Structure of the European Upper Mantle Revealed by Adjoint Tomography

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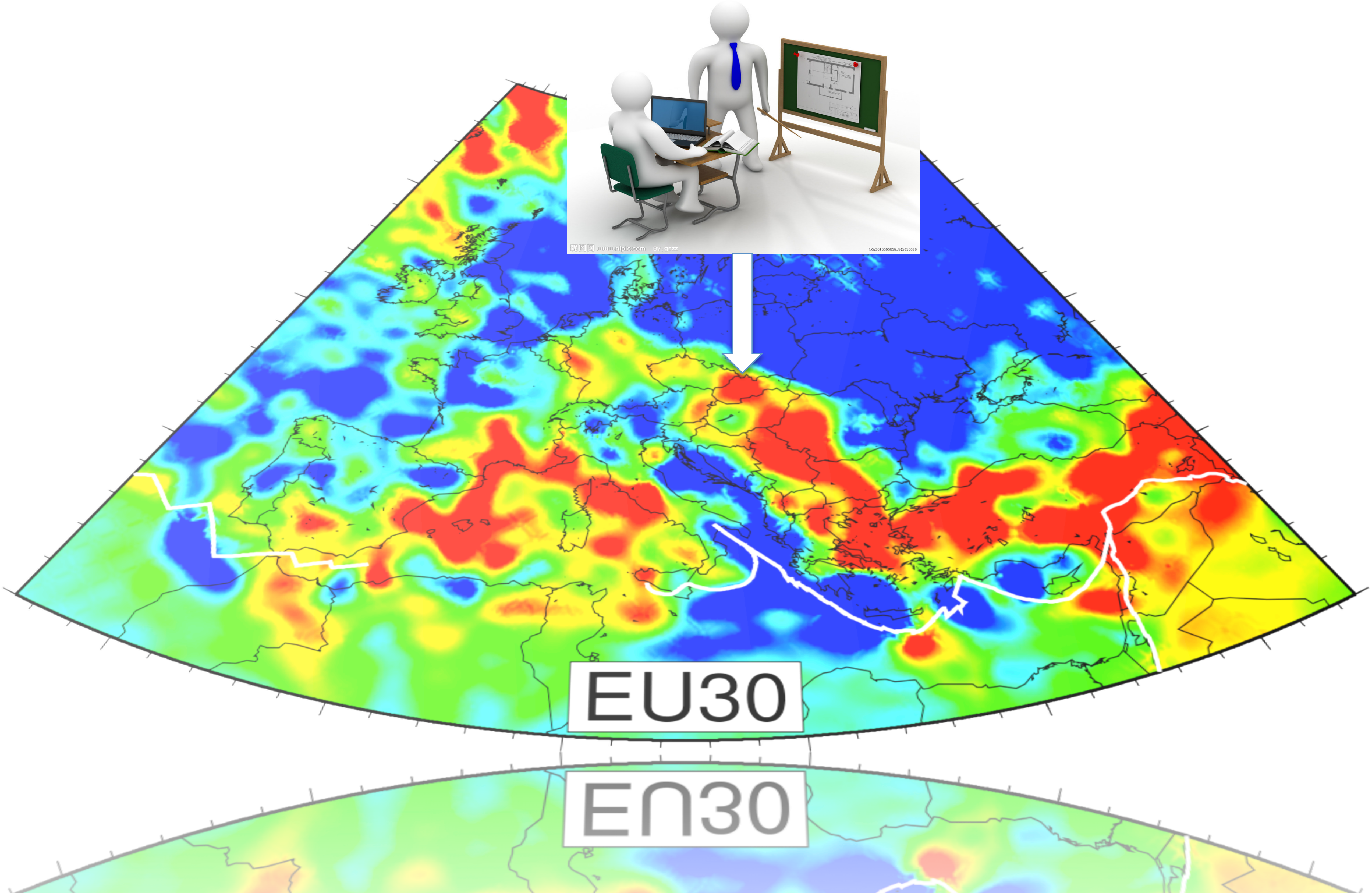
Department of Geosciences, Princeton University

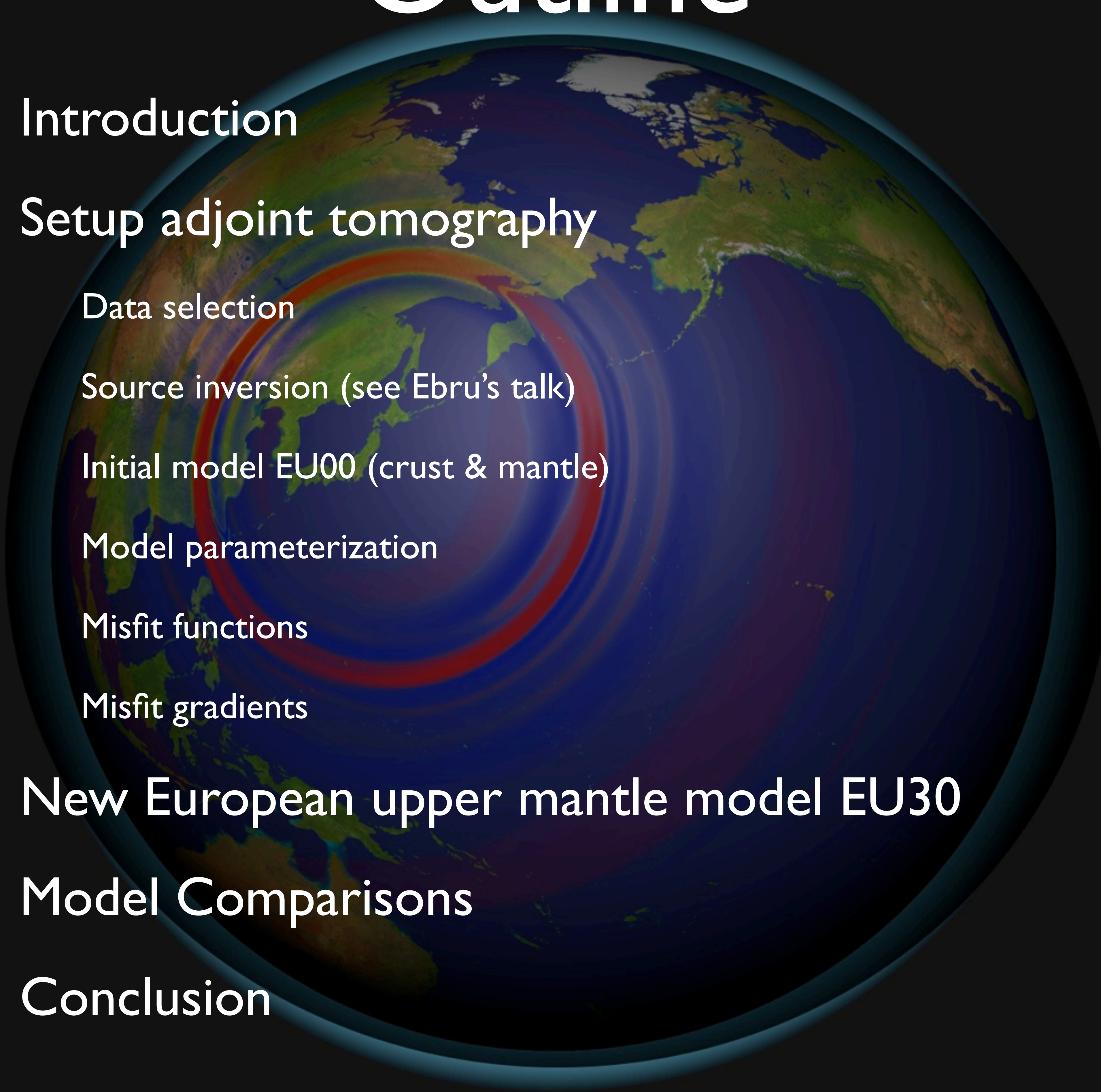
May 25th, 3rd QUEST Workshop, Slovakia

Acknowledgement: All current & former students and postdoctoral scholars in Tromp's group

WARNING! Hot materials



Outline



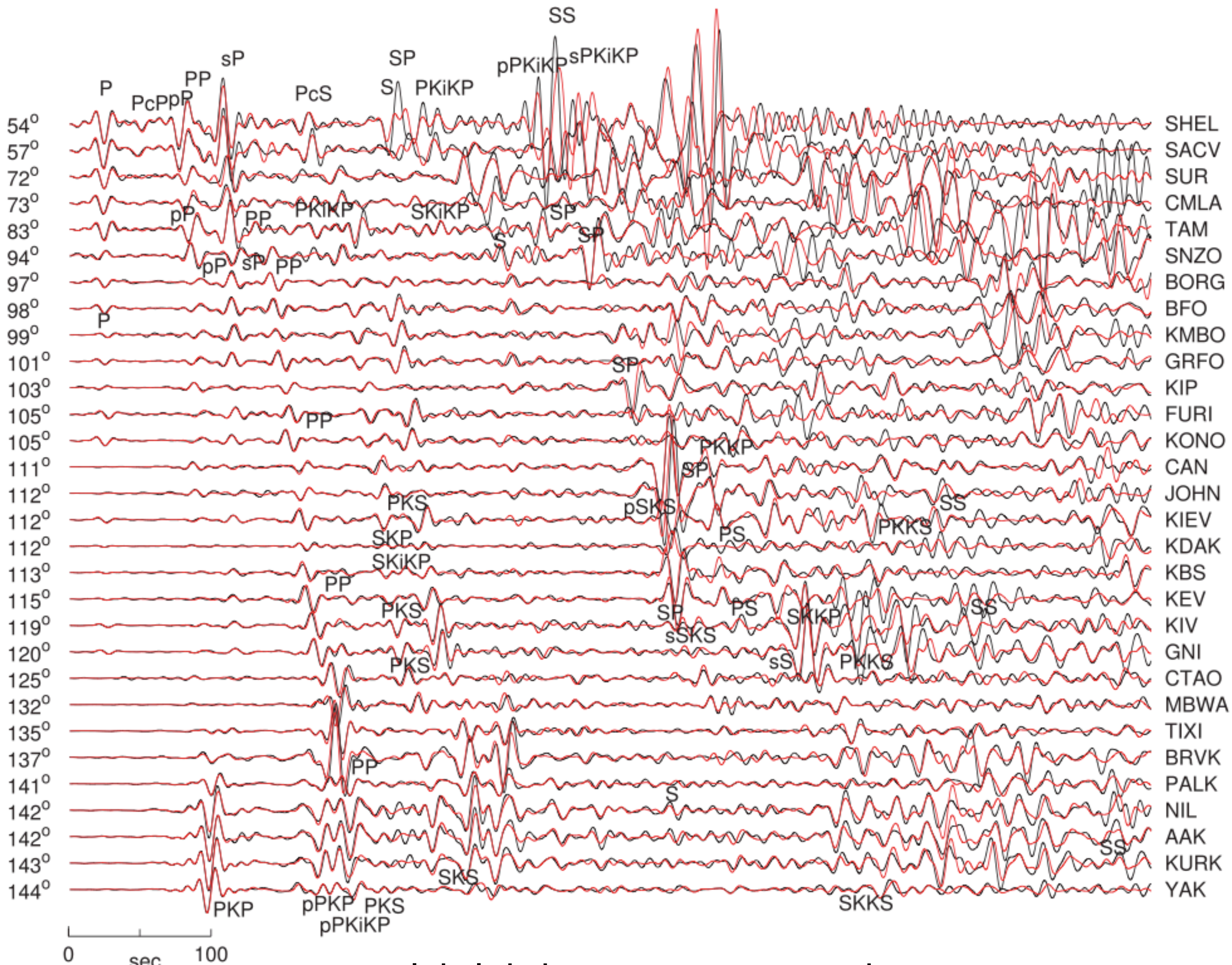
1. Introduction
2. Setup adjoint tomography
    - Data selection
    - Source inversion (see Ebru’s talk)
    - Initial model EU00 (crust & mantle)
    - Model parameterization
    - Misfit functions
    - Misfit gradients
3. New European upper mantle model EU30
4. Model Comparisons
5. Conclusion

Modern numerical simulations and Imaging the Earth

global.shakemovie.princeton.edu

Spectral-element method; 3D Earth model: S362ANI+Crust2.0; Shortest period: 17 seconds

Modern numerical simulations and Imaging the Earth



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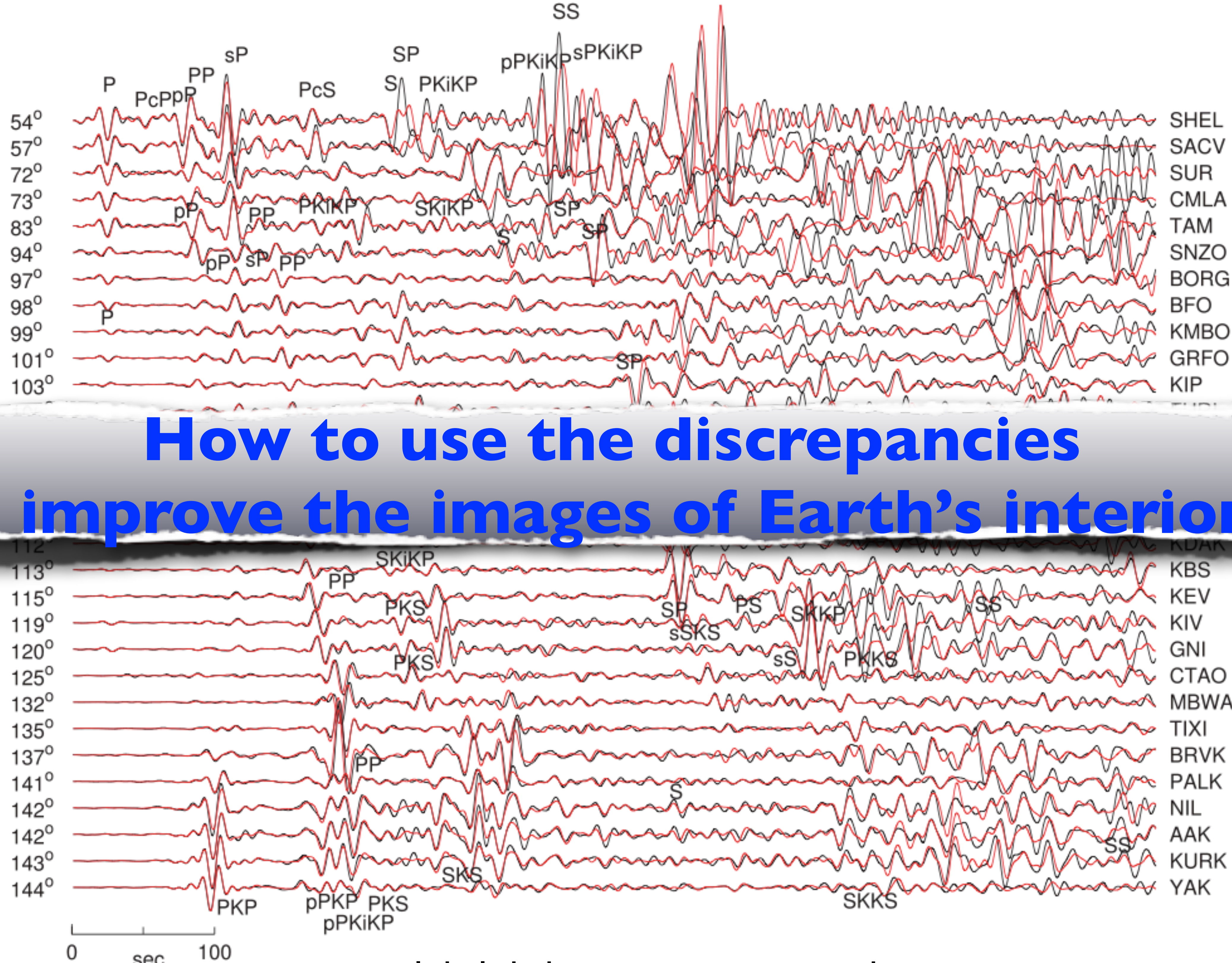
Modern numerical simulations and Imaging the Earth



How to use the discrepancies to improve the images of Earth's interior ?

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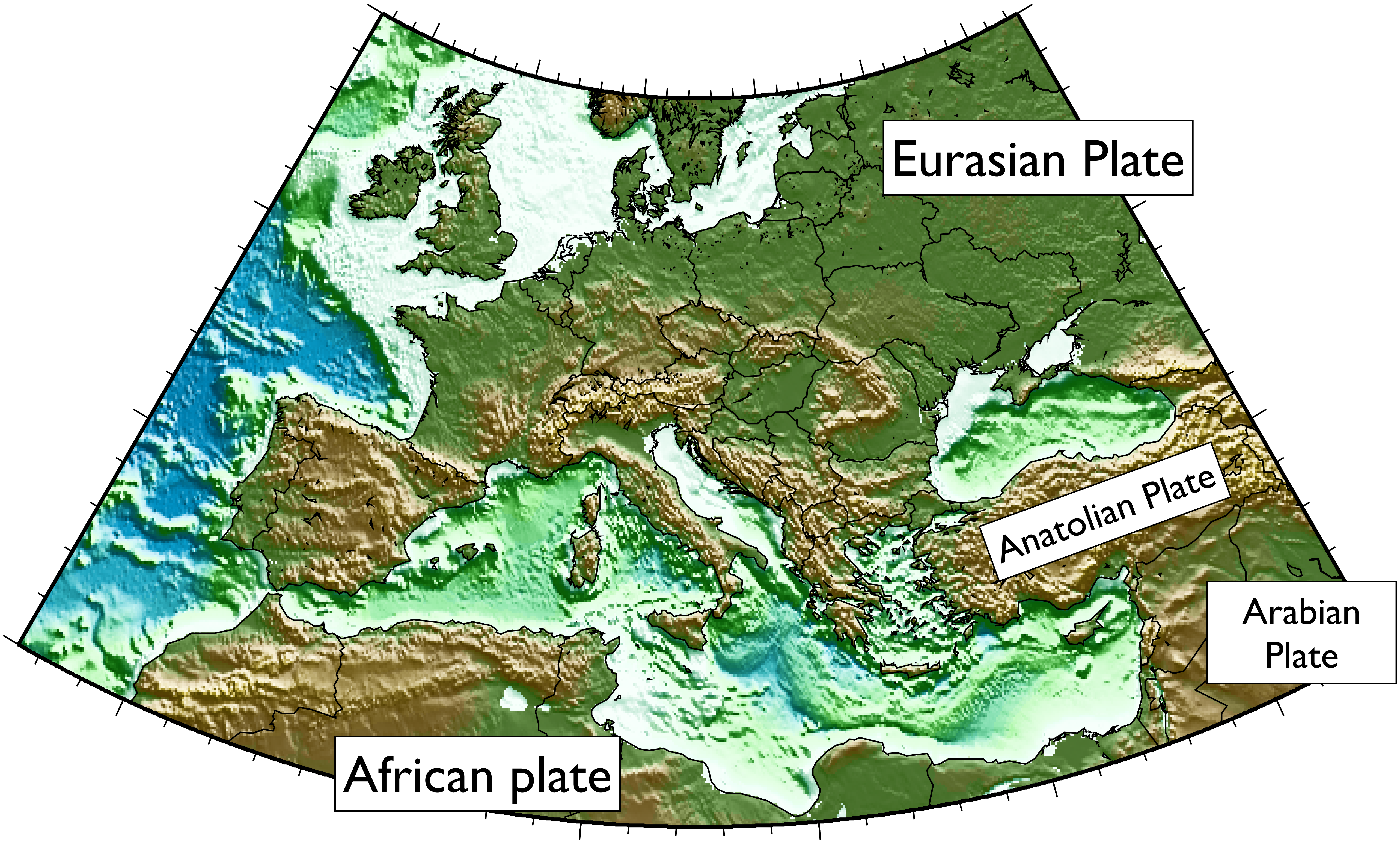
Spectral-element method; 3D Earth model: S362ANI+Crust2.0; Shortest period: 17 seconds

