Toward Global Seismic Imaging based on Spectral-Element and Adjoint Methods

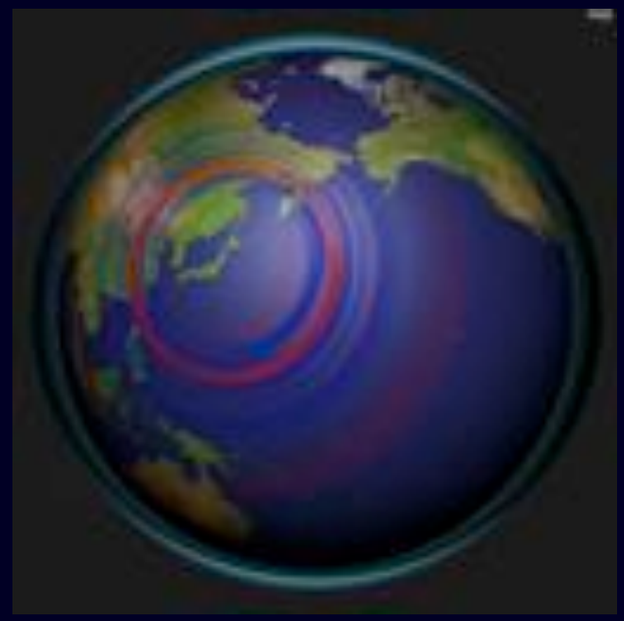
Jeroen Tromp

ACSS 2012

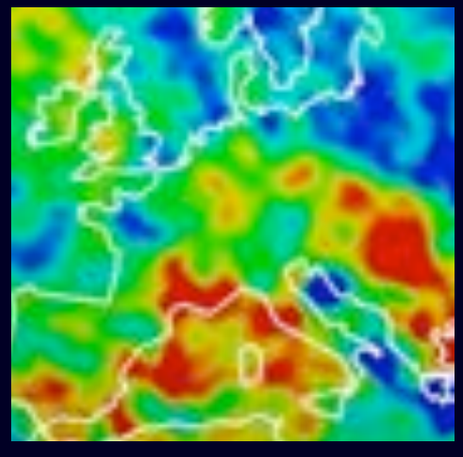
Collaborators: Ebru Bozdag, Joseph Charles, Dimitri Komatitsch, Daniel Peter, Max Riethmann, Olaf Schenk, and Hejun Zhu

Outline

Forward Modeling

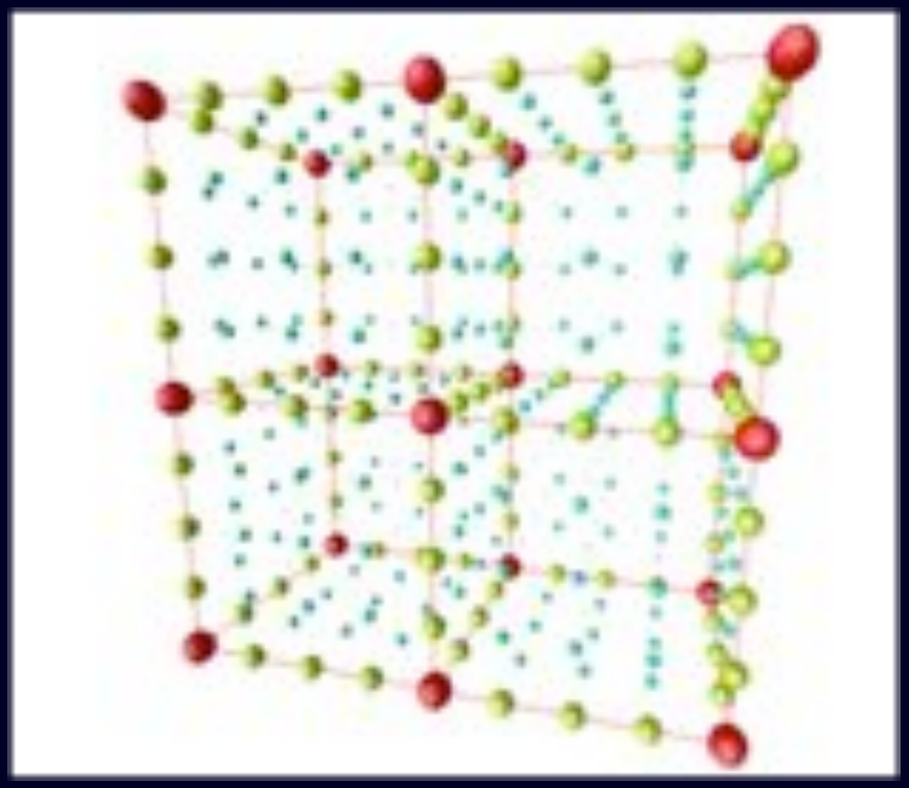


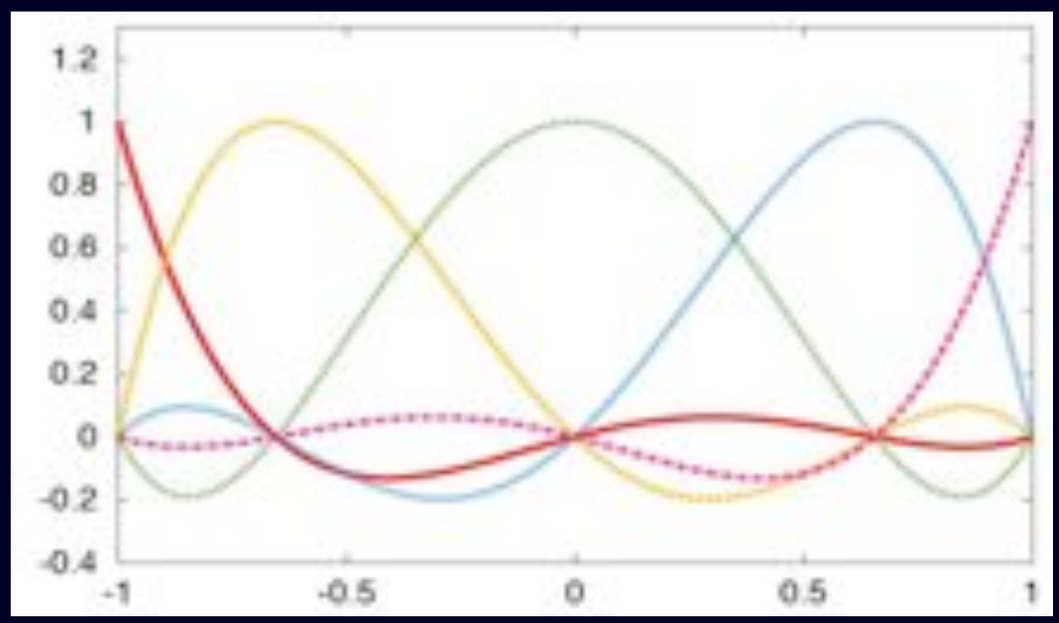
Adjoint Tomography



Spectral-Element Method

Finite-elements:

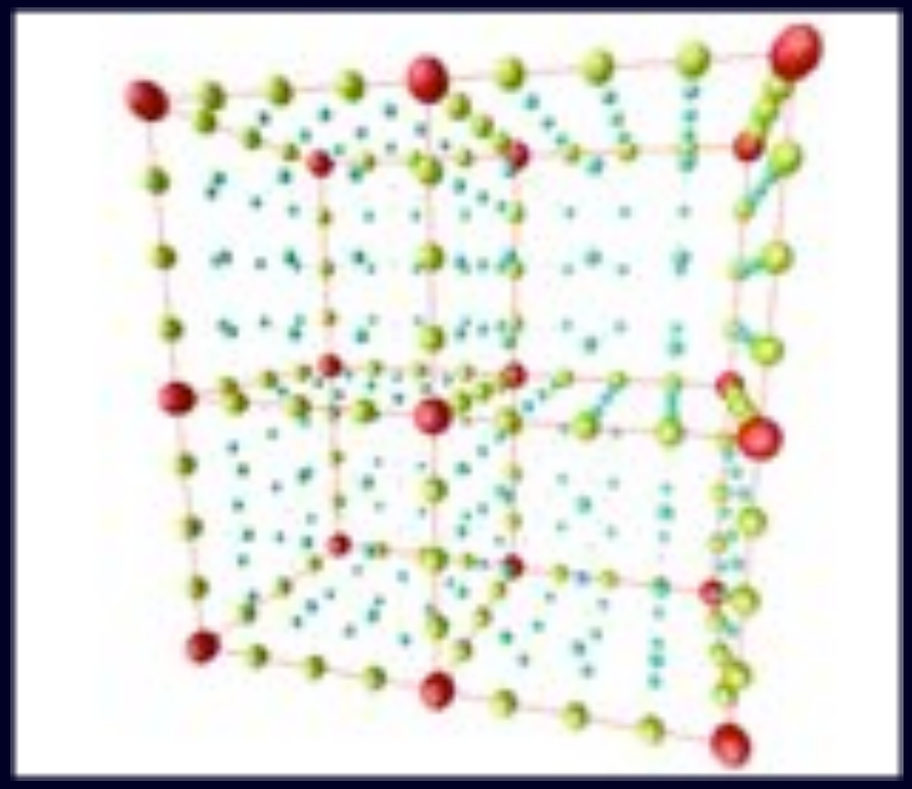


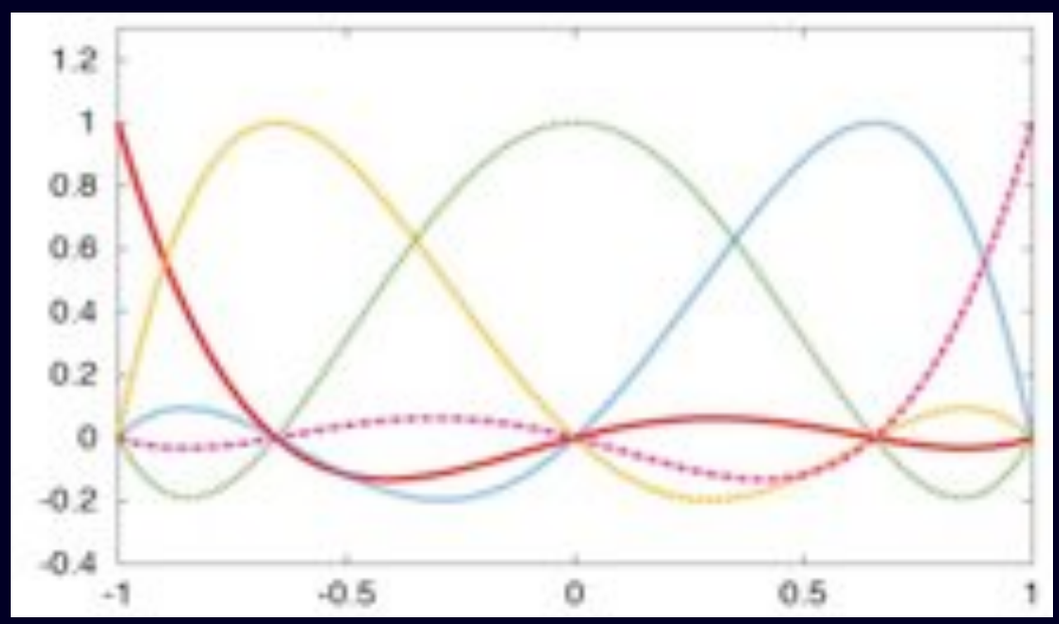


Spectral-Element Method

Finite-elements:

- hexahedral elements



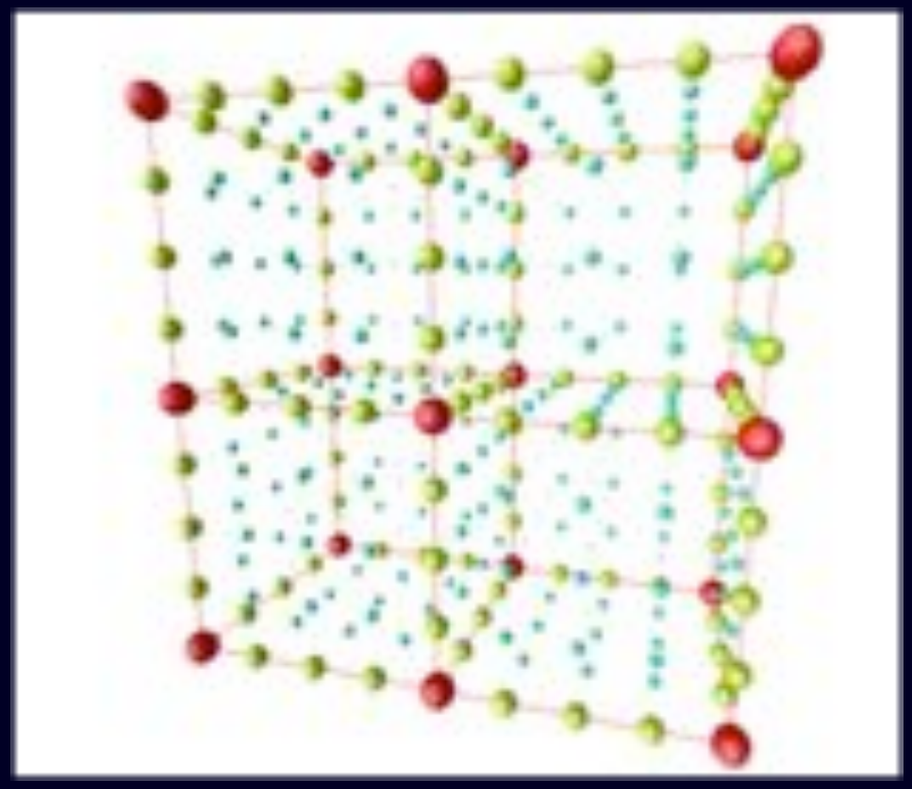


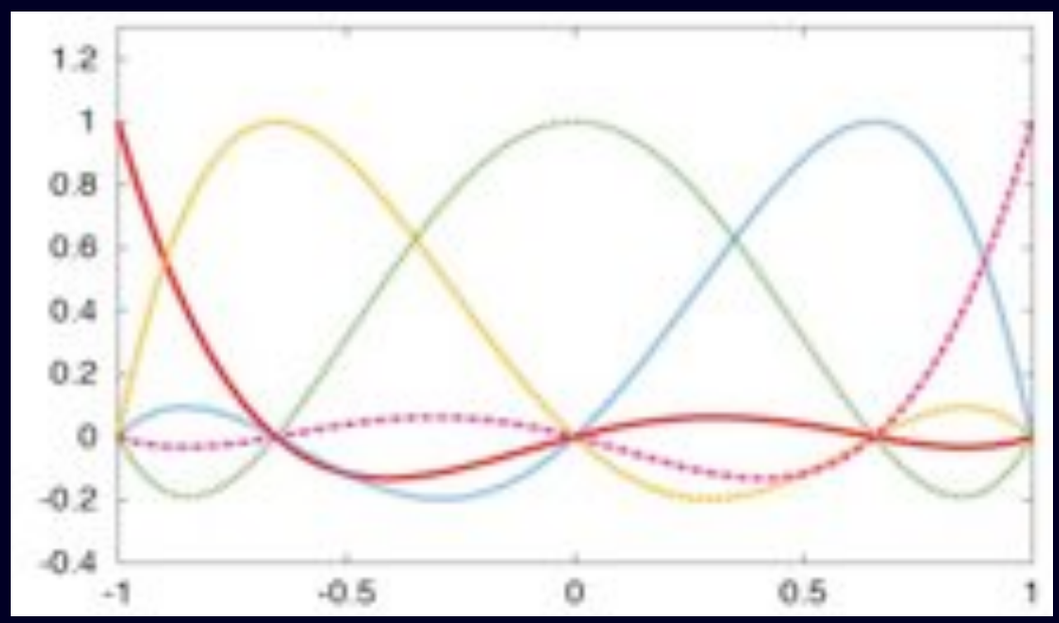
Spectral-Element Method

Finite-elements:

- hexahedral elements

- Gauss-Lobatto-Legrendre quadrature

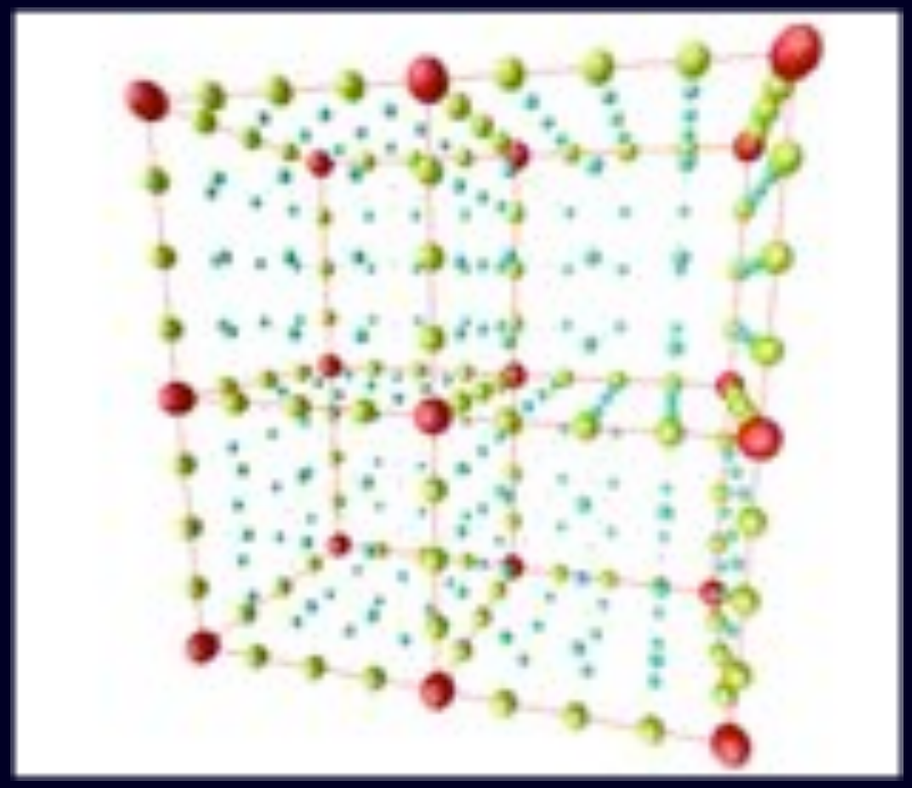


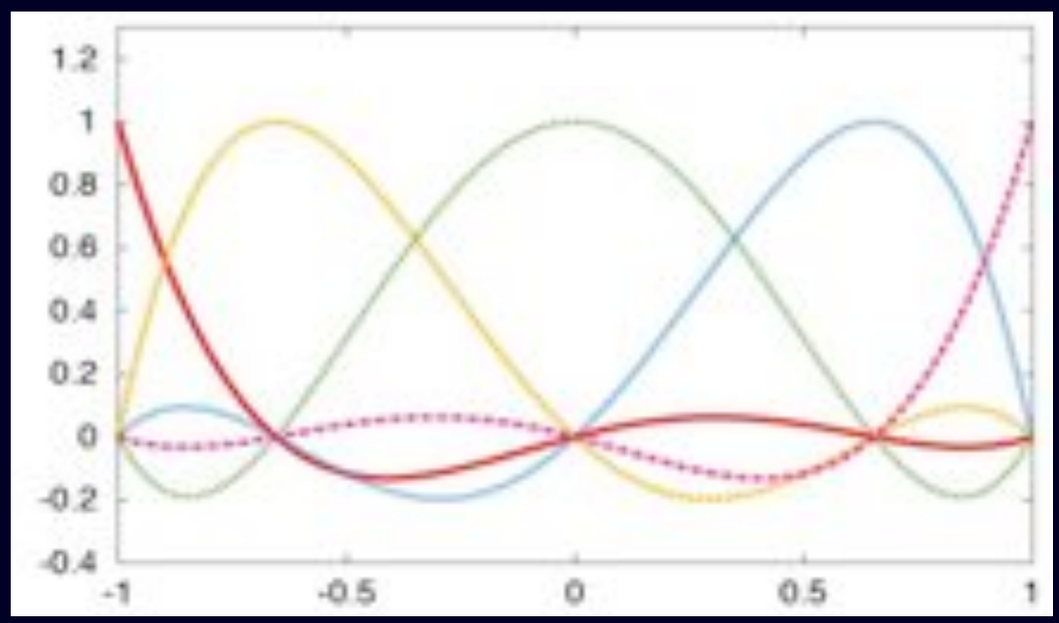


Spectral-Element Method

Finite-elements:

- hexahedral elements
- Gauss-Lobatto-Legrendre quadrature
- diagonal mass matrix





Spectral-Element Method

Finite-elements:

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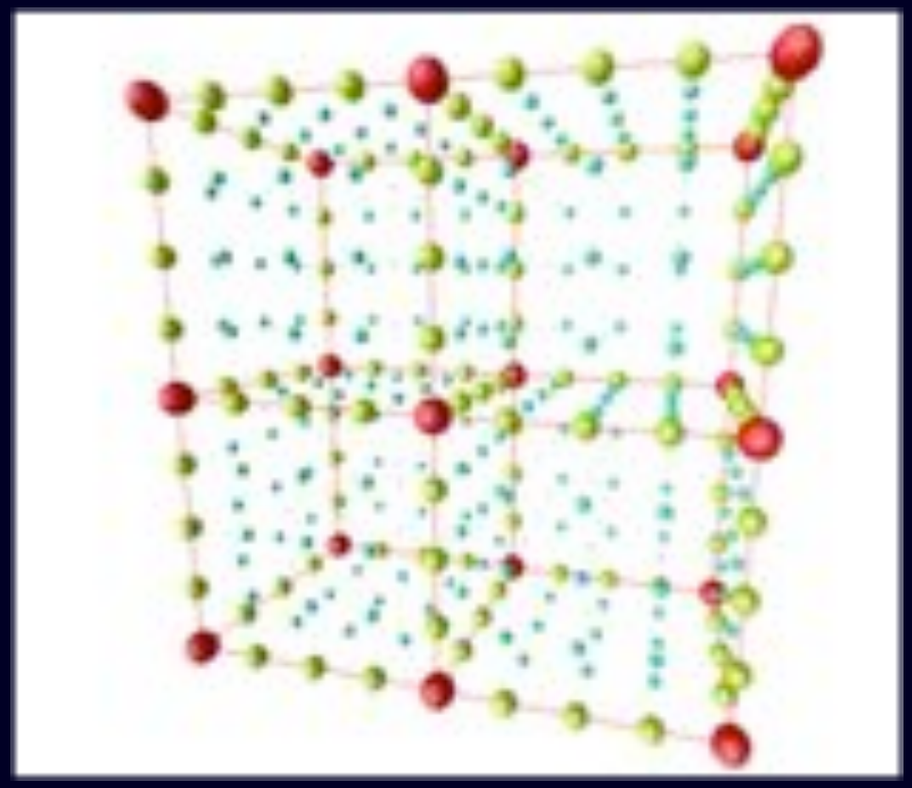
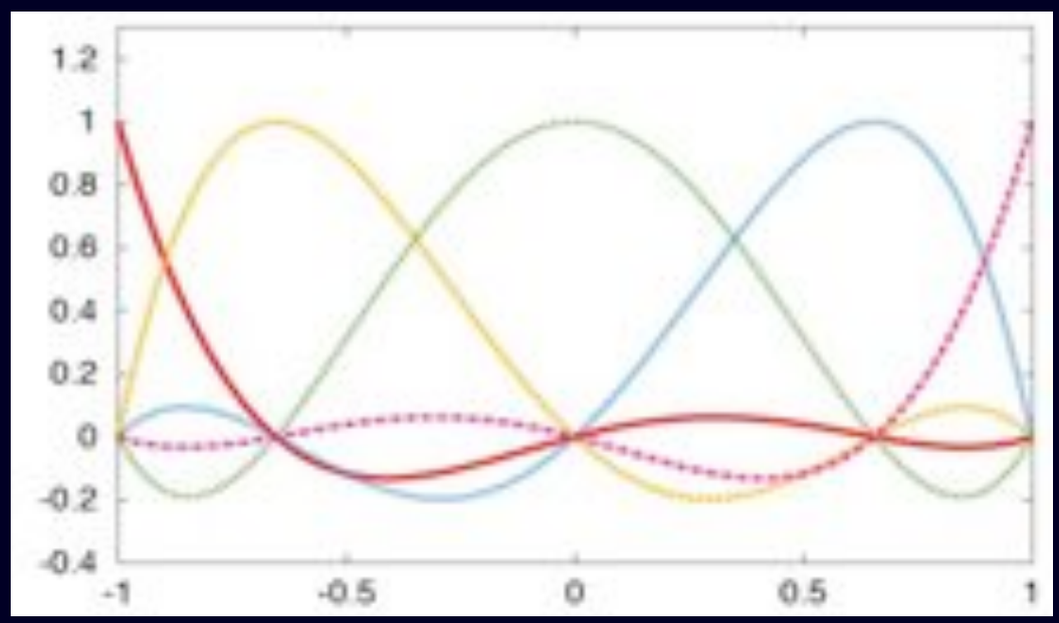
- diagonal mass matrix
- explicit time-marching scheme





Spectral-Element Method

Finite-elements:

