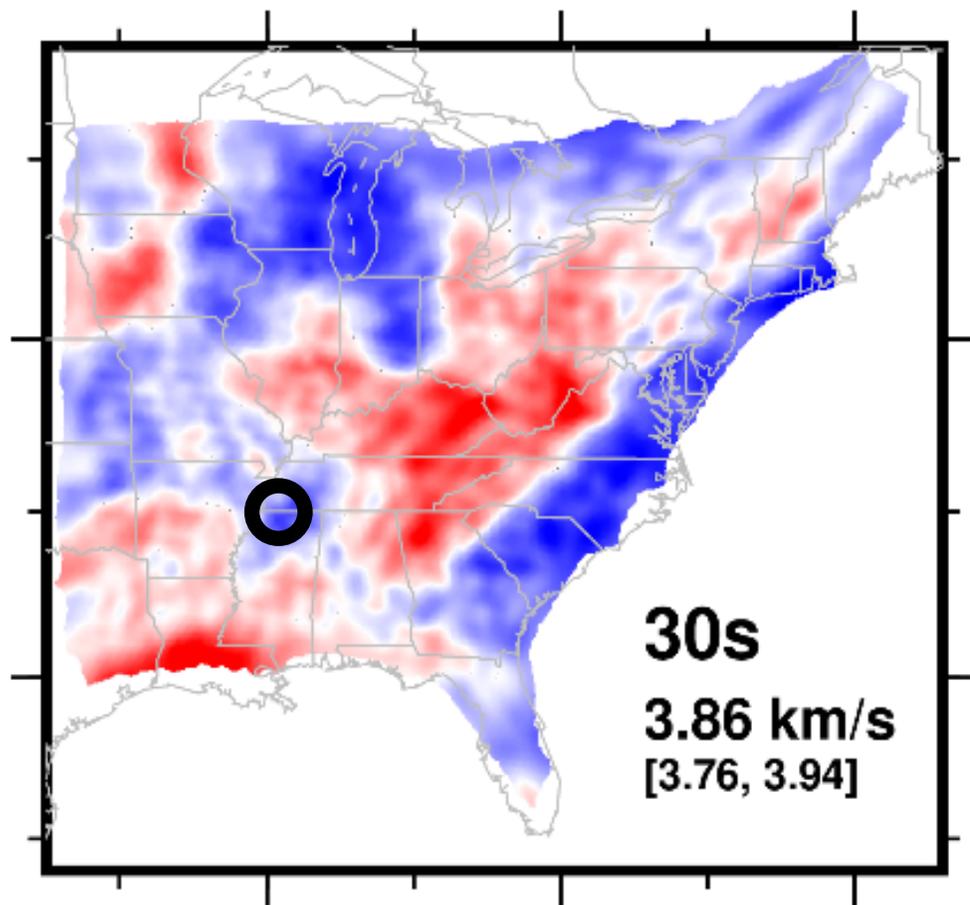


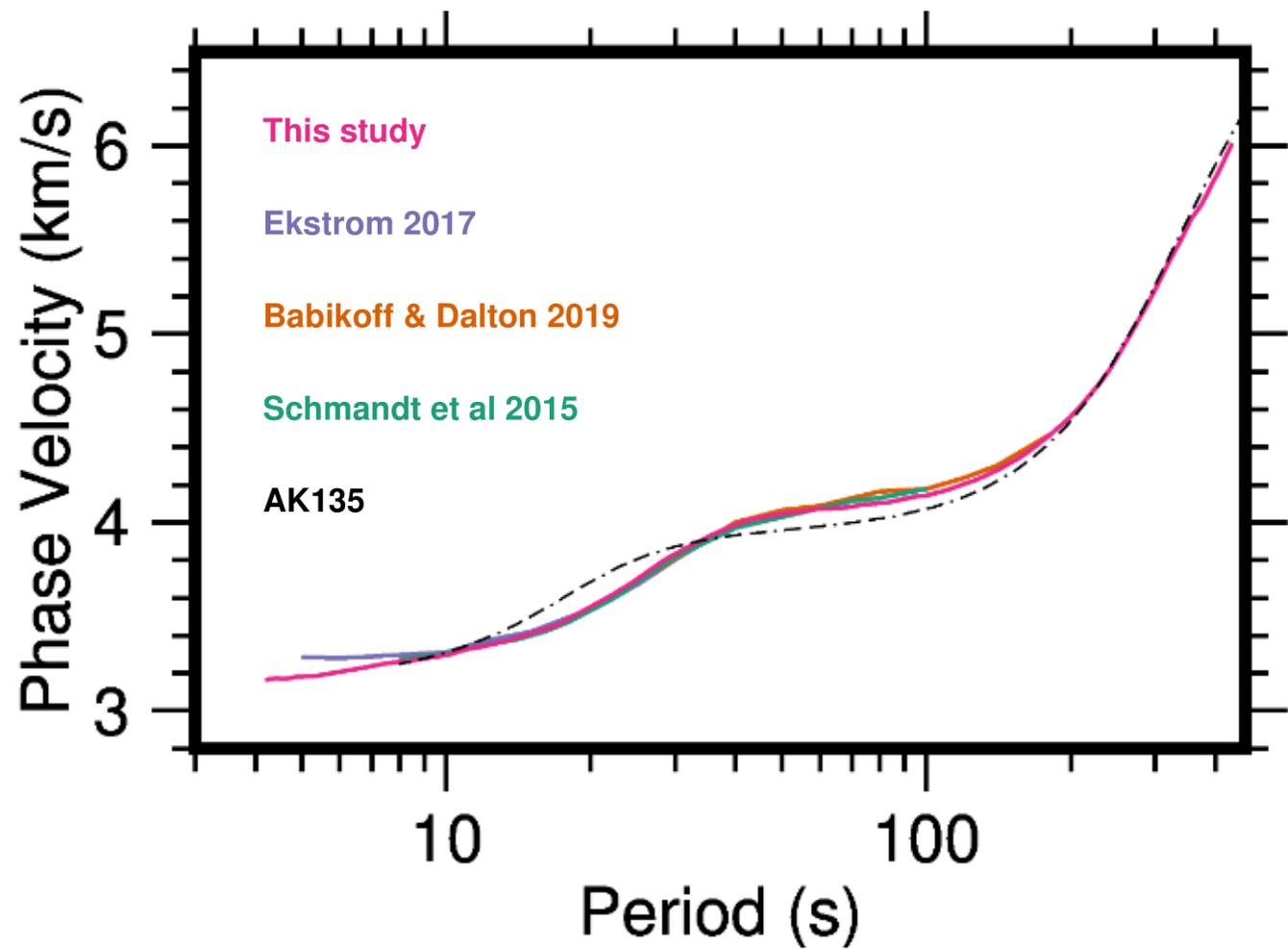