Tectonic map of Europe



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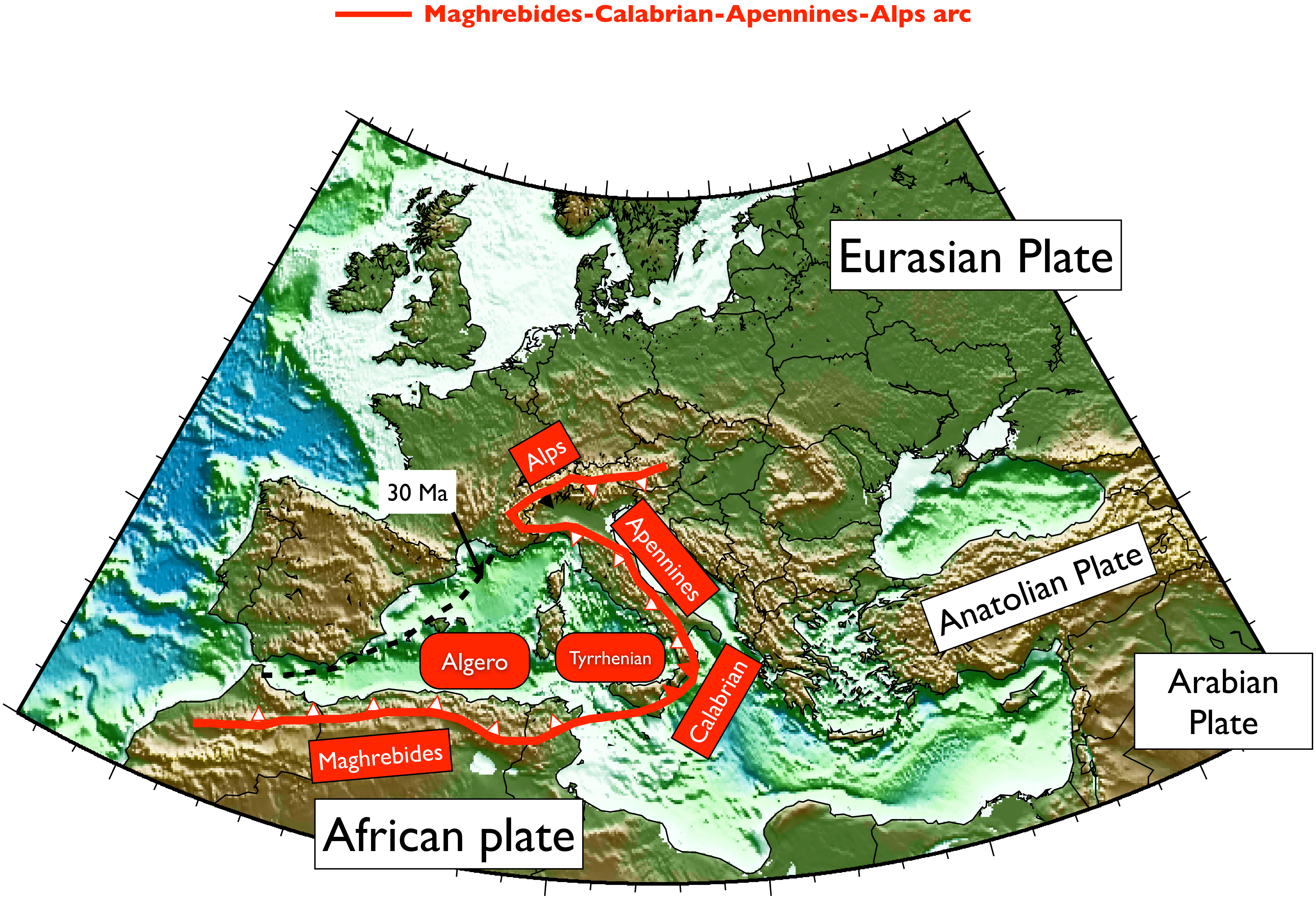

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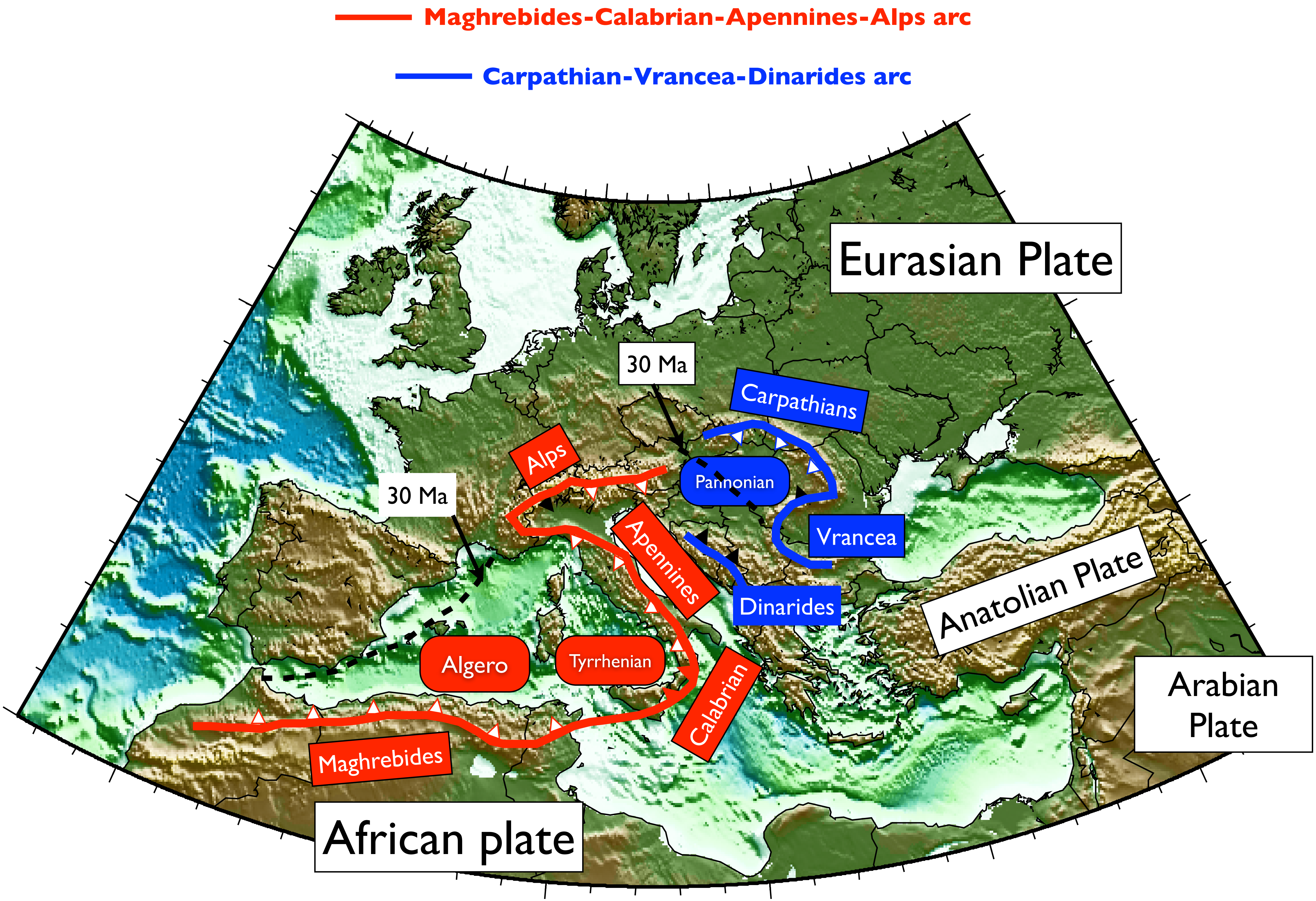

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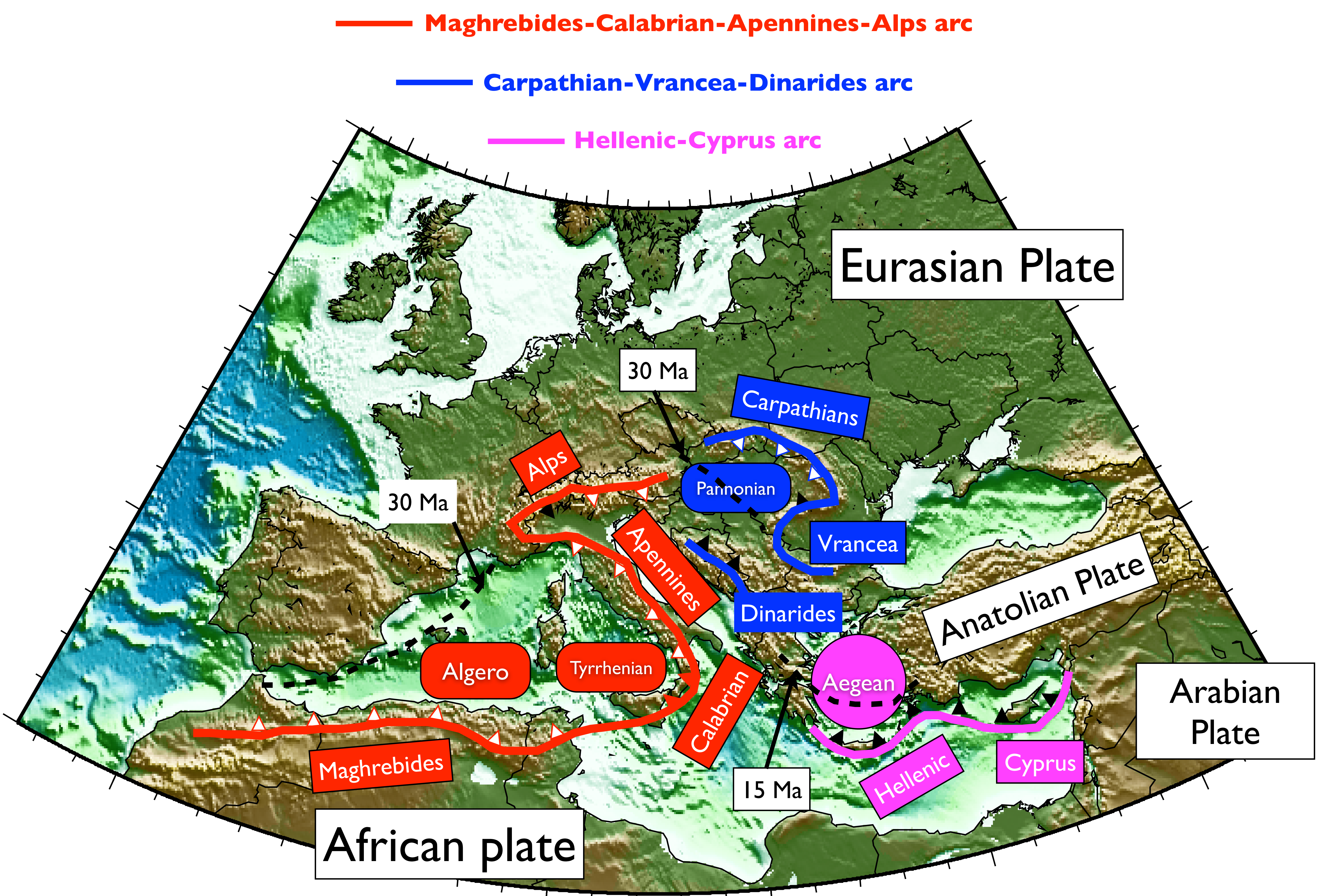


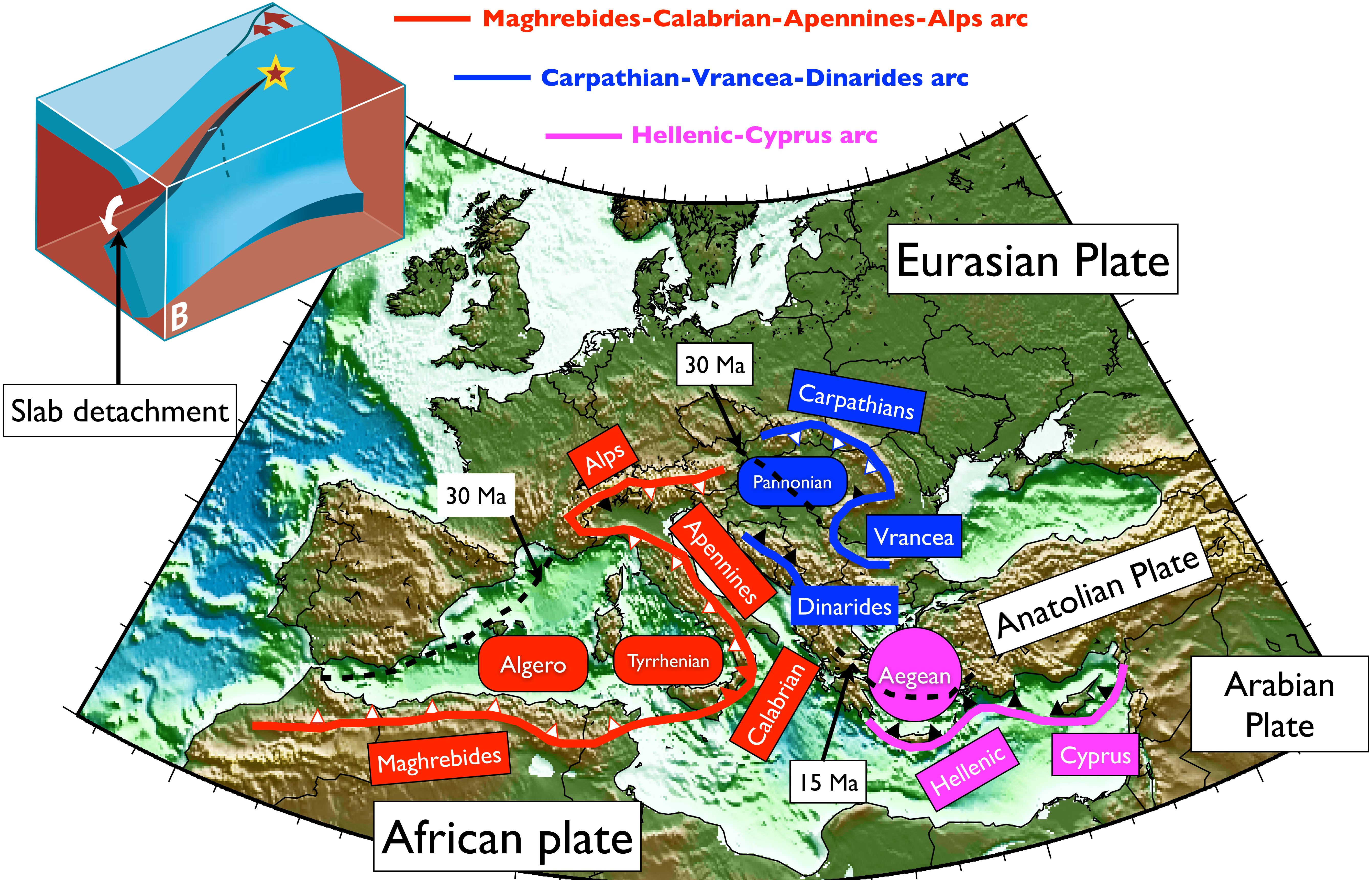
Tectonic map of Europe

(Wortel & Spakman, 2000)

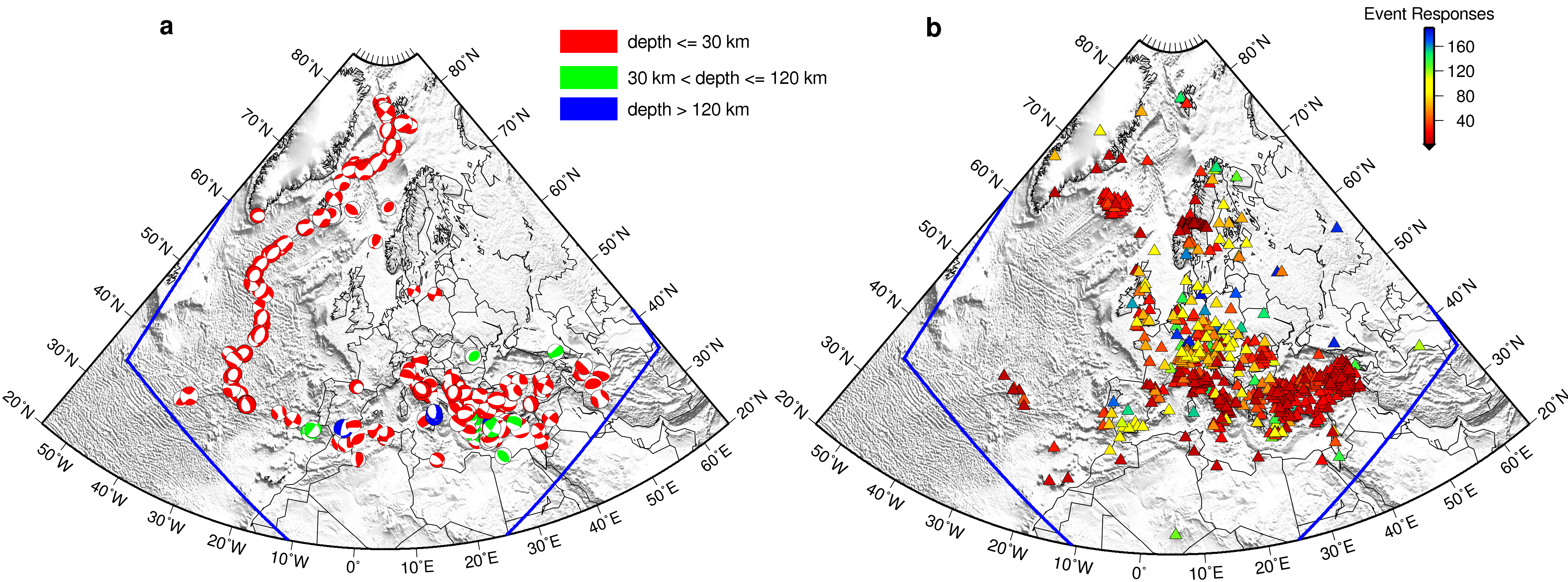
Maghrebides-Calabrian-Apennines-Alps arc