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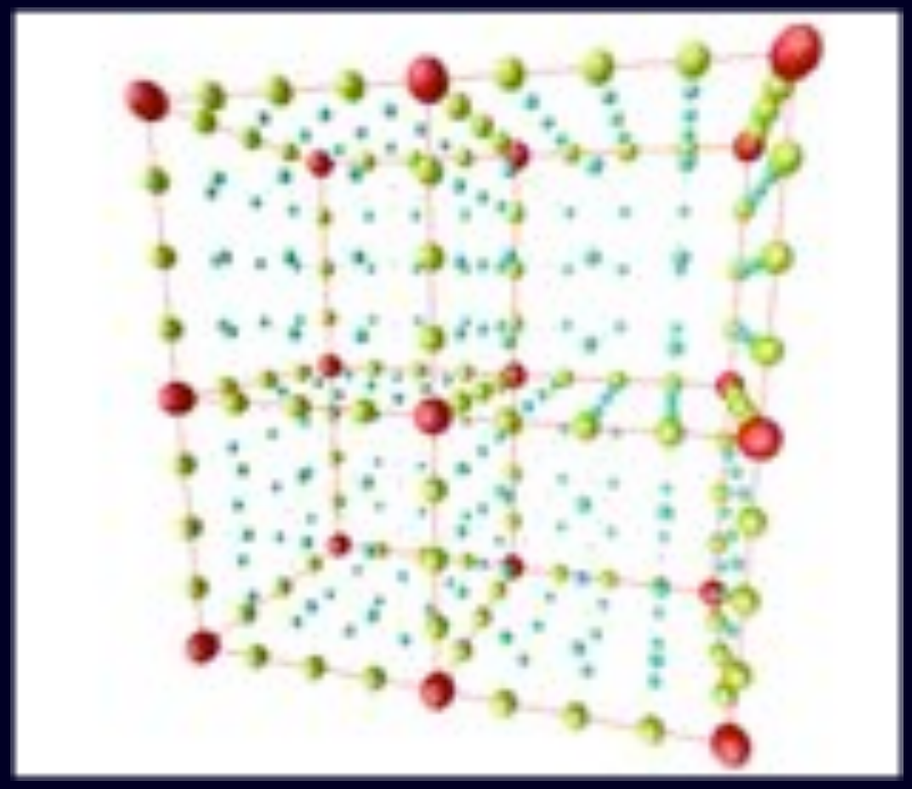
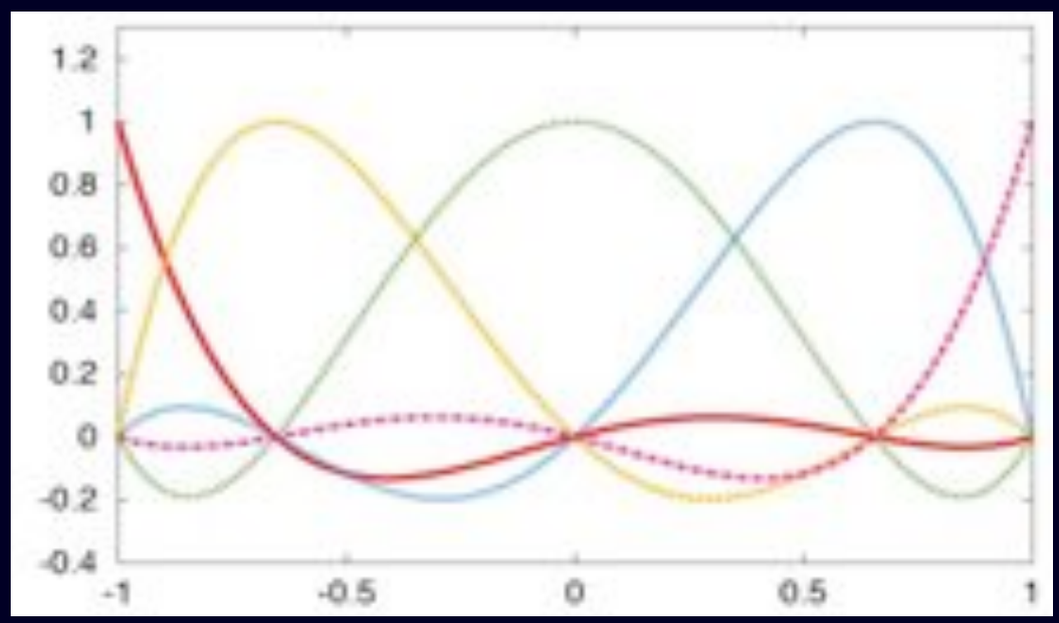
- explicit time-marching scheme

$$\mathbf{M}\ddot{\mathbf{U}} = -\mathbf{K}\mathbf{U} + \mathbf{F}$$





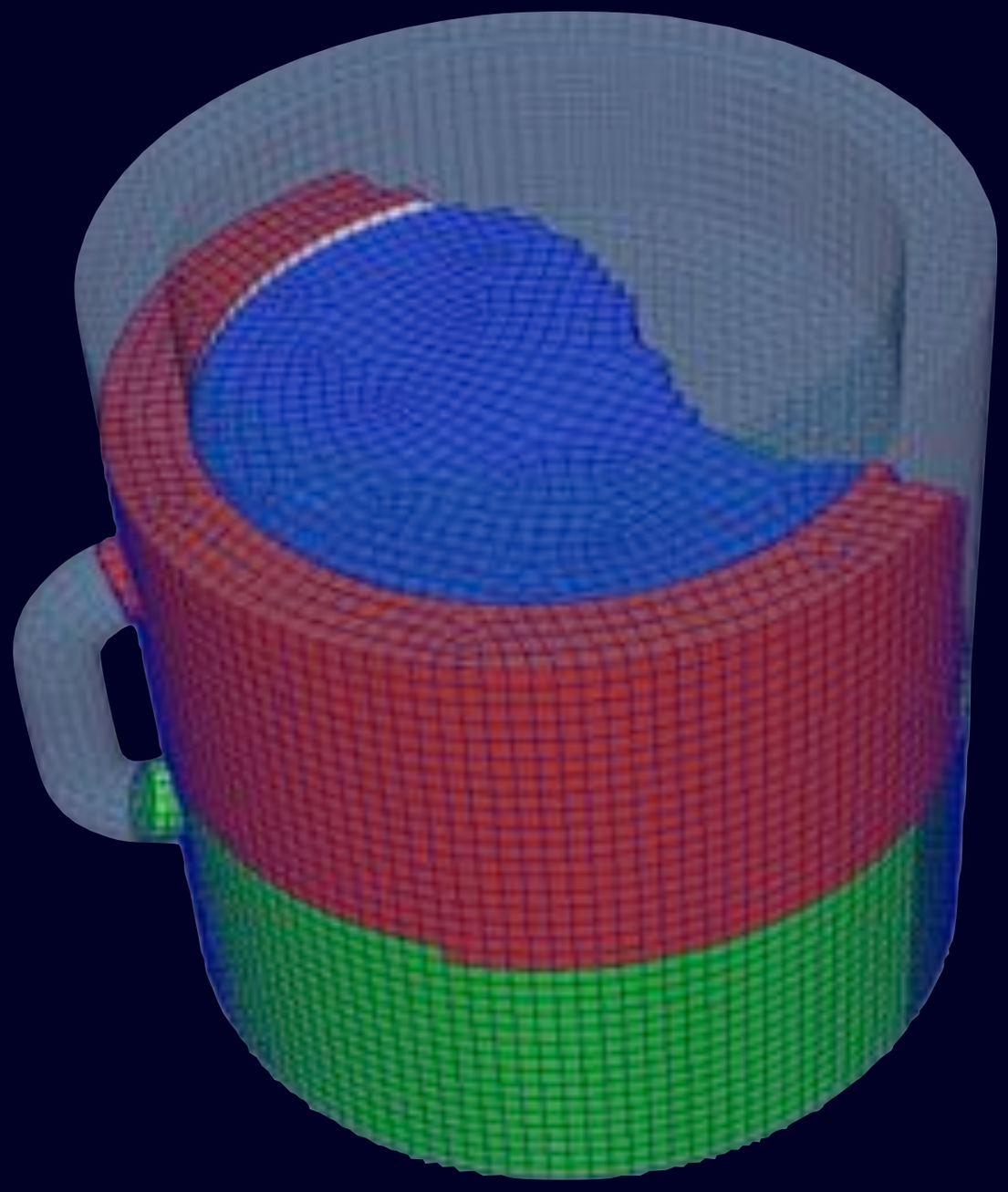
Open Source Software

SPECFEM3D & SPECFEM3D_GLOBE

www.geodynamics.org

- 3D crust and mantle models
- Topography & Bathymetry
- Rotation
- Ellipticity
- Gravitation
- Anisotropy
- Attenuation

Coffee Cup Simulation



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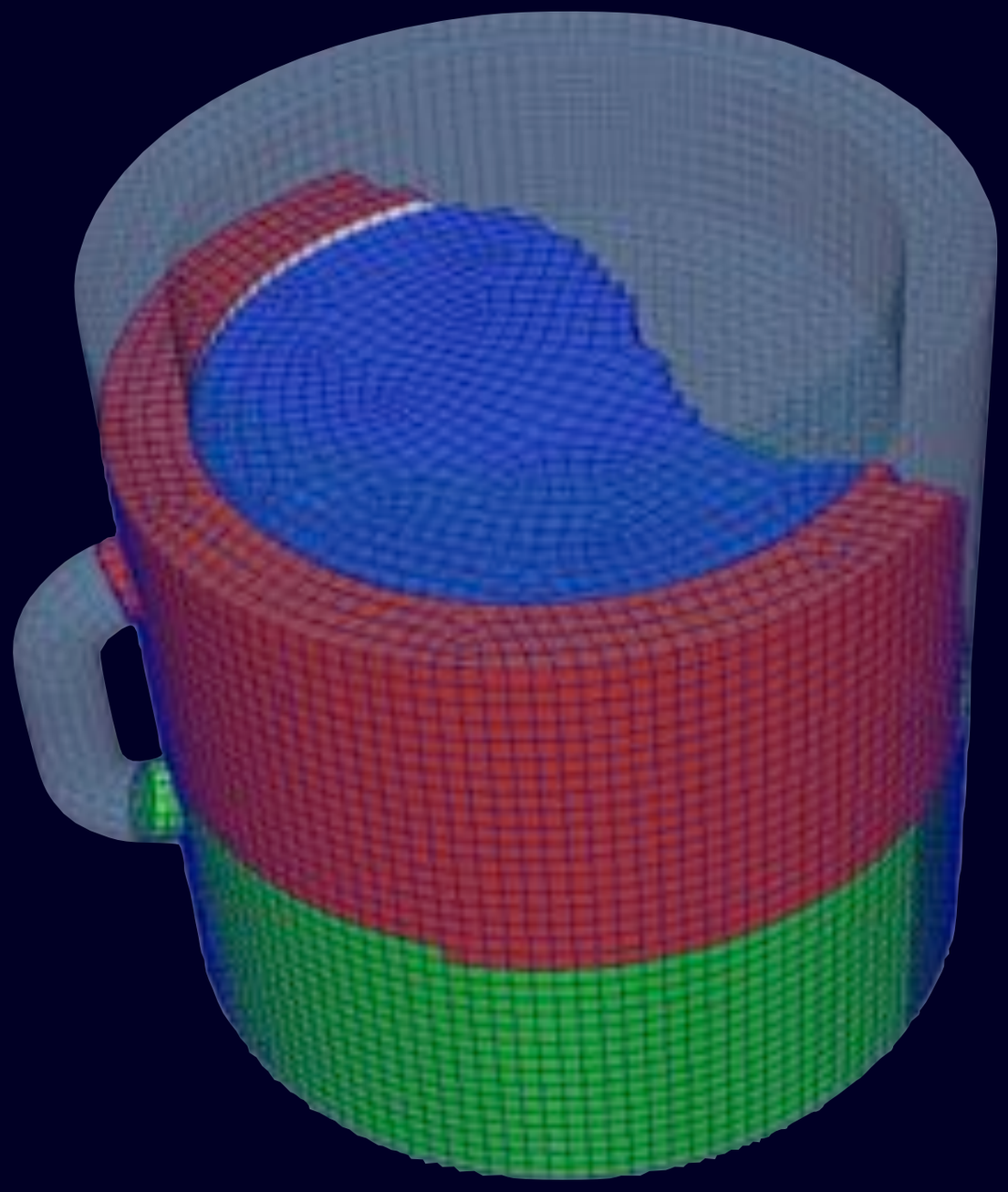
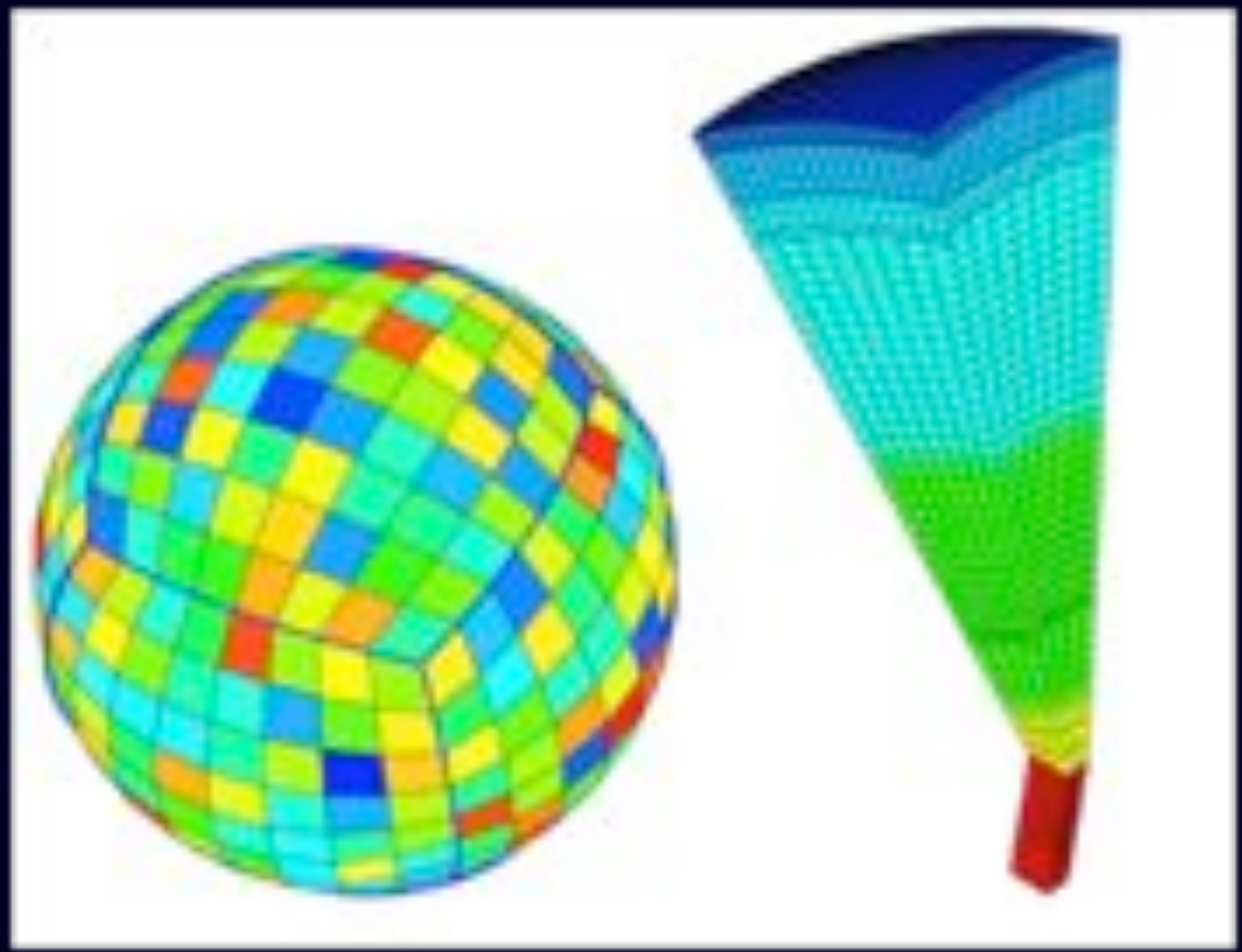


SPECFEM3D

Parallel Implementation

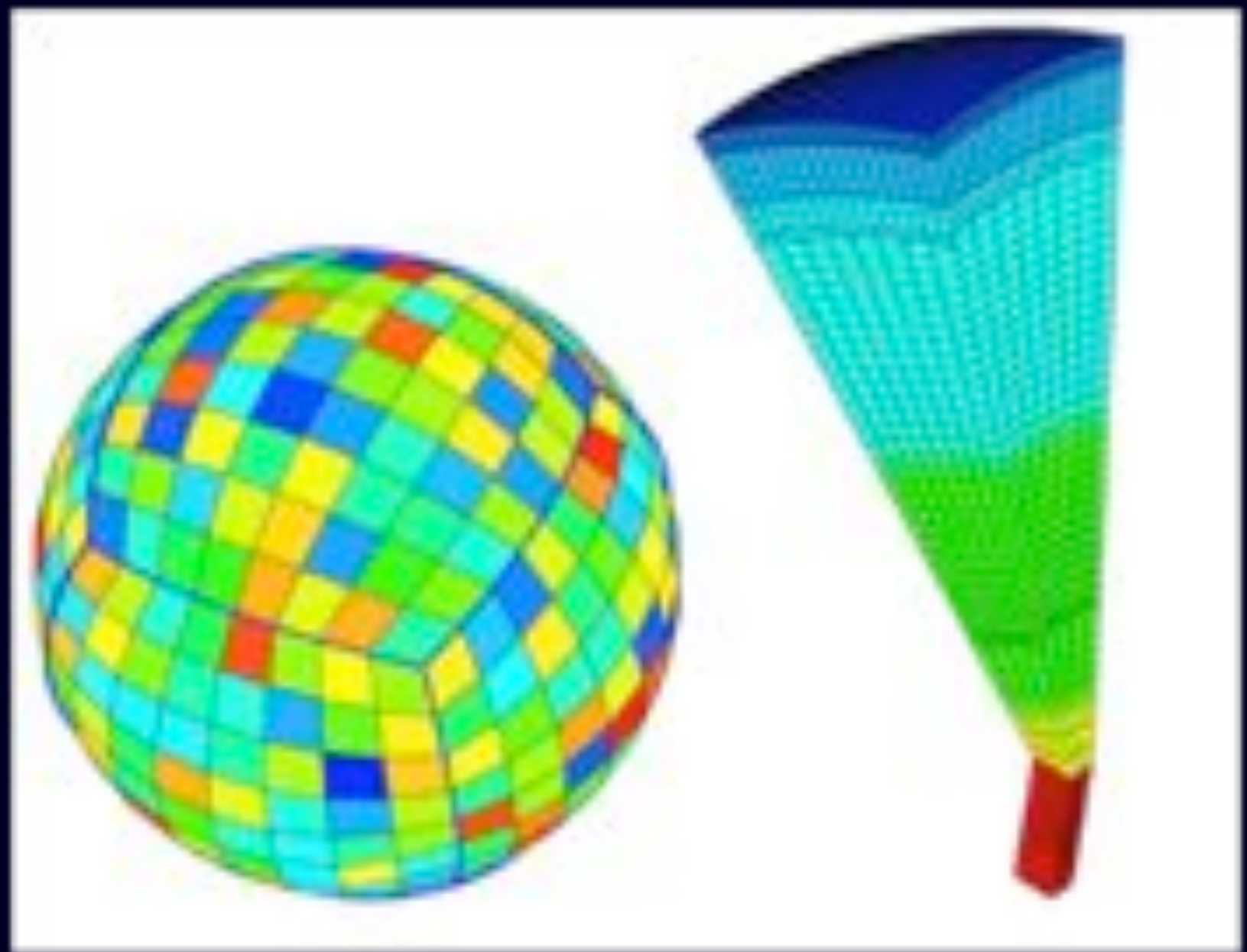
Global mesh partitioning



Cubed Sphere: 6 n^2 mesh slices

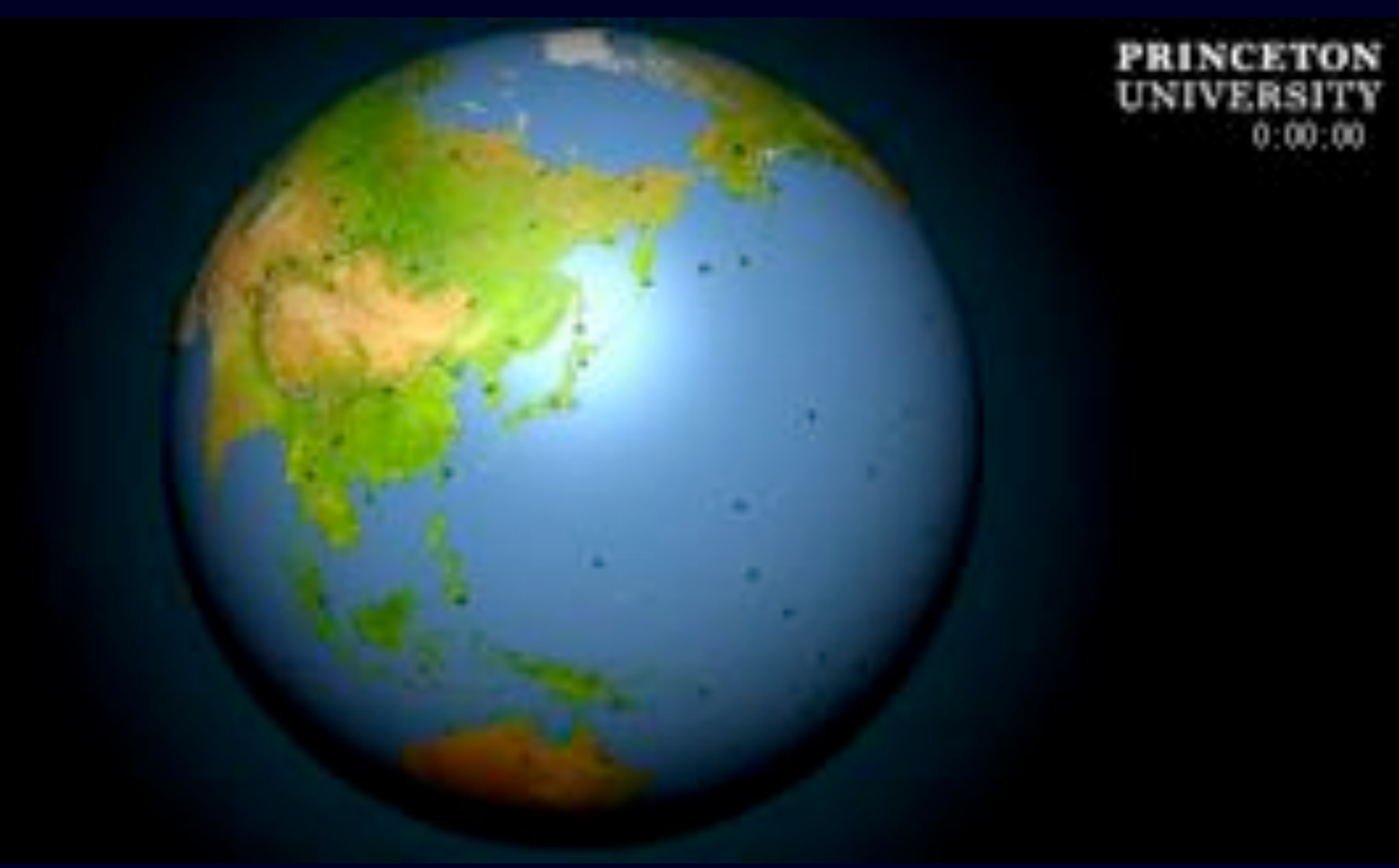
Parallel Implementation

Global mesh partitioning



SPECFEM3D_GLOBE

Cubed Sphere: 6 n^2 mesh slices



Tohoku Earthquake
March 11, 2011, M=9.1

resolution 17 s
5 h on 384 cores

Dennis McRitchie

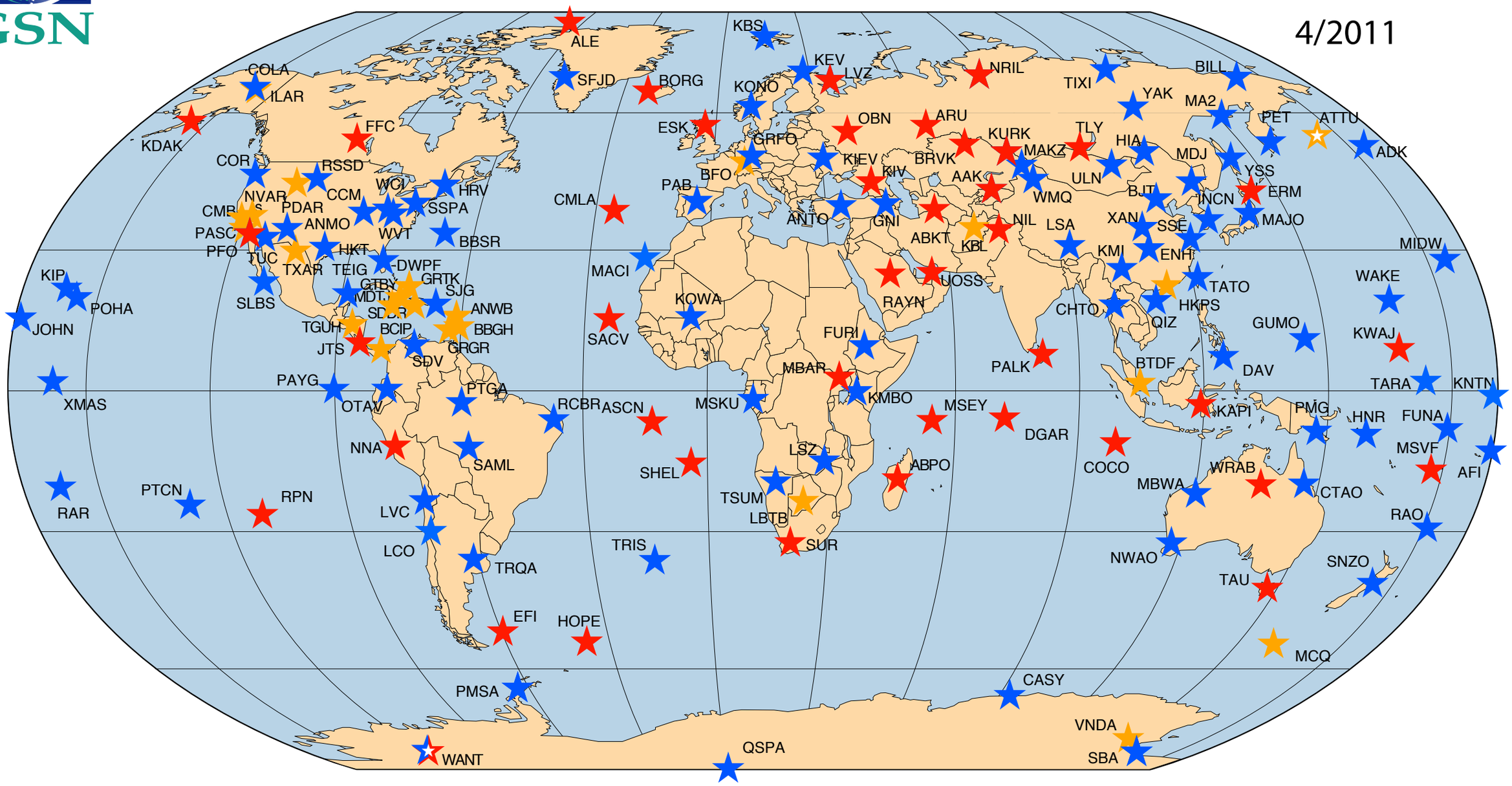
Near Real-Time Earthquake Information

global.shakemovie.princeton.edu

GLOBAL SEISMOGRAPHIC NETWORK

GSN

4/2011



★ IRIS / IDA Stations

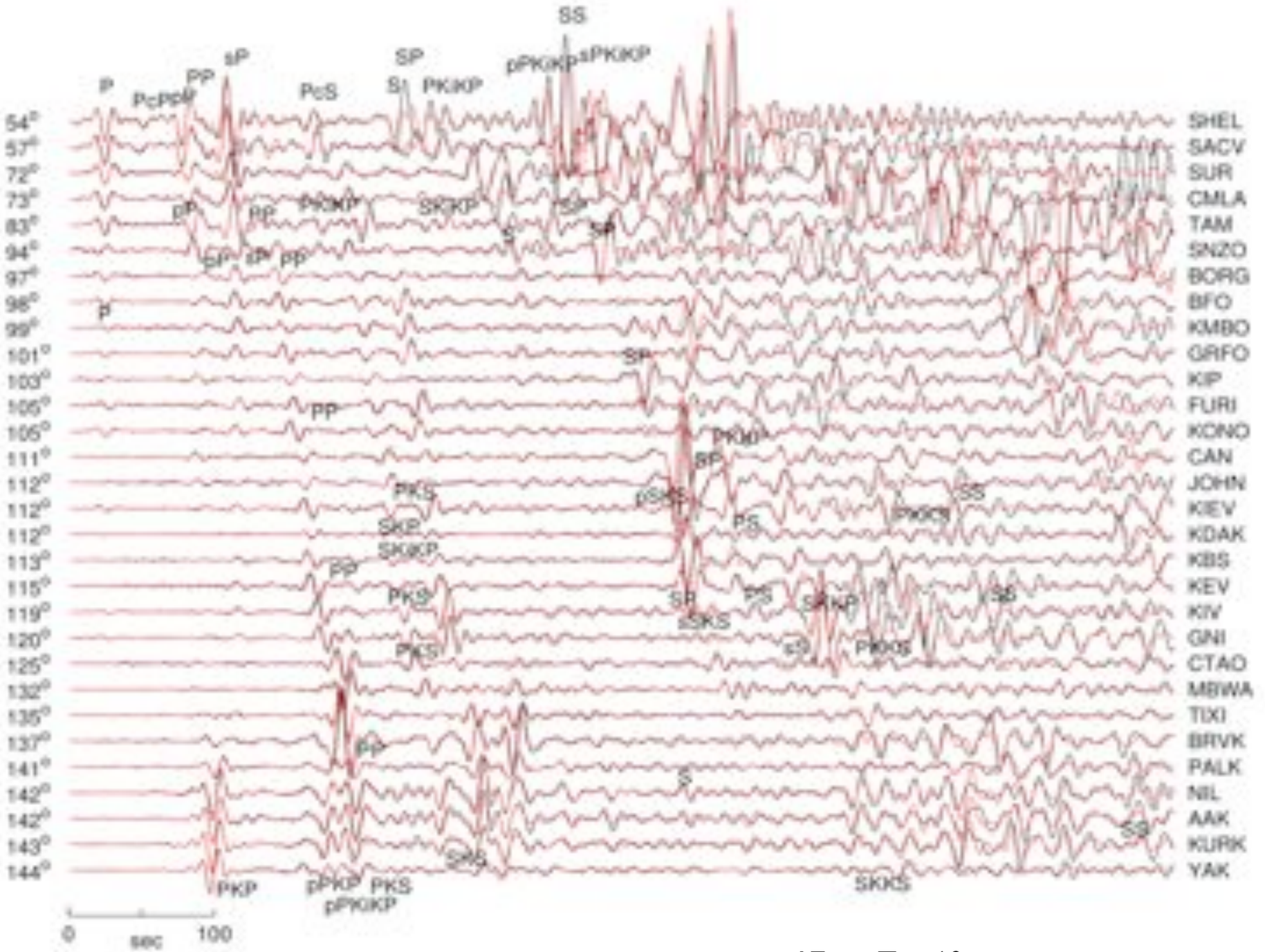
★ IRIS / USGS Stations

★ Affiliate Stations

☆ Planned Stations

Observed and Simulated Seismograms

September 3, 2008, Argentina (M=6.3, 571 km)

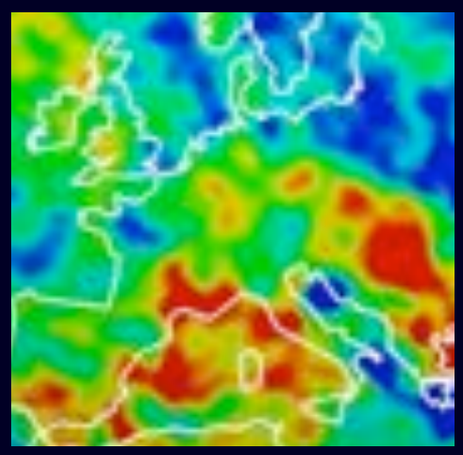


17 s < T < 60 s

Another Seismometer....