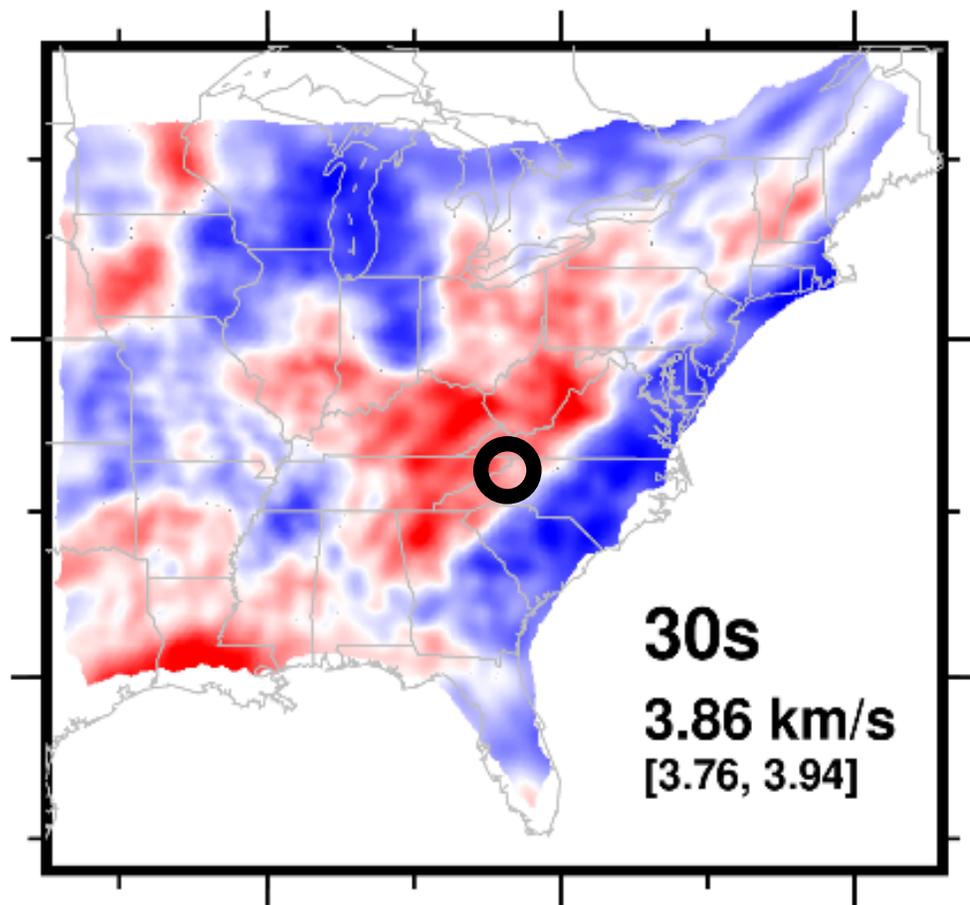