Carpathian-Vrancea-Dinarides arc

Hellenic-Cyprus arc



Dataset

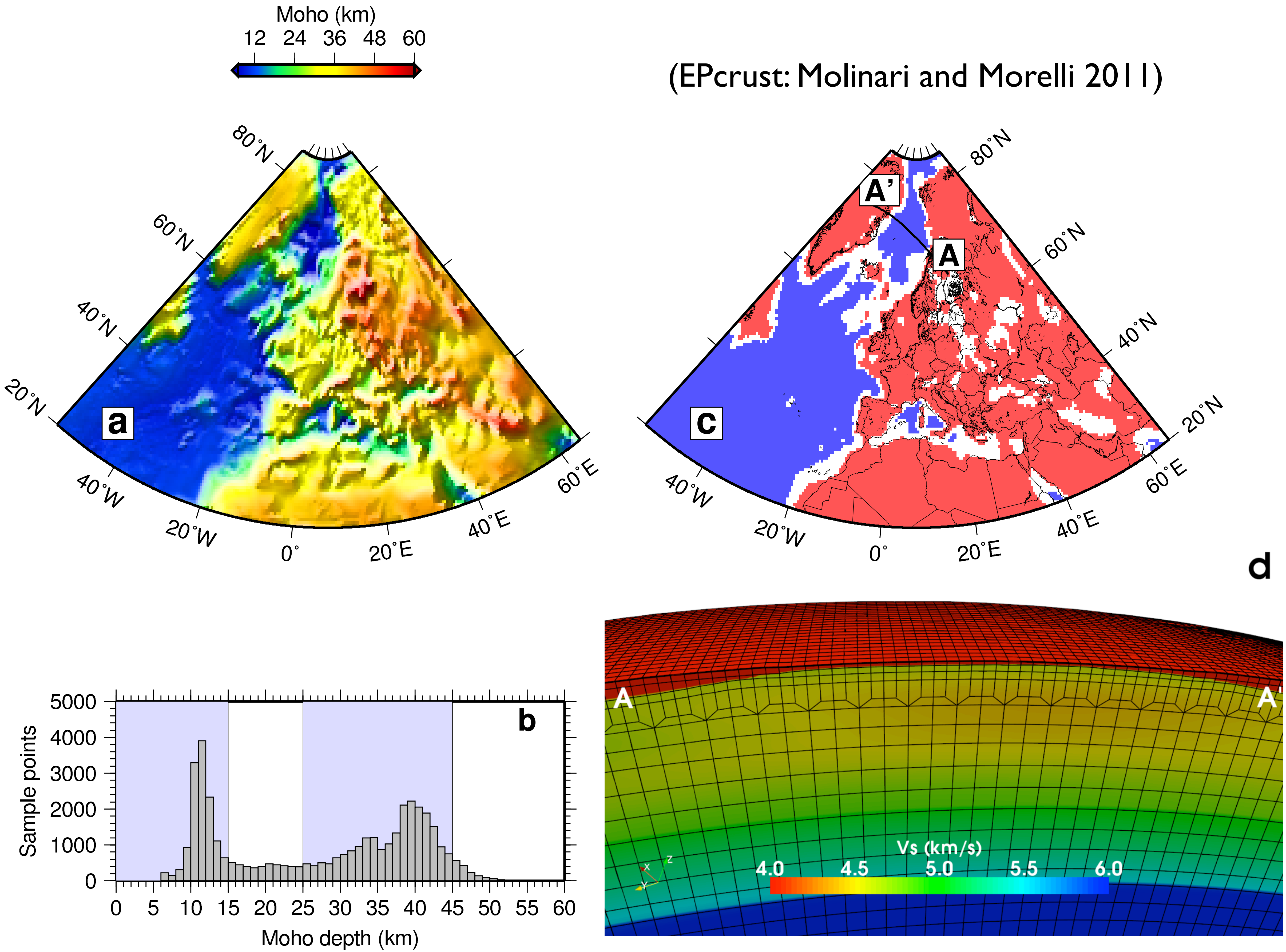


Sesame cluster PICSciE
www.princeton.edu/researchcomputting

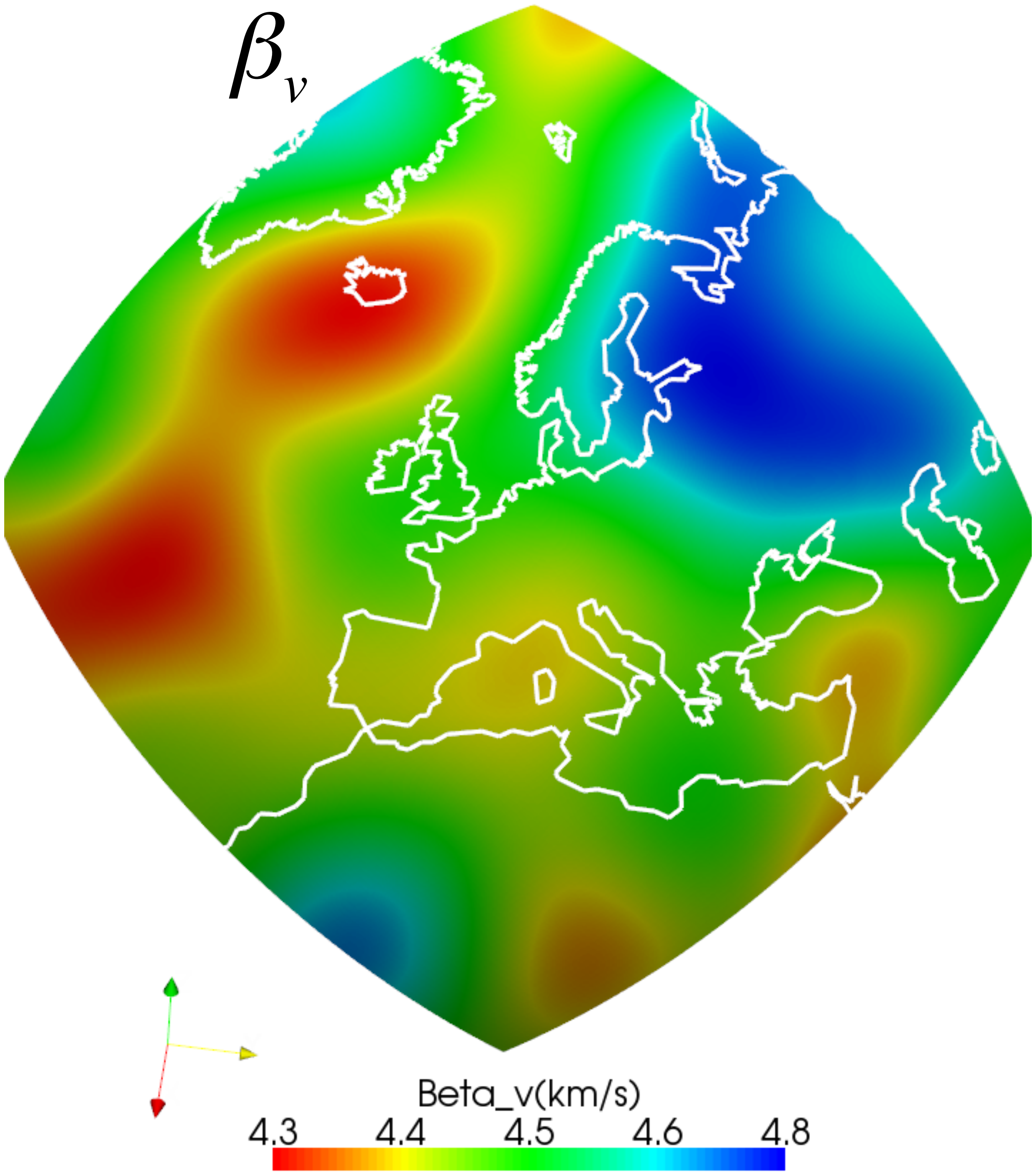
earthquakes	stations	iterations	simulations	CPU hours	measurements
190	745	30	17,100	2.3 million	123,205

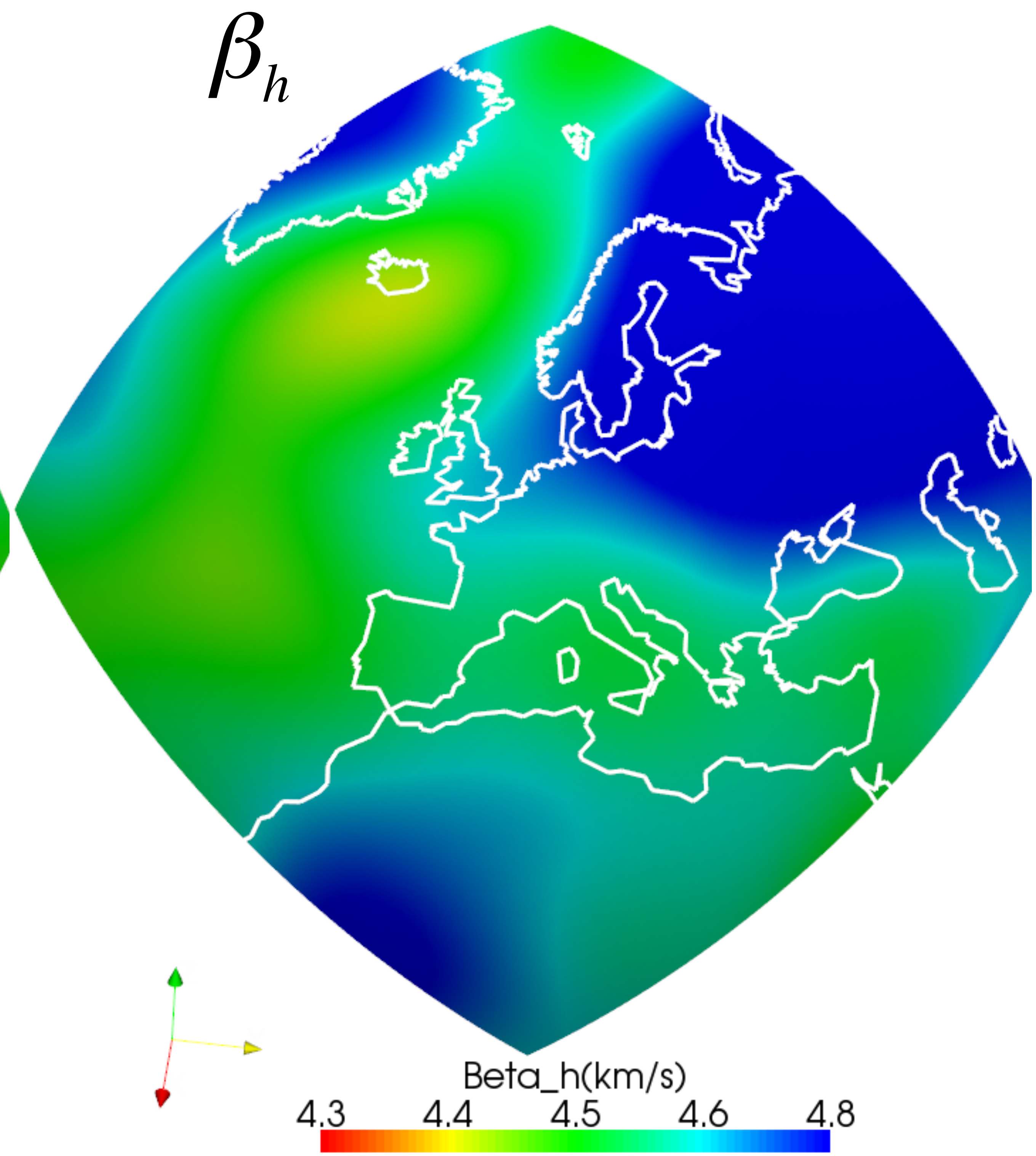
SPECFEM3D mesh for EPcrust

(EPcrust: Molinari and Morelli 2011)

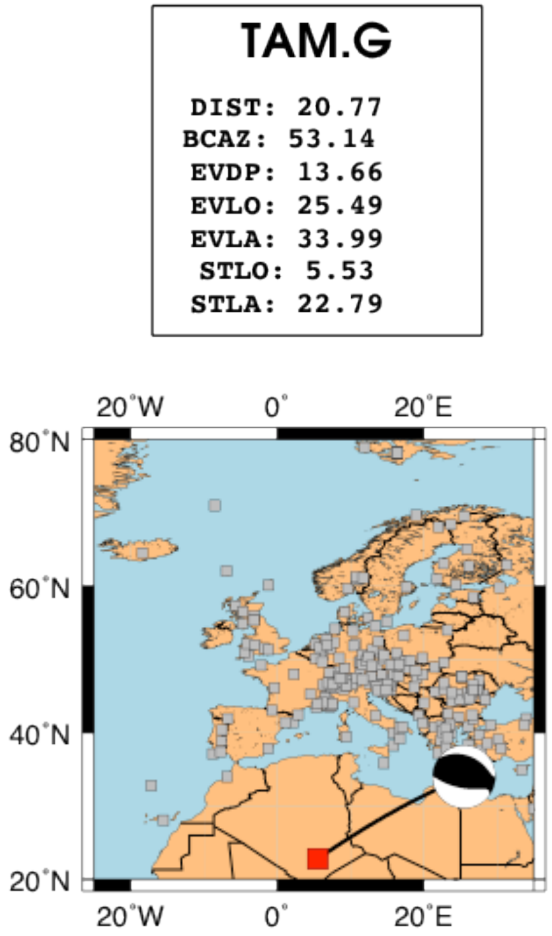


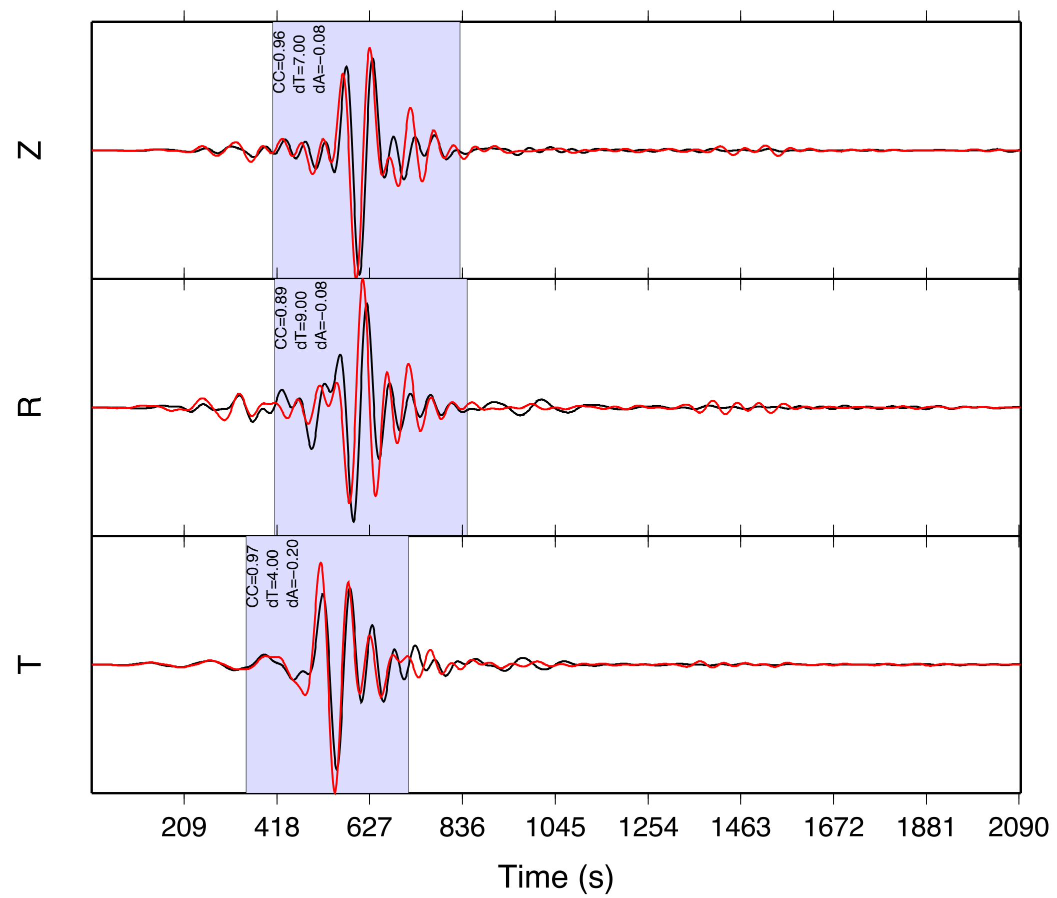
S362ANI at 75 km depth





Radial anisotropic sensitivity kernels





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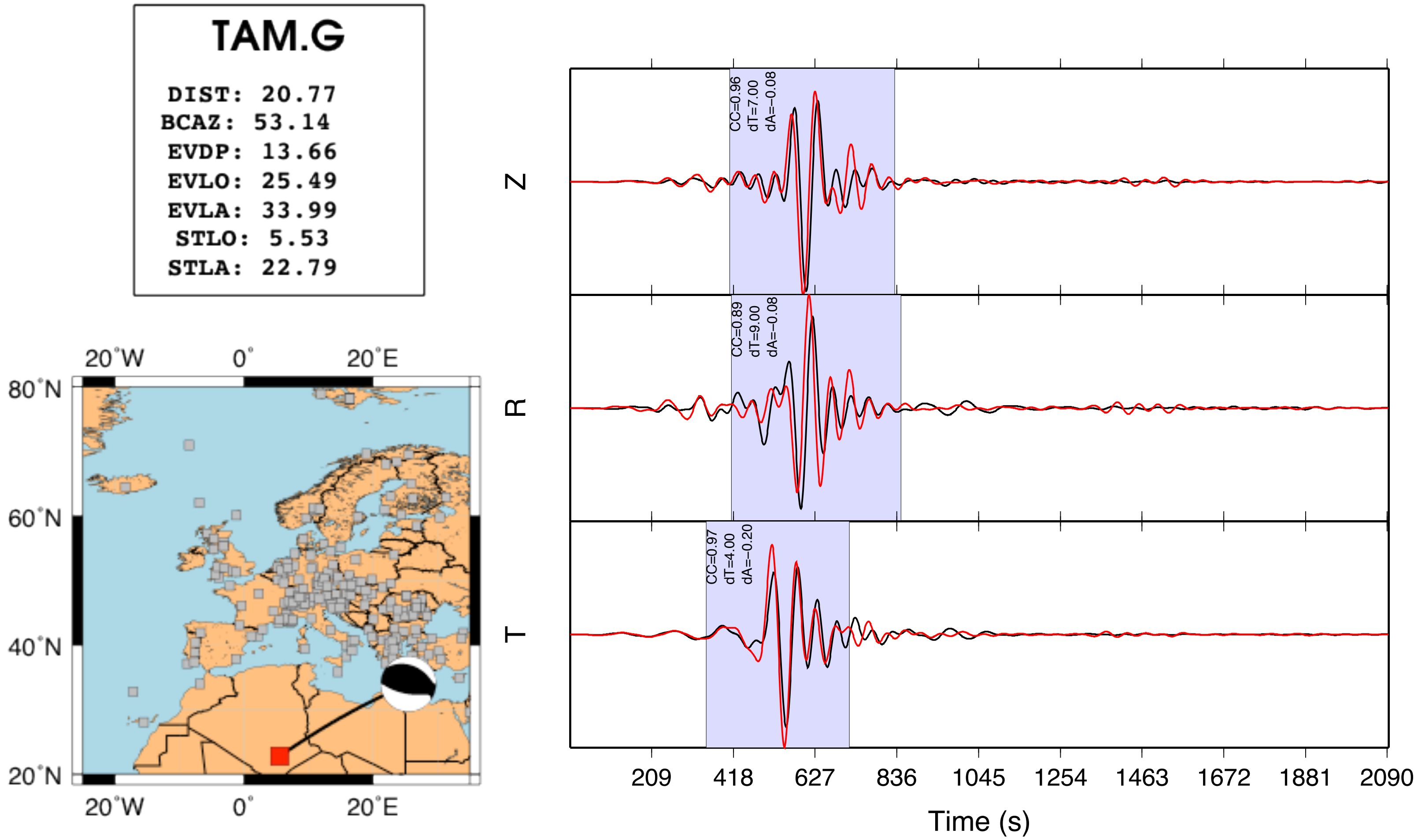
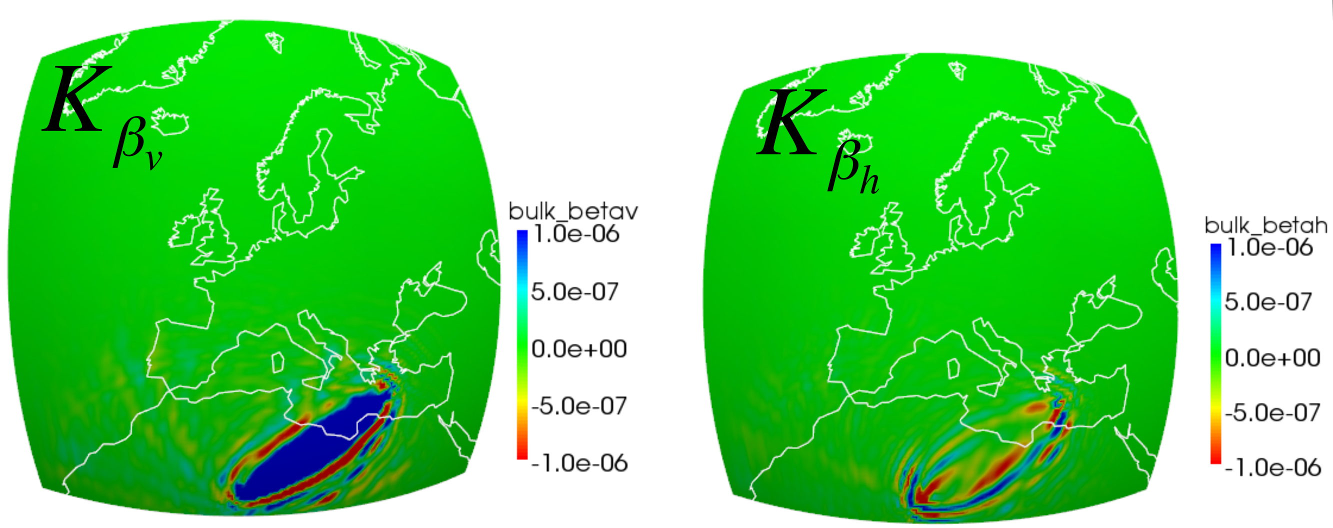
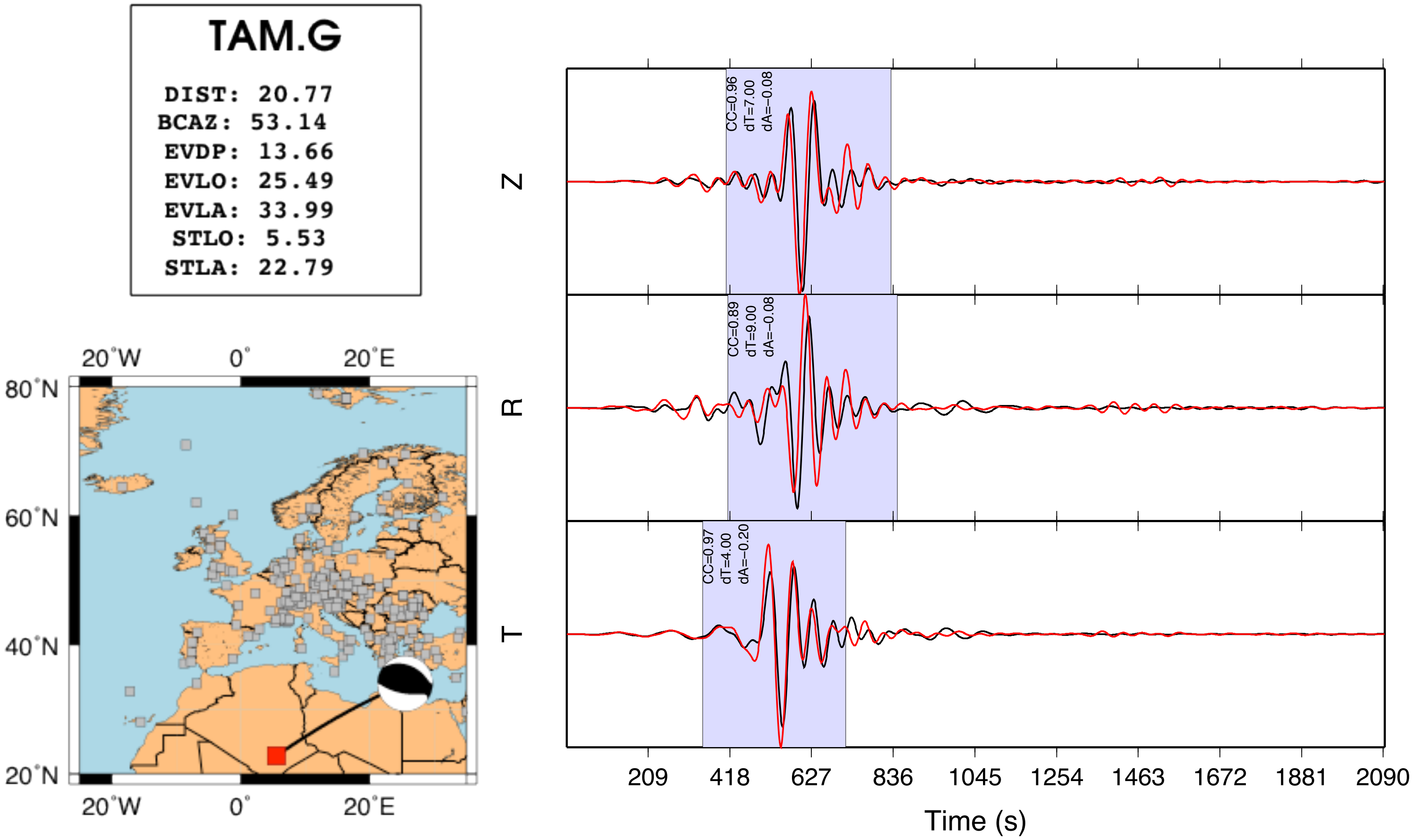