Forward Modeling

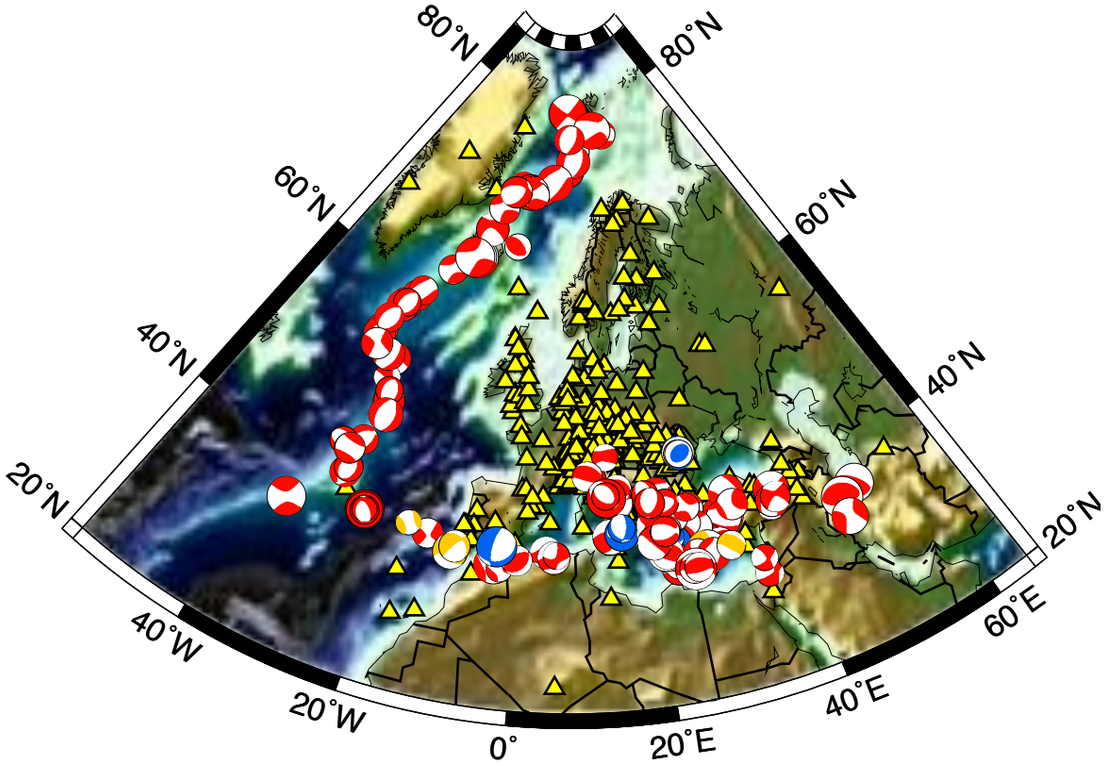
Adjoint Tomography



Seismic Imaging of Europe

160 earthquakes

750 seismographic stations



Hejun Zhu

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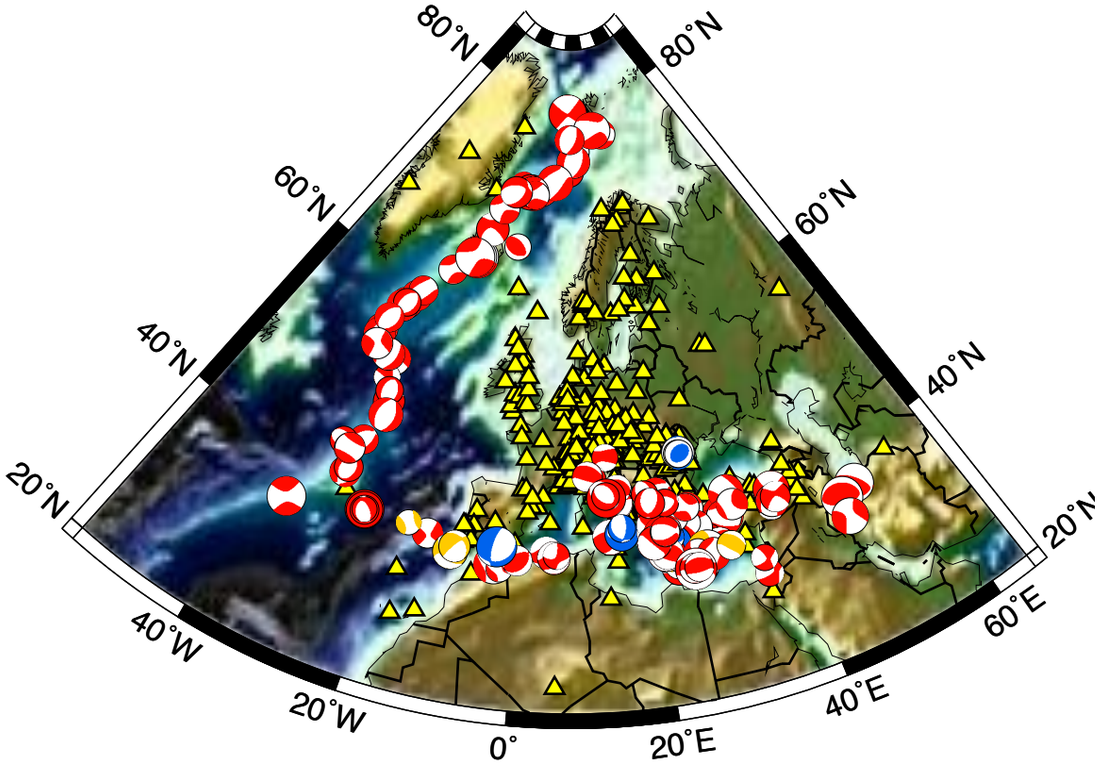
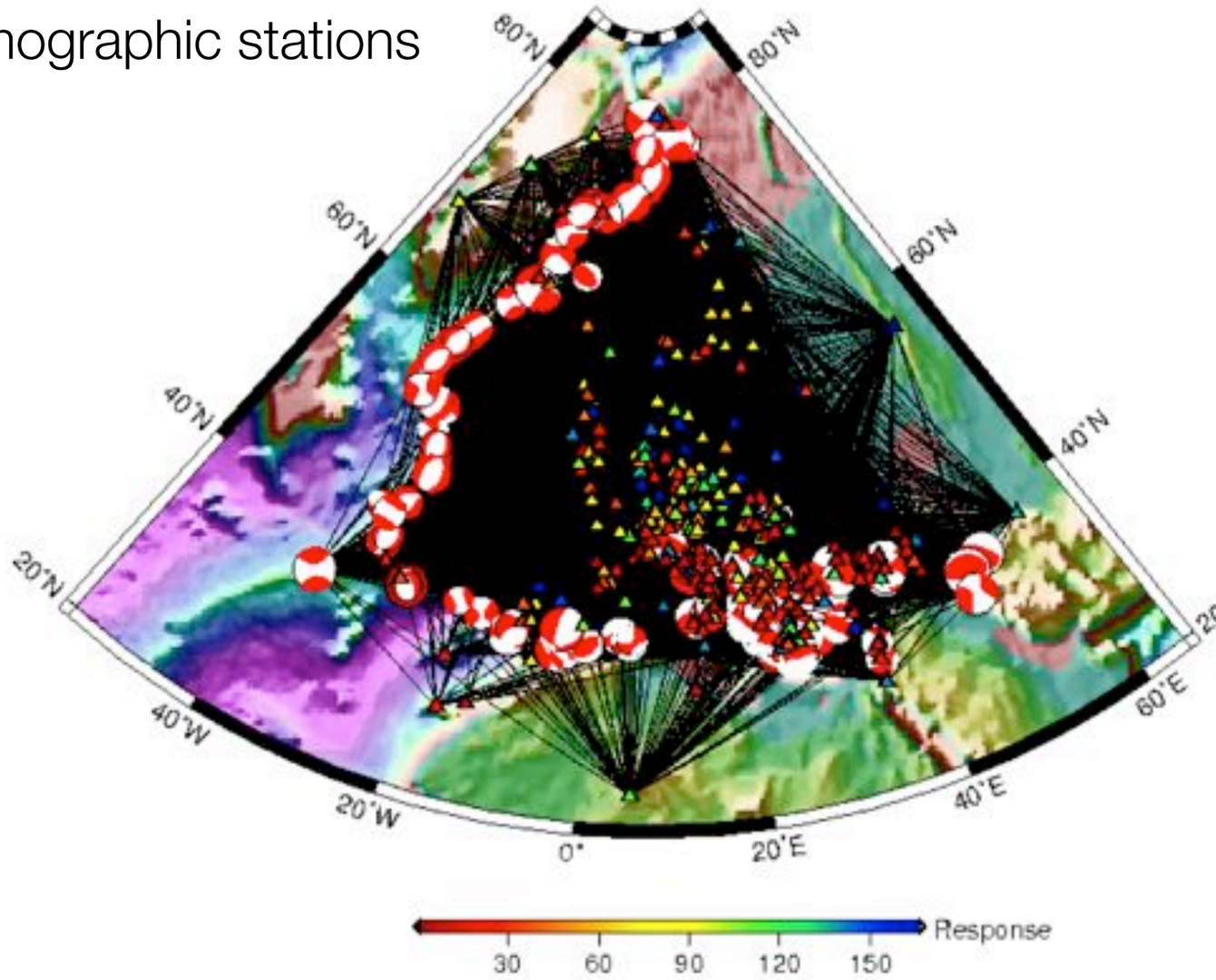
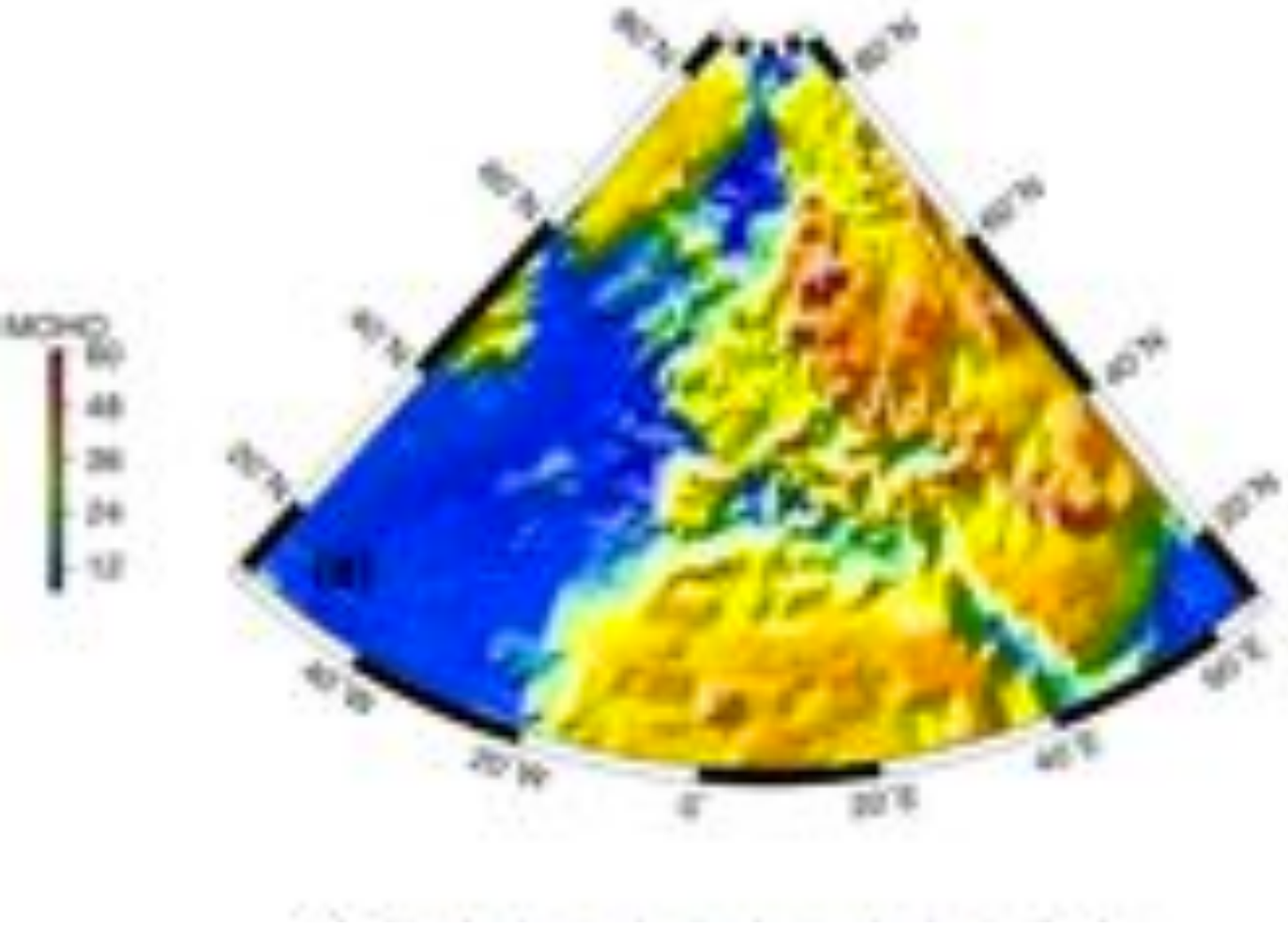




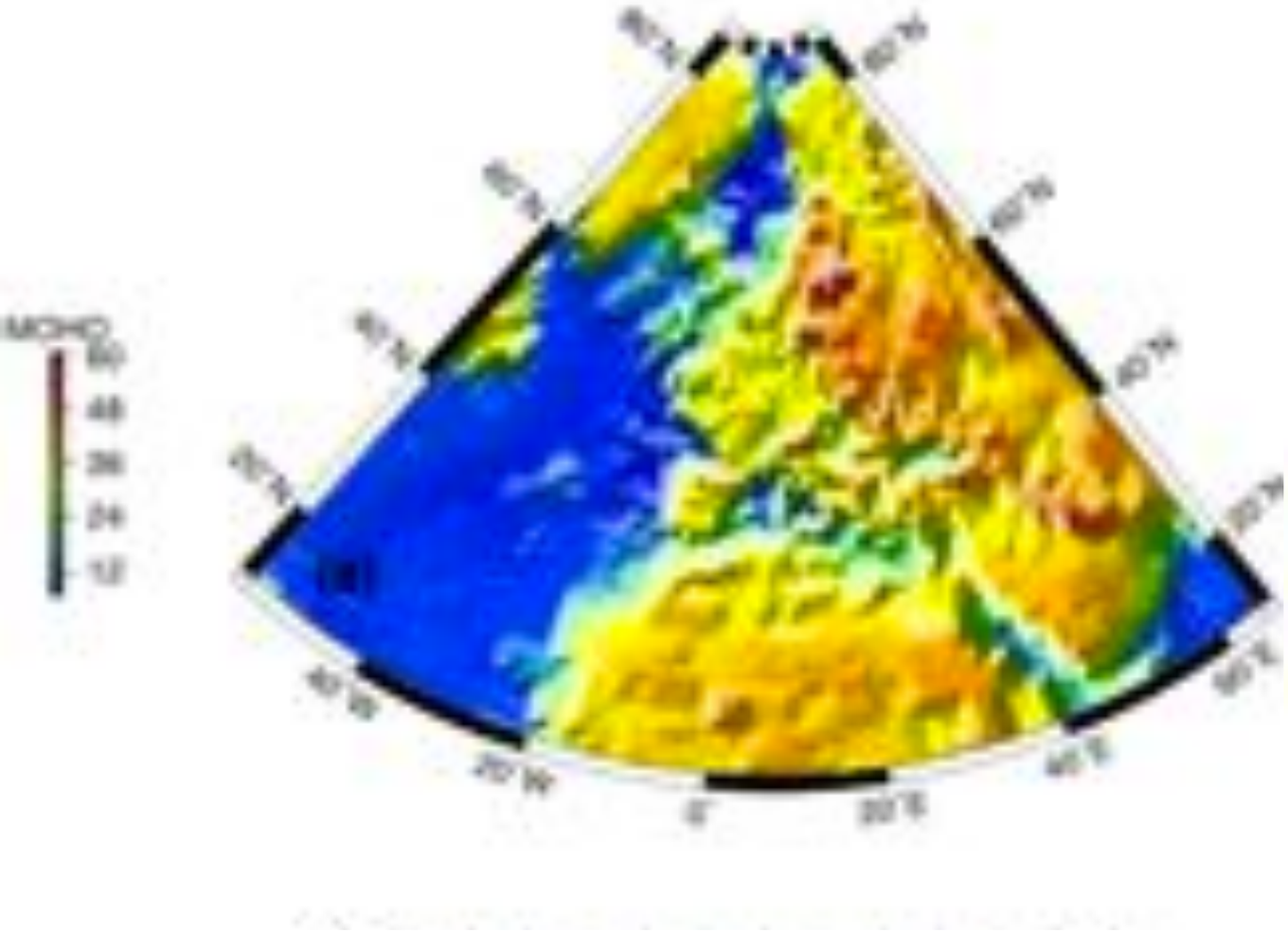
Hejun Zhu

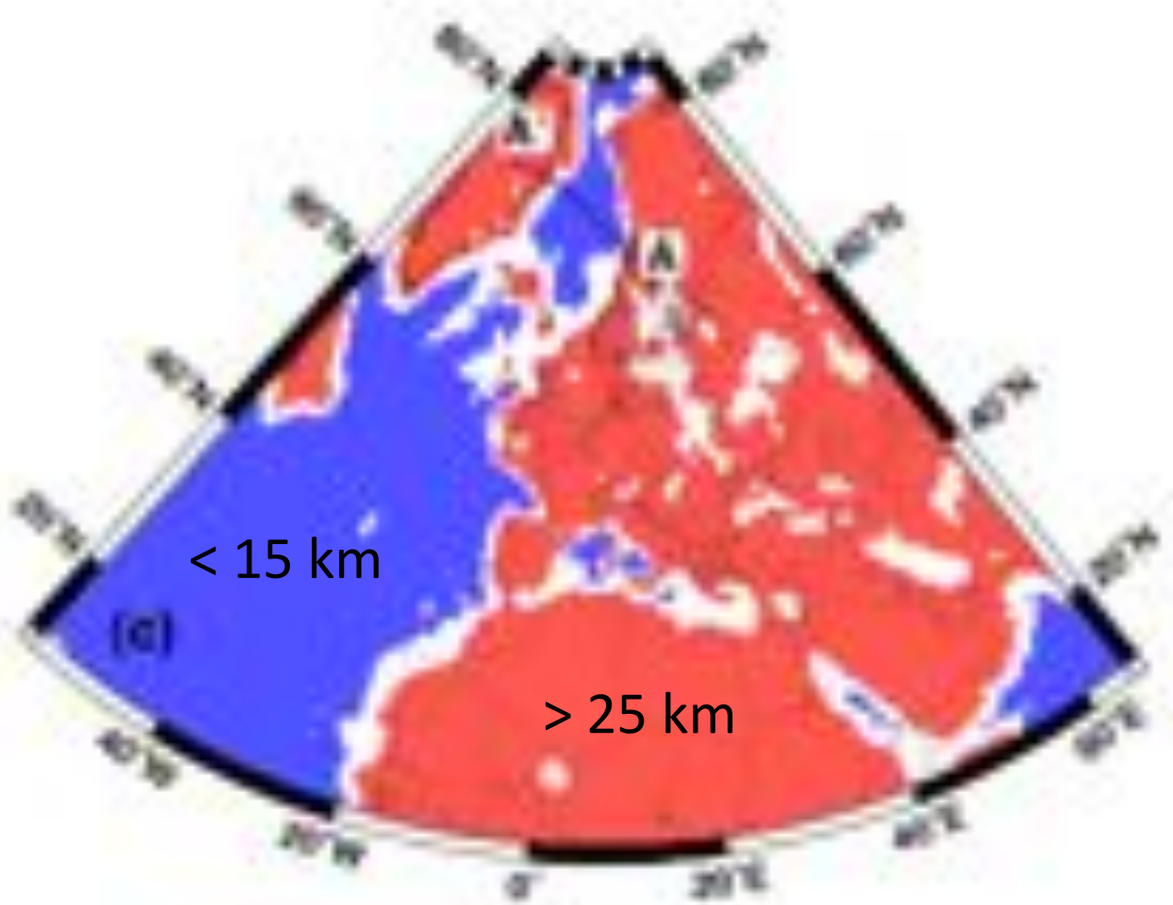
Starting 3D Crustal Model



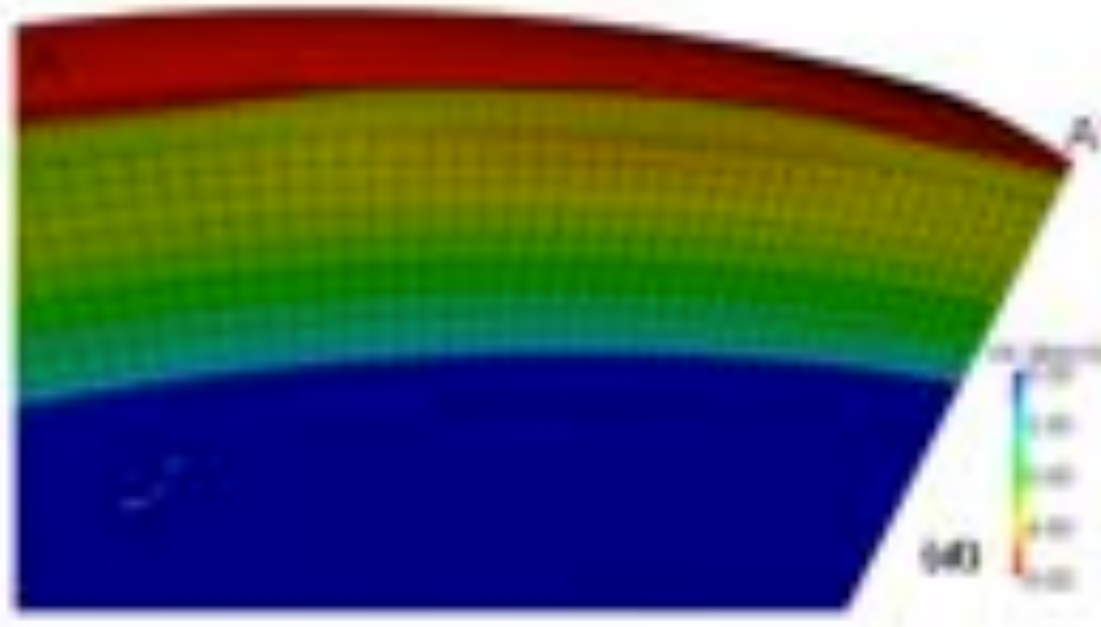
Molinari & Morelli (2011)

Starting 3D Crustal Model

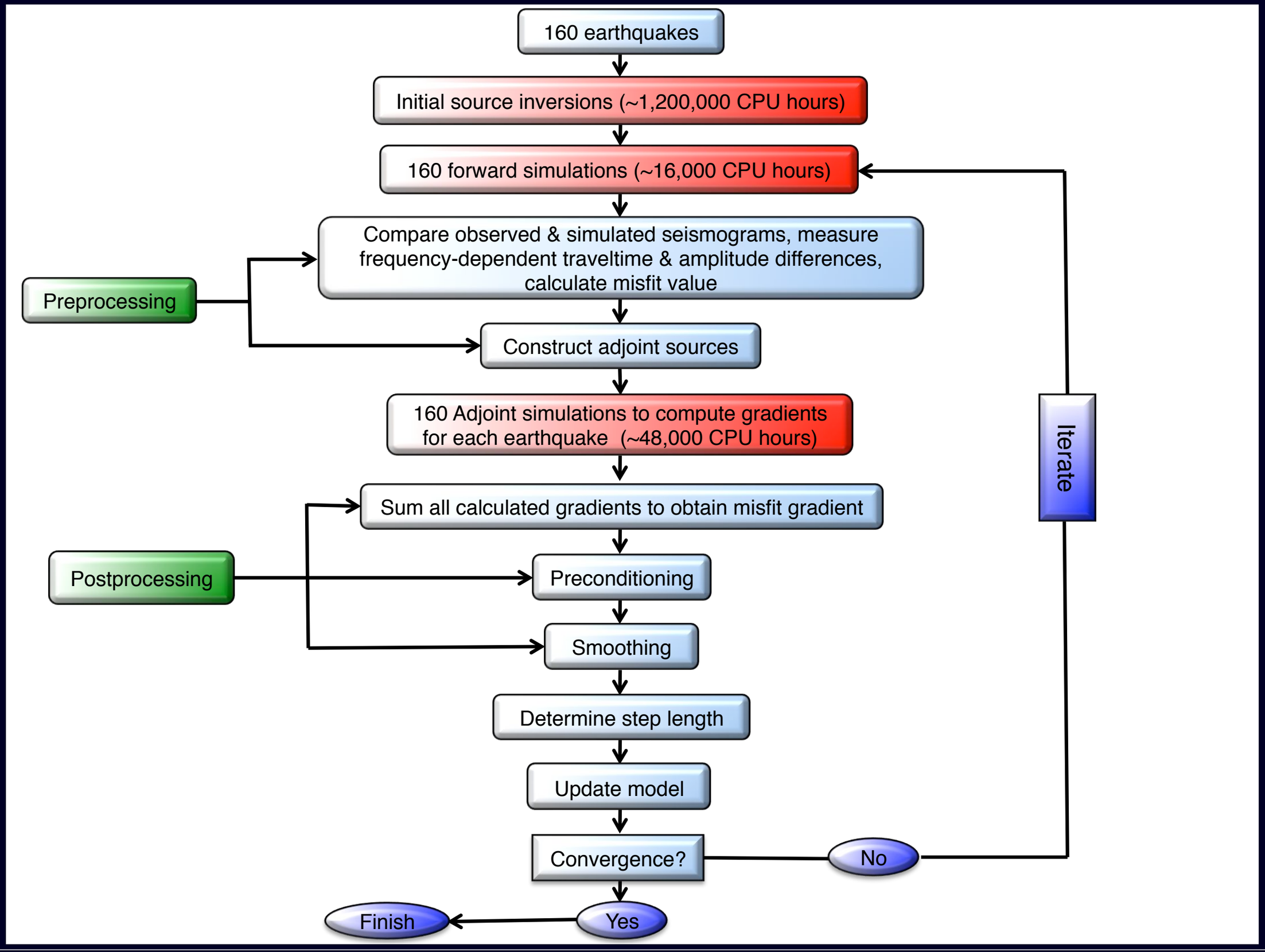




finite-element mesh

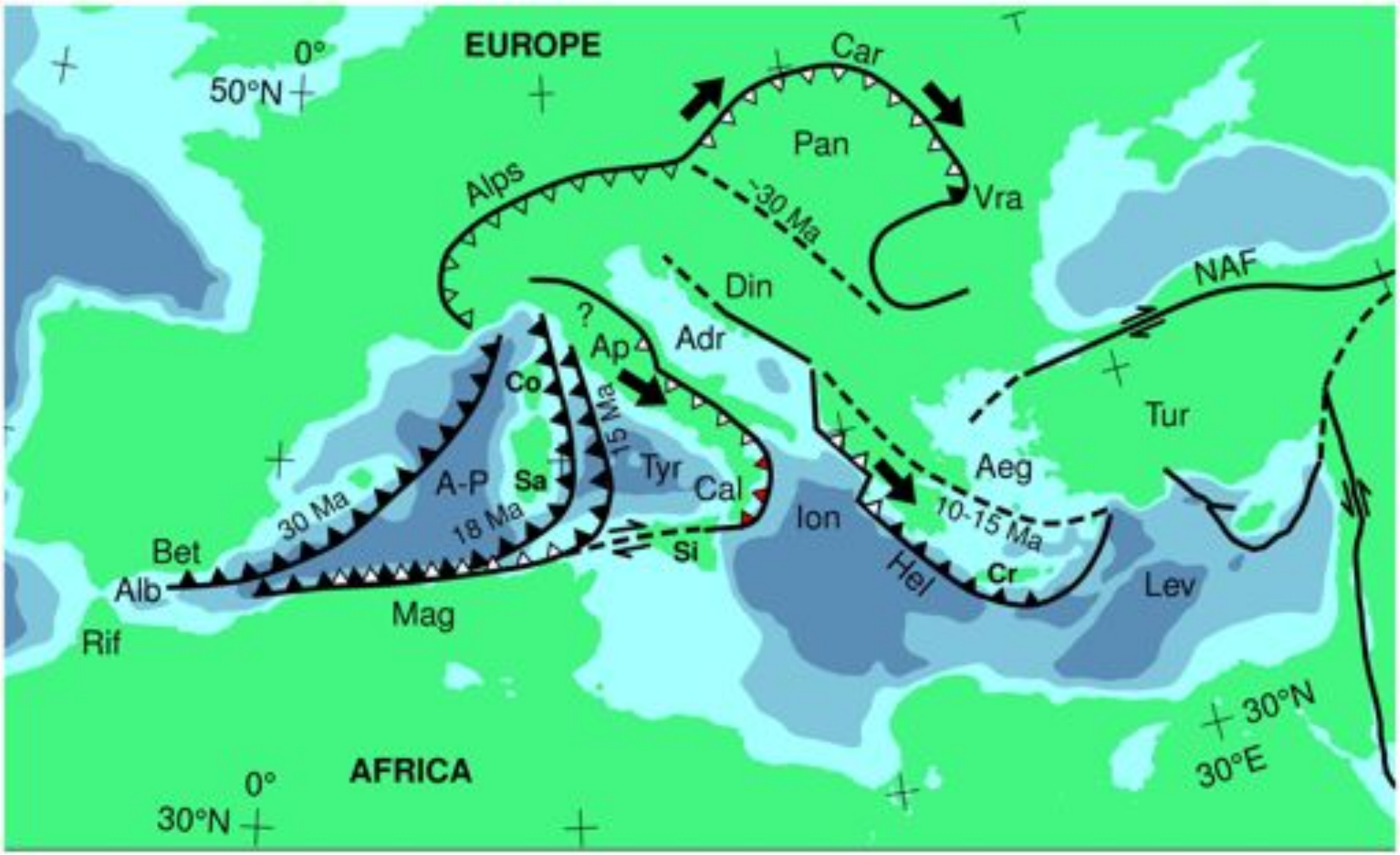


Adjoint Tomography: Workflow



http://magma.earth.uq.edu.au/rosenbaum/Movies.html

Mediterranean-Calabria Paleotectonics



Wortel & Spakman (2000)