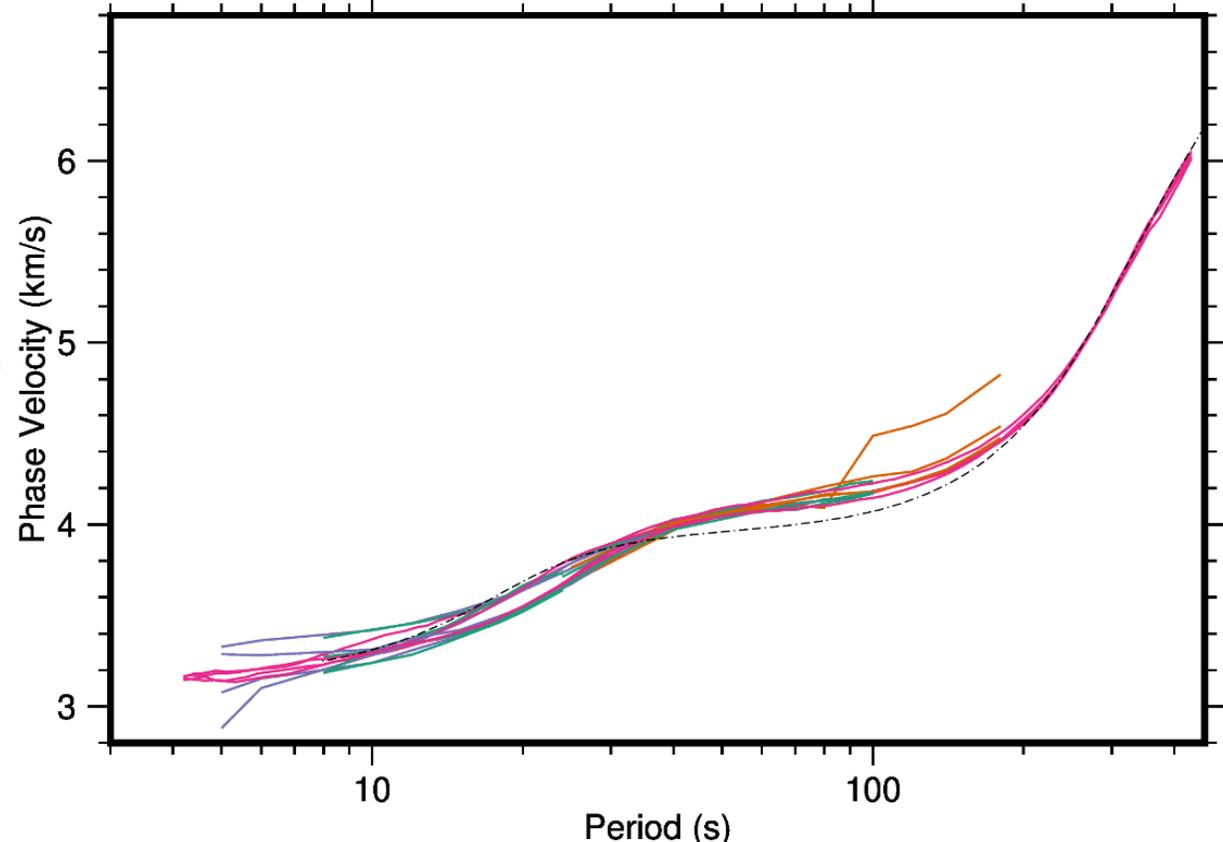
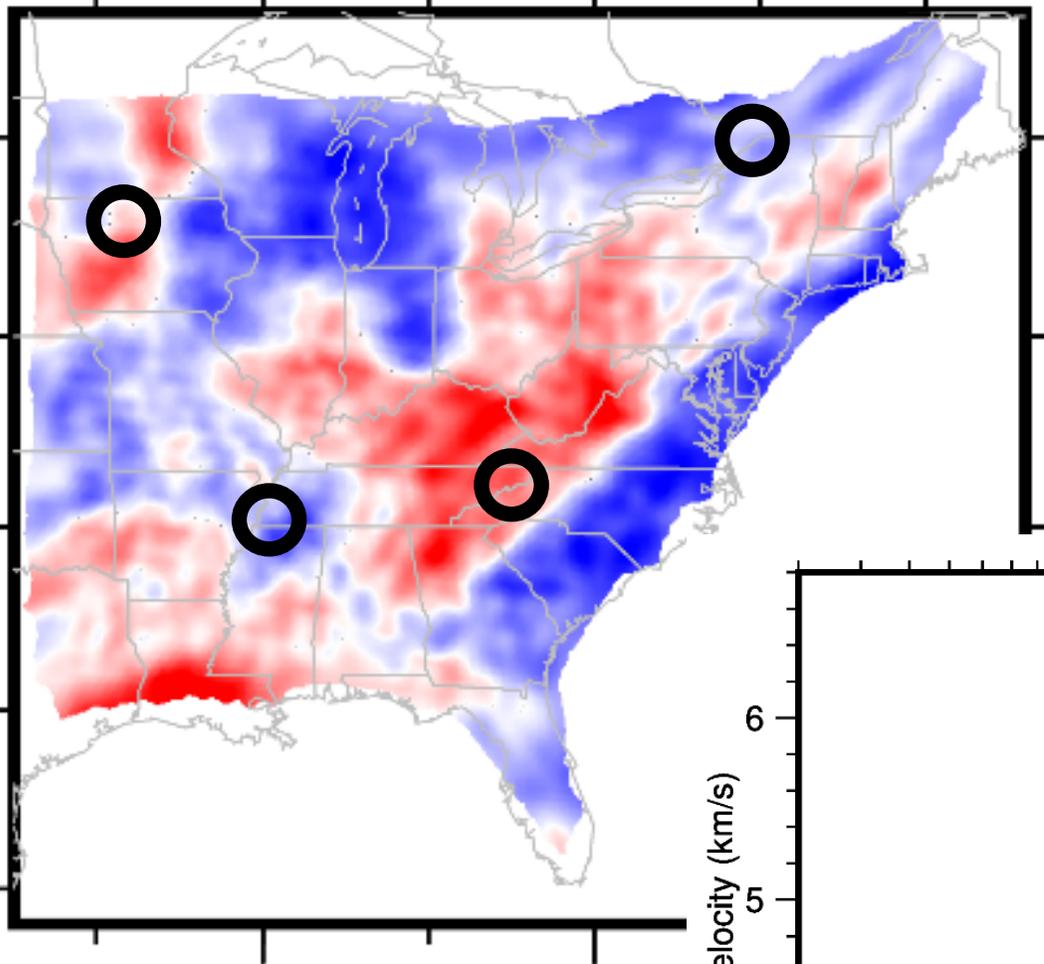
Devenish Arzuza et al., *work in progress*