Rayleigh wave measurements



Radial anisotropic sensitivity kernels



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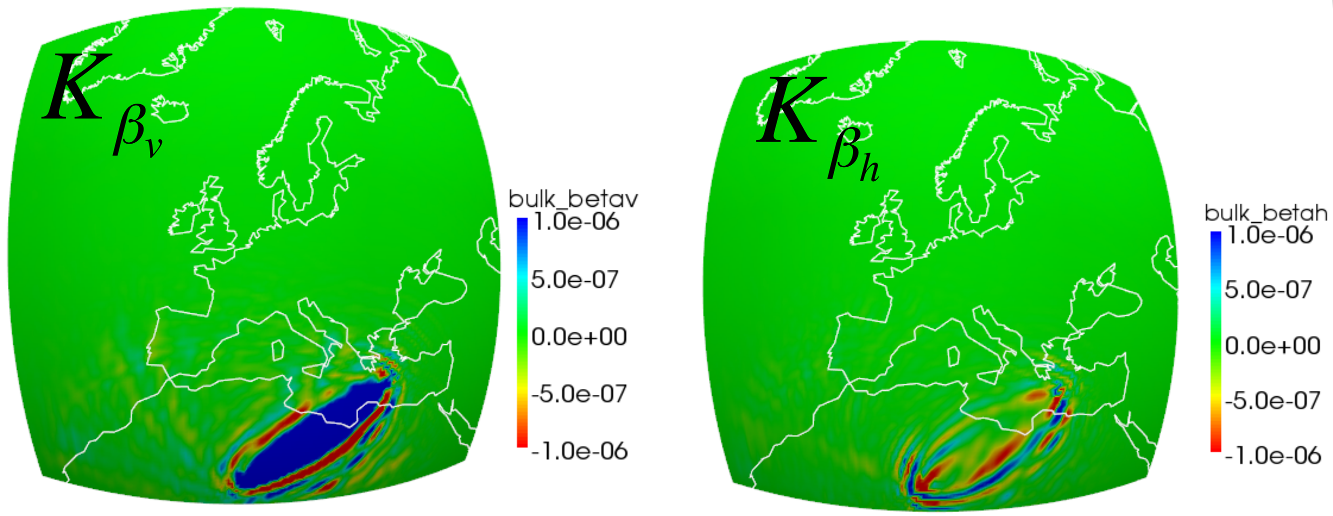
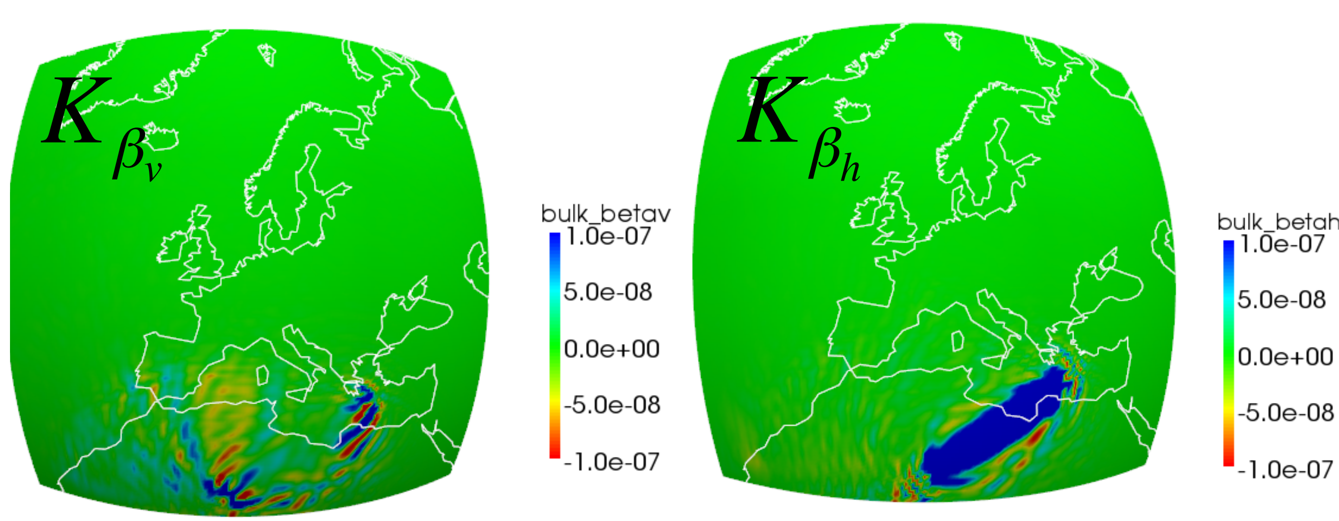


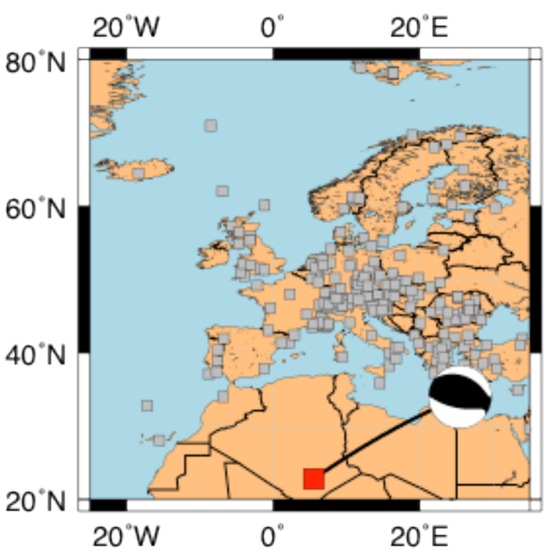
Love wave measurements

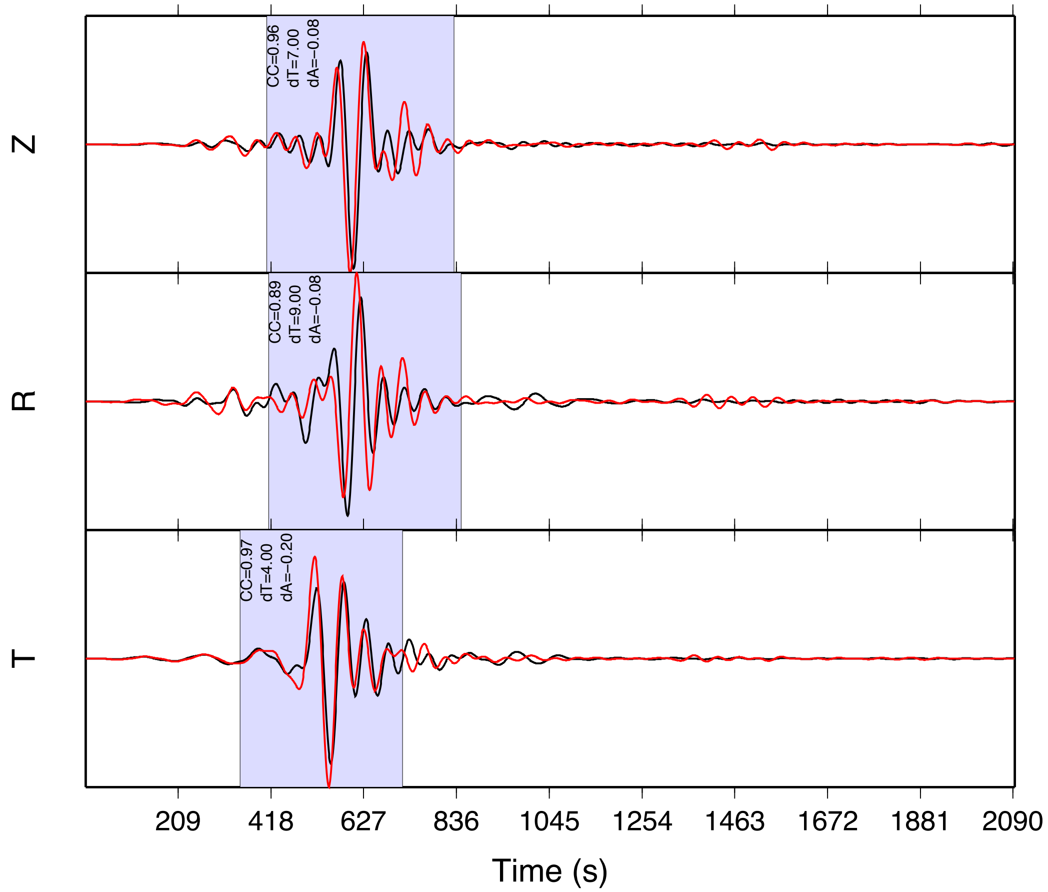


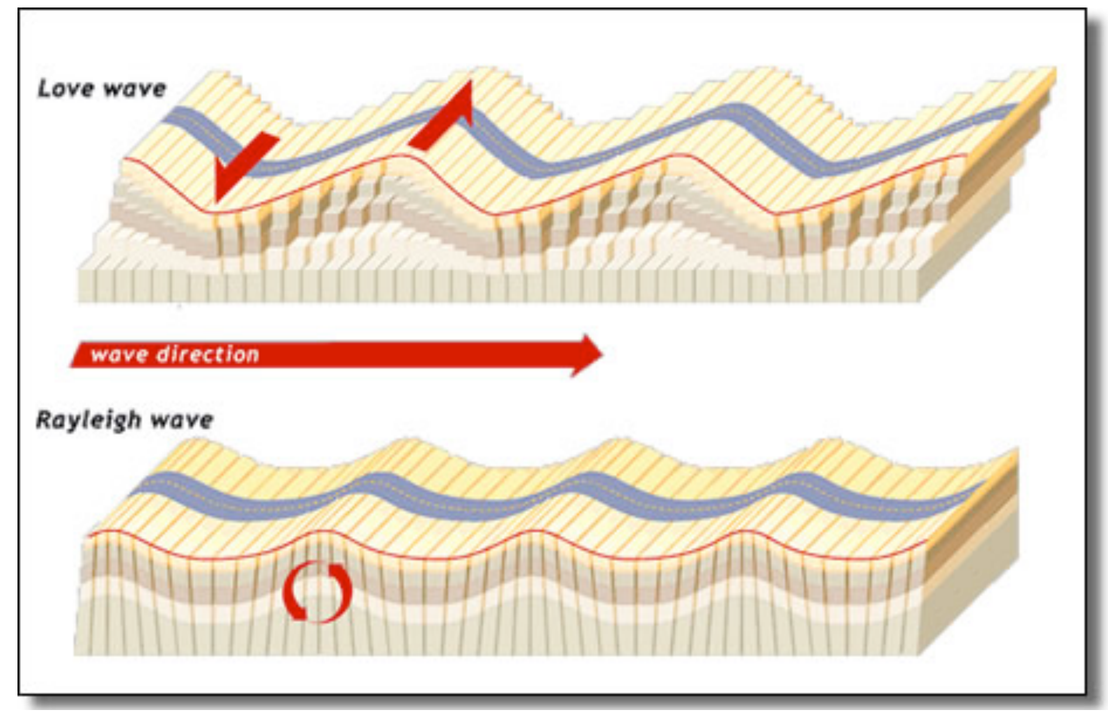
Radial anisotropic sensitivity kernels

TAM.G

DIST: 20.77
BCAZ: 53.14
EVDP: 13.66
EVLO: 25.49
EVLA: 33.99
STLO: 5.53
STLA: 22.79







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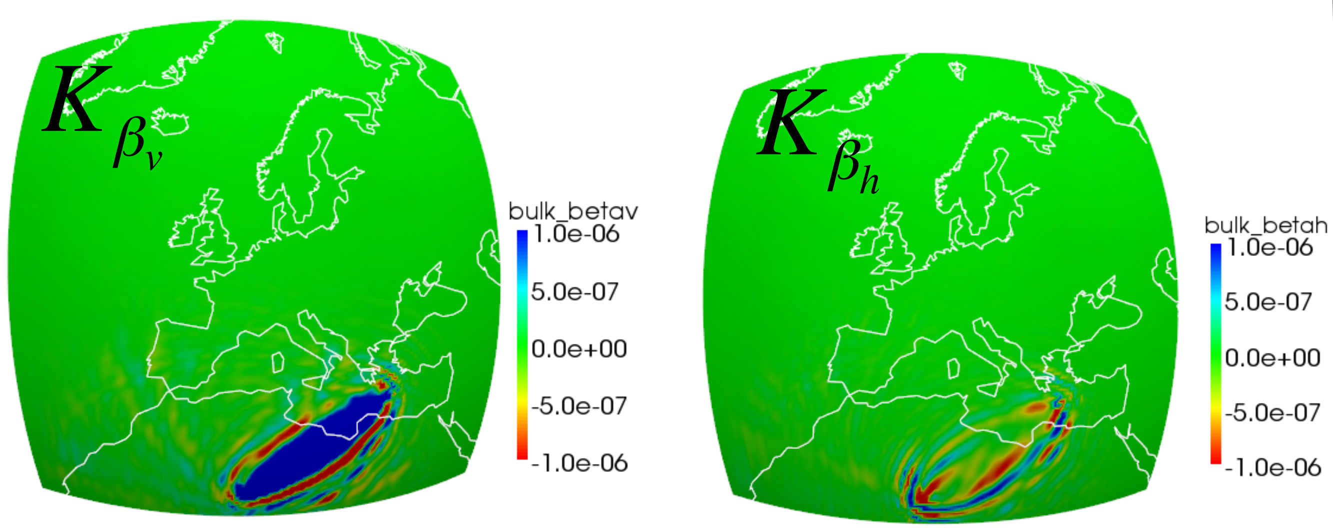

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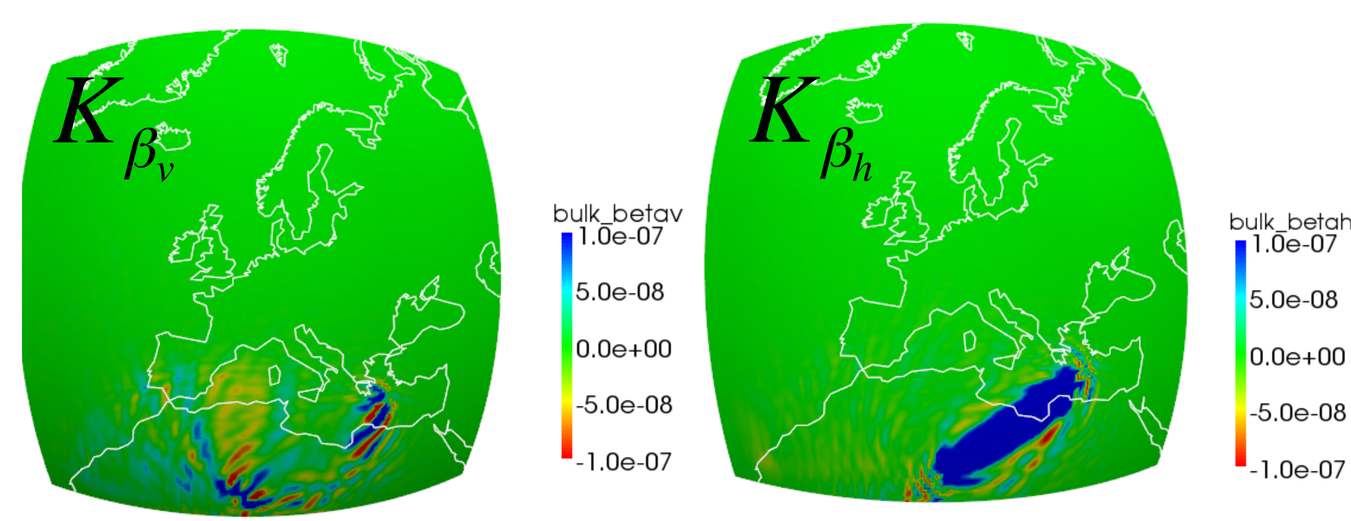
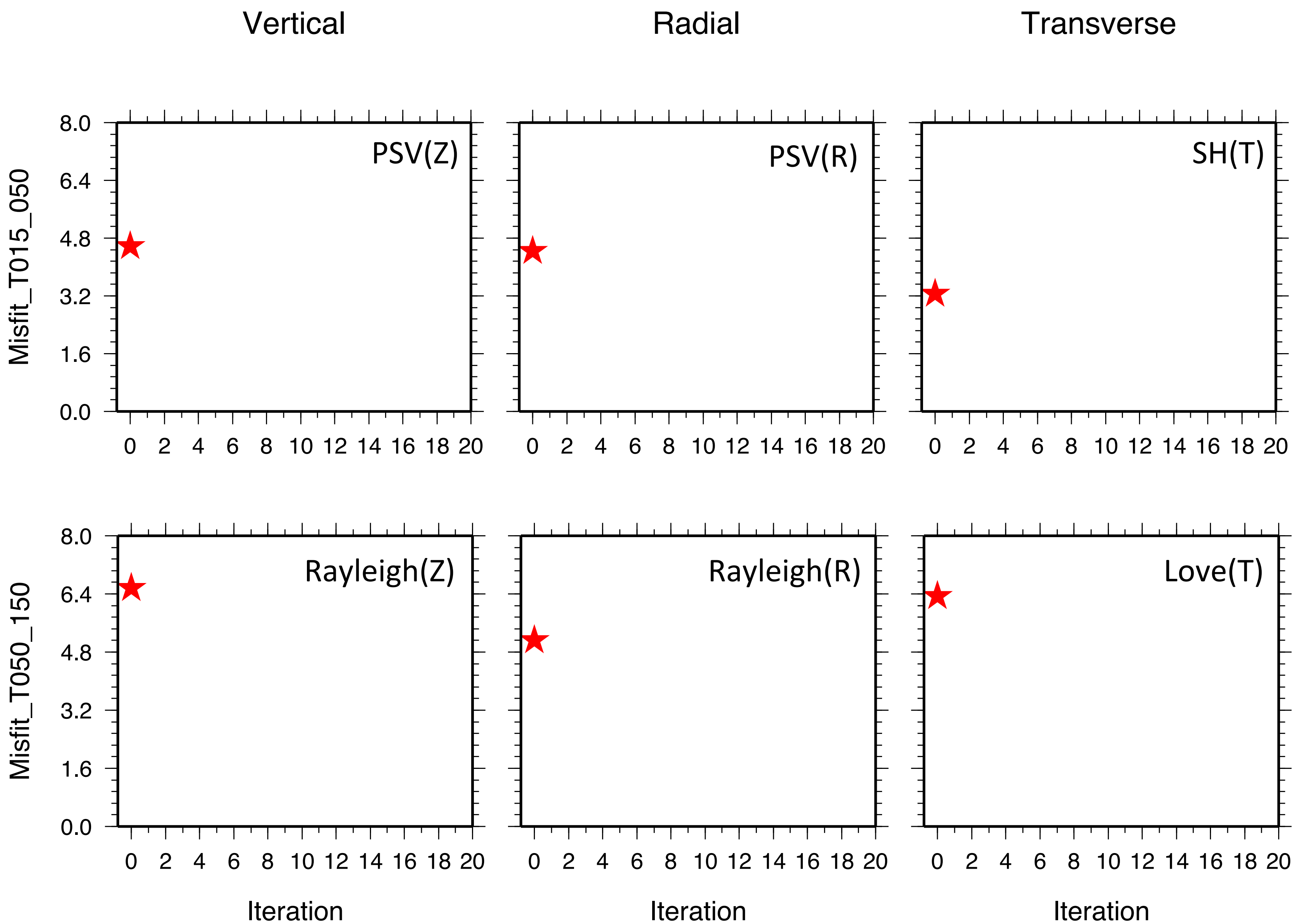
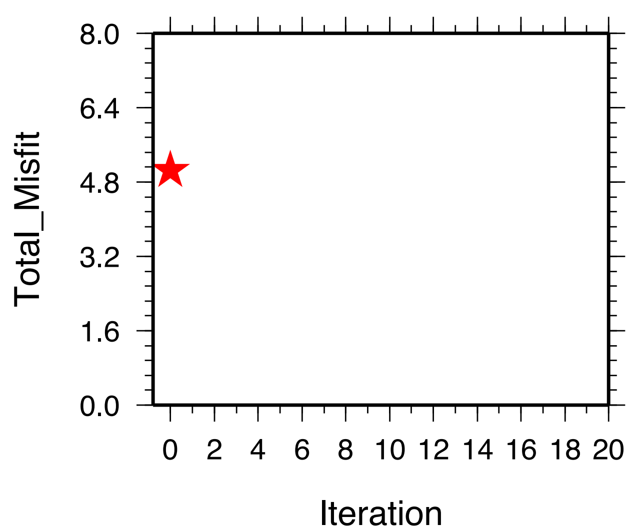