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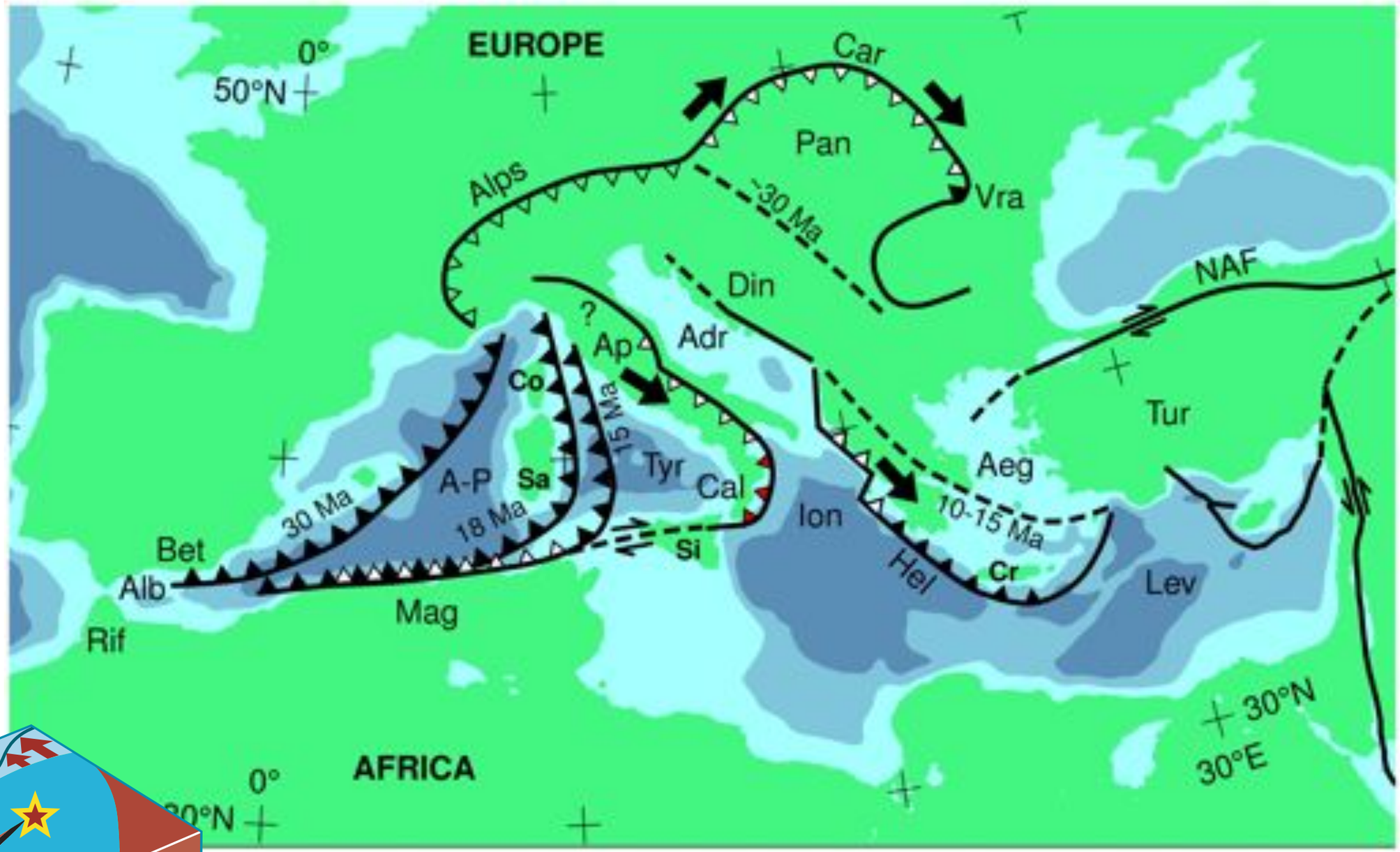
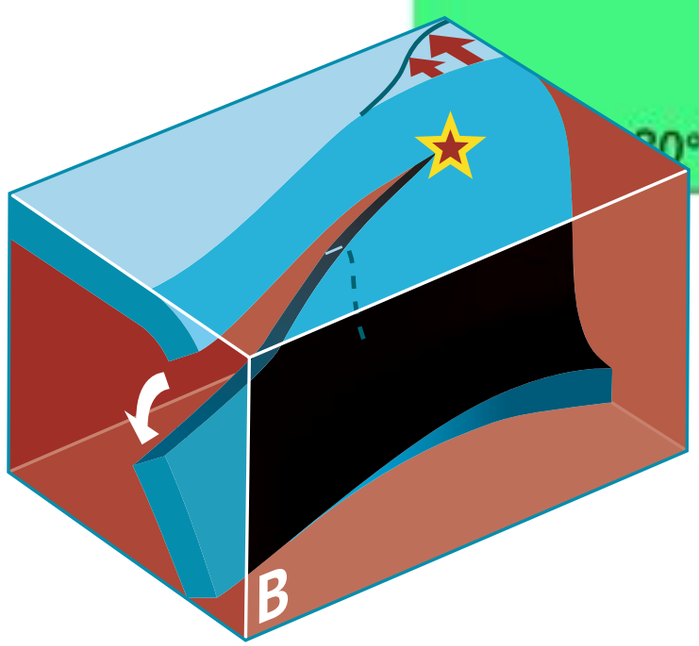
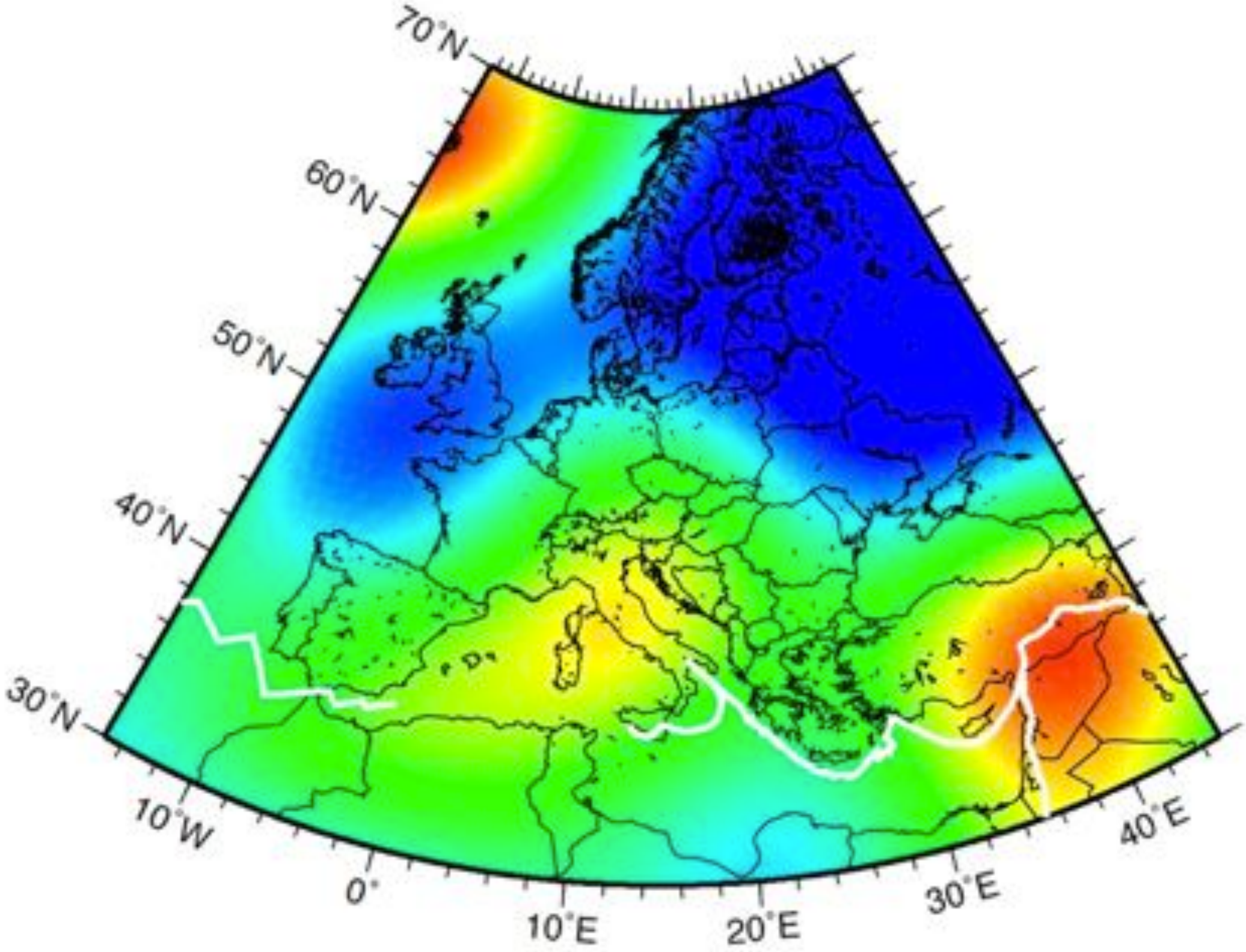




Wortel & Spakman (2000)

Depth 75 km



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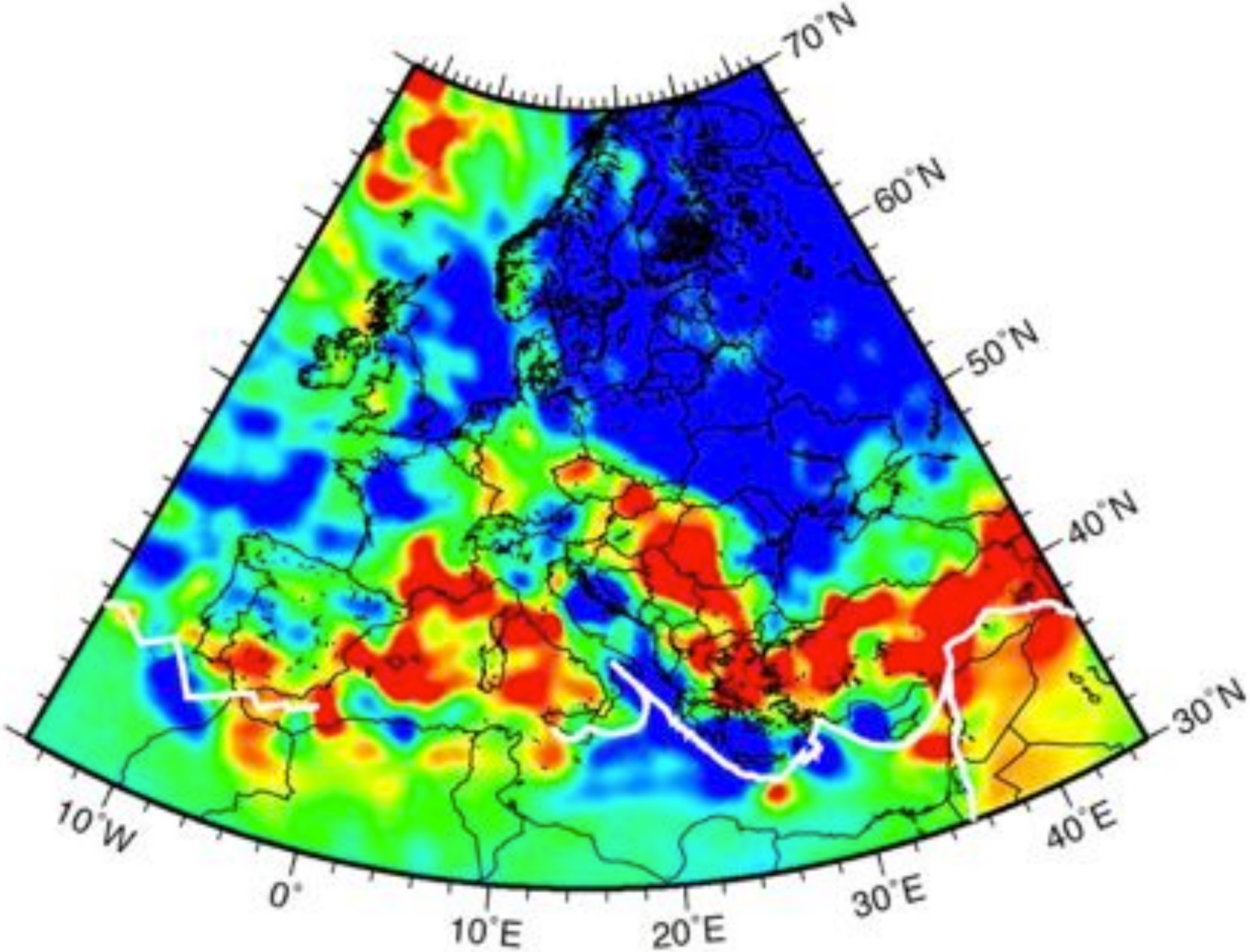

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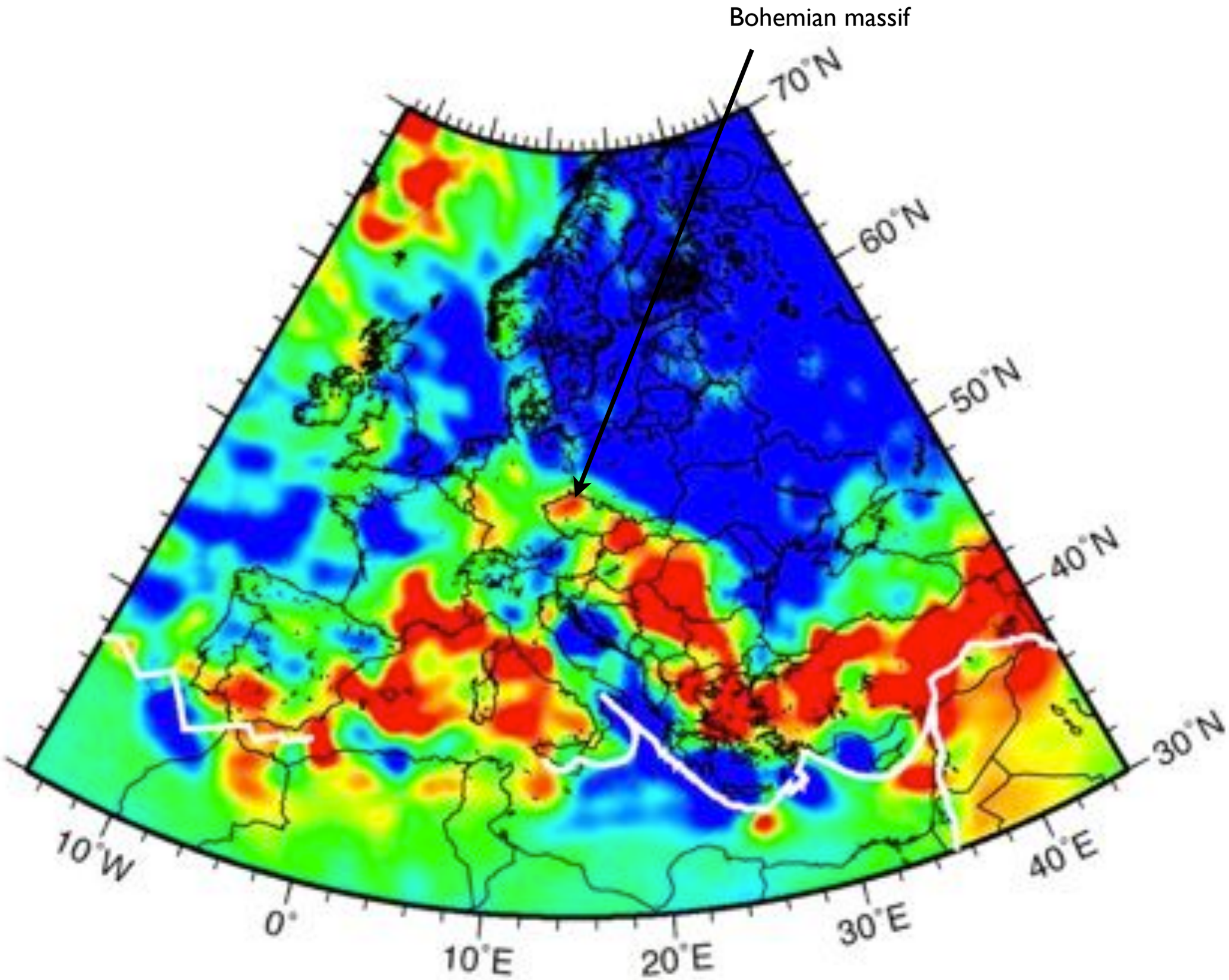

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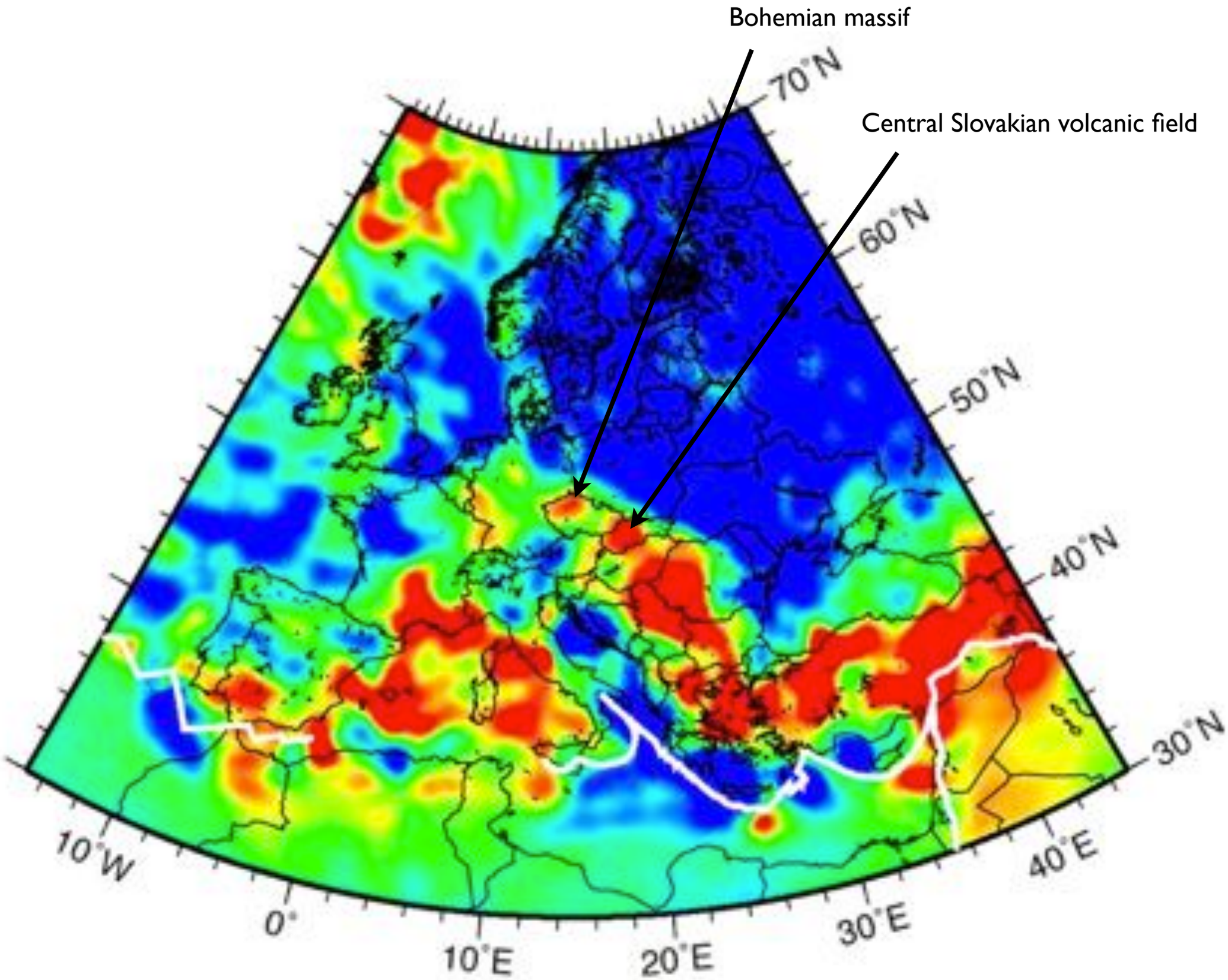
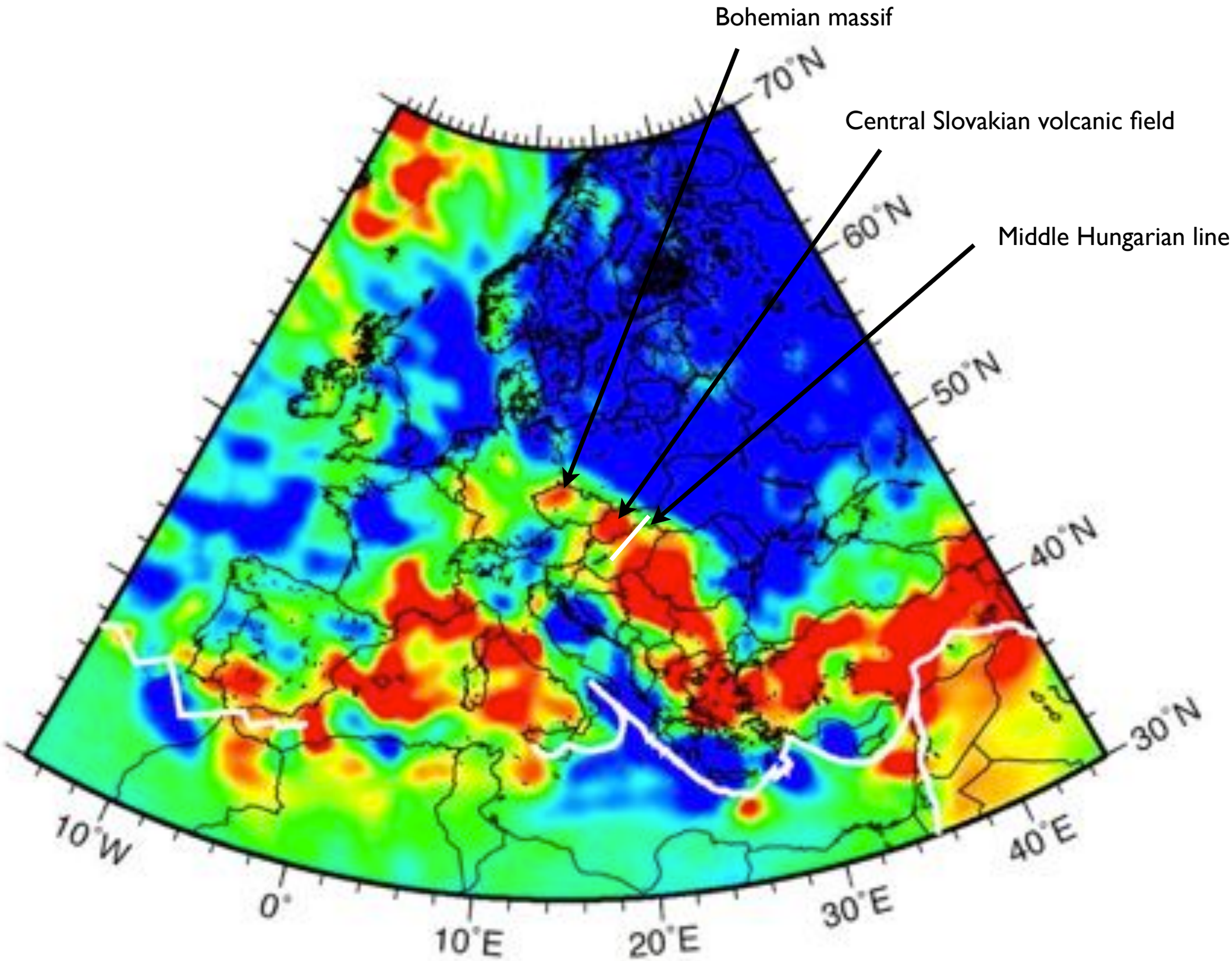

Bohemian massif
Central Slovakian volcanic field
70°N
60°N
50°N
40°N
30°N
10°W
0°
10°E
20°E
30°E
40°E