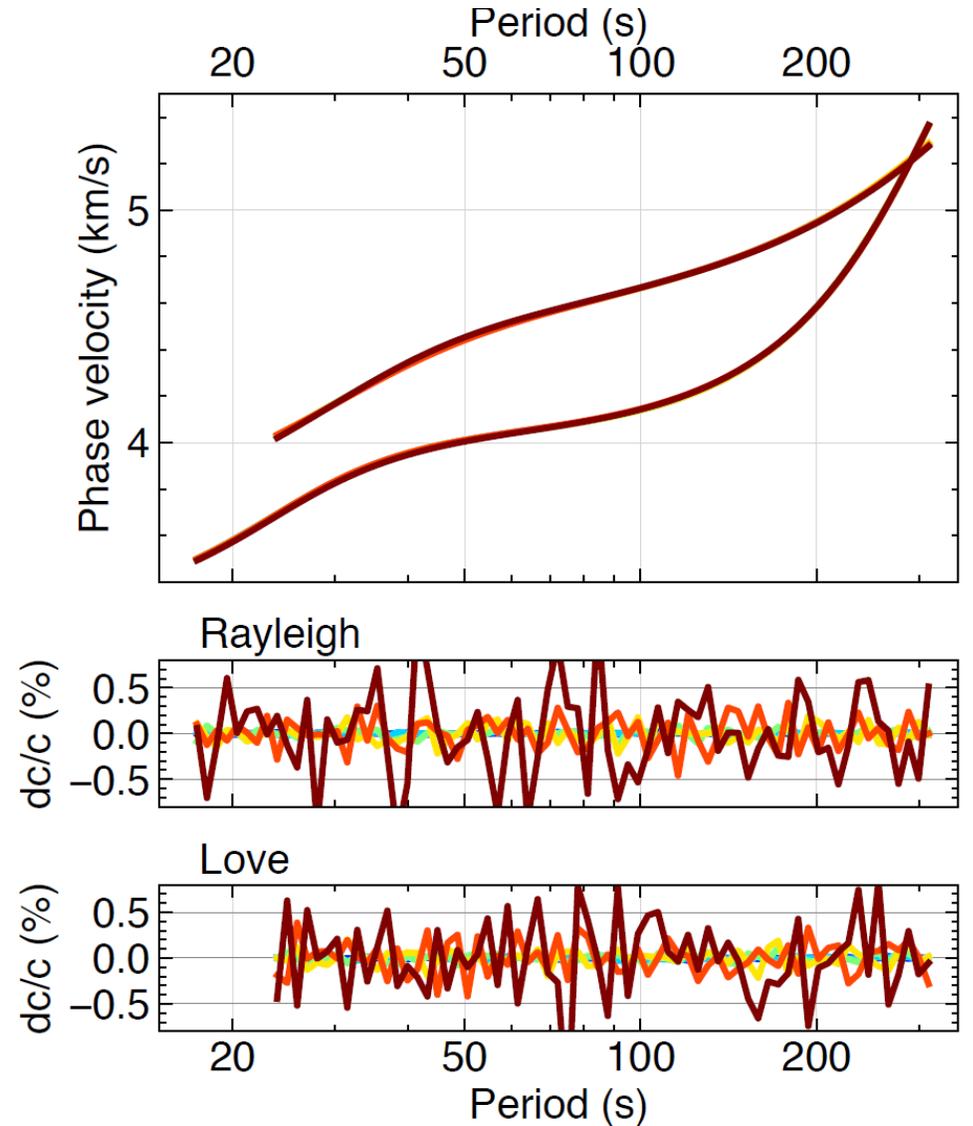
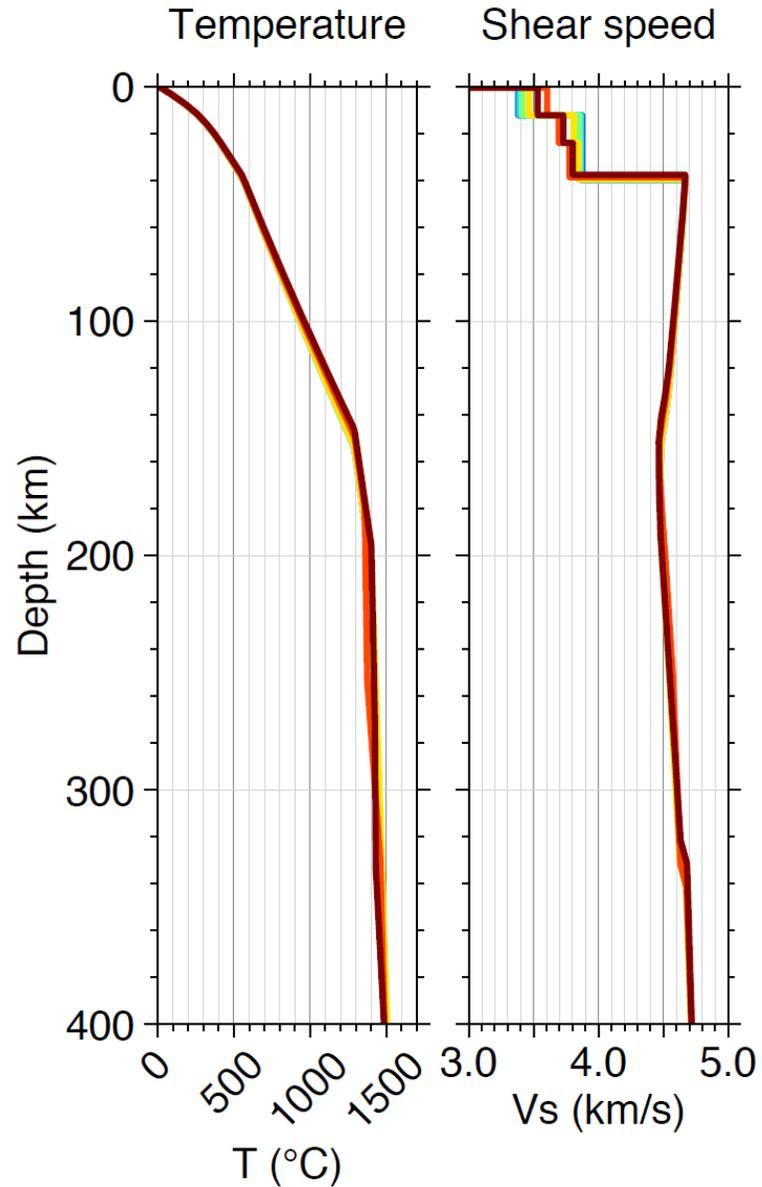


- This study** (pink)
- Ekstrom 2017** (blue)
- Babikoff & Dalton 2019** (orange)
- Schmandt et al 2015** (green)
- AK135** (black)

Thermodynamic inversion: random errors matter little

Random error, σ
(Normal distribution)