Misfit function for EU00





$$\chi_c = \frac{1}{N_s}\sum_s \frac{1}{N_p}\sum_p \int W_p \left(\frac{\Delta\tau_p(\omega)}{\sigma_p(\omega)}\right)^2 d\omega$$

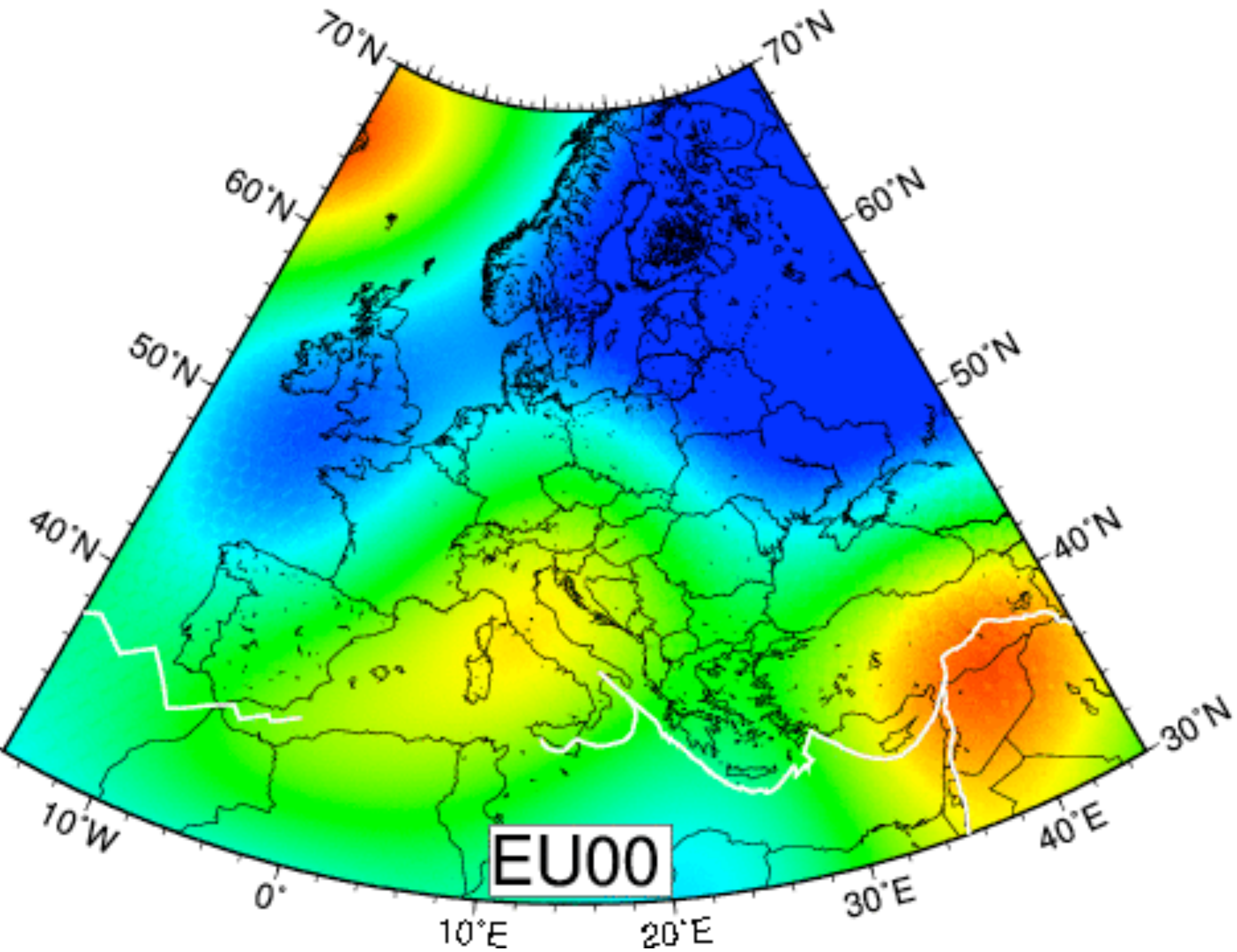
$$\chi = \frac{1}{N_c}\sum_c \chi_c$$

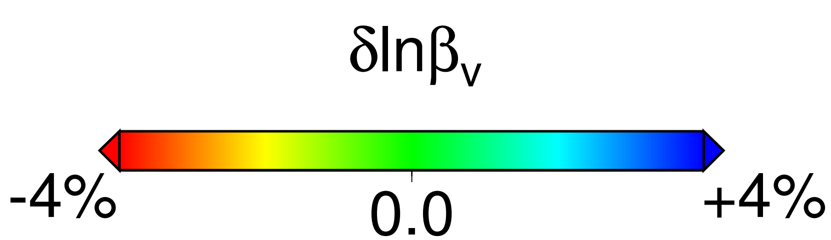
Np: number of measurements per event
Ns: number of events
Nc: number of contributions

EU00 versus iterative models at 75 km

S362ANI

(Kustowski, Ekström and Dziewoński, 2008)





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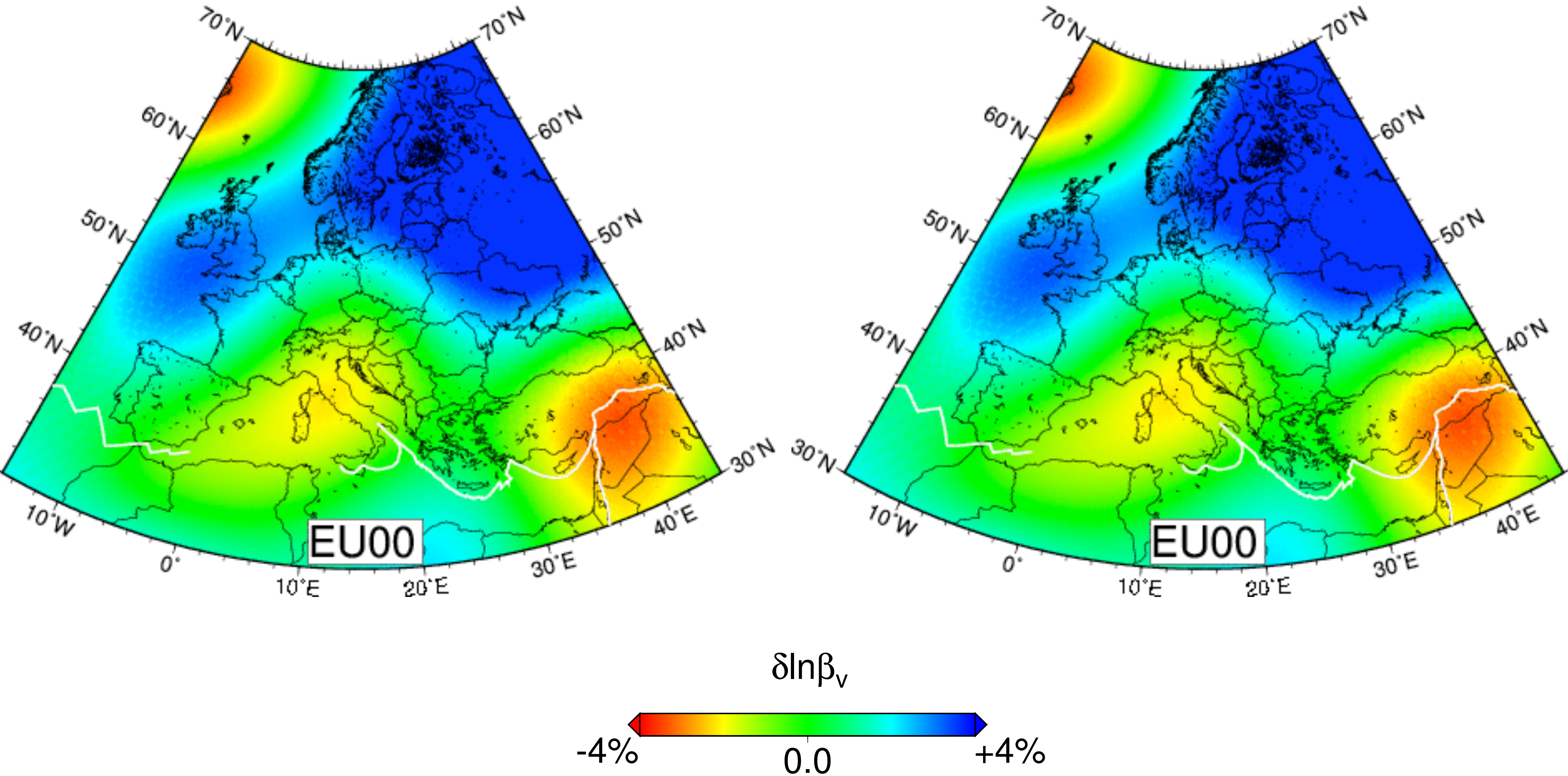
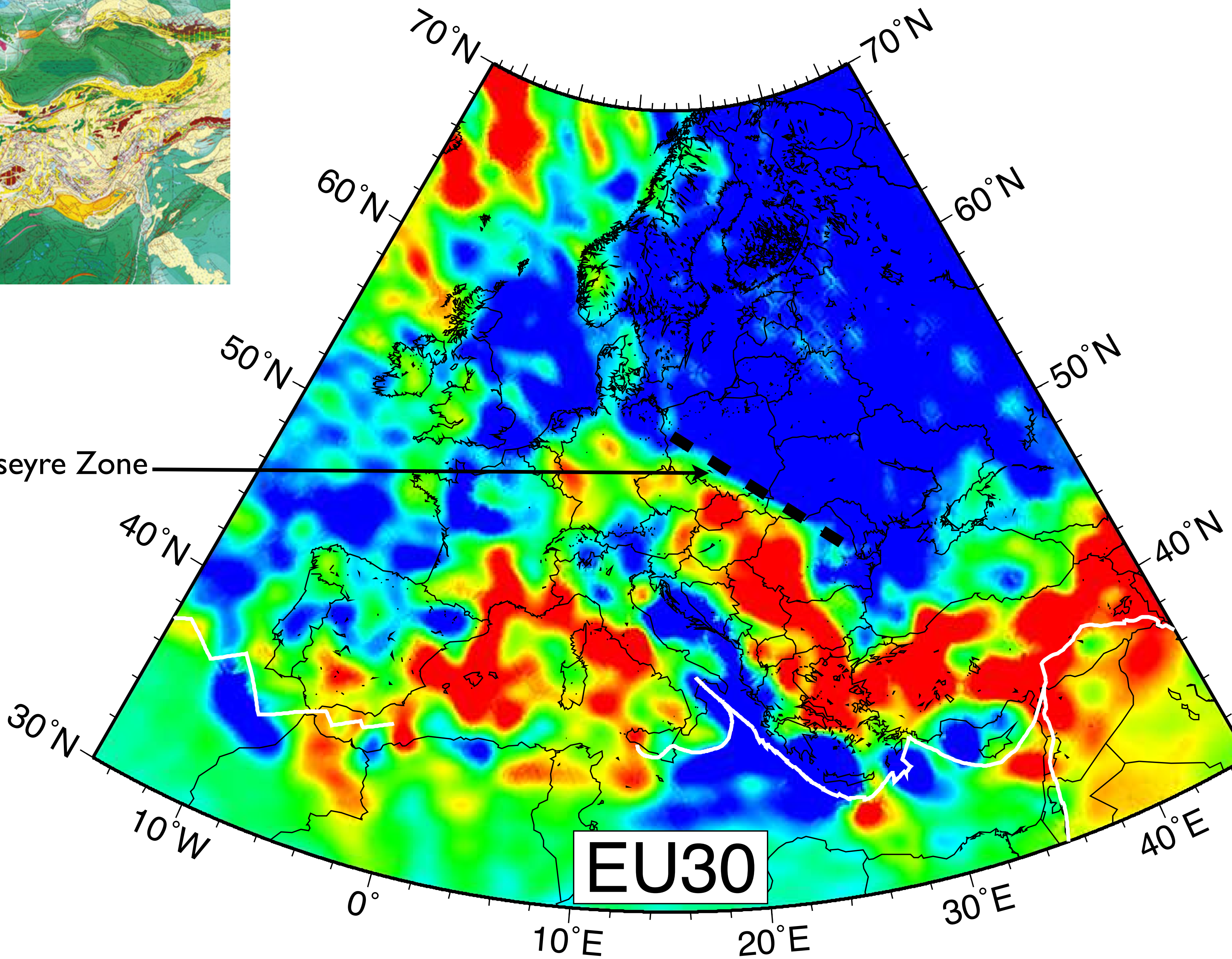
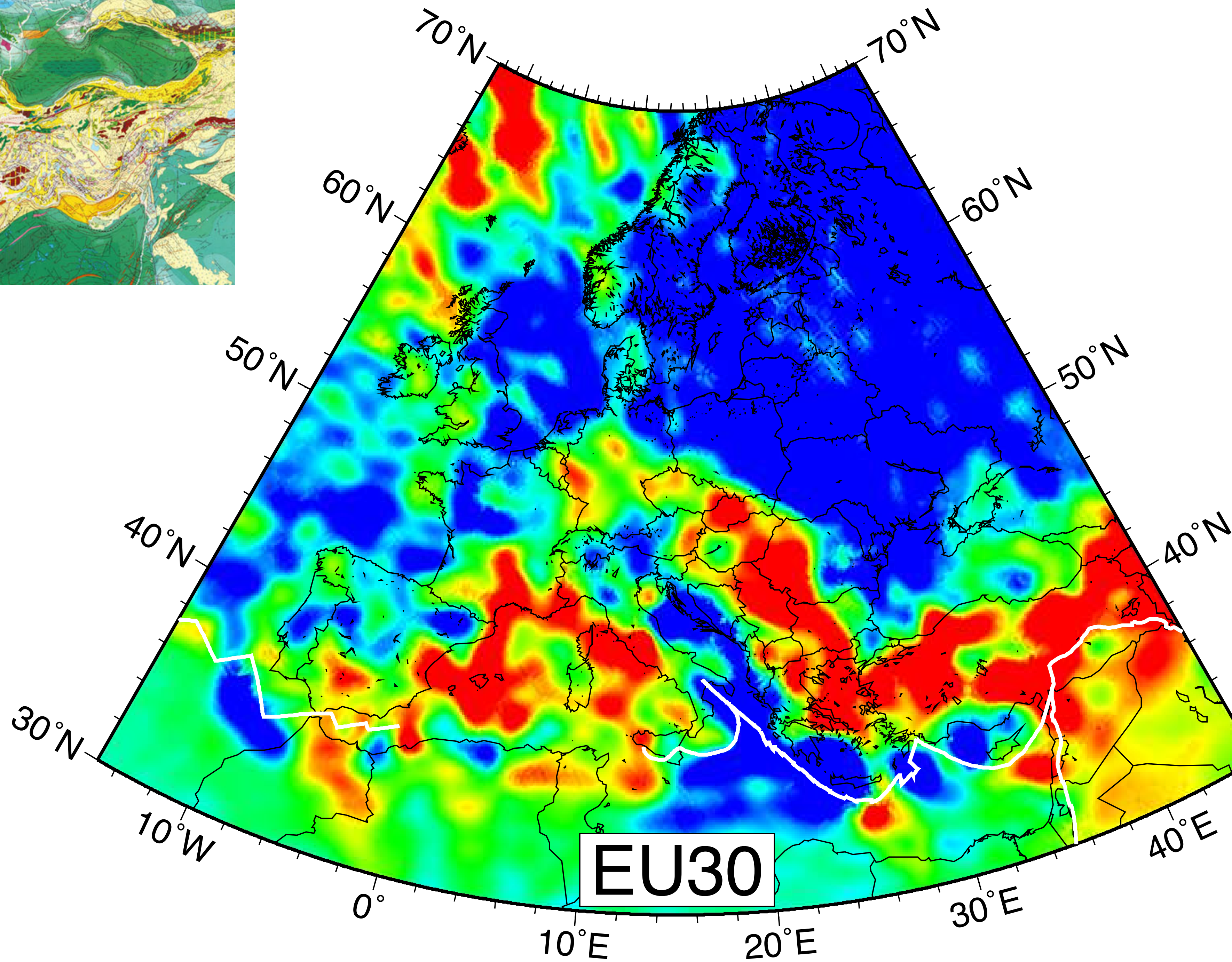


Geological features of EU30 at 75 km



Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone



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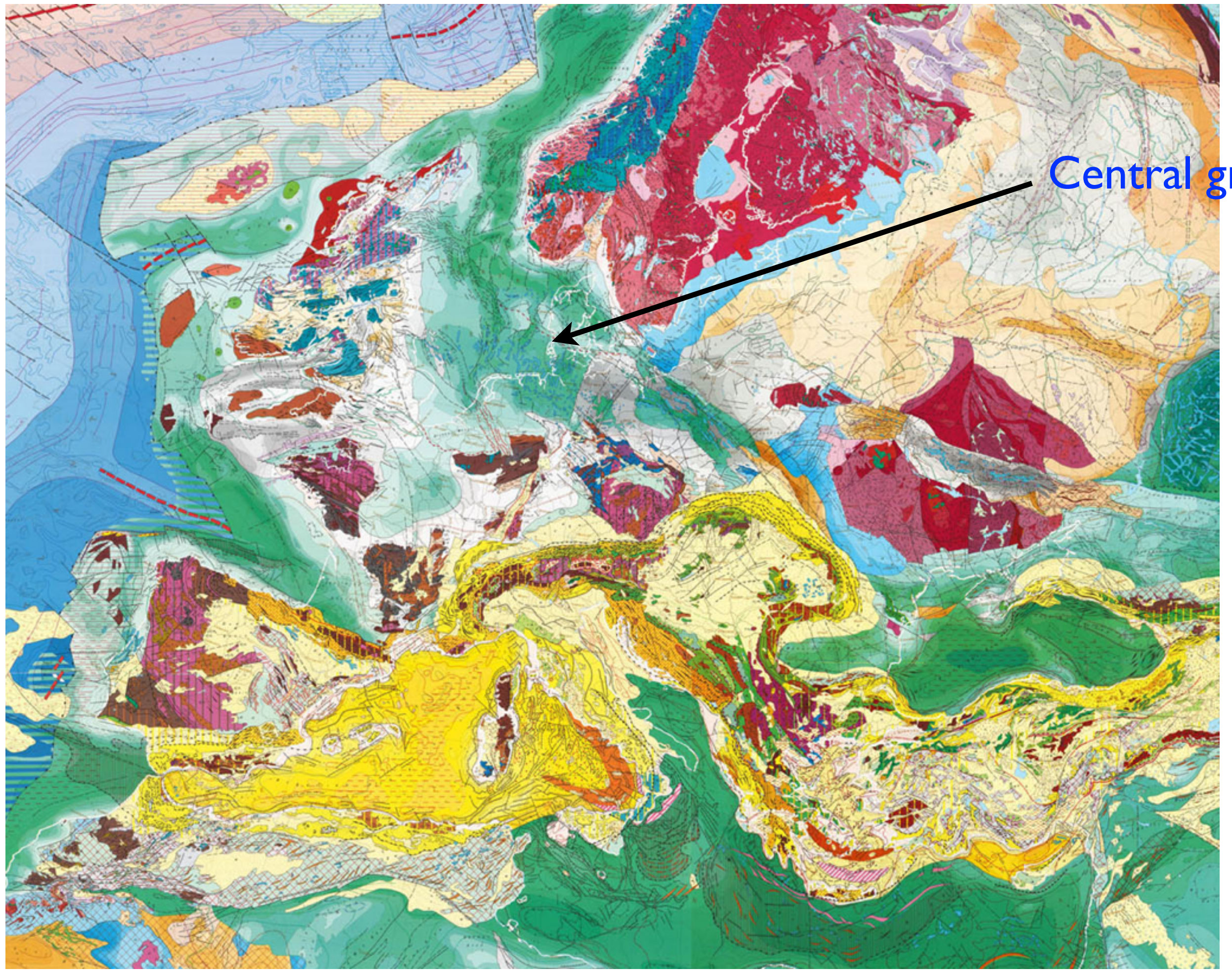
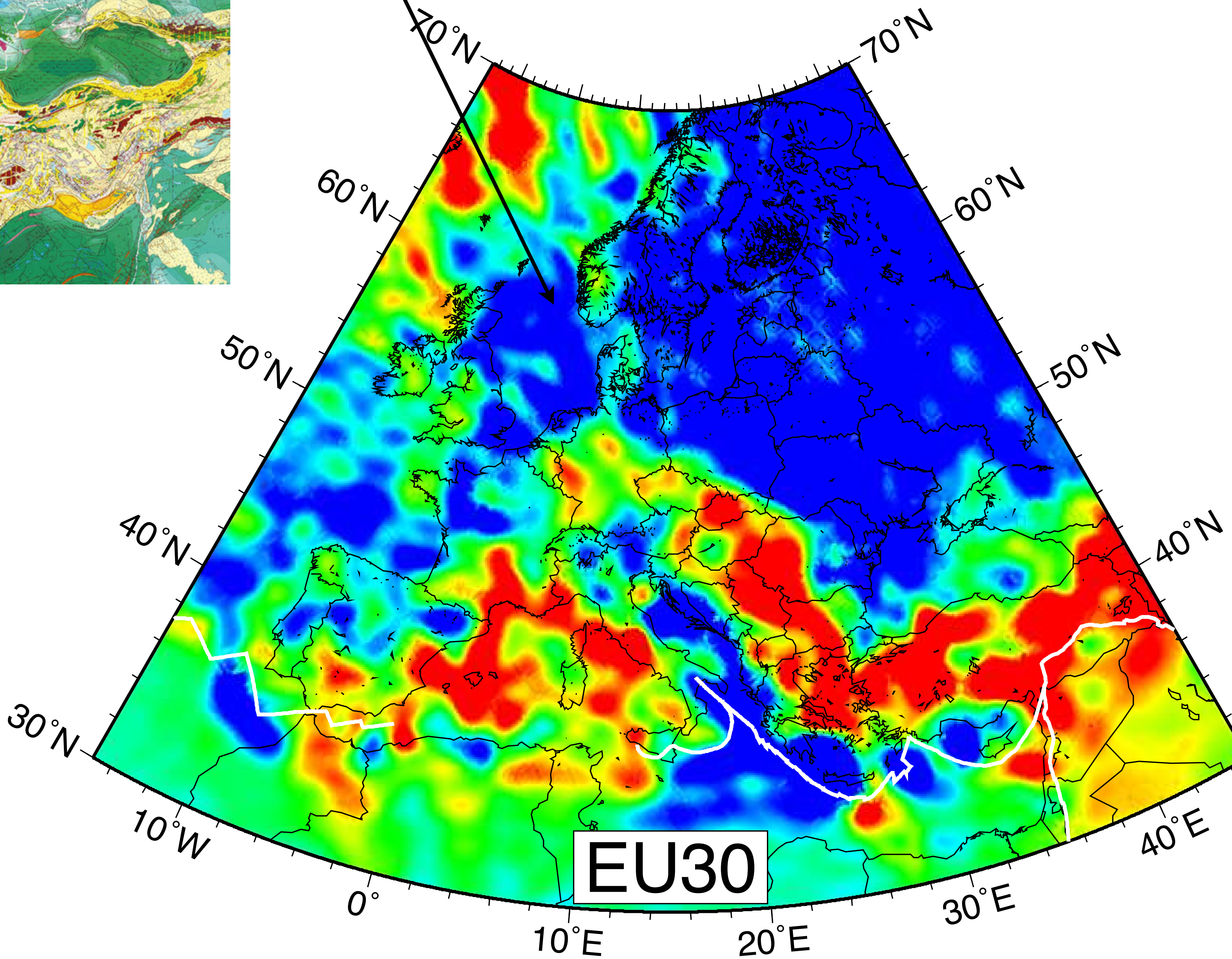