Depth 75 km


Bohemian massif
Central Slovakian volcanic field
Middle Hungarian line
70°N
60°N
50°N
40°N
30°N
10°W
0°
10°E
20°E
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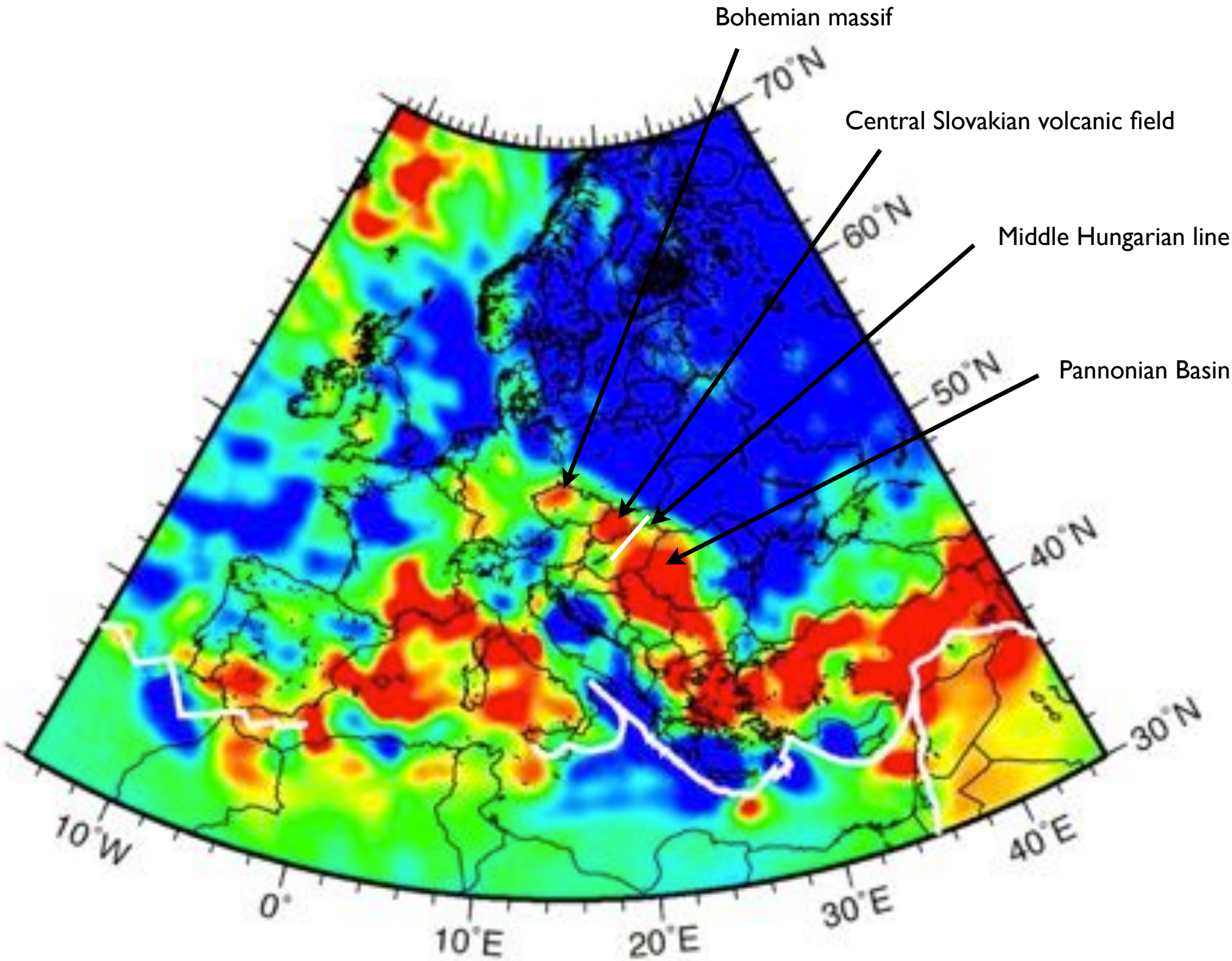
Depth 75 km


Bohemian massif
Central Slovakian volcanic field
Middle Hungarian line
Pannonian Basin
70°N
60°N
50°N
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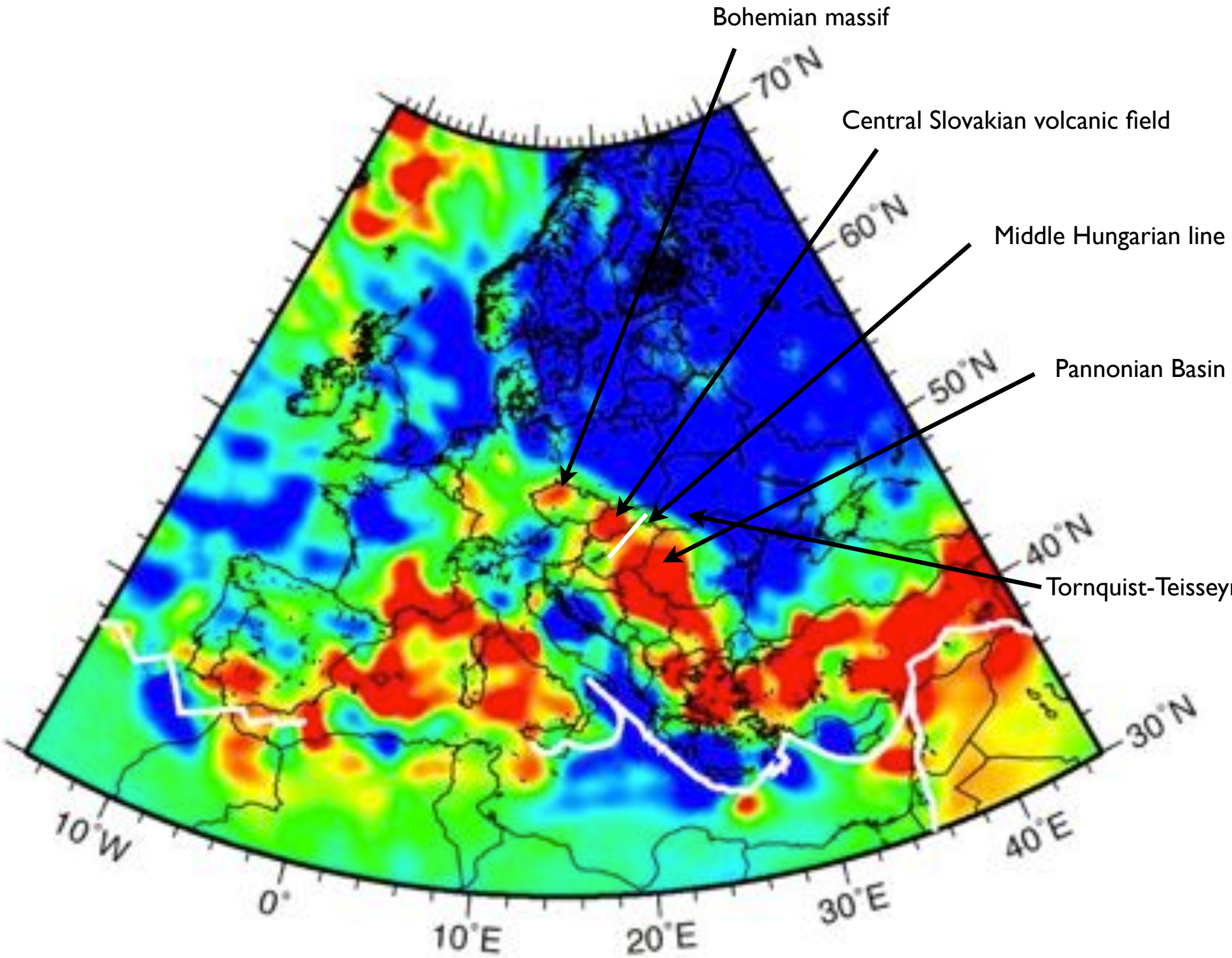
Depth 75 km


Bohemian massif
Central Slovakian volcanic field
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Pannonian Basin
Tornquist-Teisseyre Zone
70°N
60°N
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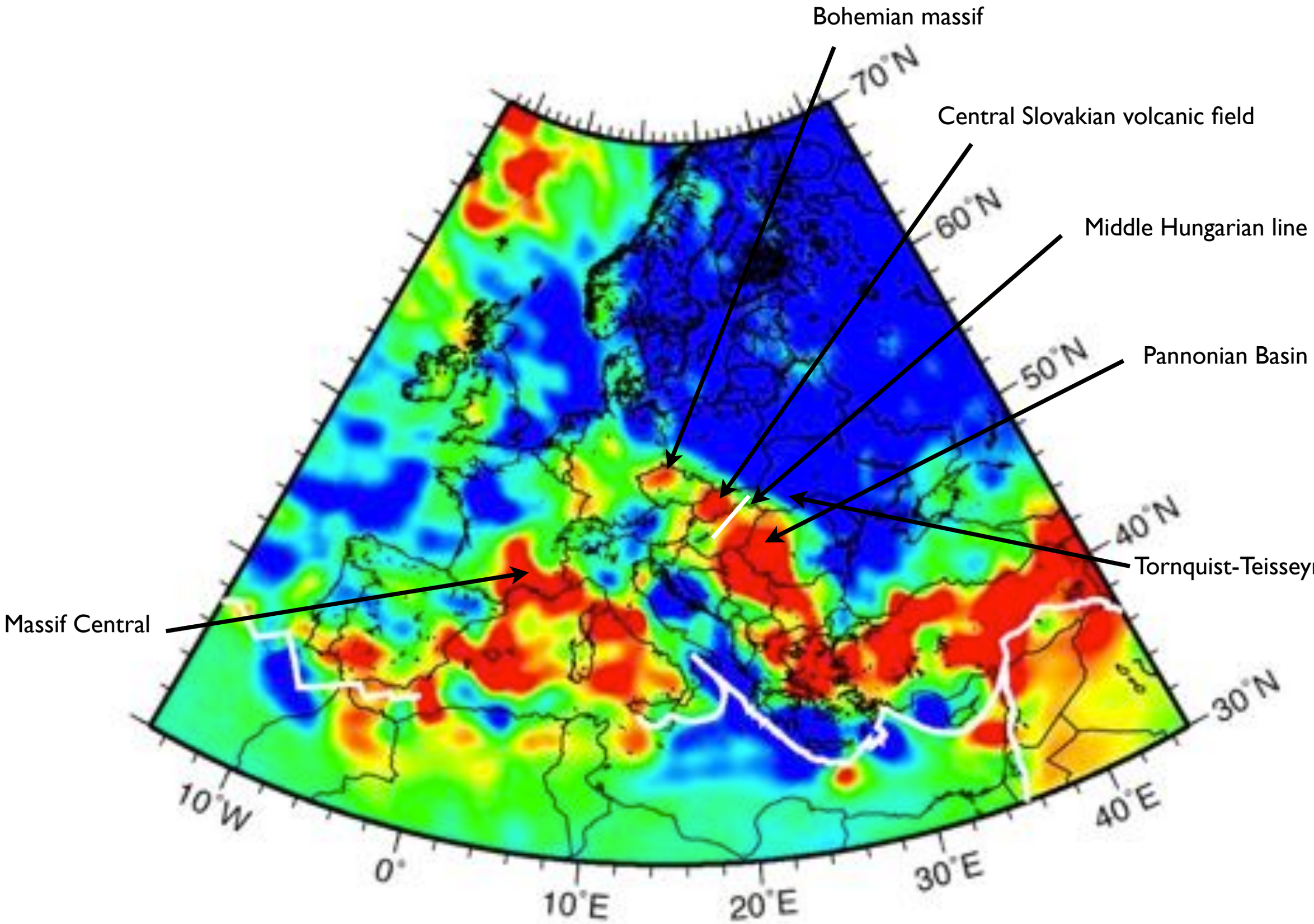
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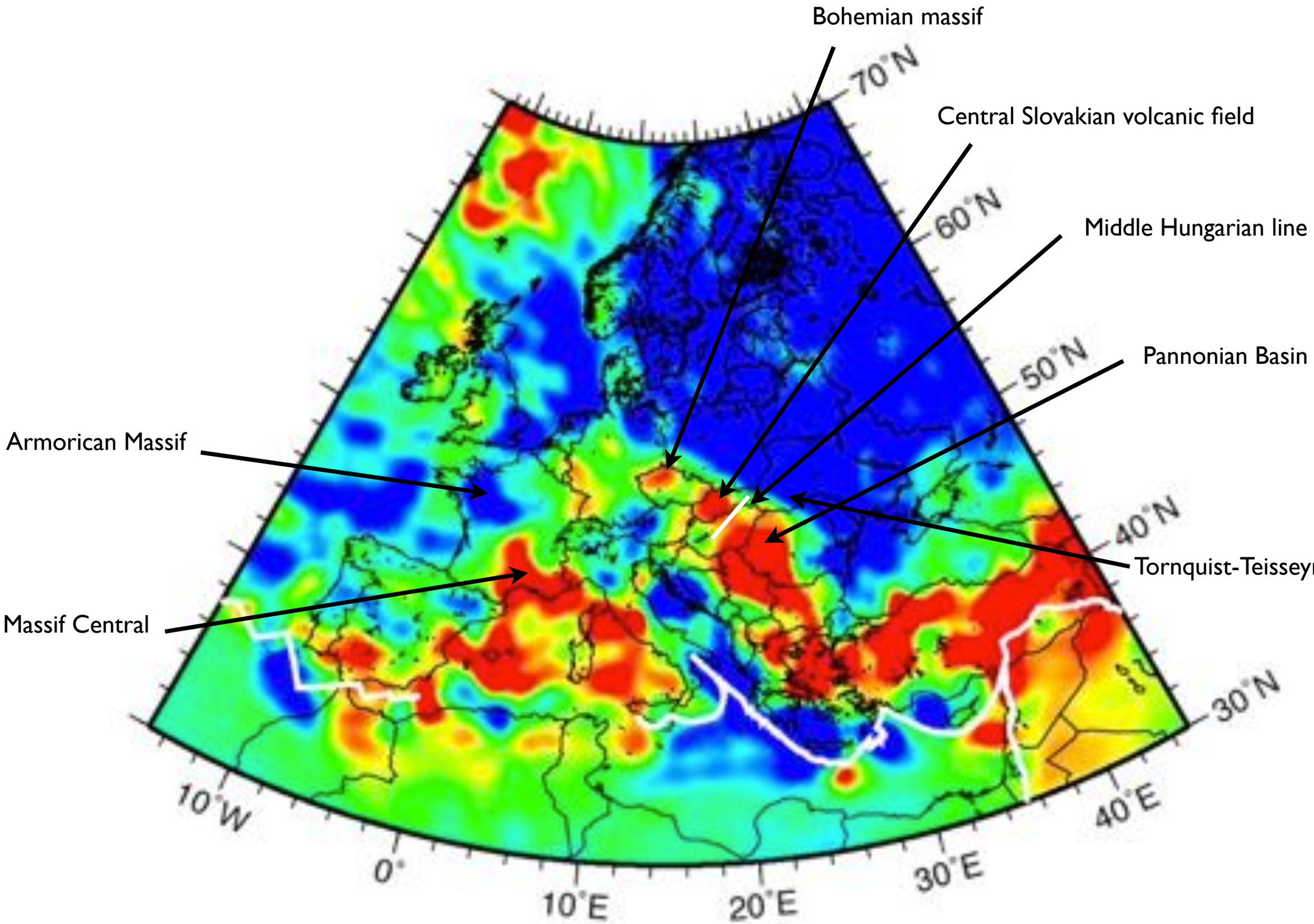
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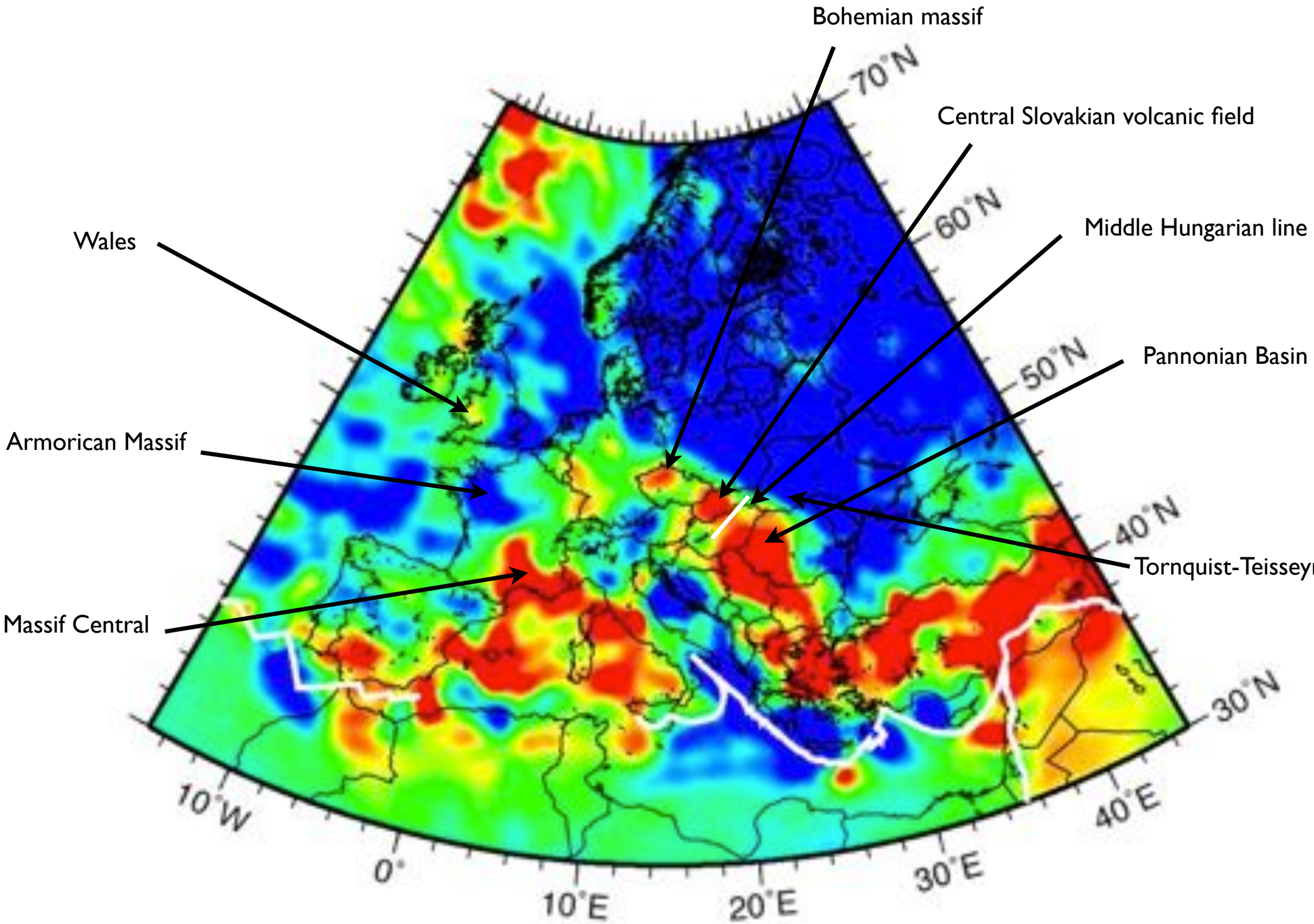
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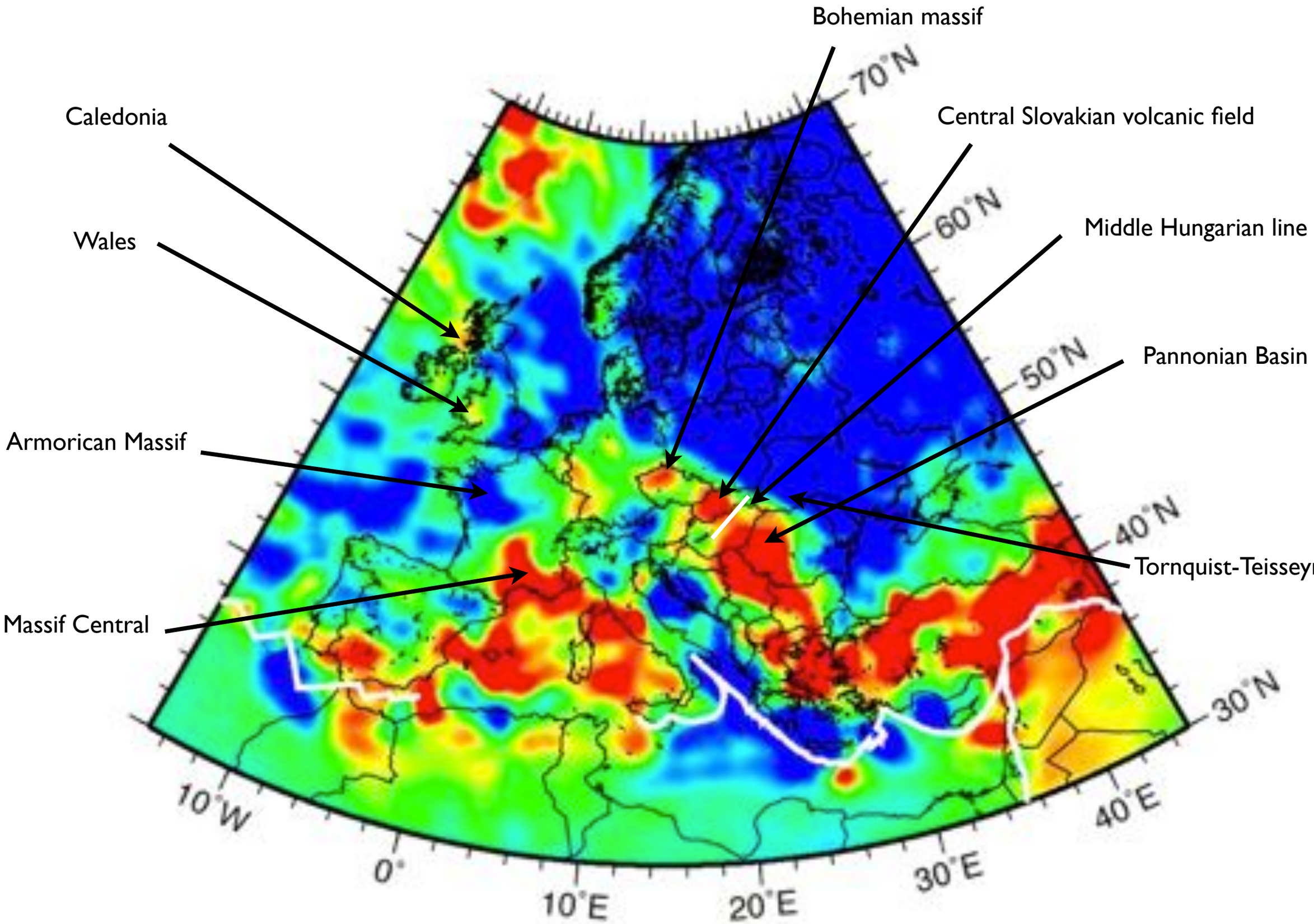
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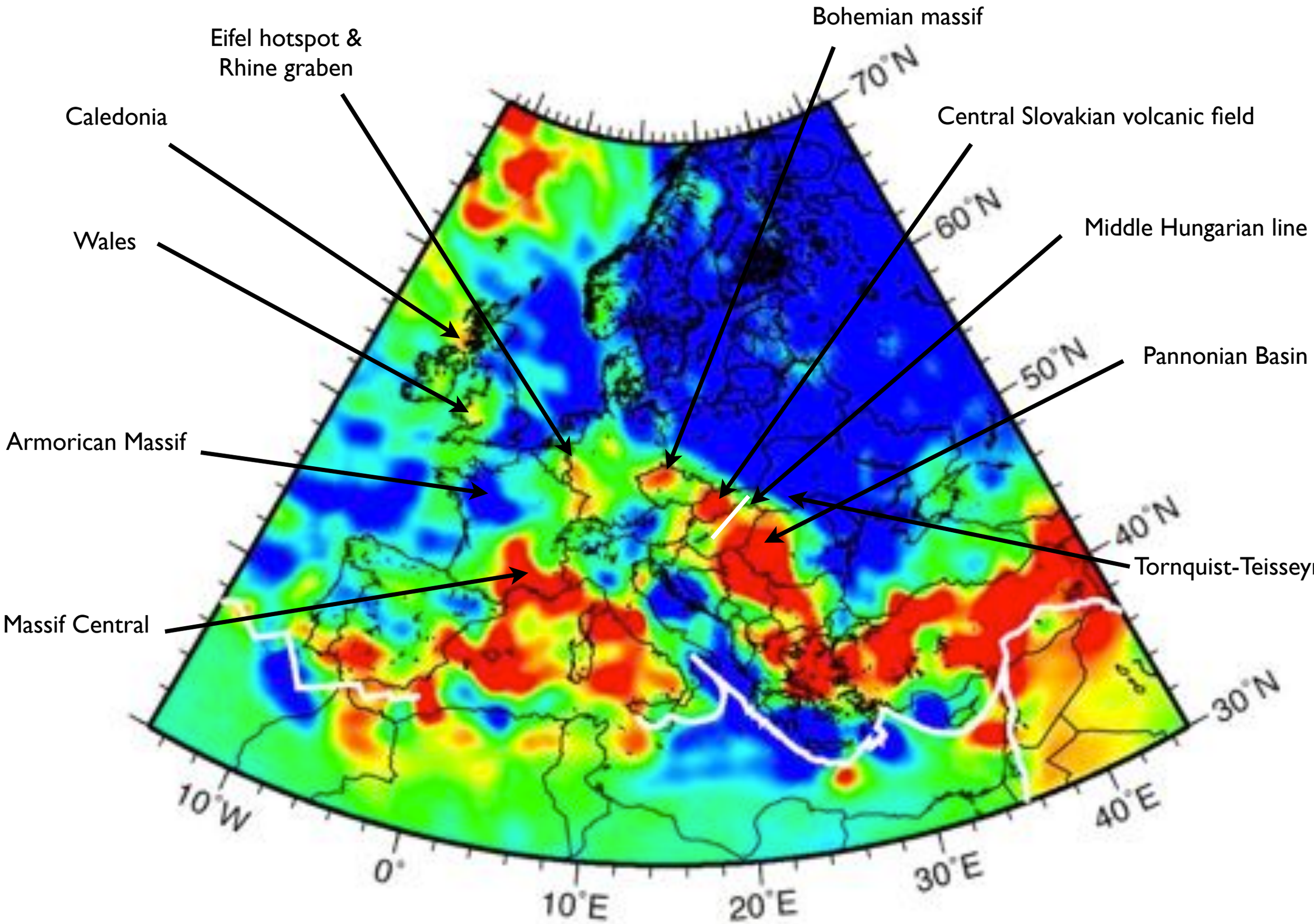
Bohemian massif
Eifel hotspot &
Rhine graben
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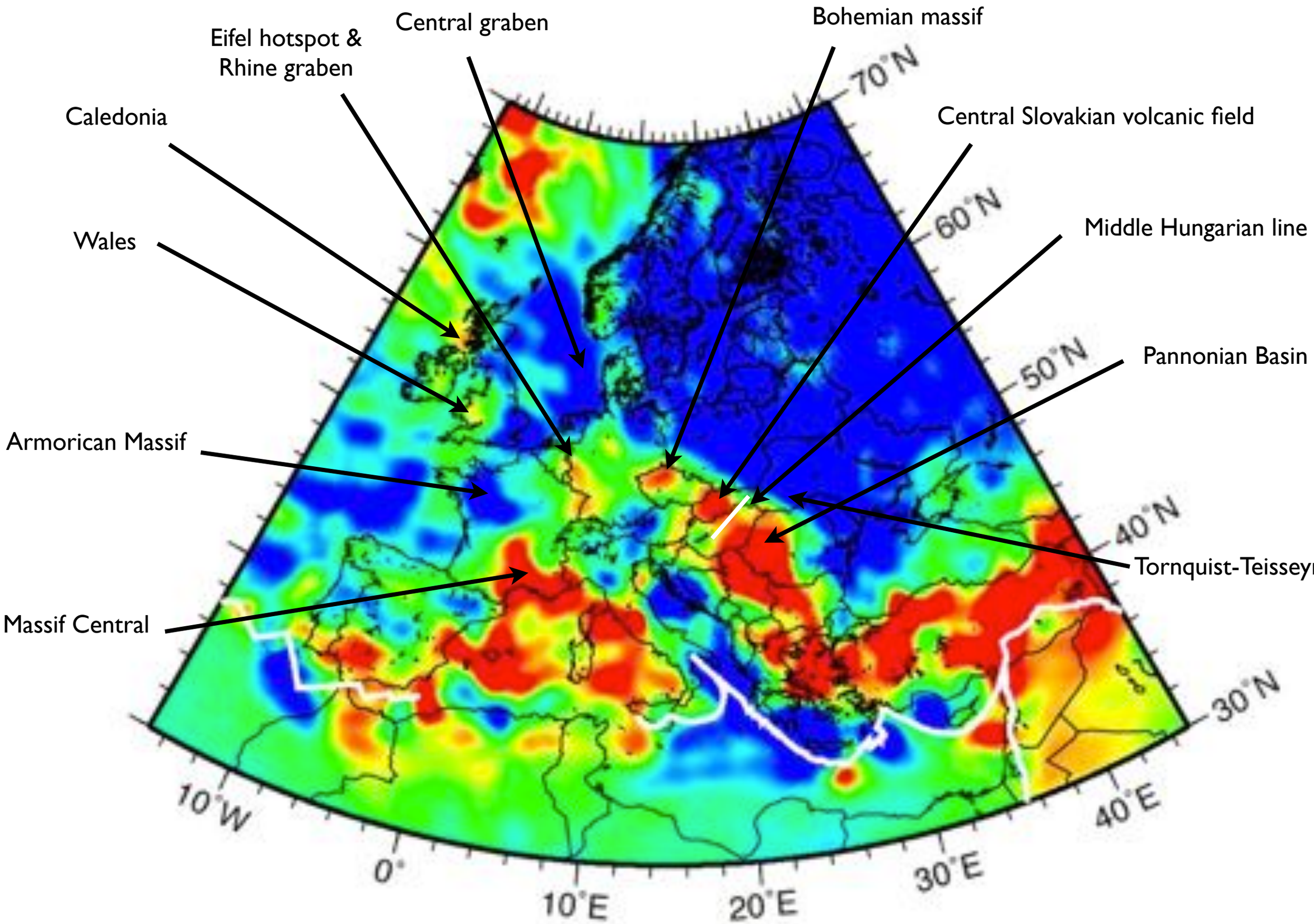
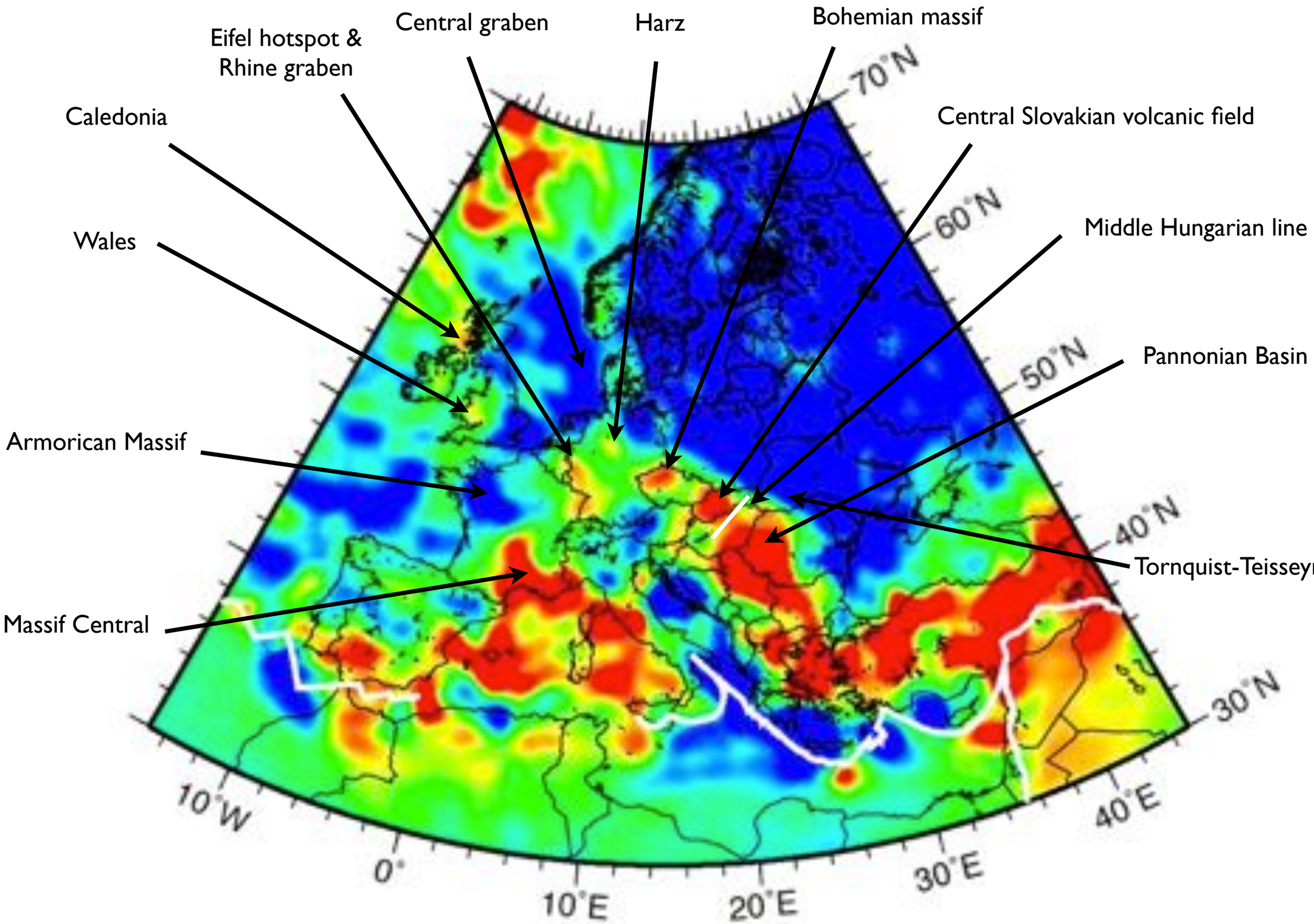
40°E