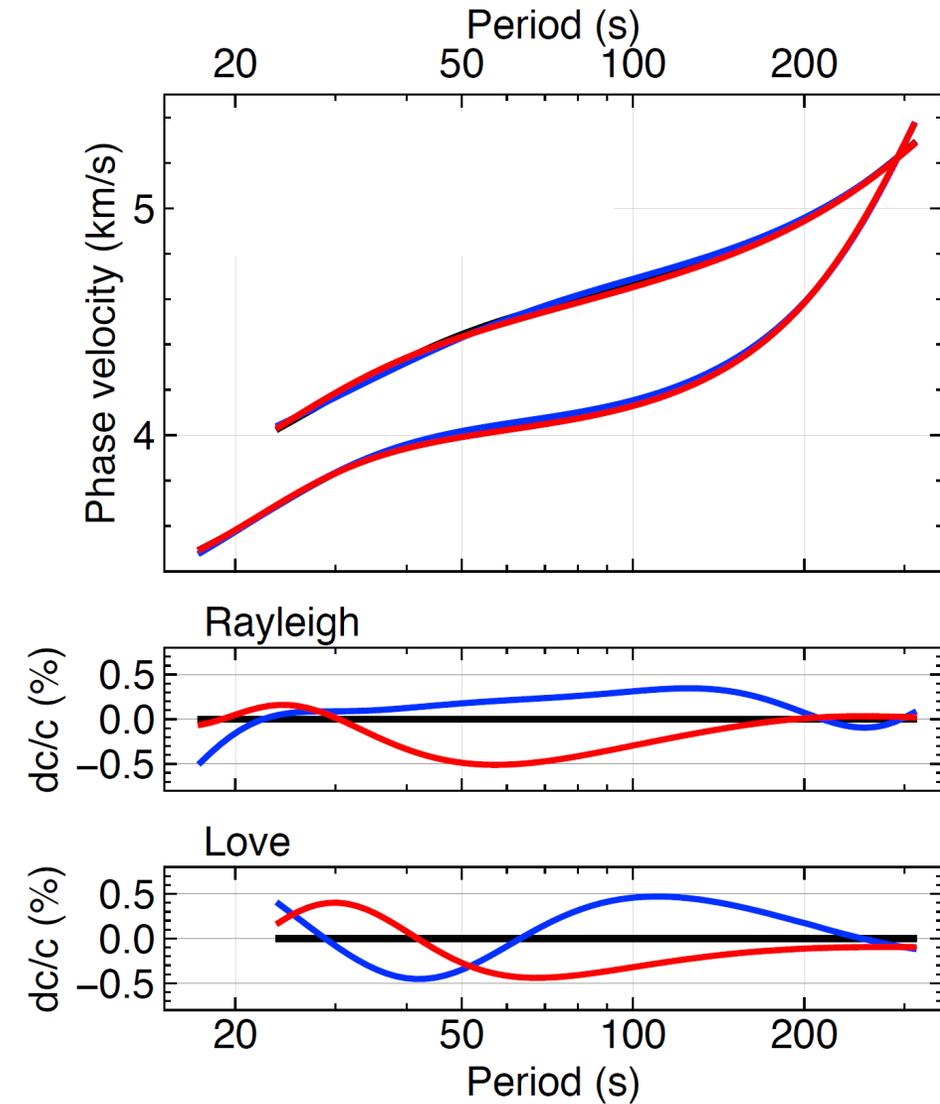
- 0%
- 0.01%
- 0.02%
- 0.05%
- 0.1%
- 0.2%
- 0.5%