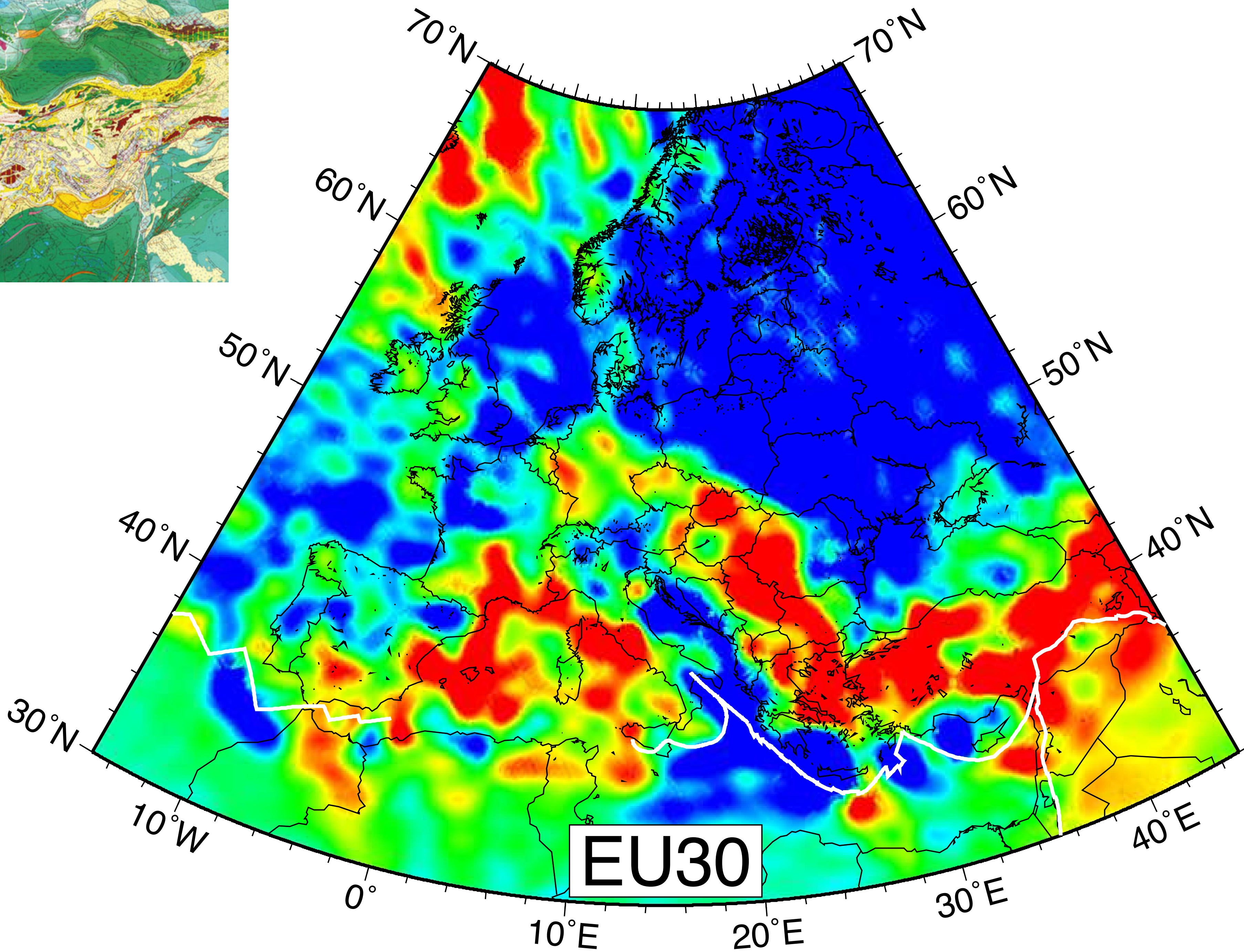
Tornquist-Teisseyre Zone



Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben

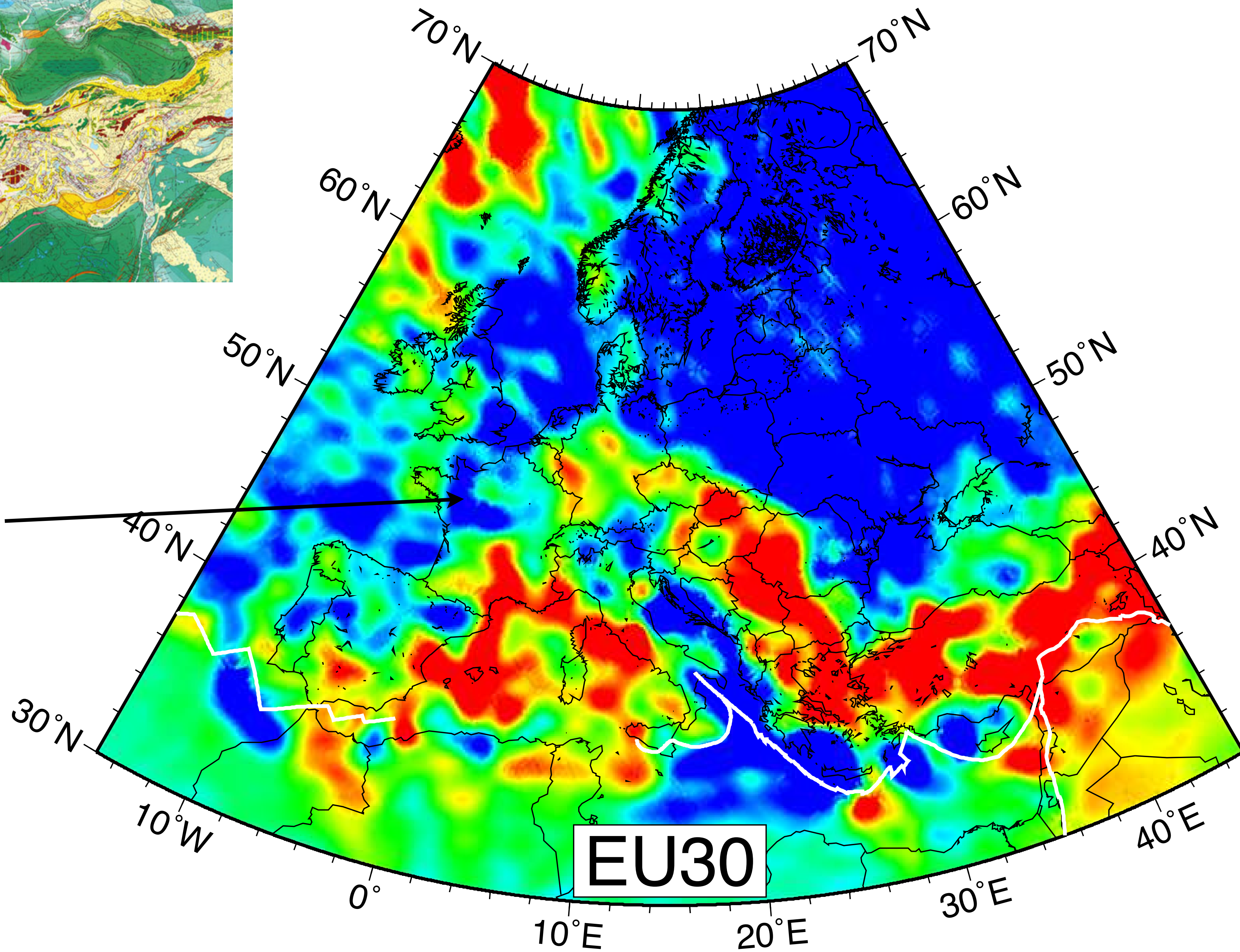


Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben

Armorican massif



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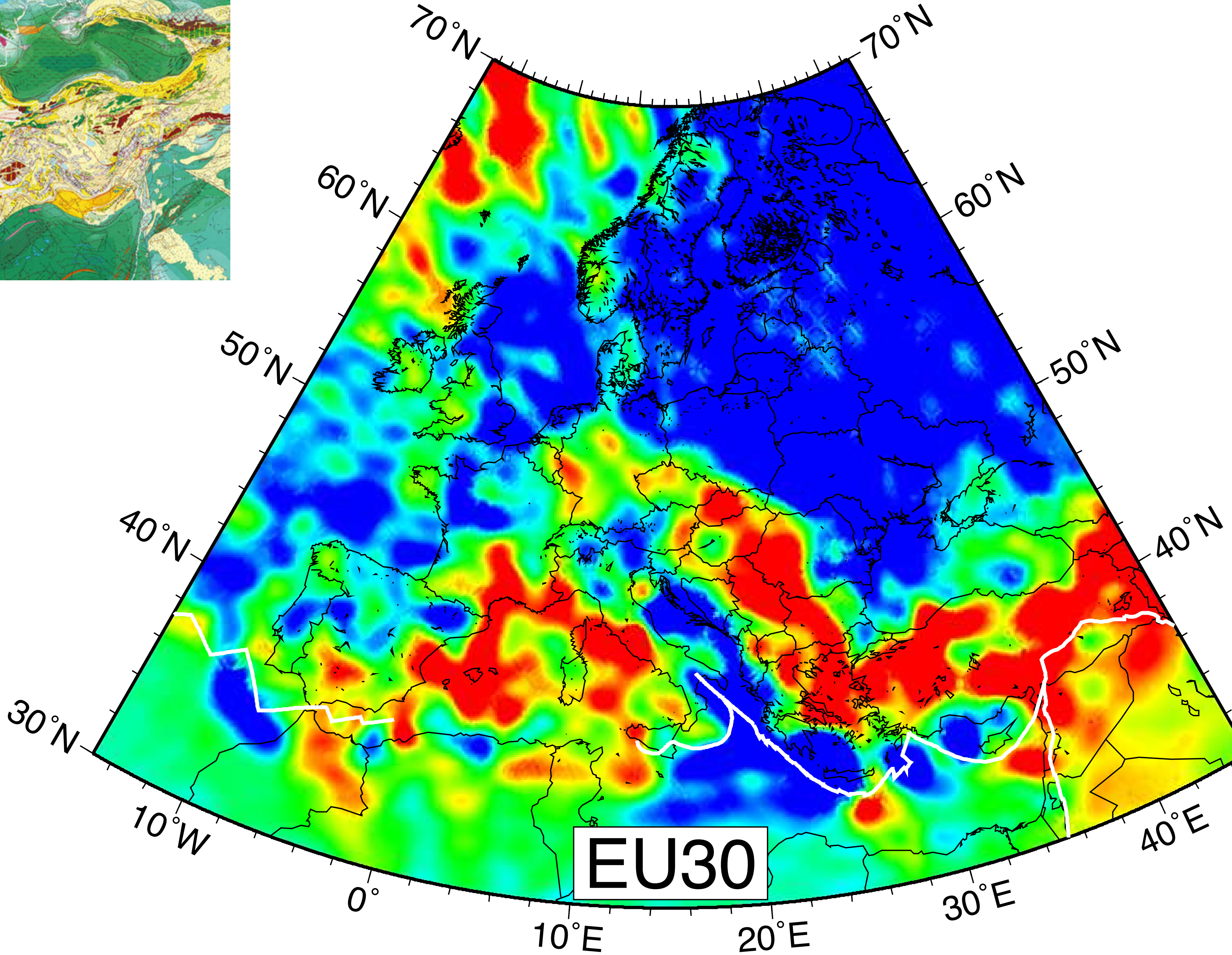
Tornquist-Teisseyre Zone

Central graben

Armorican massif



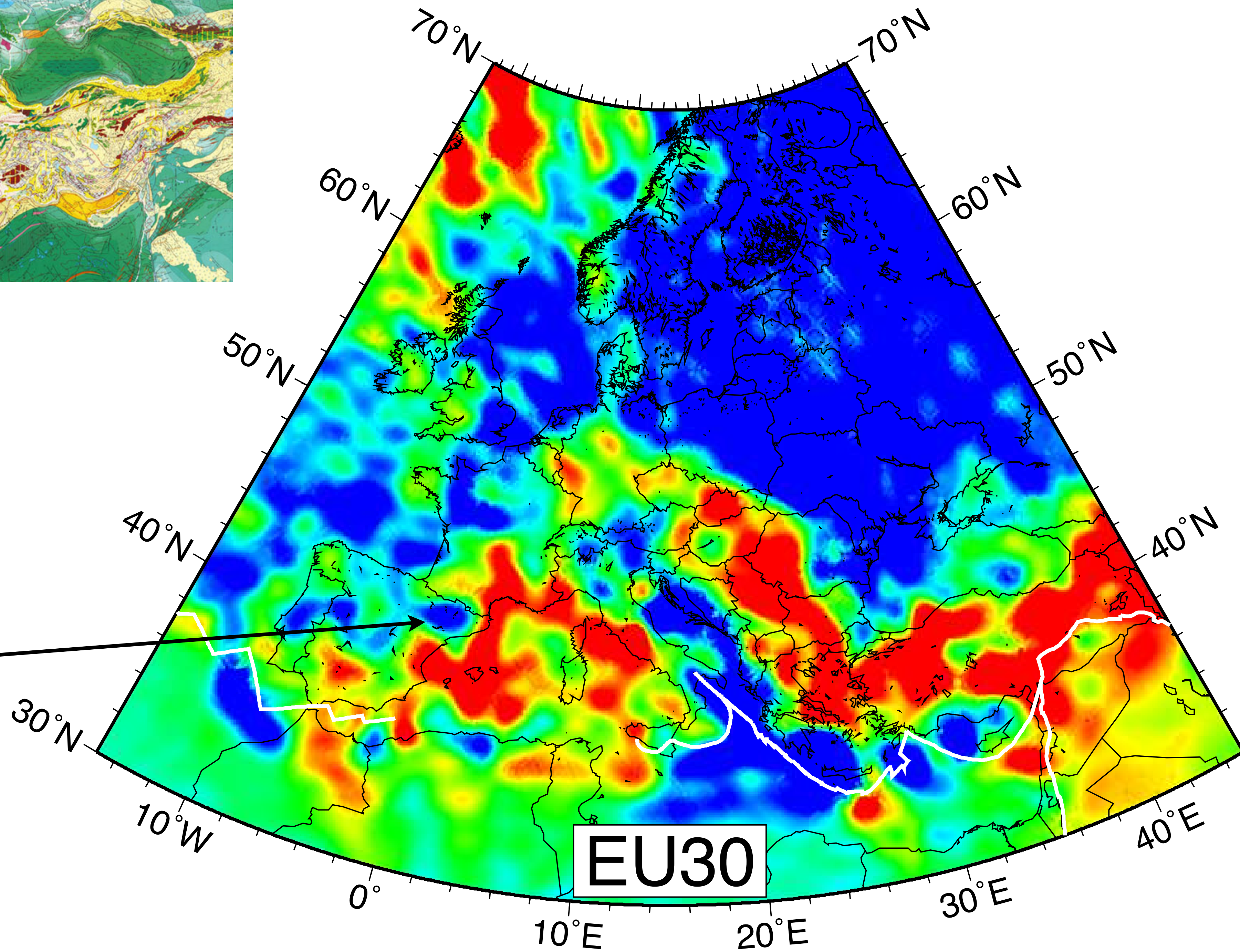
Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben

Armorican massif

Pyrenees



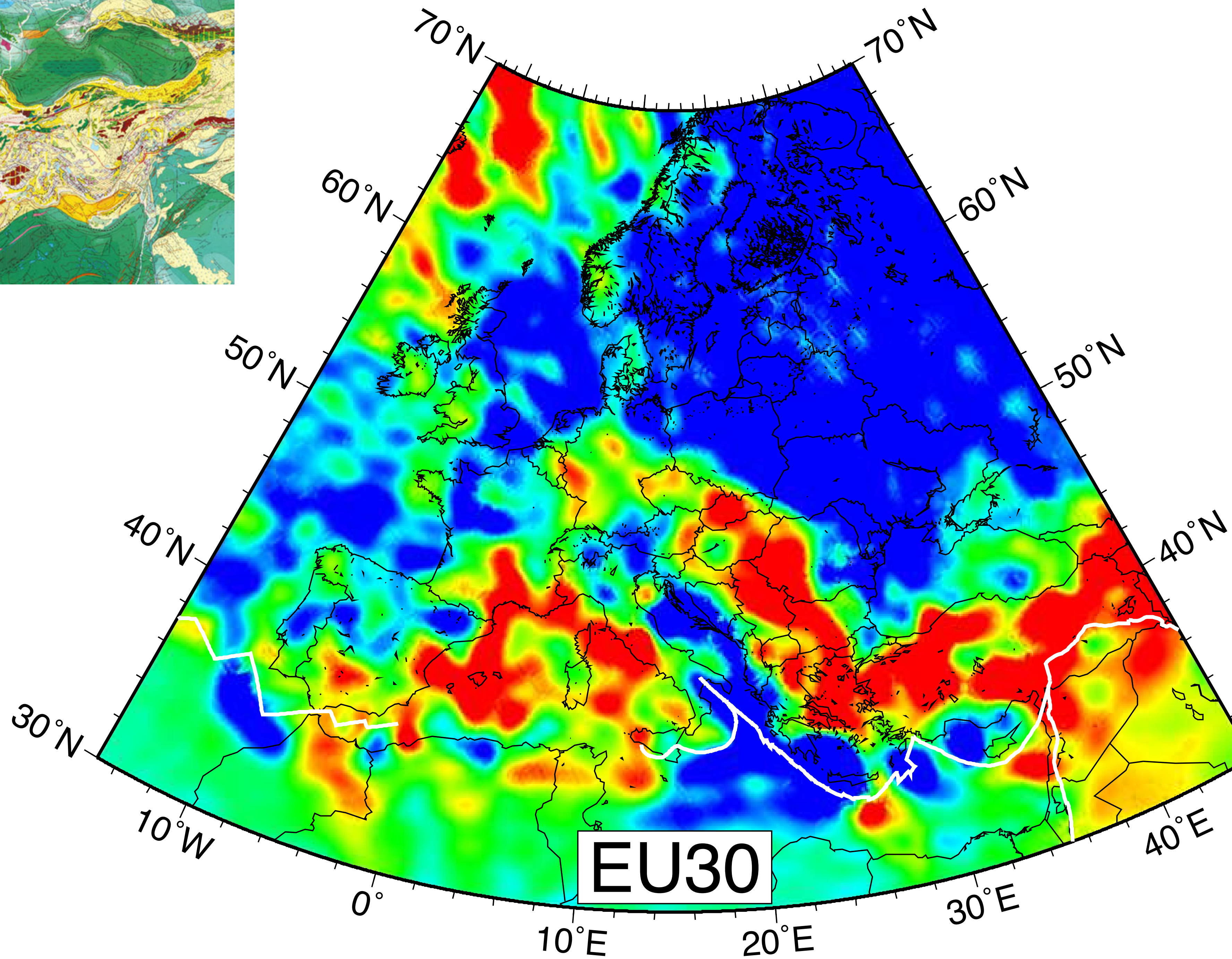
Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben