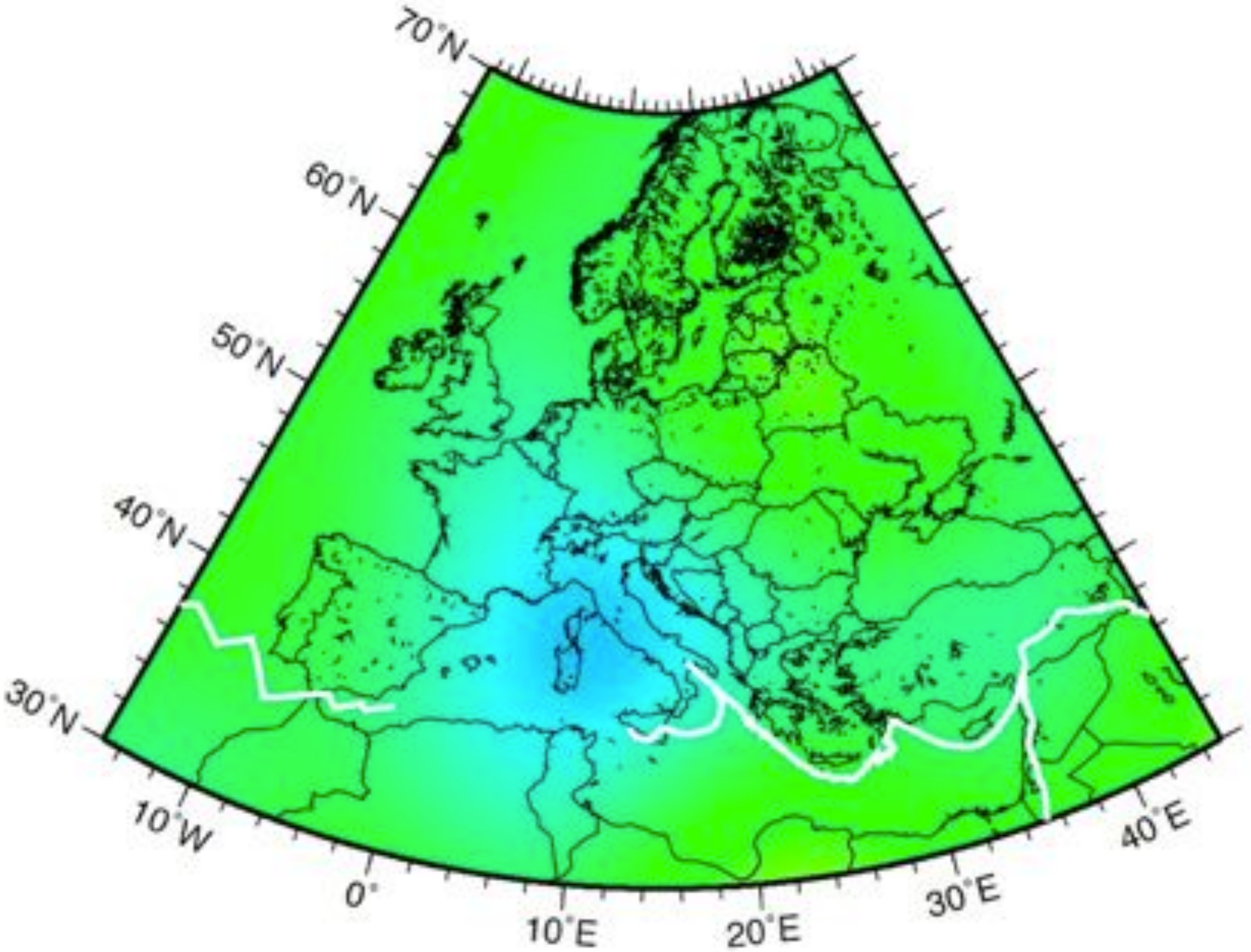
Depth 75 km


Eifel hotspot &
Rhine graben
Central graben
Bohemian massif
Caledonia
Central Slovakian volcanic field
Wales
Middle Hungarian line
Pannonian Basin
Armorican Massif
Tornquist-Teisseyre Zone
Massif Central
70°N
60°N
50°N
40°N
30°N
10°W
0°
10°E
20°E
30°E
40°E

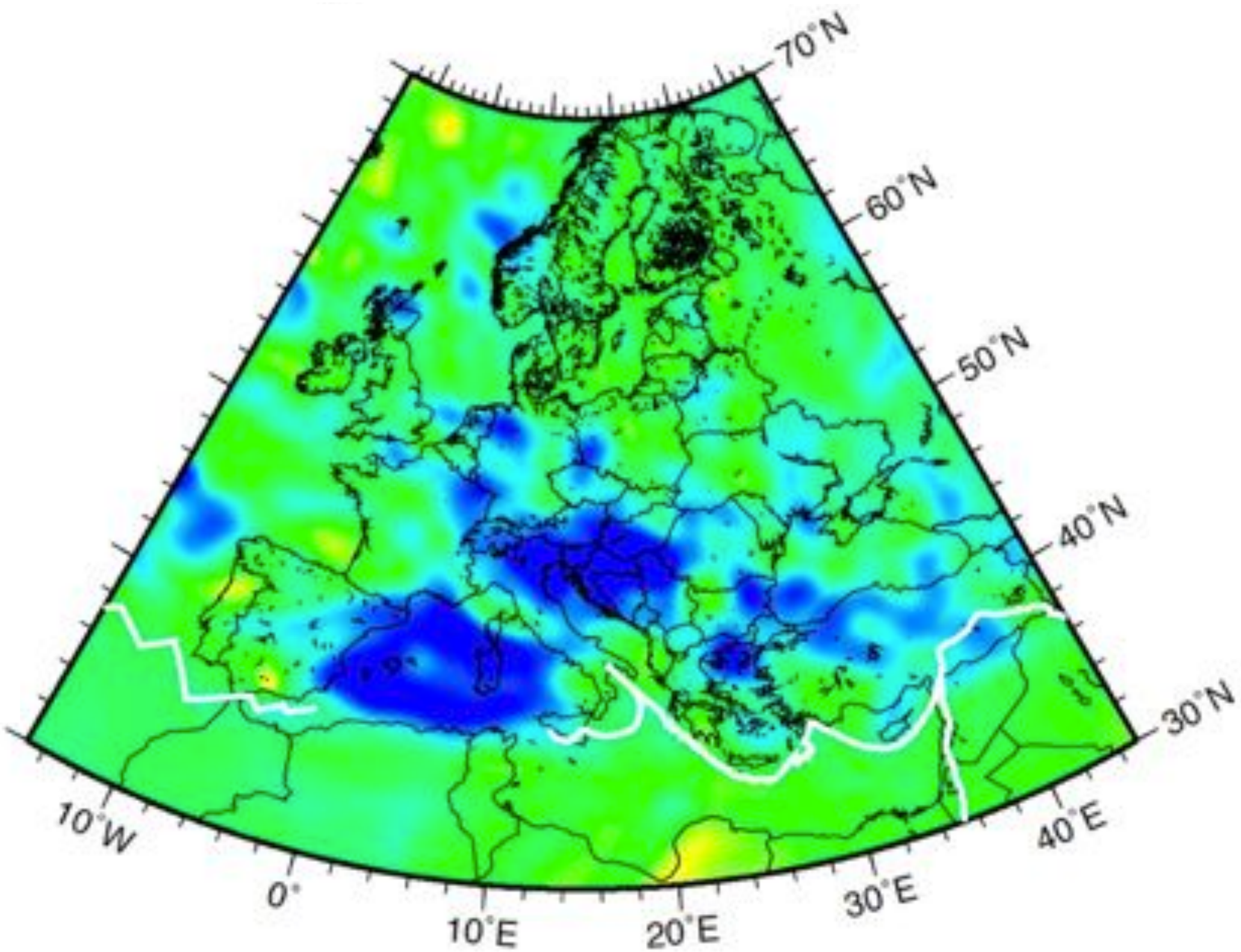
Depth 75 km


Eifel hotspot &
Rhine graben
Central graben
Harz
Bohemian massif
Caledonia
Central Slovakian volcanic field
Wales
Middle Hungarian line
Pannonian Basin
Armorican Massif
Tornquist-Teisseyre Zone
Massif Central
70°N
60°N
50°N
40°N
30°N
10°W
0°
10°E
20°E
30°E
40°E

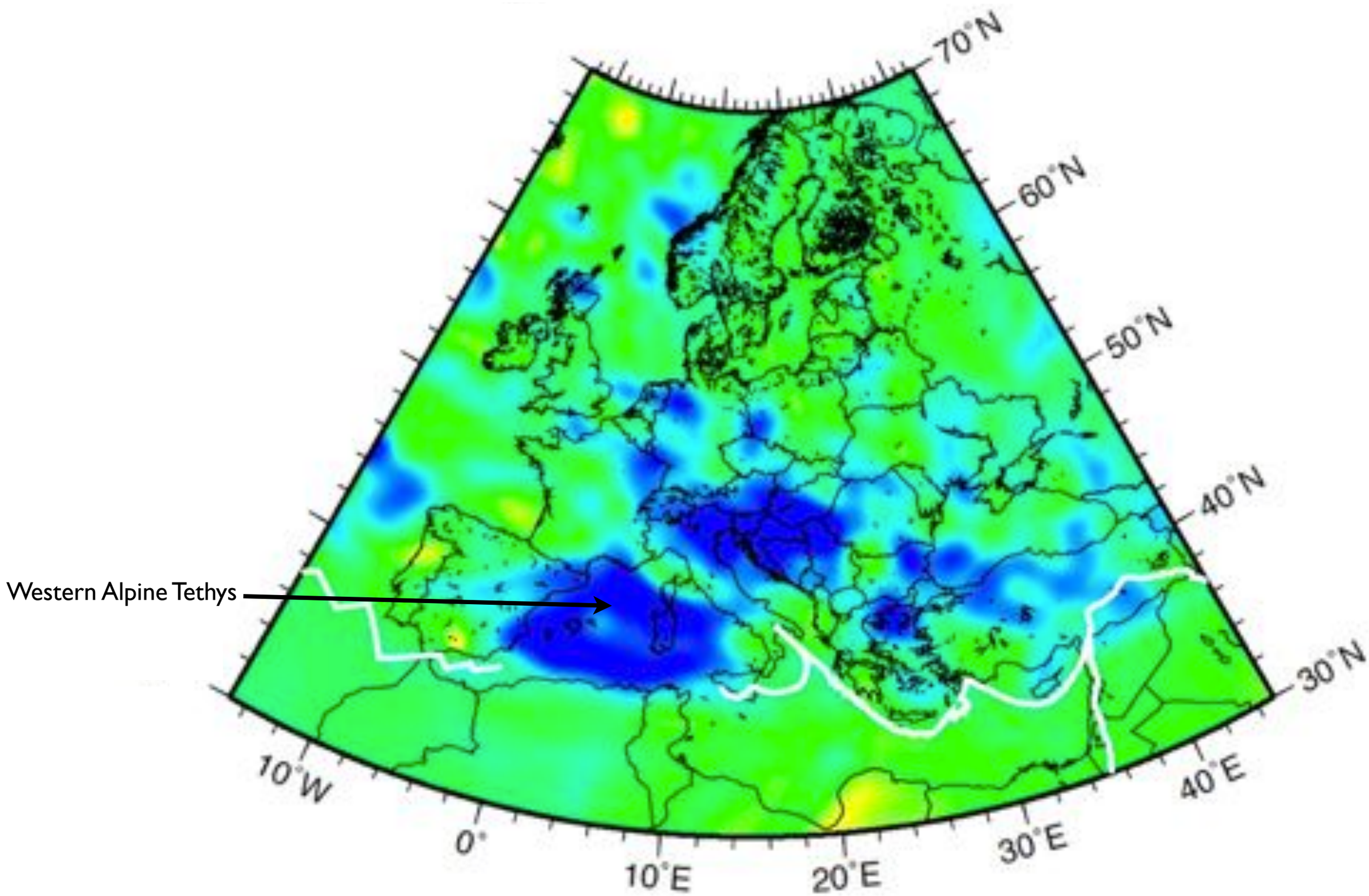
Depth 625 km



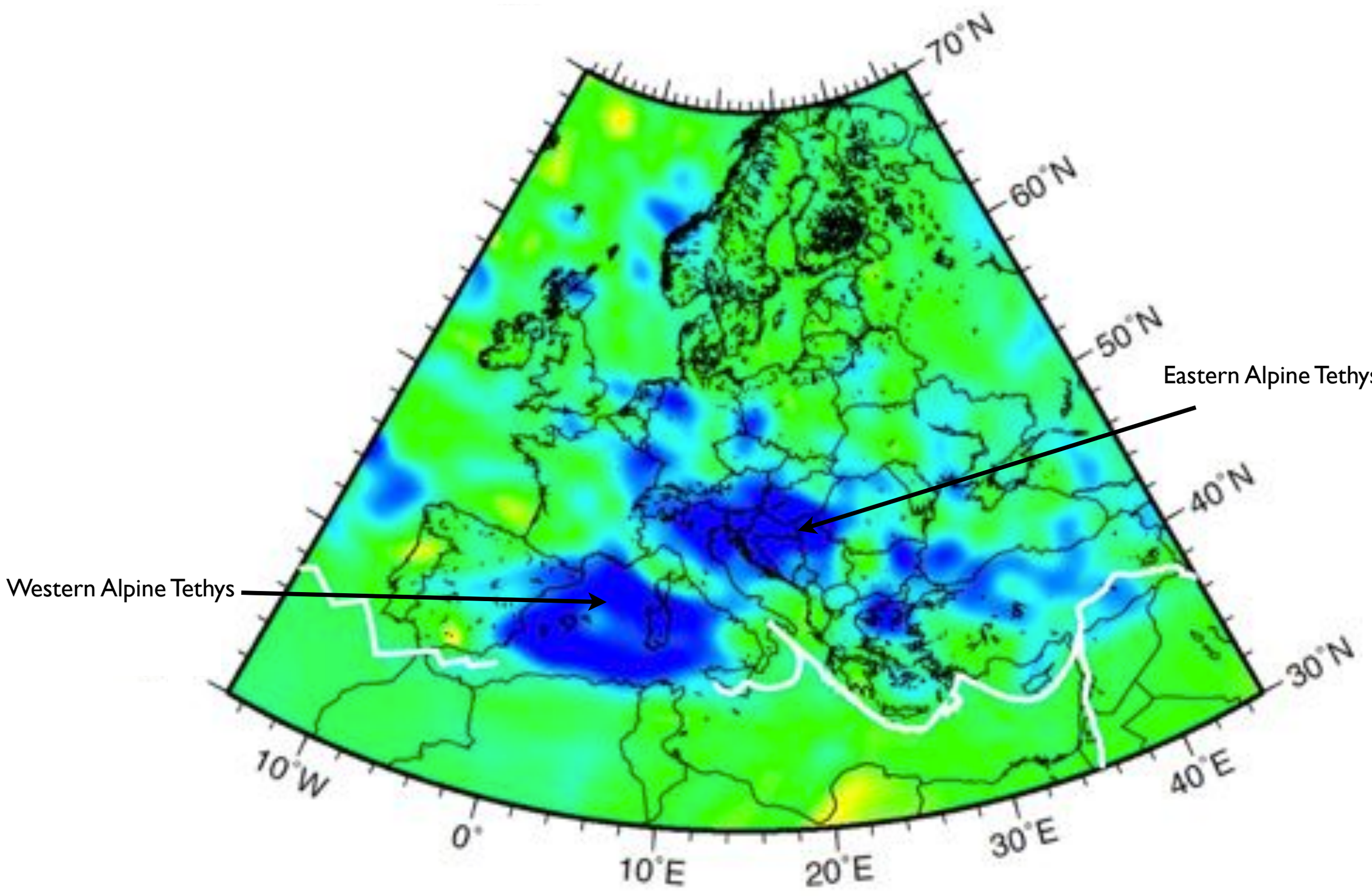
Depth 625 km



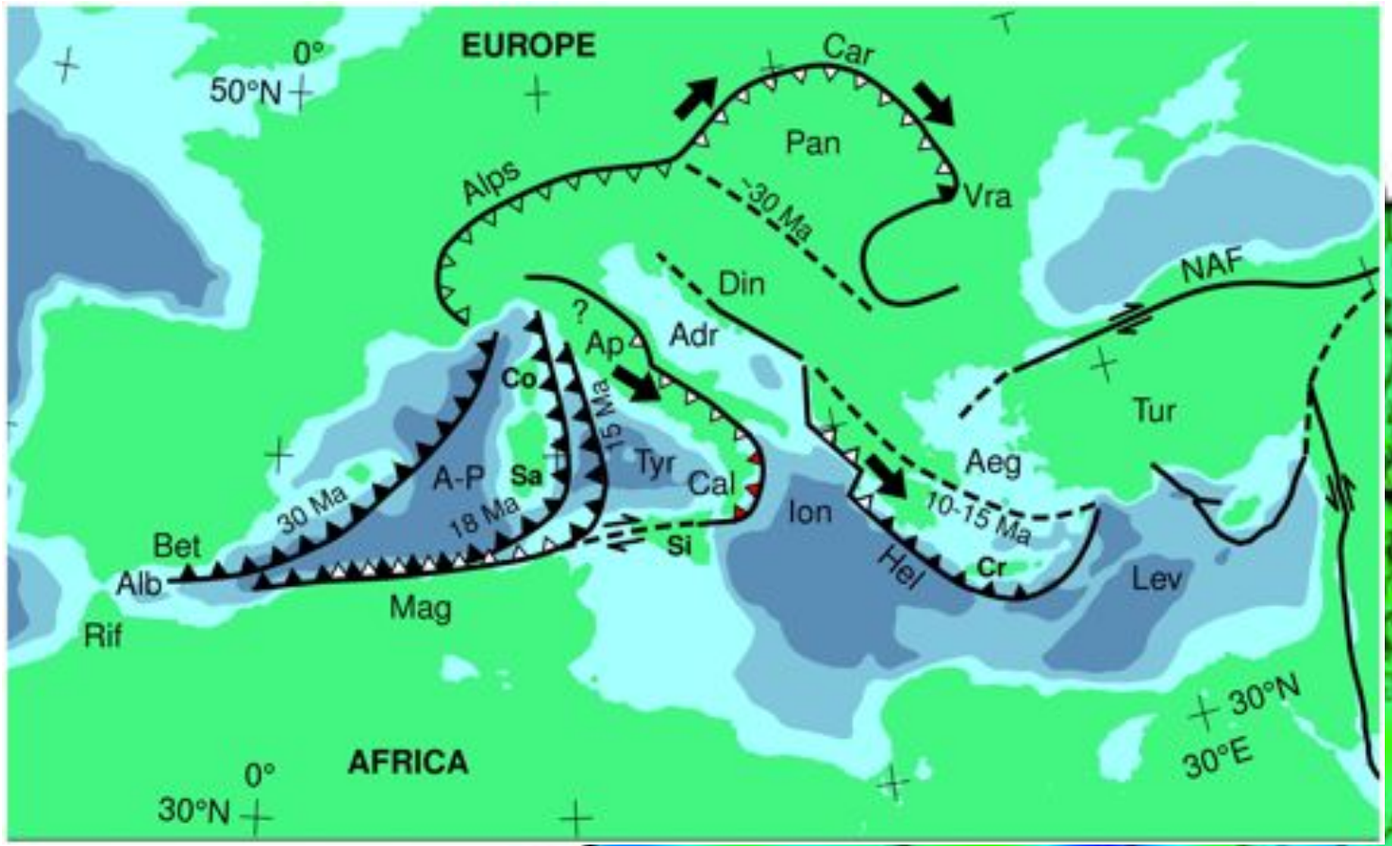
Depth 625 km

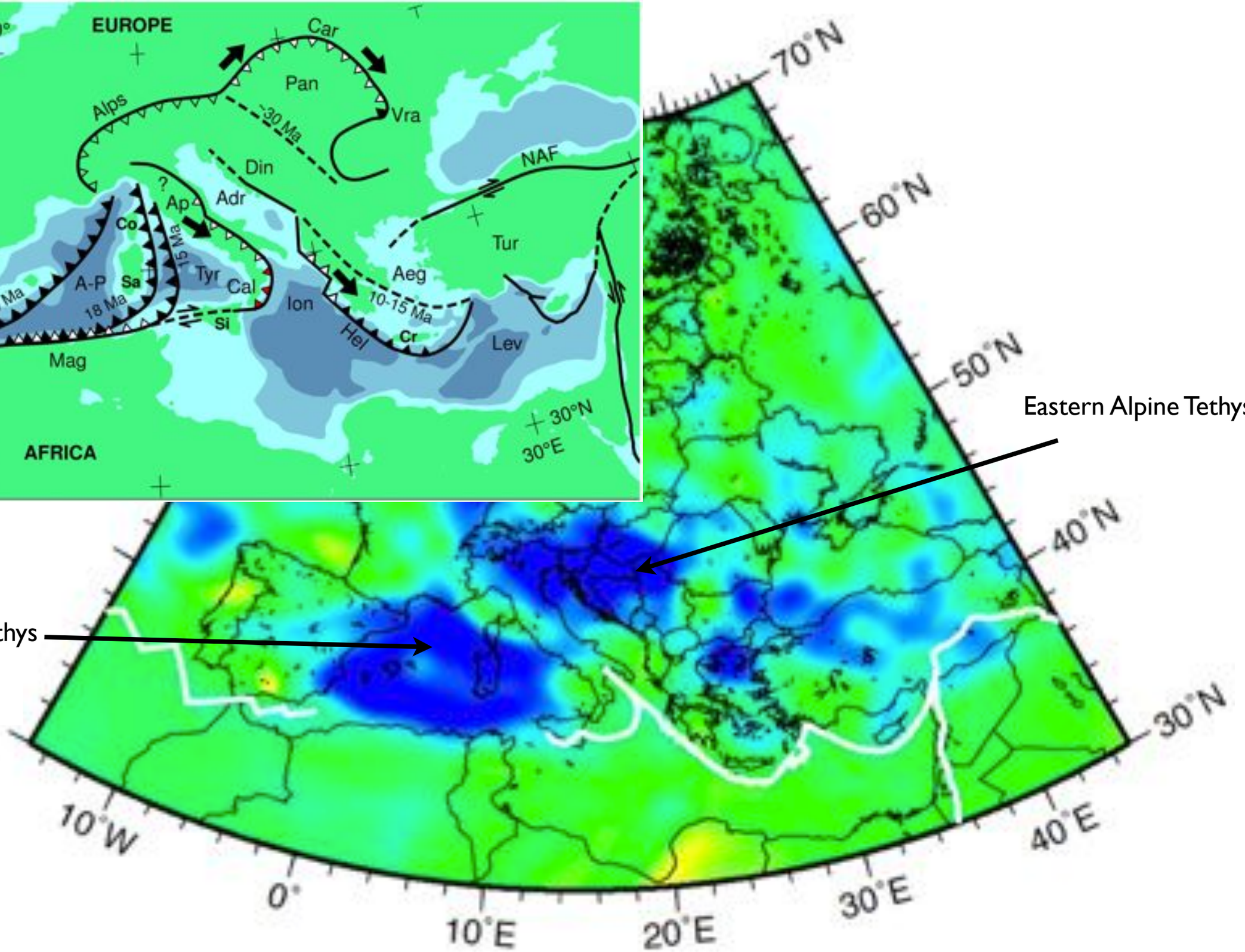

70°N
60°N
50°N
40°N
30°N
10°W
0°
10°E
20°E
30°E
40°E
Western Alpine Tethys

Depth 625 km


70°N
60°N
50°N
40°N
30°N
10°W
0°
10°E
20°E
30°E
40°E
Eastern Alpine Tethys
Western Alpine Tethys