Correlated errors can matter a lot

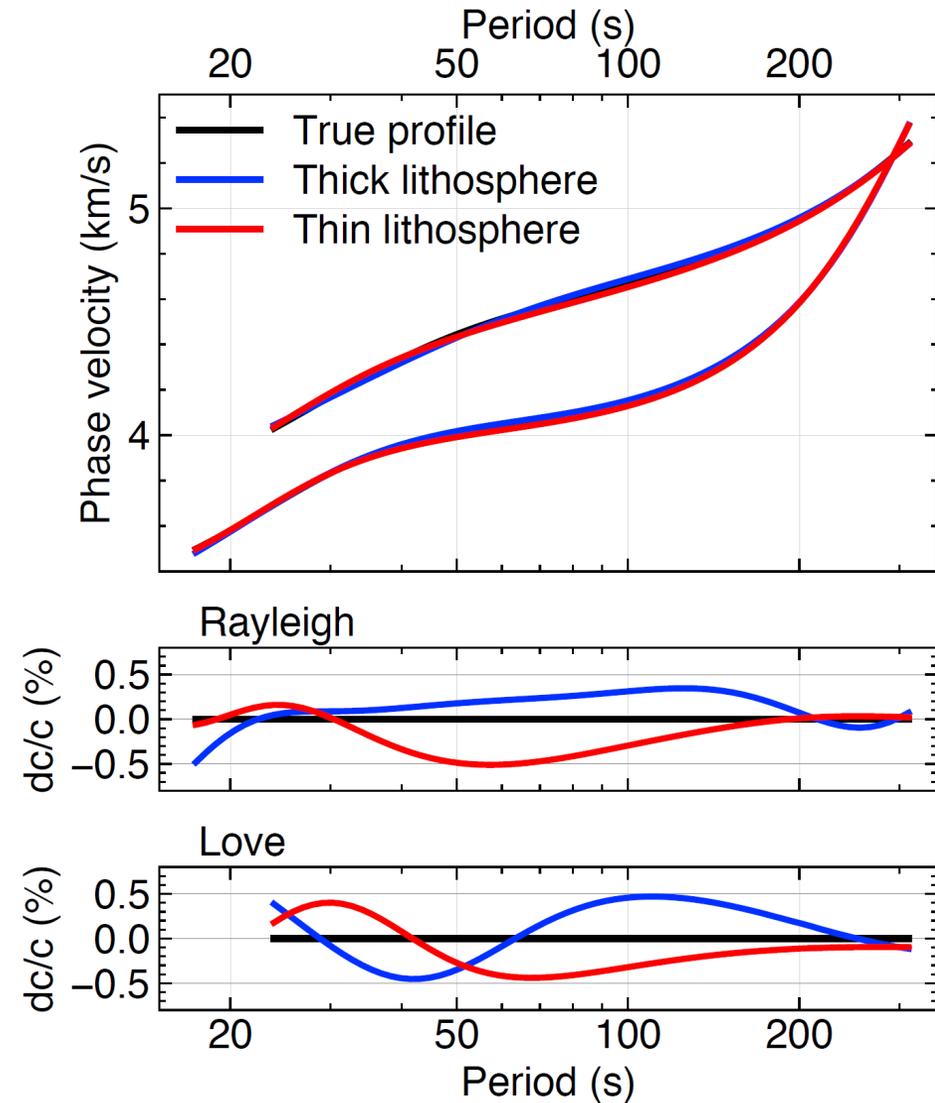
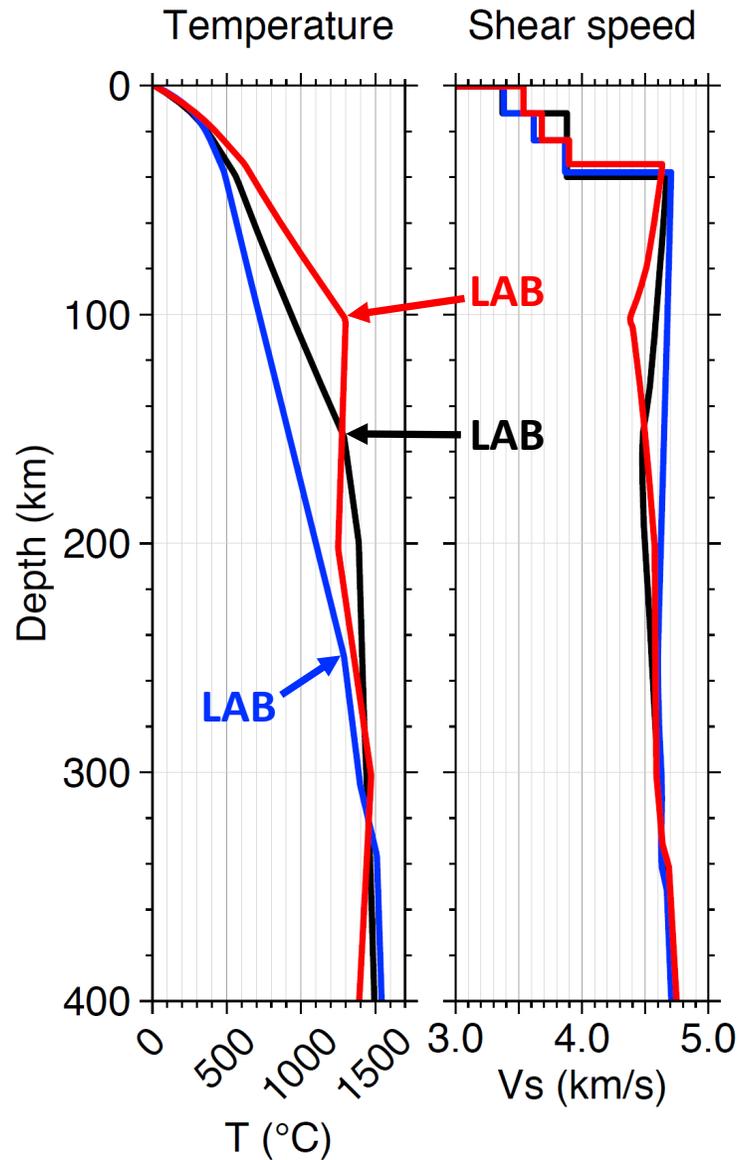
0.5% correlated errors

- What's the worst that can happen?