Armorican massif

Pyrenees



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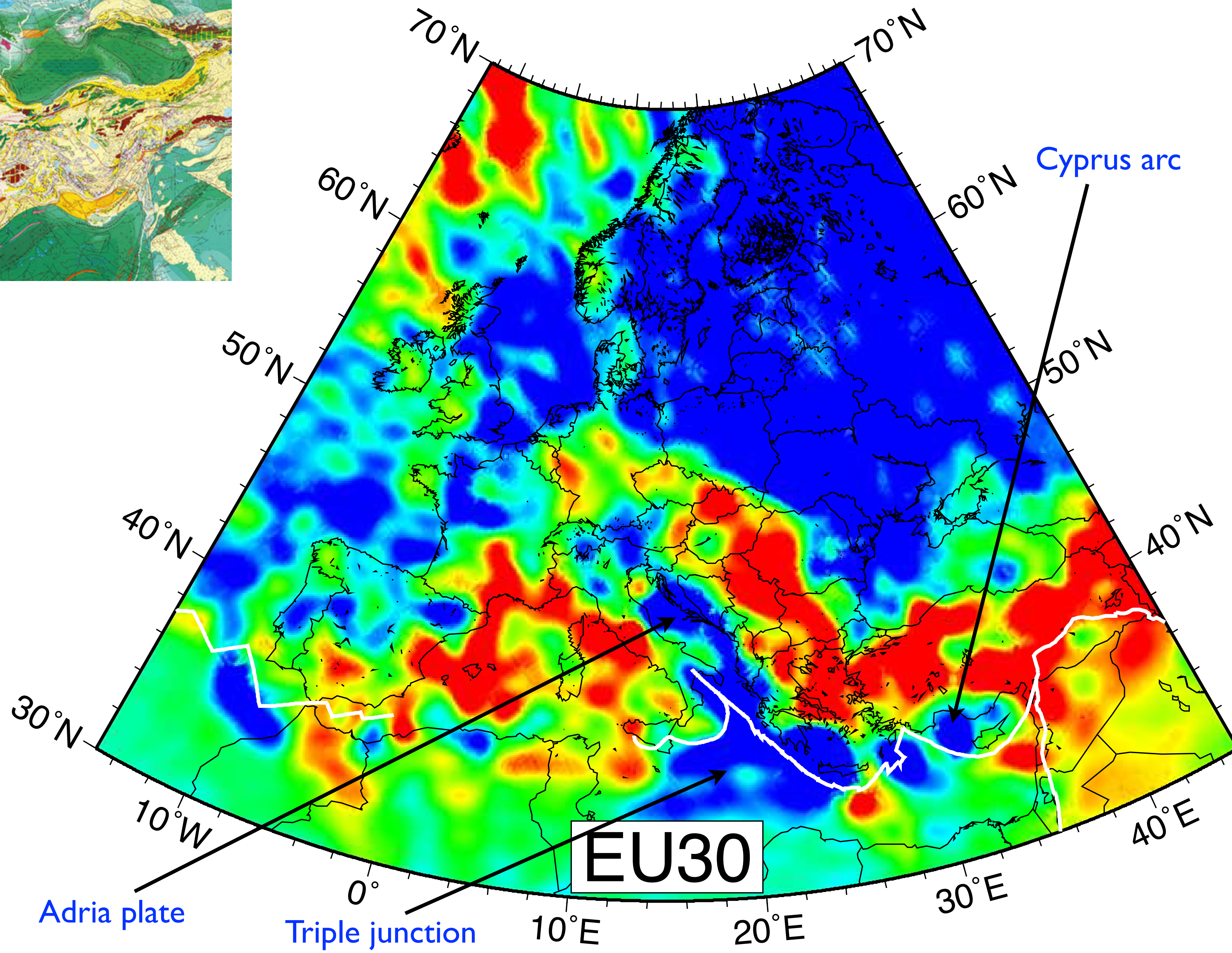


Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben

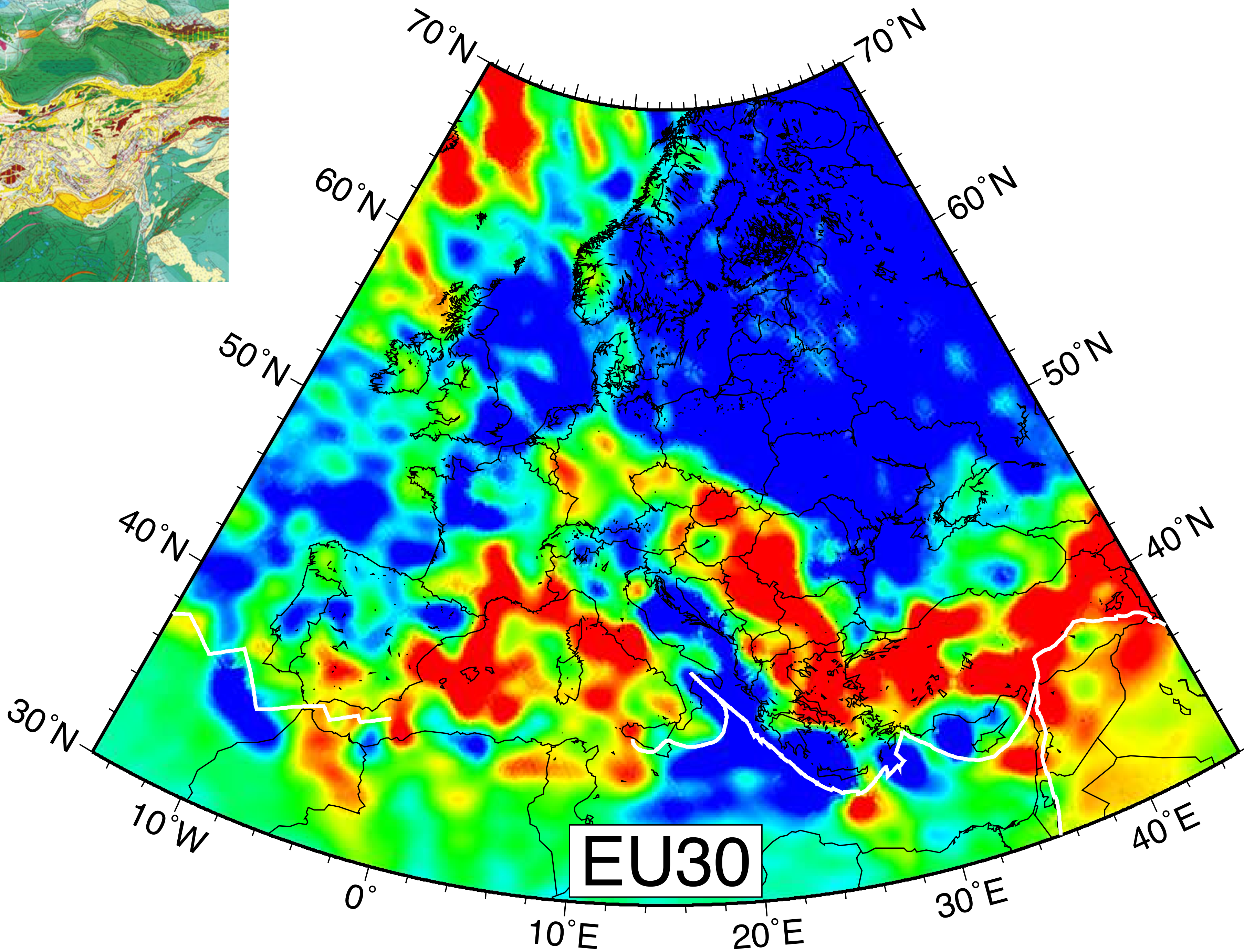
Armorican massif

Pyrenees

Adria plate

Triple junction

Cyprus arc



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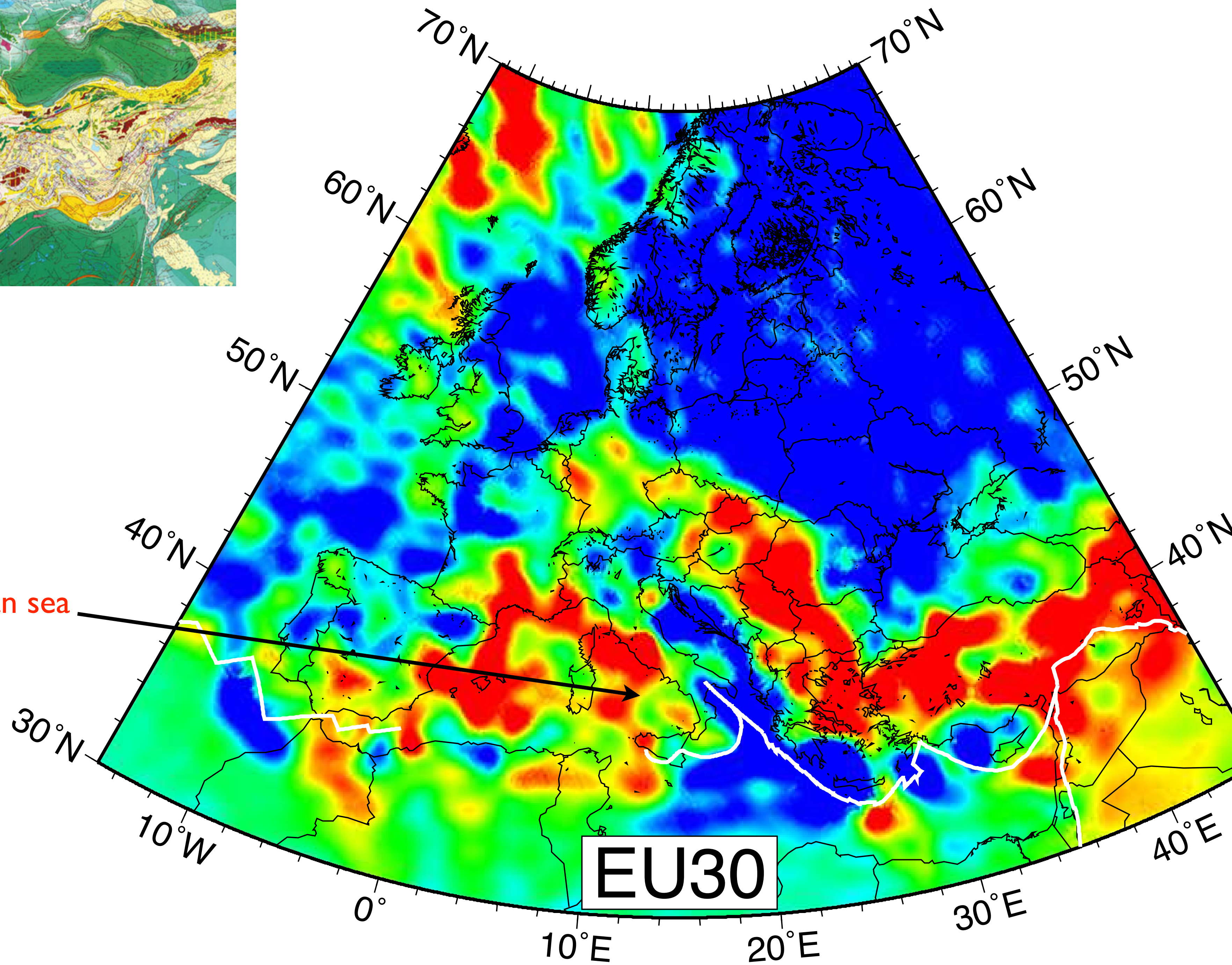

Tornquist-Teisseyre Zone

Central graben

Armorican massif

Pyrenees

Adria plate

Triple junction

Cyprus arc

Tyrrhenian sea

Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

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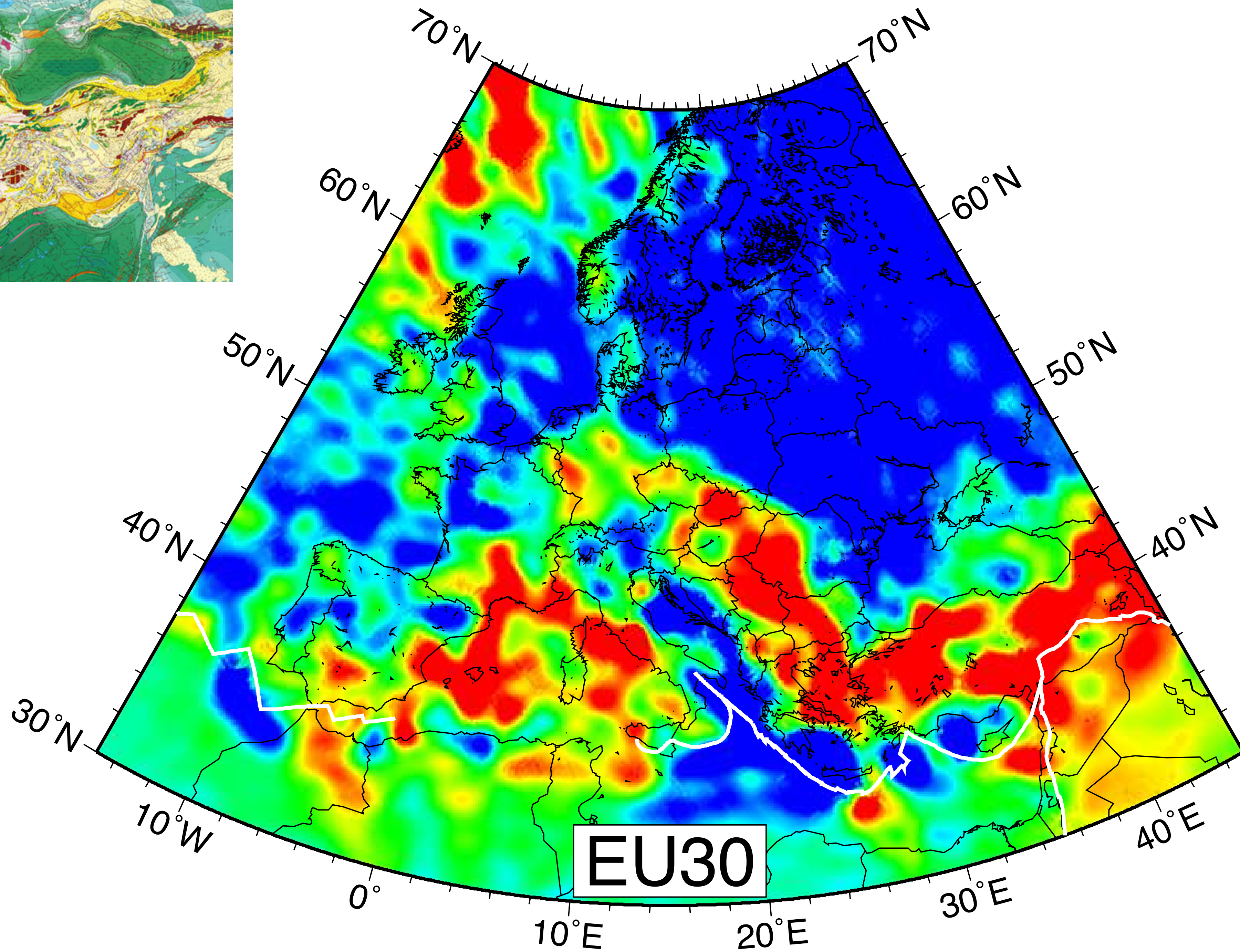
Tyrrhenian sea



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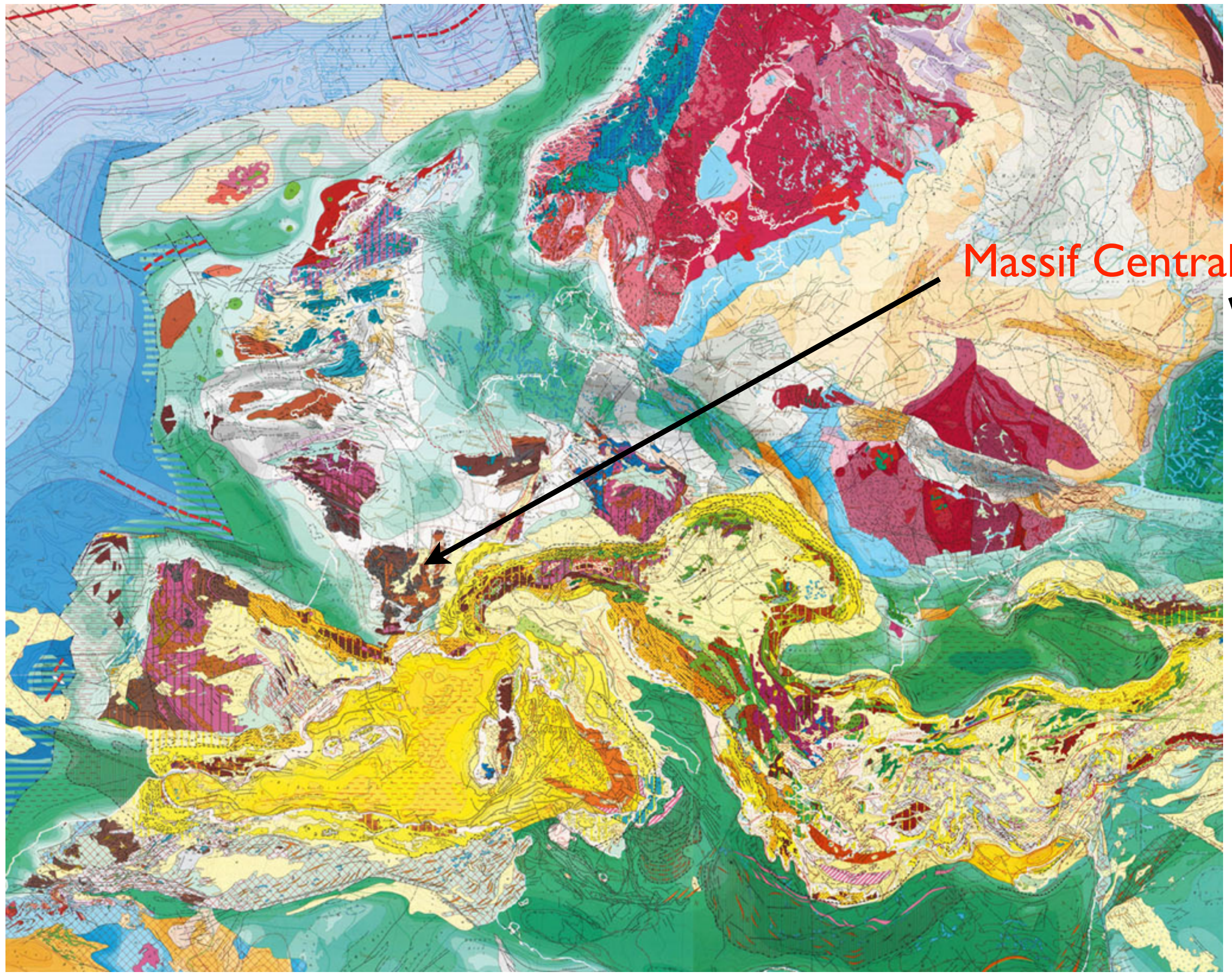

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Central graben

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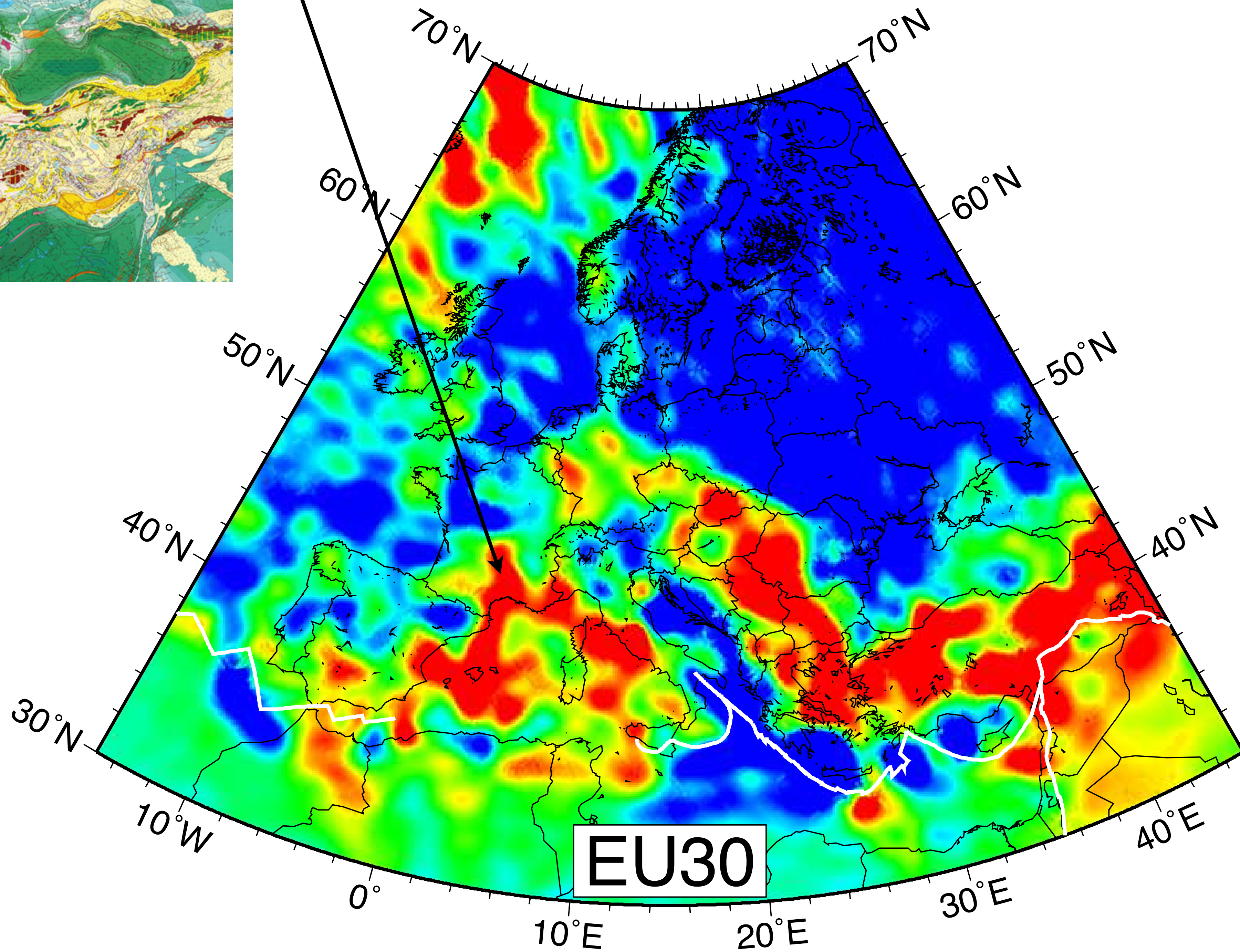
Adria plate