Depth 625 km

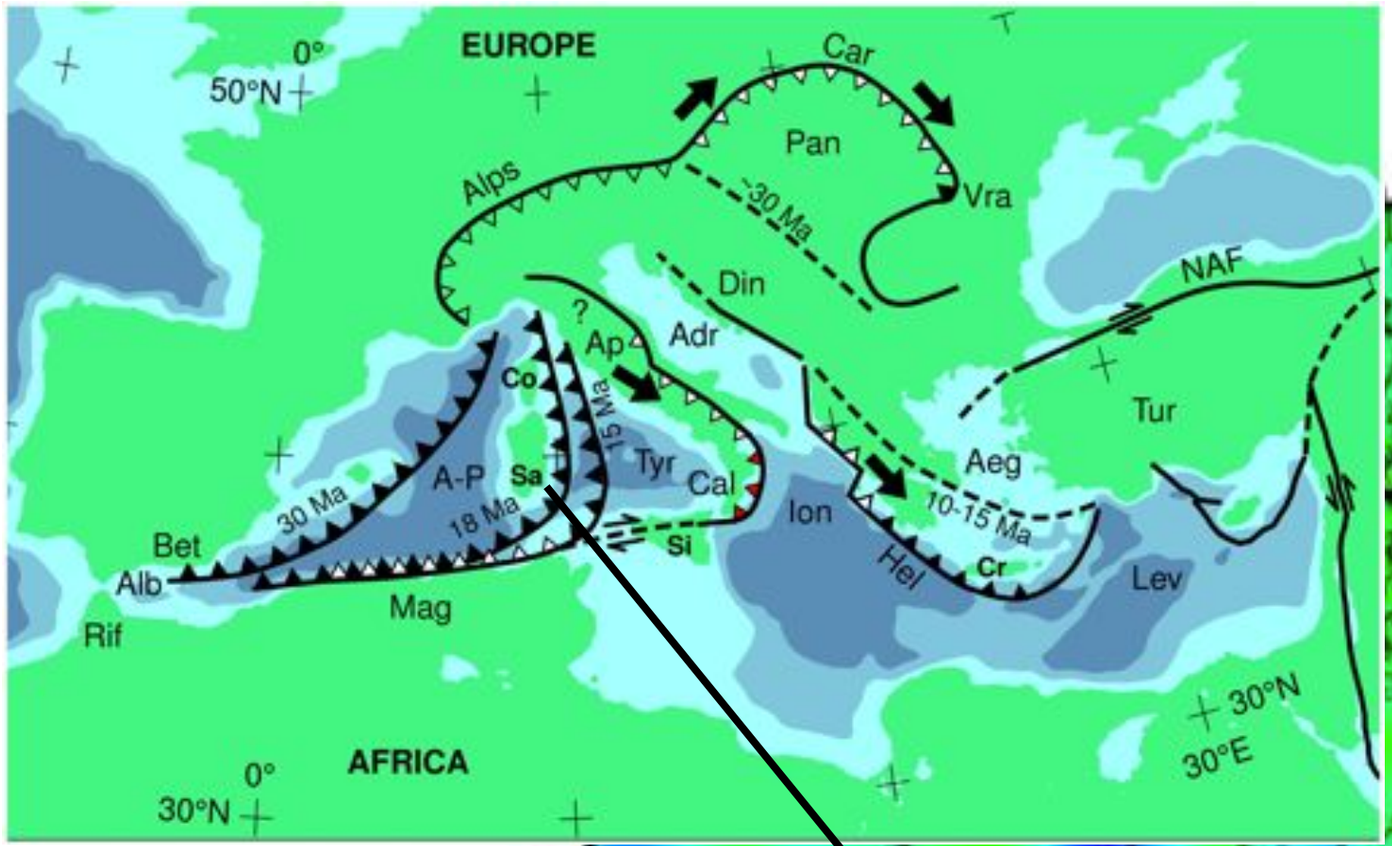


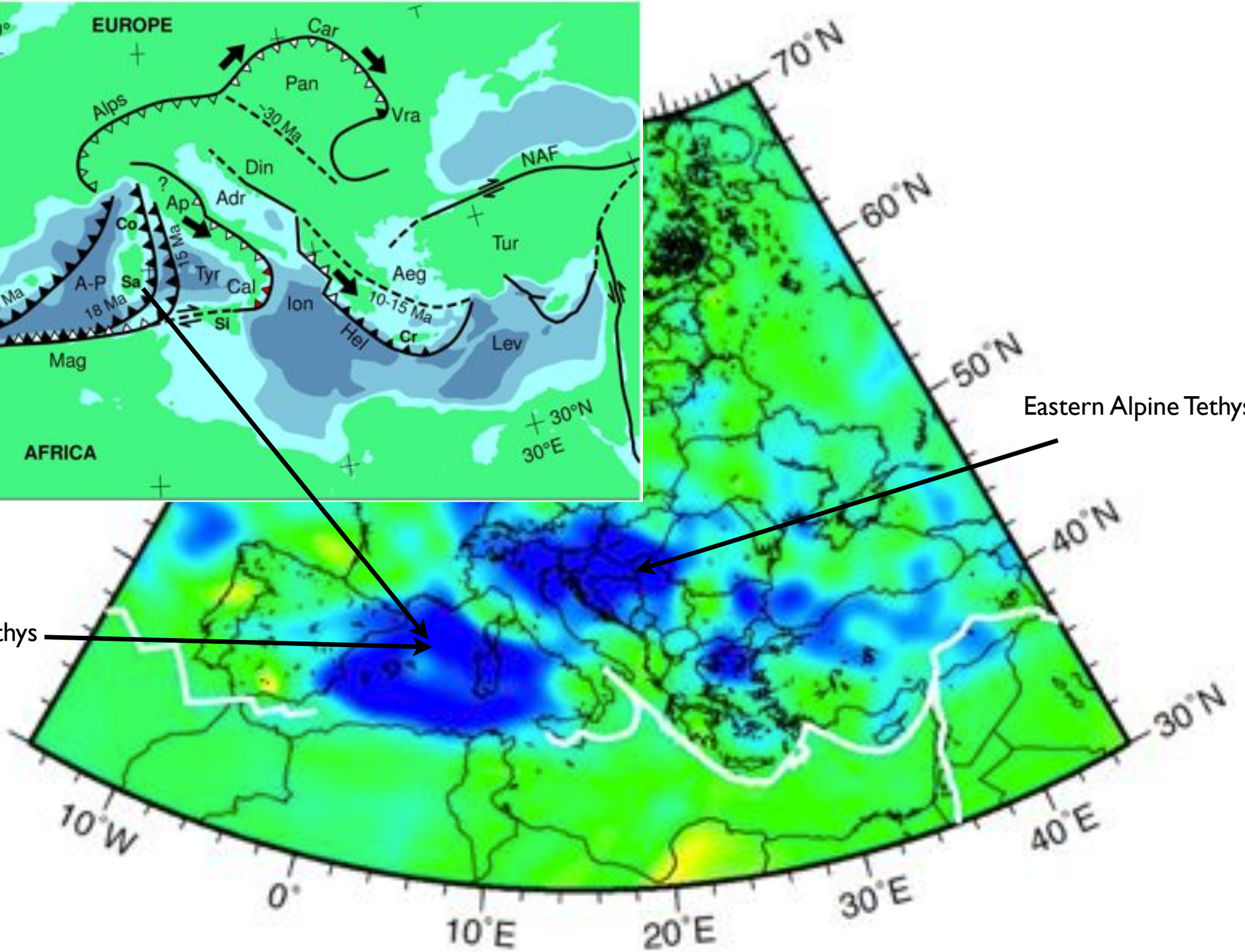


Eastern Alpine Tethys

Western Alpine Tethys

Depth 625 km

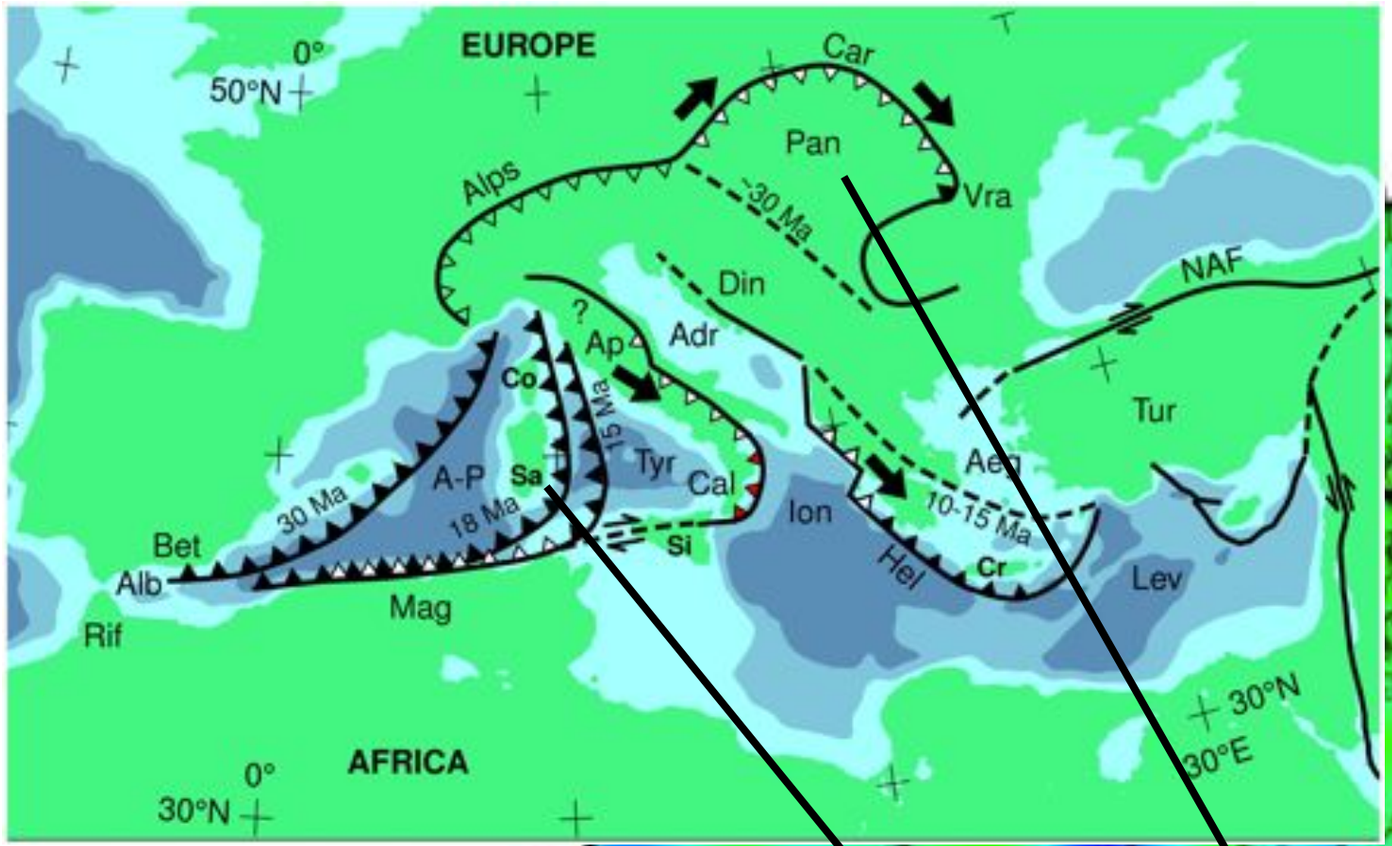


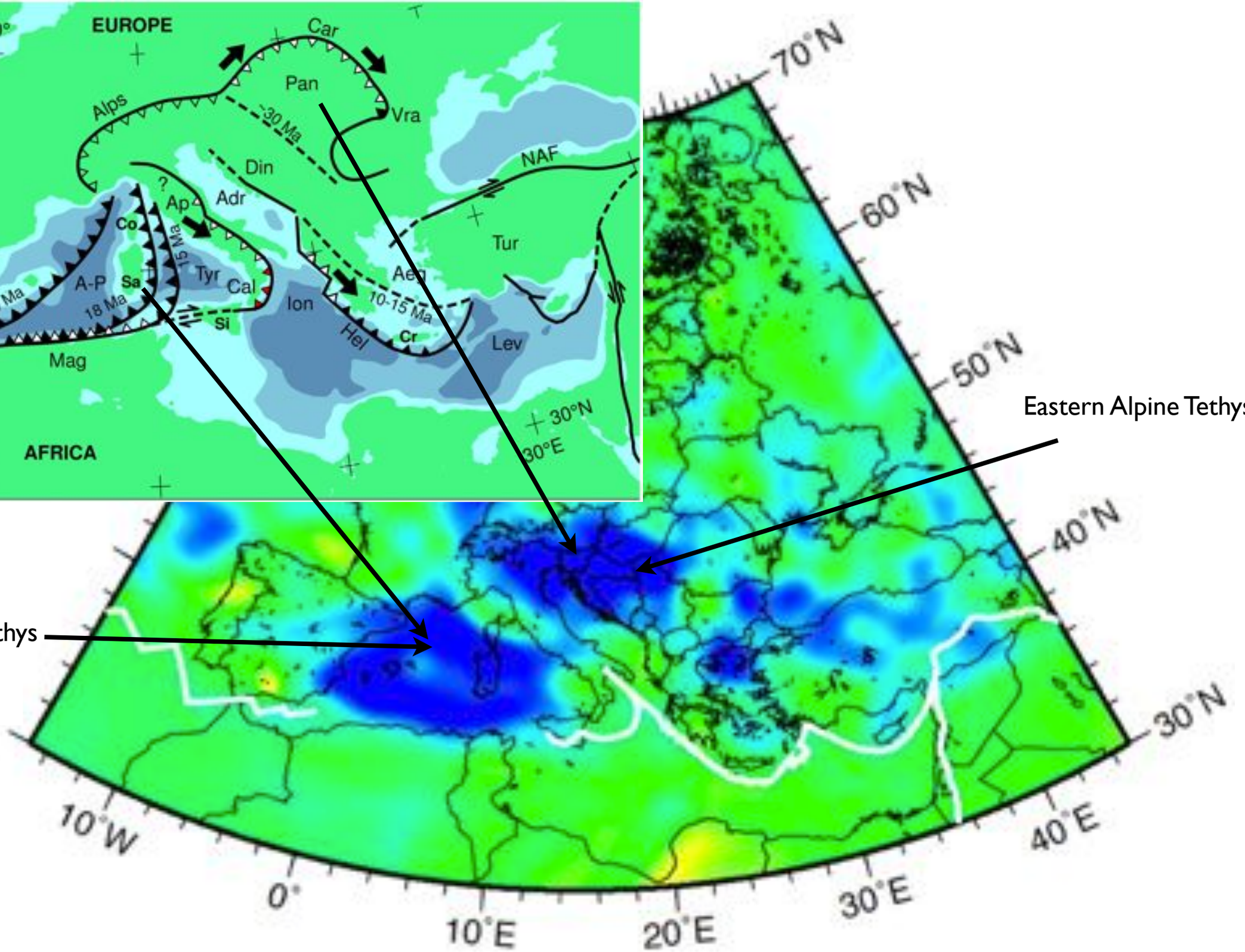


Eastern Alpine Tethys

Western Alpine Tethys

Depth 625 km

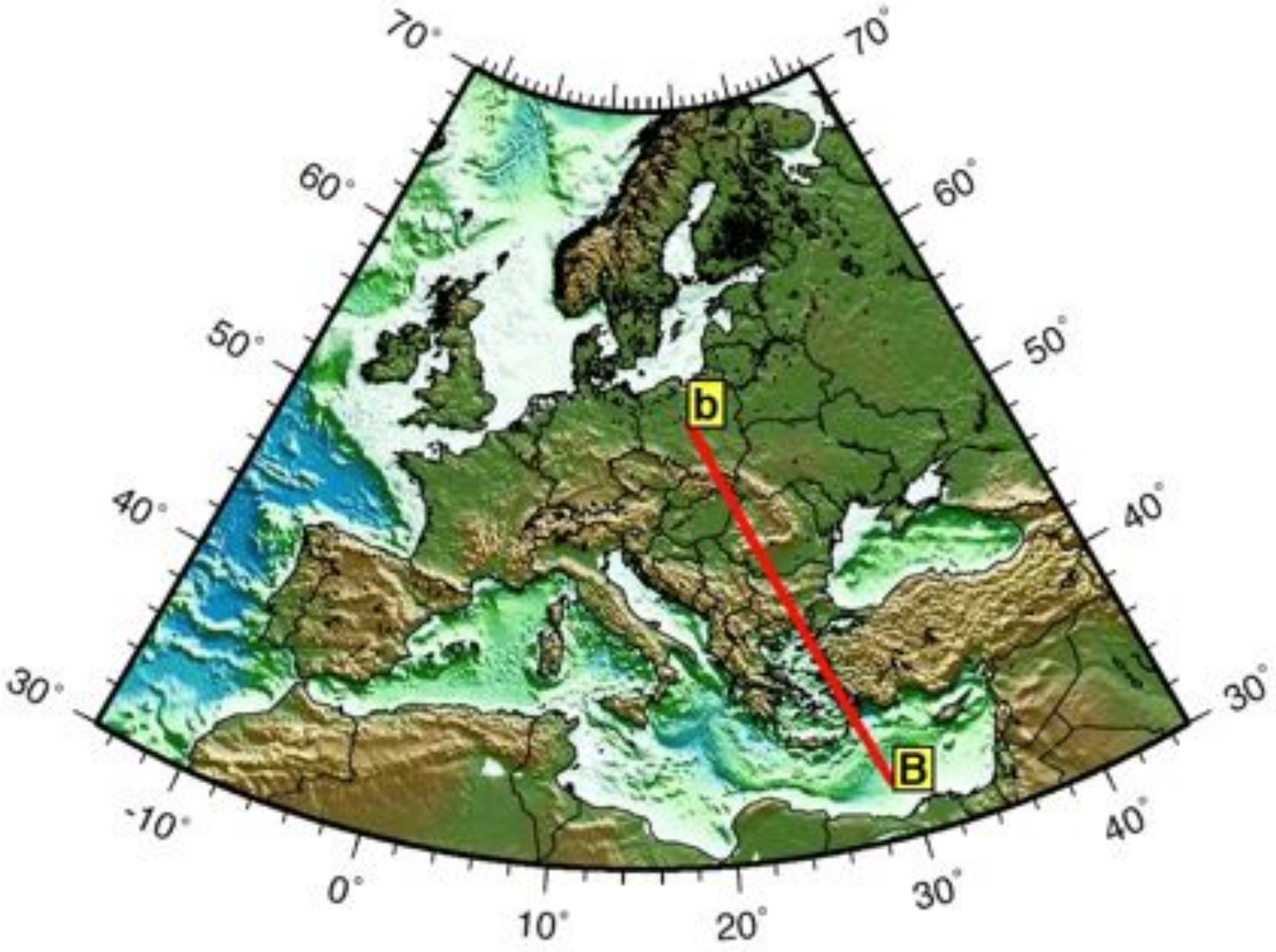




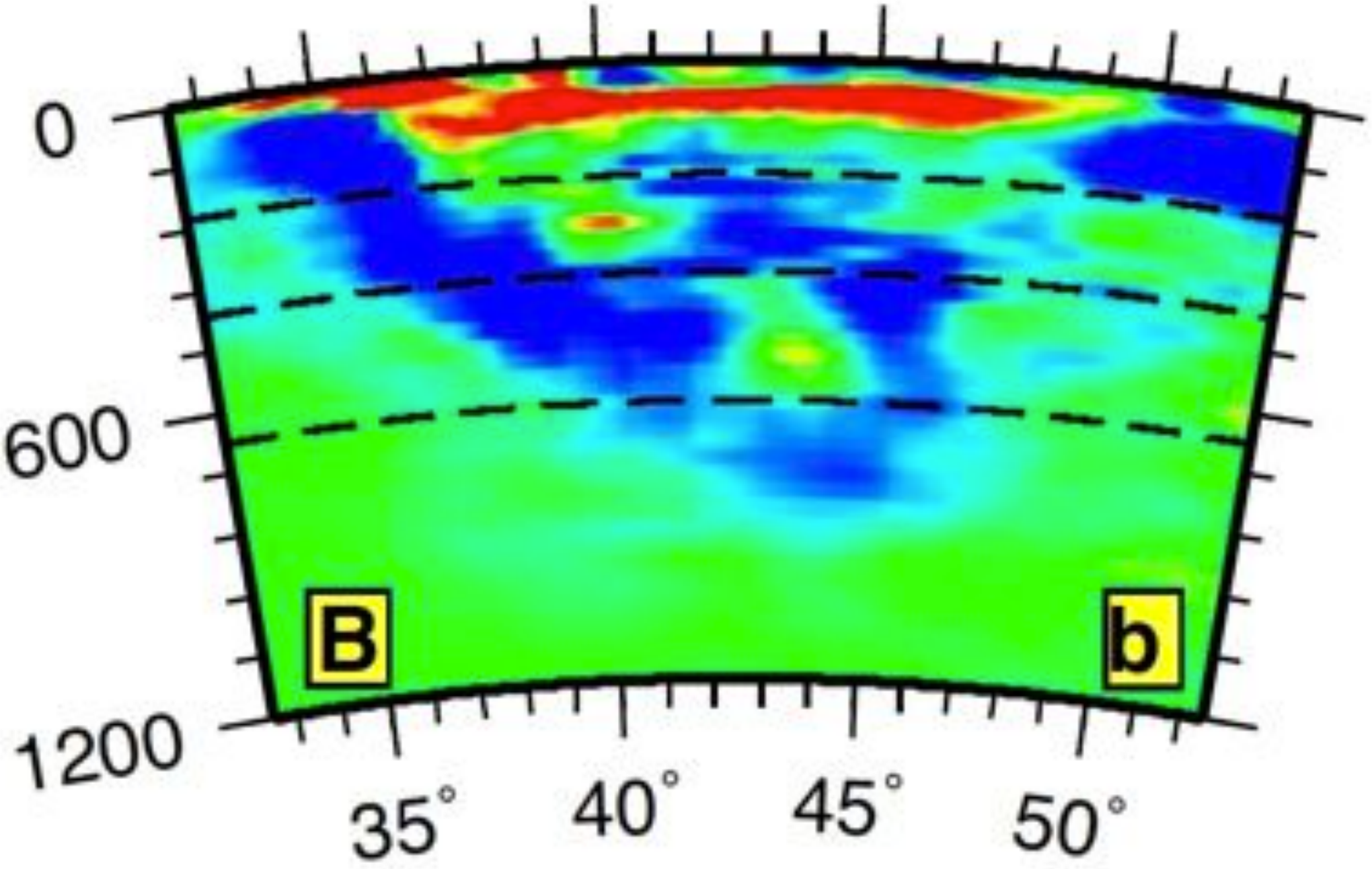
Eastern Alpine Tethys

Western Alpine Tethys

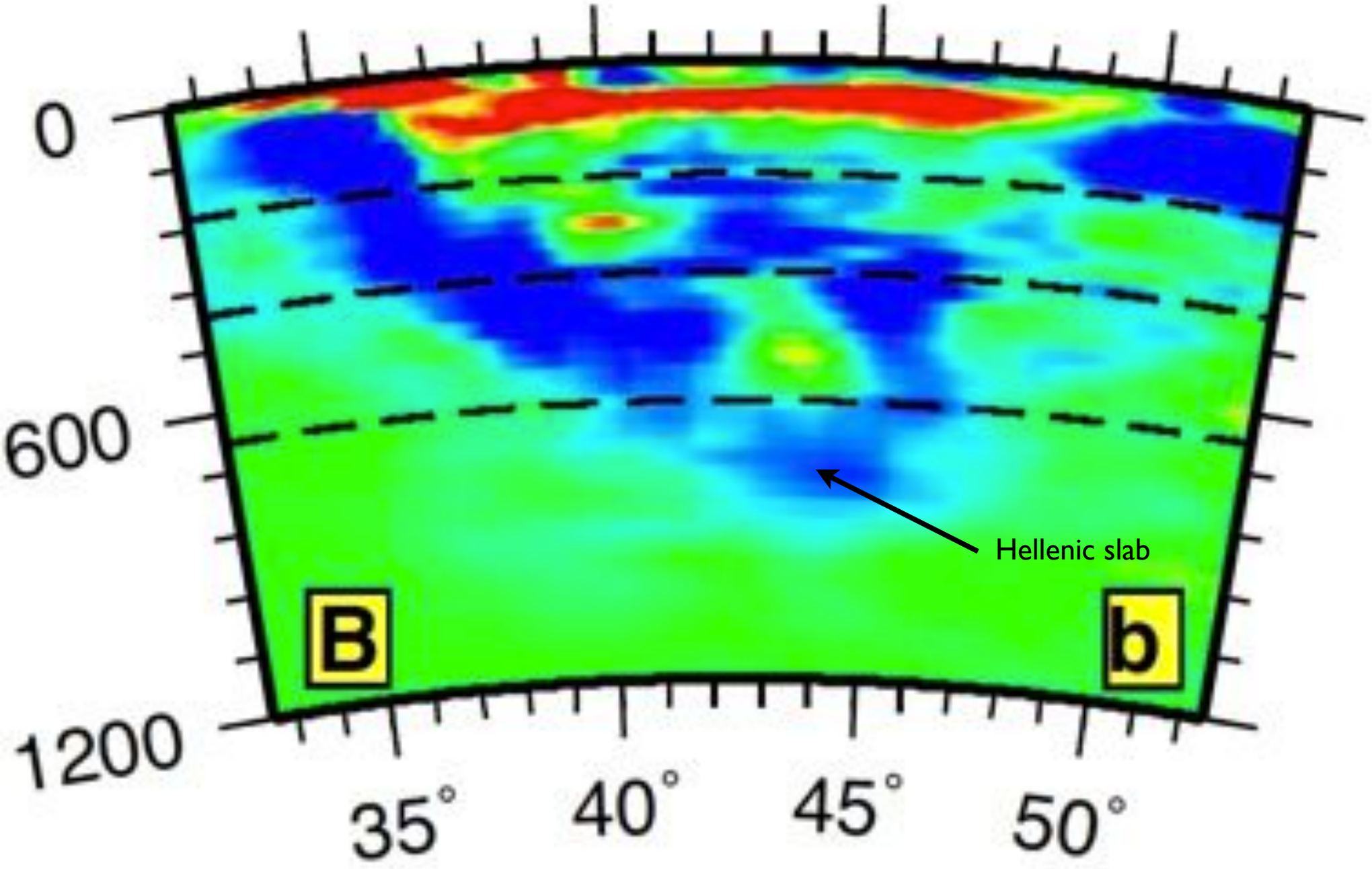
Hellenic Subduction



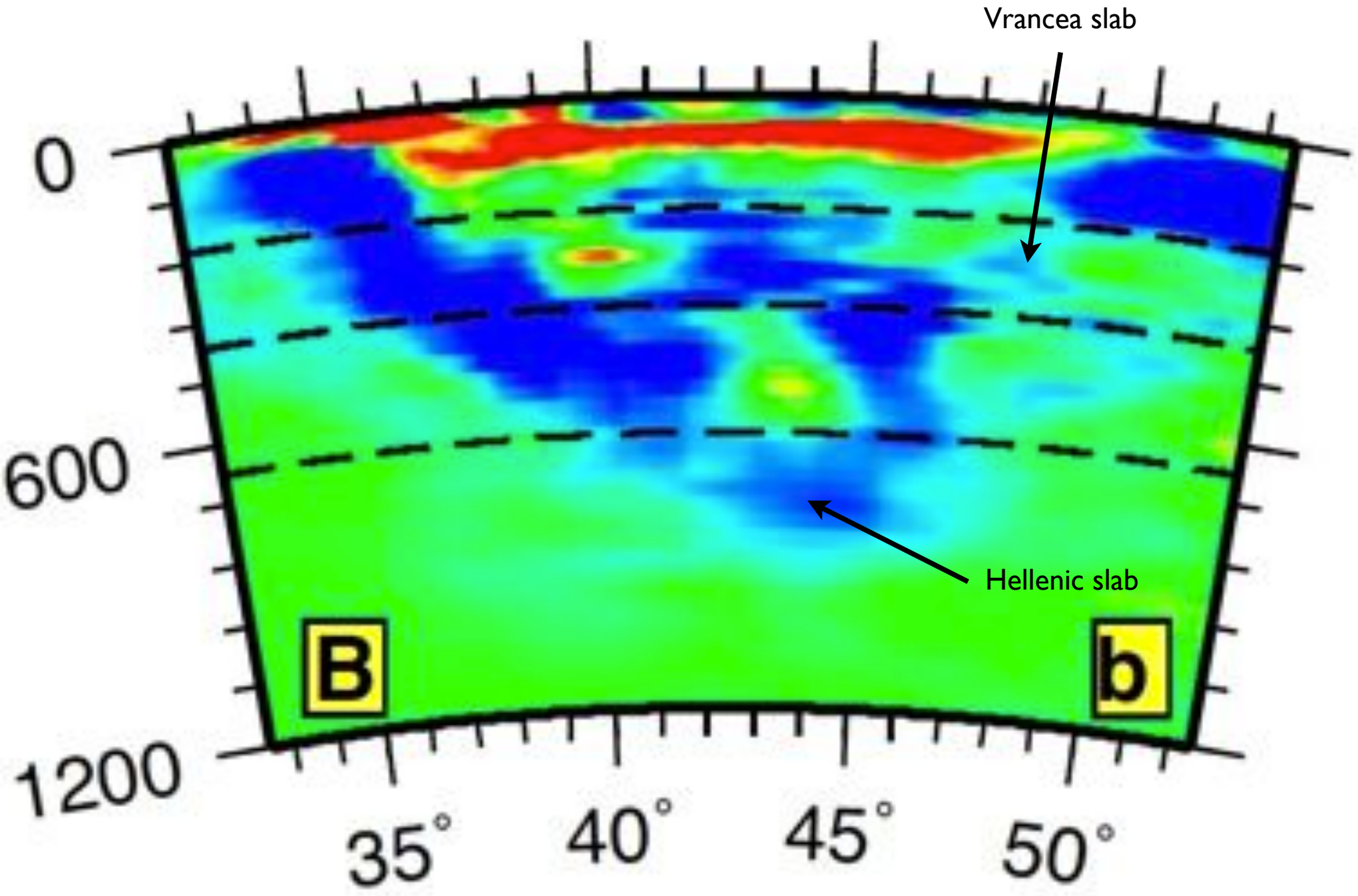
Hellenic Subduction



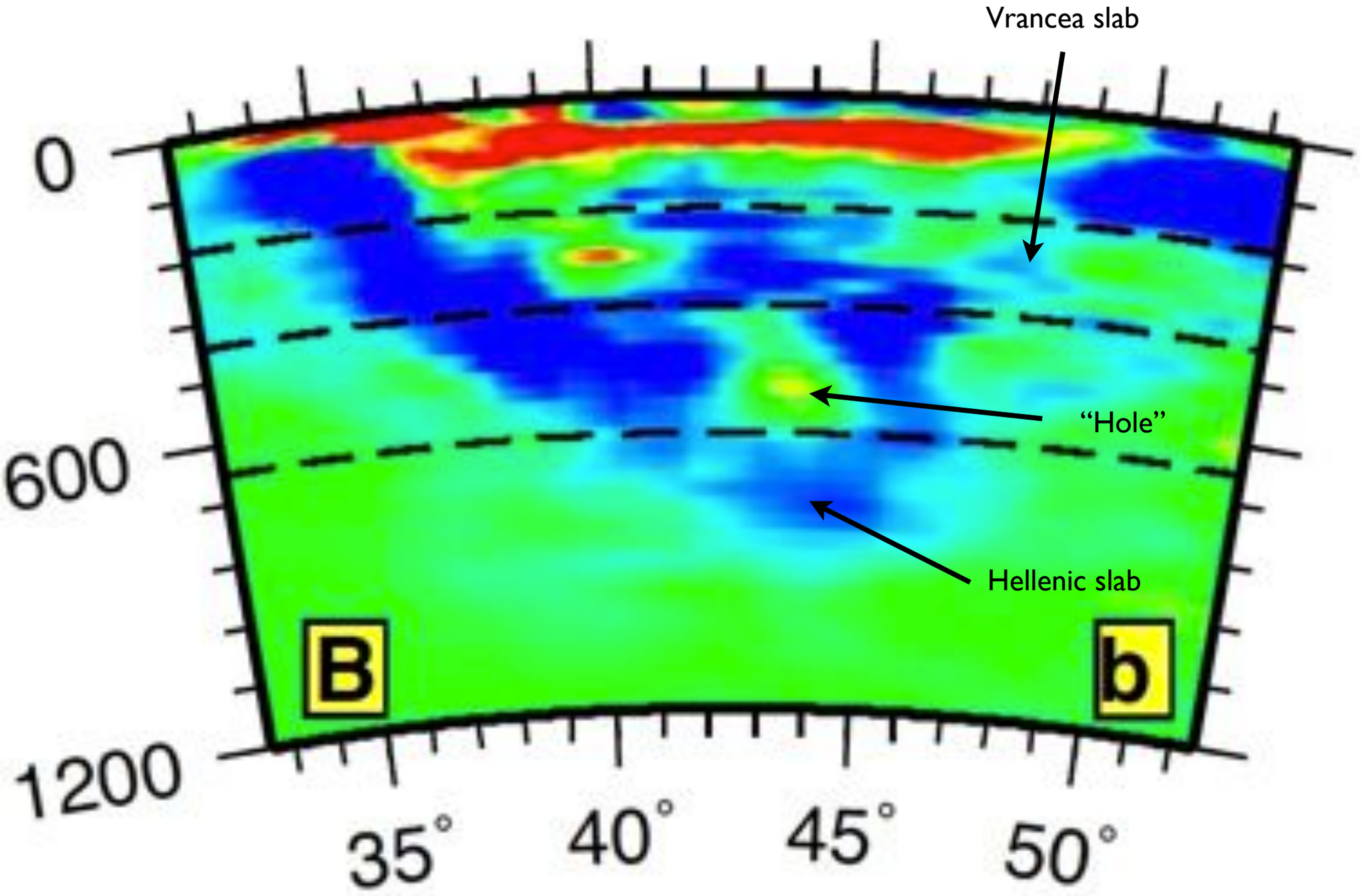
Hellenic Subduction



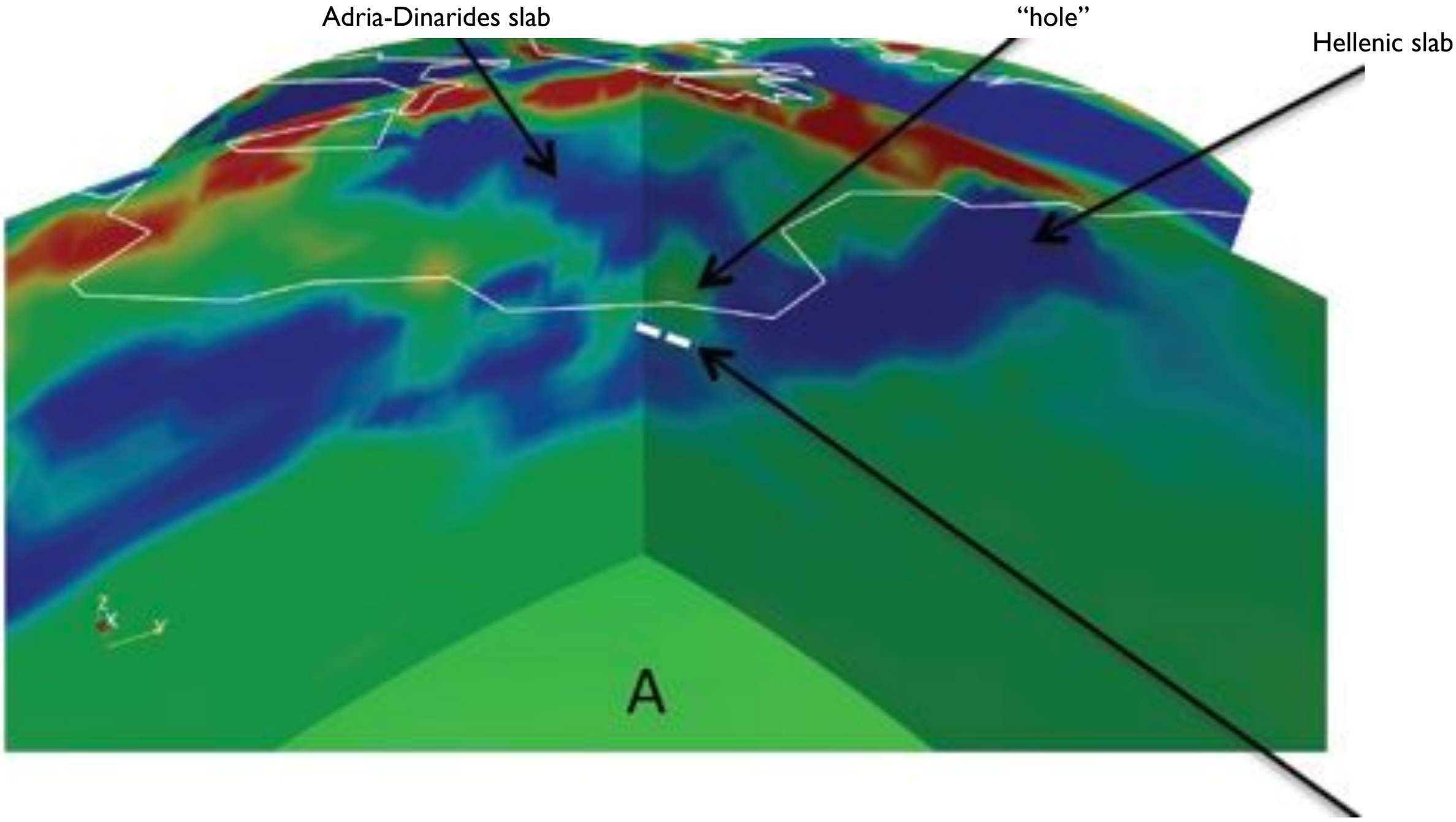
Hellenic Subduction



Hellenic Subduction



A "Hole" Beneath Bulgaria



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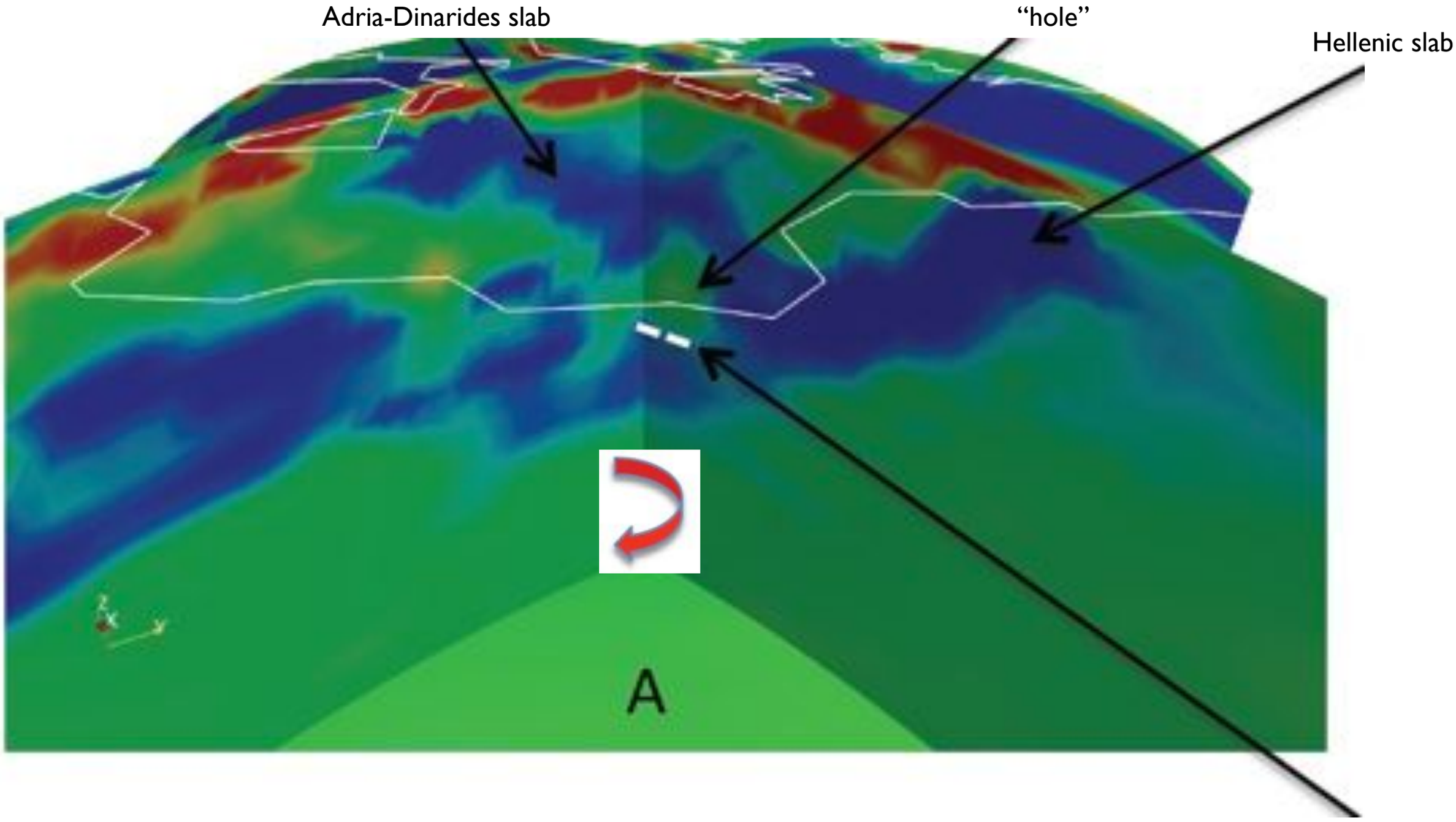