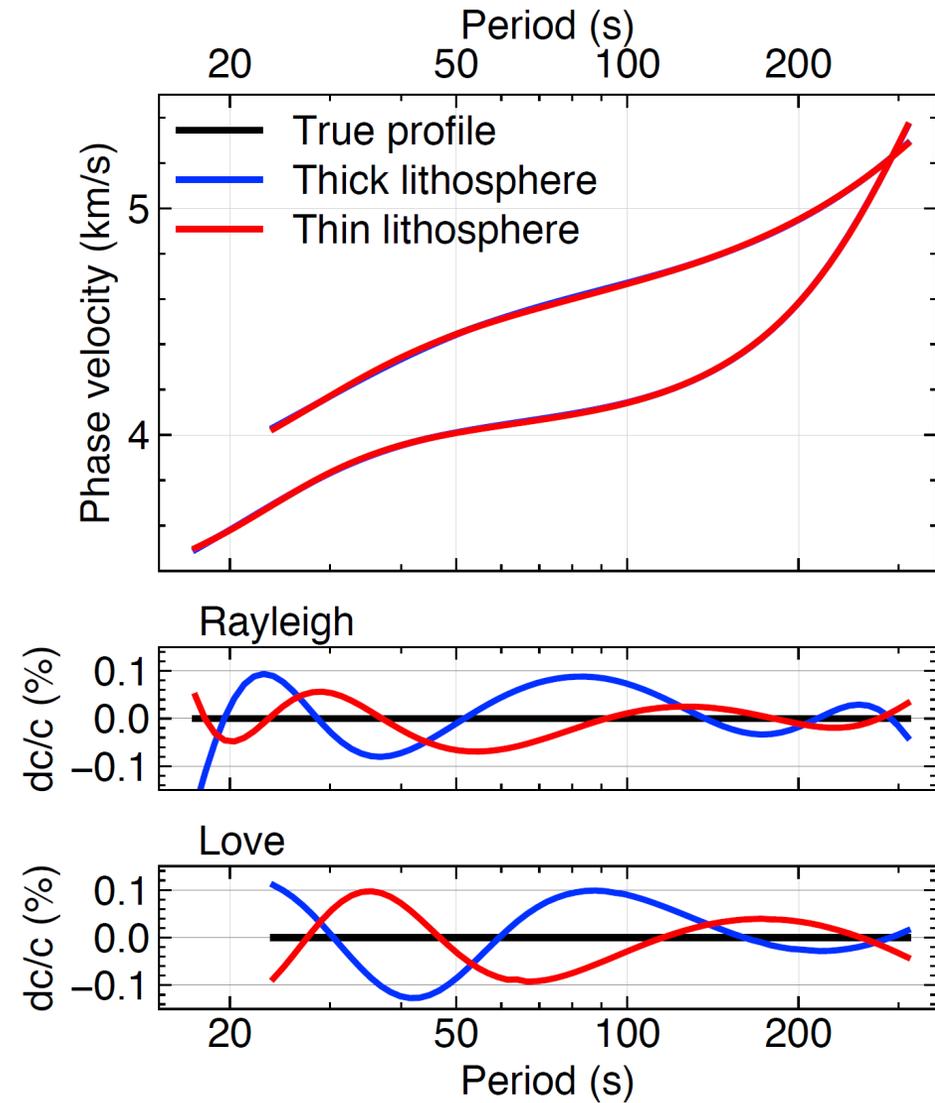
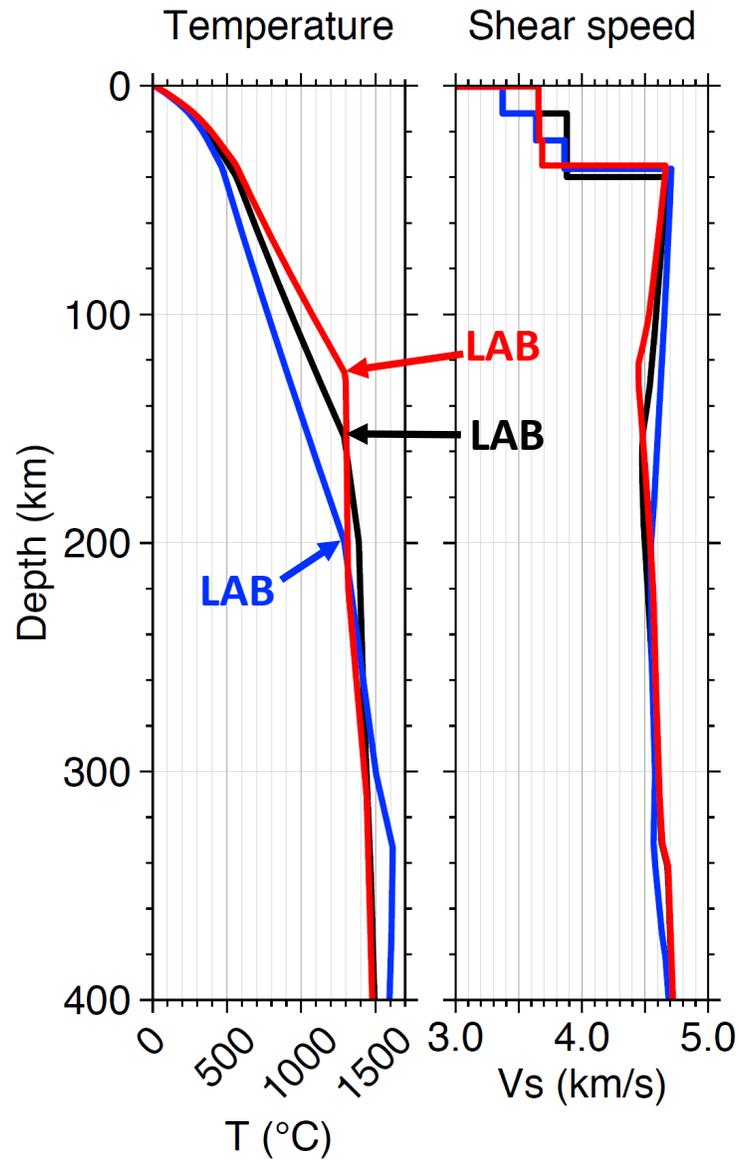
0.5% error

- What's the worst that can happen?
- Lithospheric thickness in the **100-250 km** range fits the data within 0.5%
- Strongly correlated errors in the data can do this, although unlikely to this extent
- Poorly tuned inversion can produce models anywhere in the range



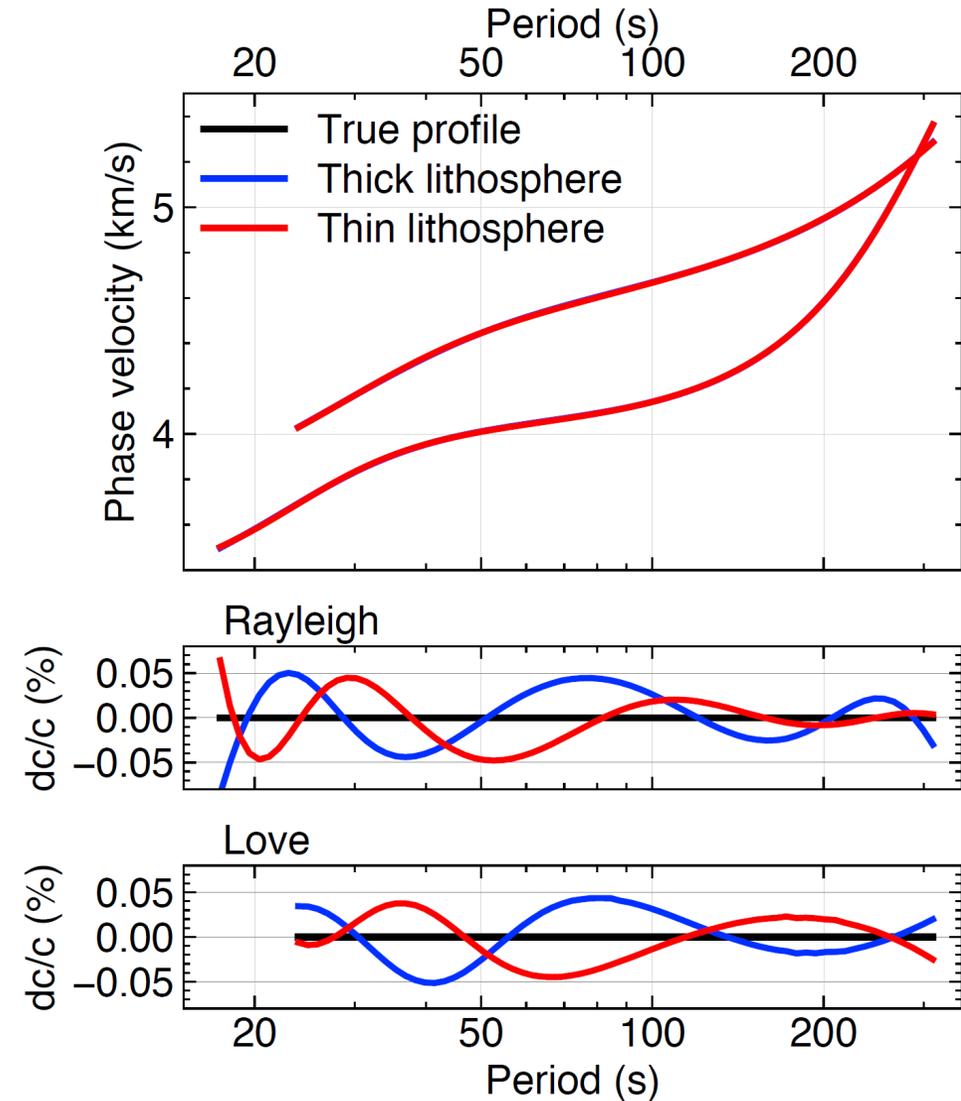
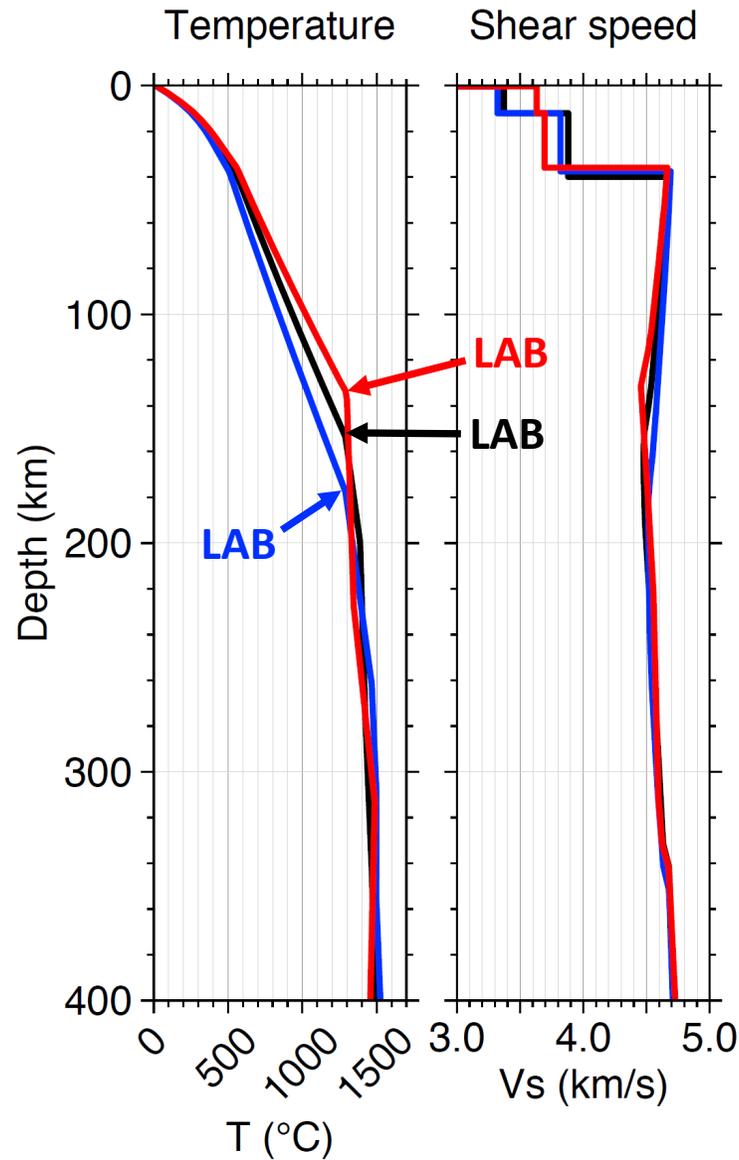
0.1% error

- What's the worst that can happen?
- Lithospheric thickness in the **125-200 km** range fits the data within 0.1%
- Strongly correlated errors in the data can do this, although unlikely to this extent
- Poorly tuned inversion can produce models anywhere in the range



0.05% error

- What's the worst that can happen?
- Lithospheric thickness in the **133-175 km** range fits the data within 0.05%
- Strongly correlated errors in the data can do this, although unlikely to this extent
- Poorly tuned inversion can produce models anywhere in the range



Summary

- **Seismic tomography**

- Increasing data sampling and improving methods yield continuing increases in resolution

- Can now combine more accurately seismic and other geophysical and geological evidence

- **Seismic *thermography***

- Inversion of seismic data directly for temperature resolves subtle variations in the thermal structure and thickness of the lithosphere

- Need accurate, broadband measurements, small misfits

Summary

- **Lithospheric thickness**
 - Exerts controls on intraplate deformation and seismicity
- **Intraplate seismicity depends on:**
 - stress transmitted from plate boundaries;
 - lateral variations in the thickness and strength of the plate.
 - Deformation and seismicity often localize in thin-lithosphere areas and at thin-thick lithospheric thickness gradients