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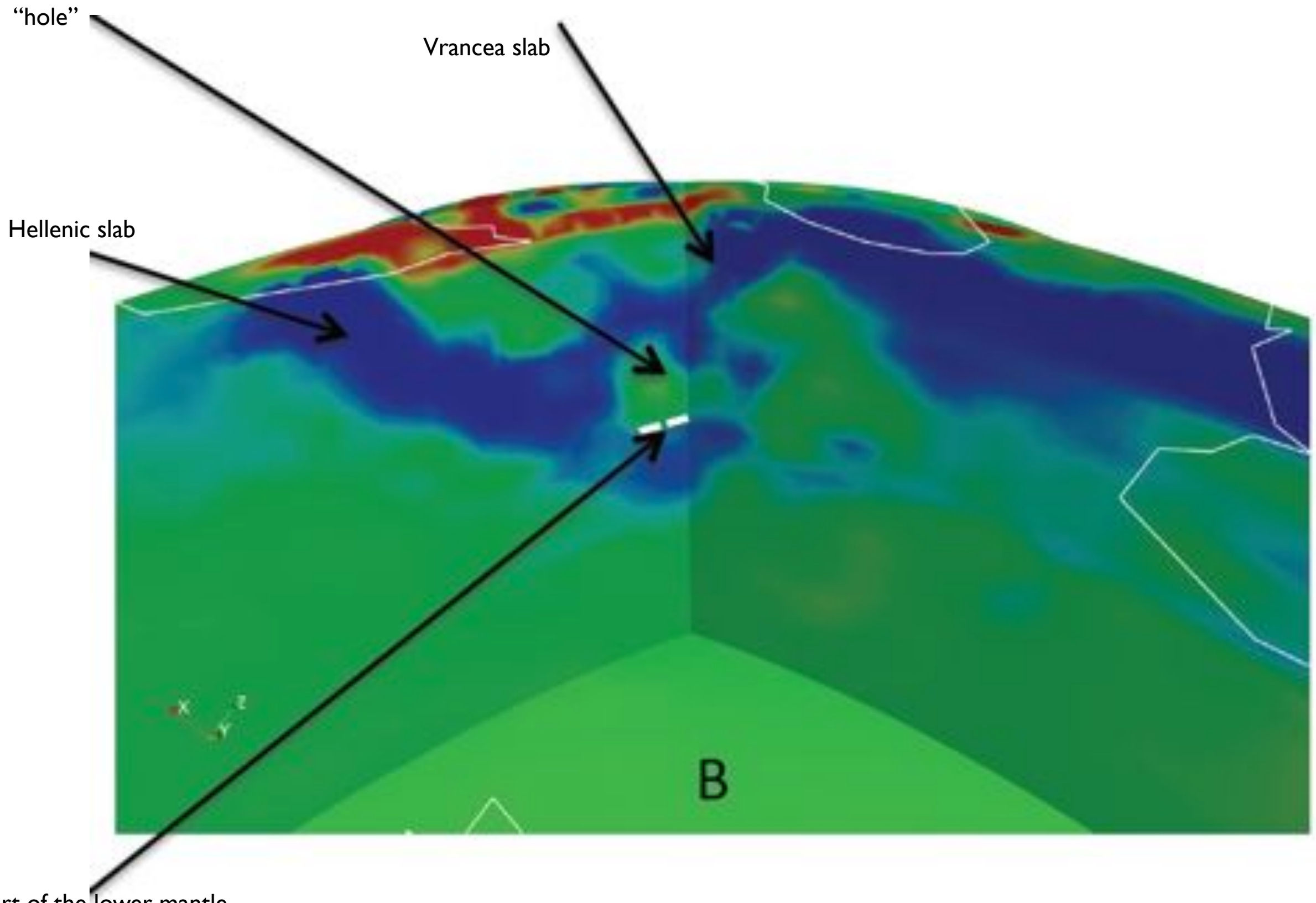

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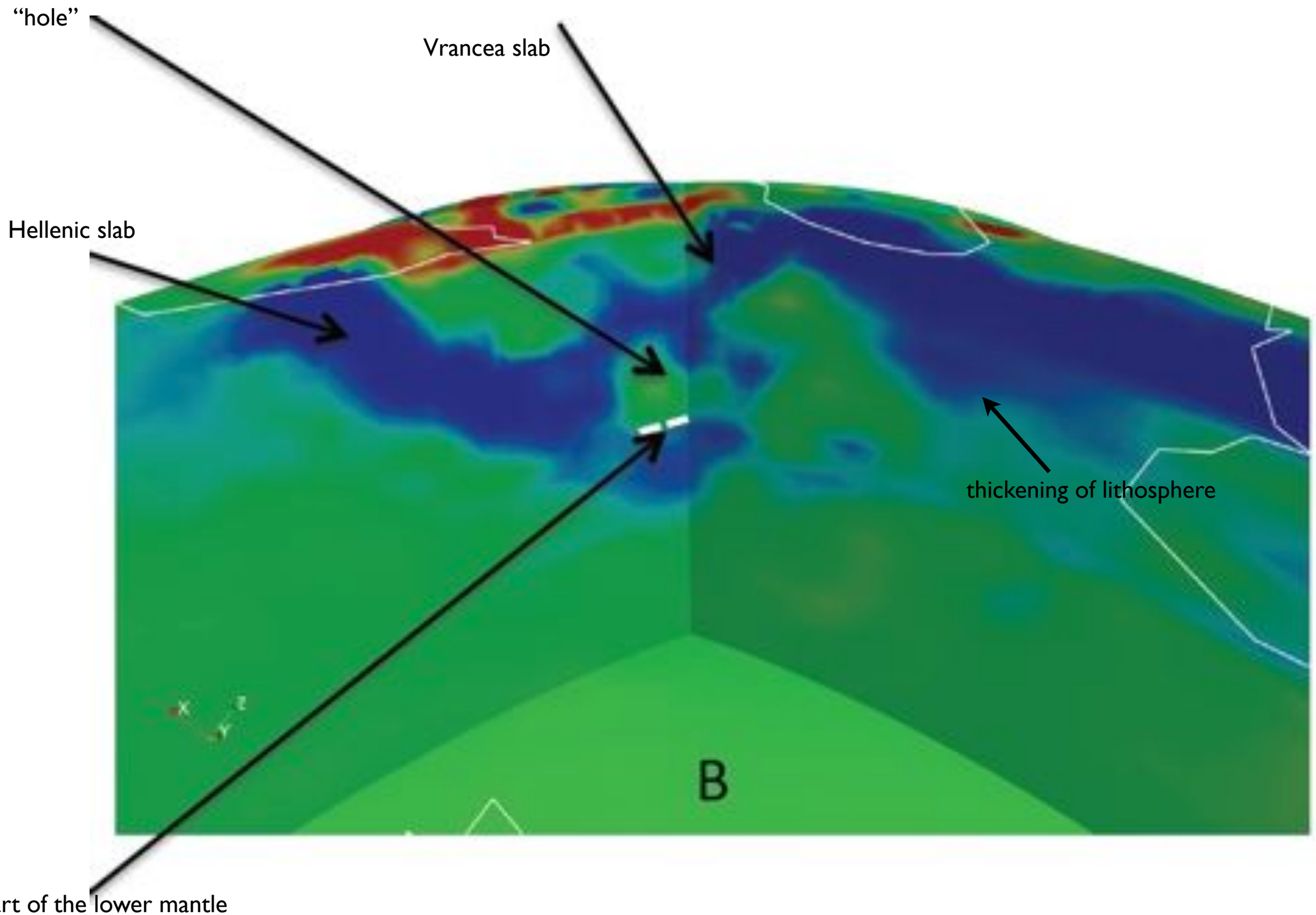
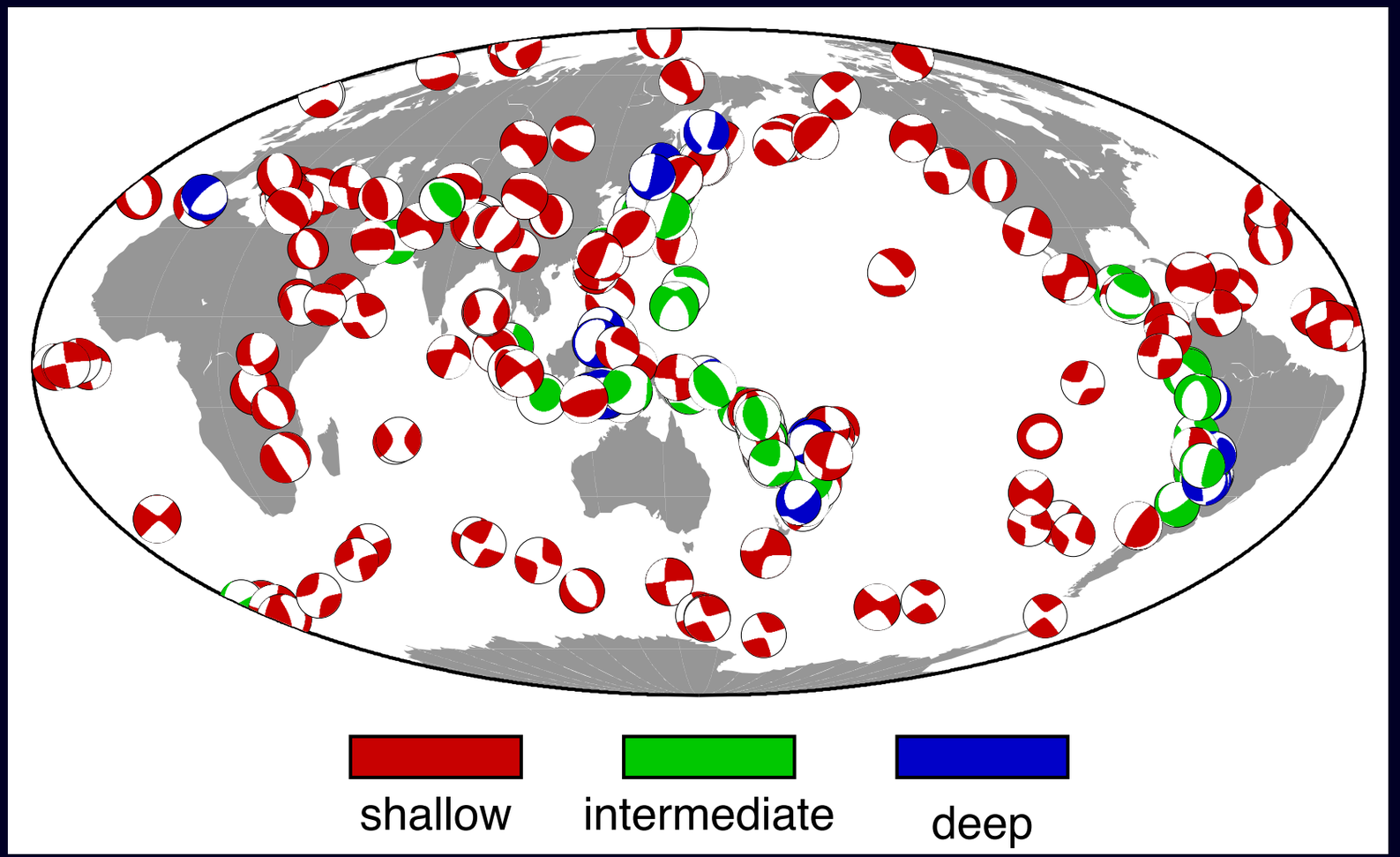


Towards Global Seismic Imaging

254 earthquakes

5.8 ≤ Mw ≤ 7

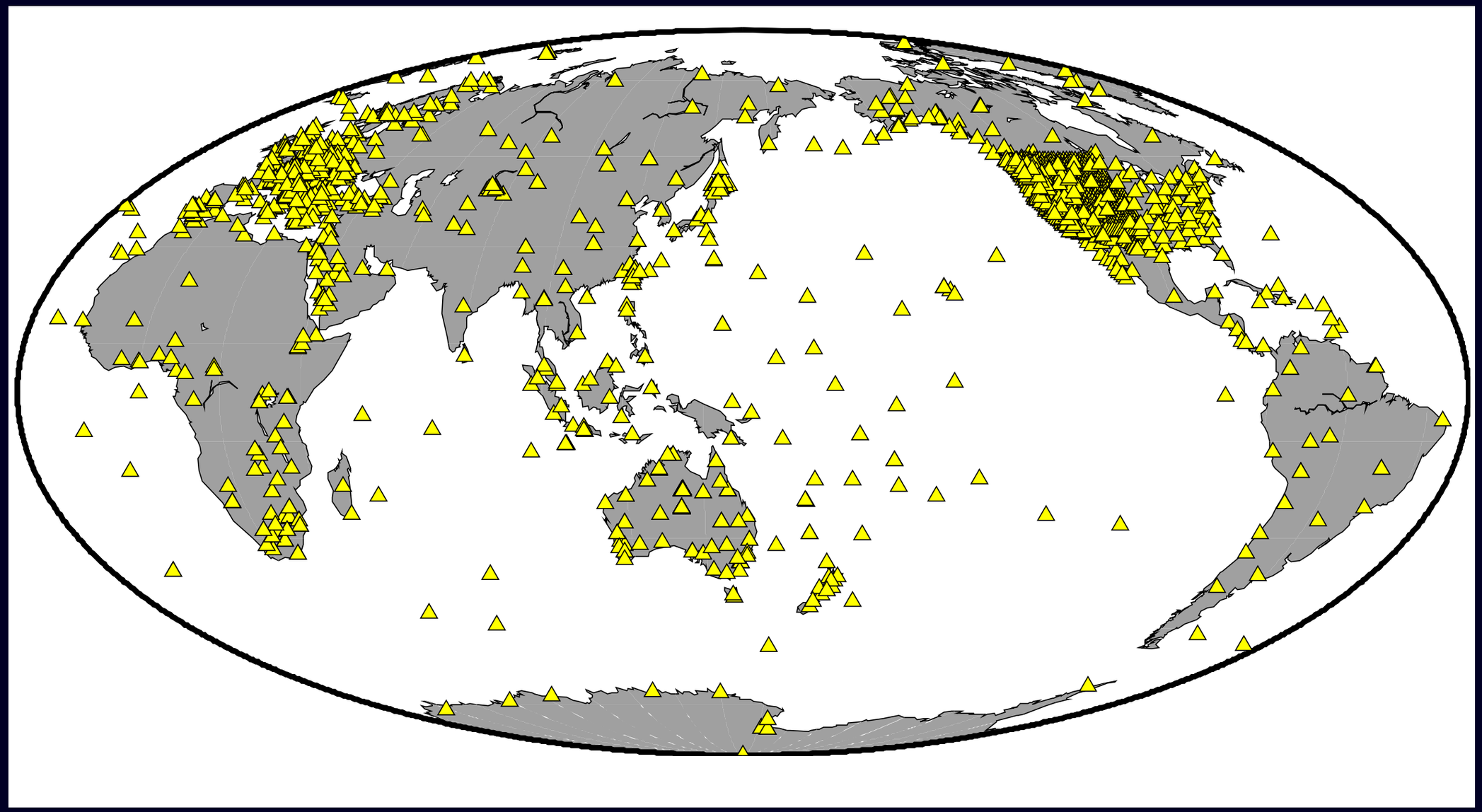


shallow: d≤ 50 km

intermediate: 50 km < d ≤ 300 km

deep: d > 300 km

Station Coverage



2.2 million measurements for 254 earthquakes

Conclusions

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- Ultimate goal: To image our entire planet

Conclusions

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	# earthquakes	# simulations	CPU core hours
Europe	160	11,200	806,400
Globe (Phase 1)	250	17,500	14,437,400
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- Assimilation of 50 million measurements