Triple junction

Cyprus arc

Tyrrhenian sea



Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben

Armorican massif

Pyrenees

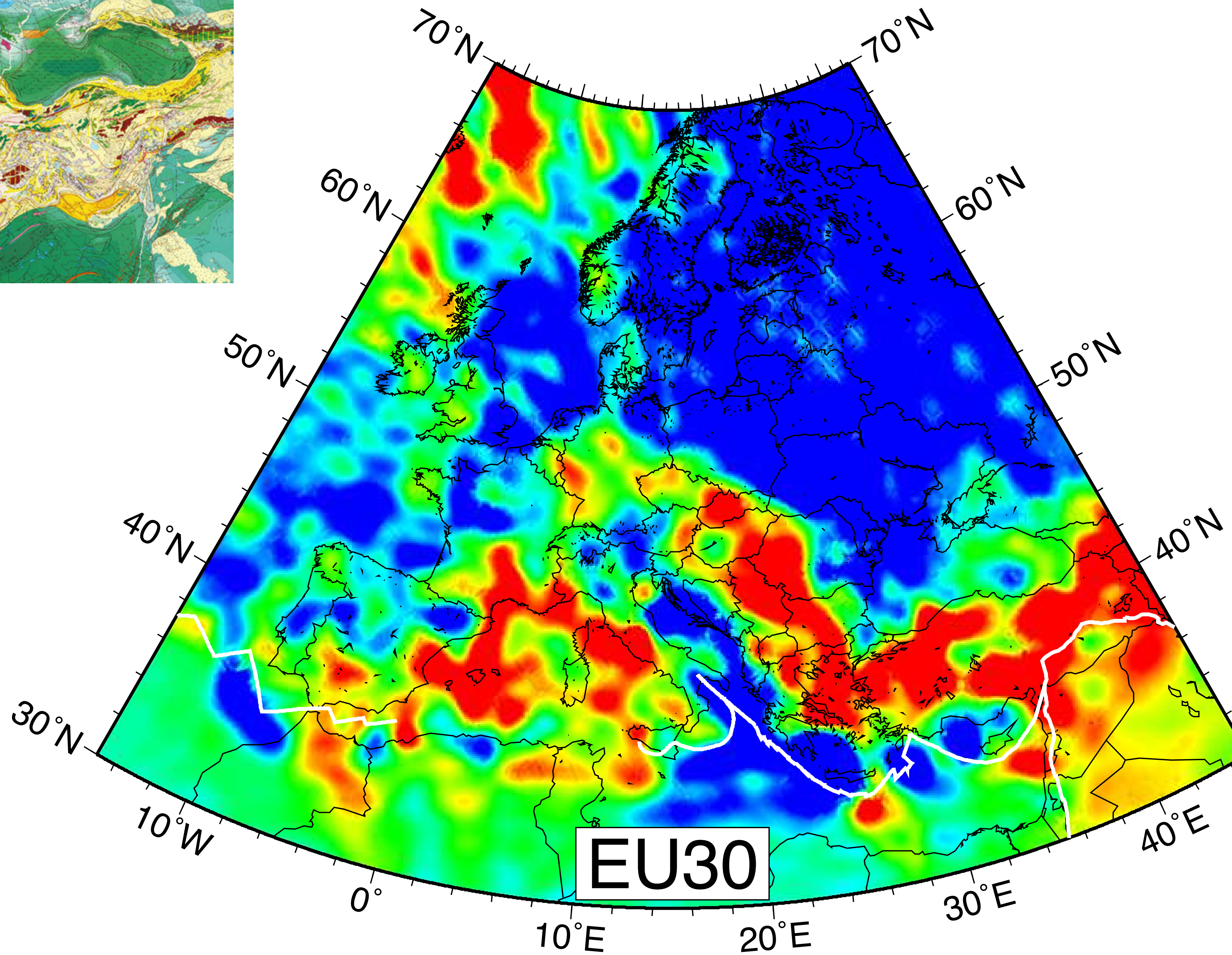
Adria plate

Triple junction

Cyprus arc

Tyrrhenian sea

Massif Central



Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

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Pyrenees

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Triple junction

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Tyrrhenian sea

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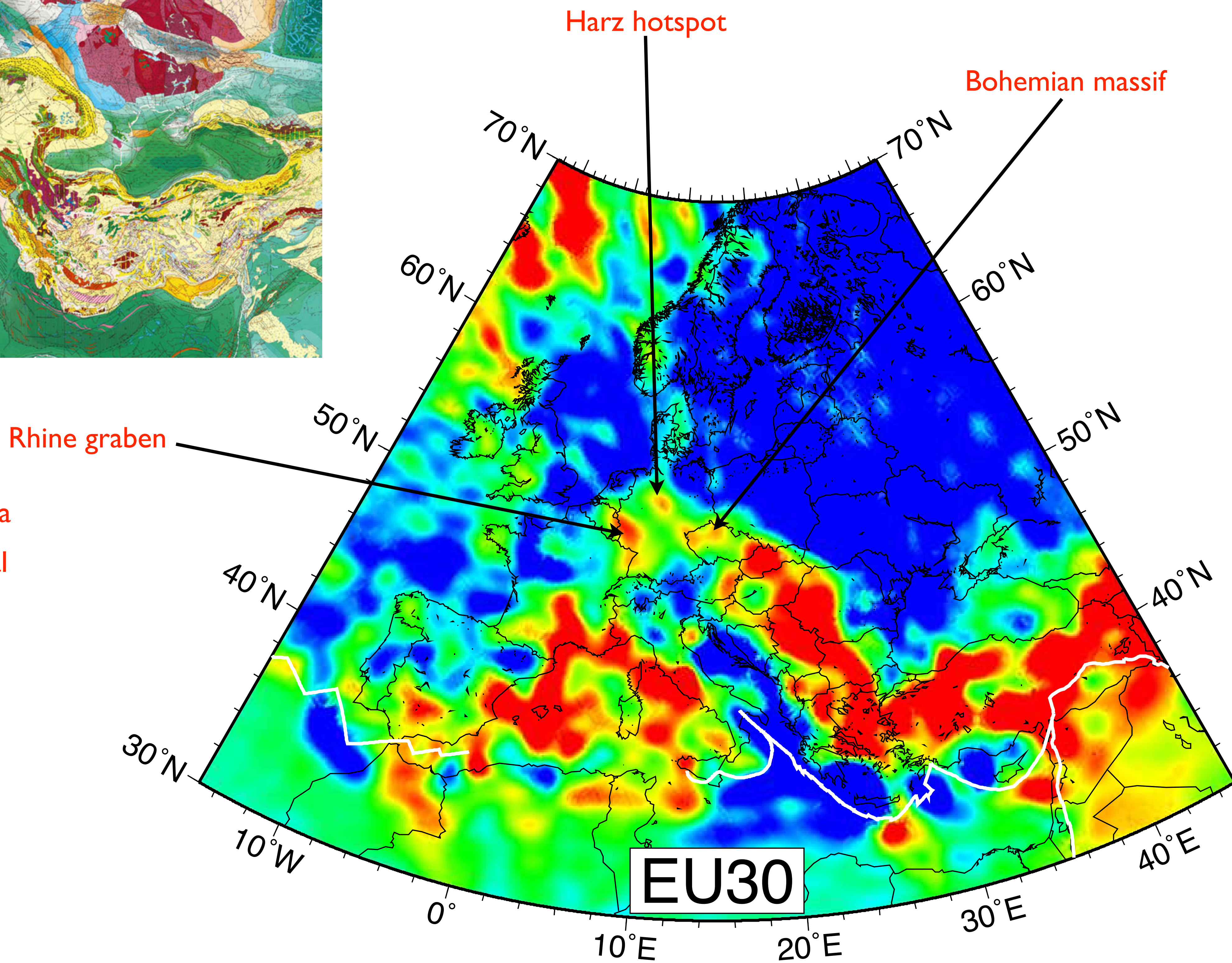
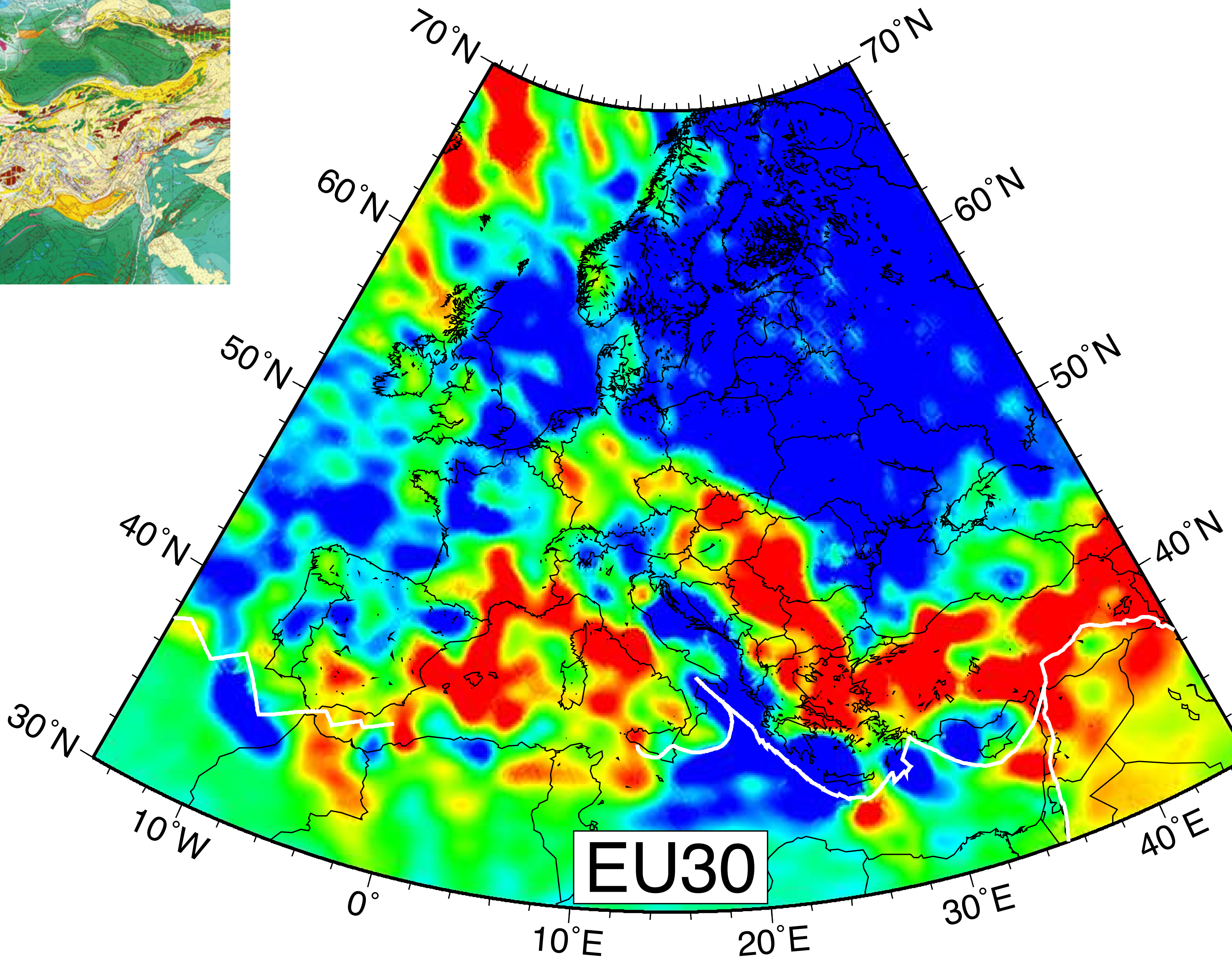


Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben	Tyrrhenian sea
Armorican massif	Massif Central
Pyrenees	Rhine graben
Adria plate	Harz hotspot
Triple junction	Bohemian massif
Cyprus arc	



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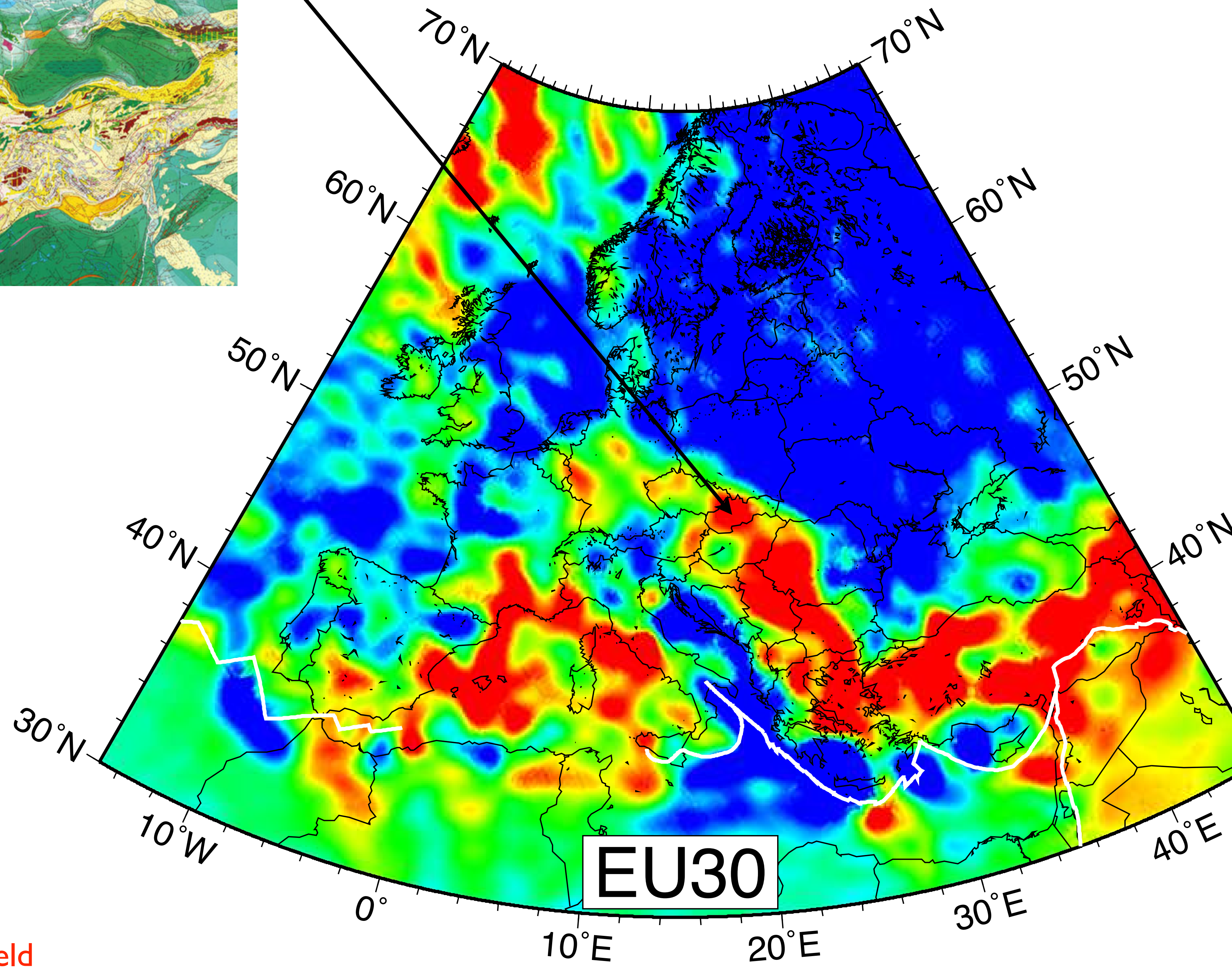

Tornquist-Teisseyre Zone

Central graben	Tyrrhenian sea
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Cyprus arc	

★ CSVF: Central Slovakian Volcanic Field

Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

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Pyrenees	Rhine graben
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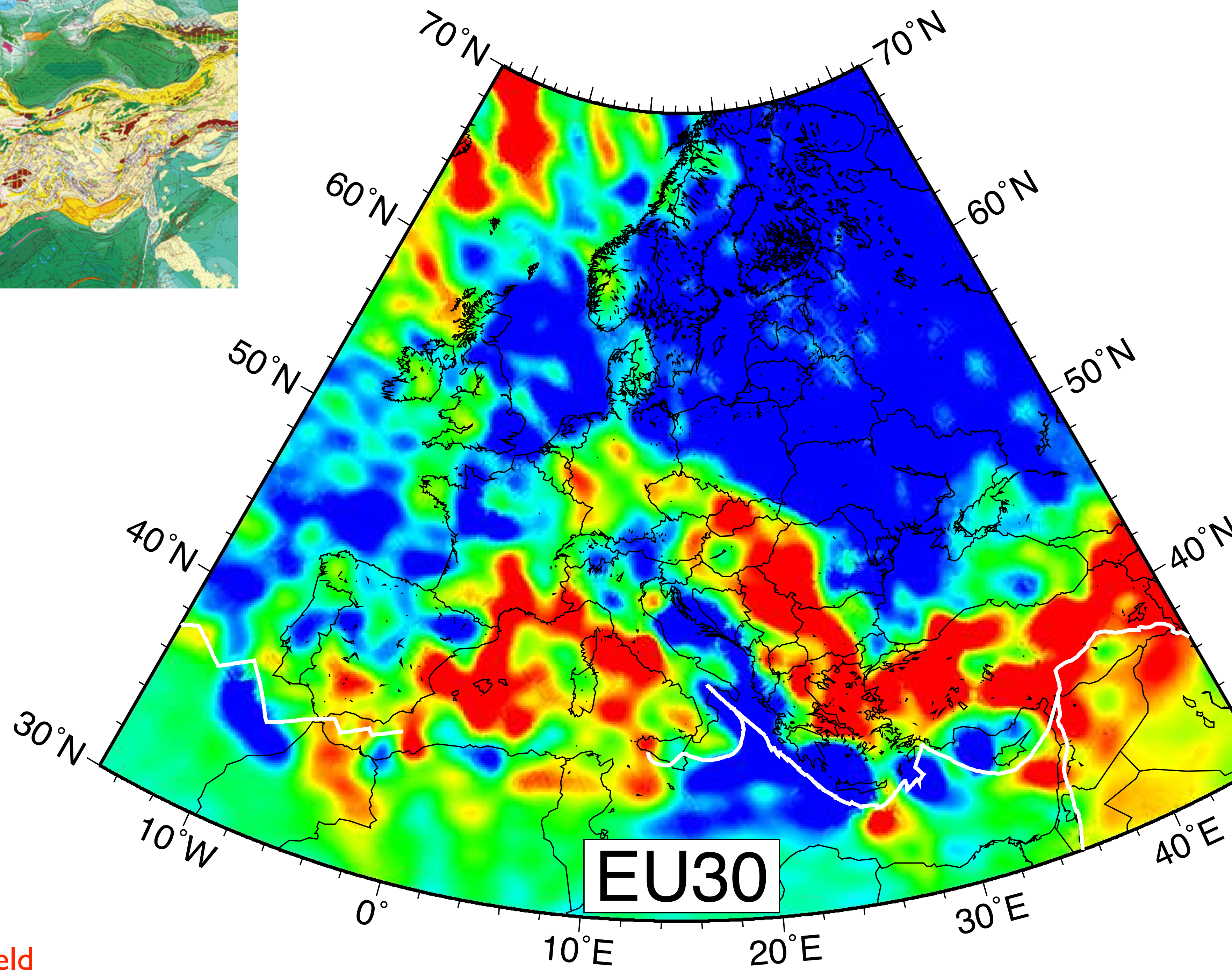
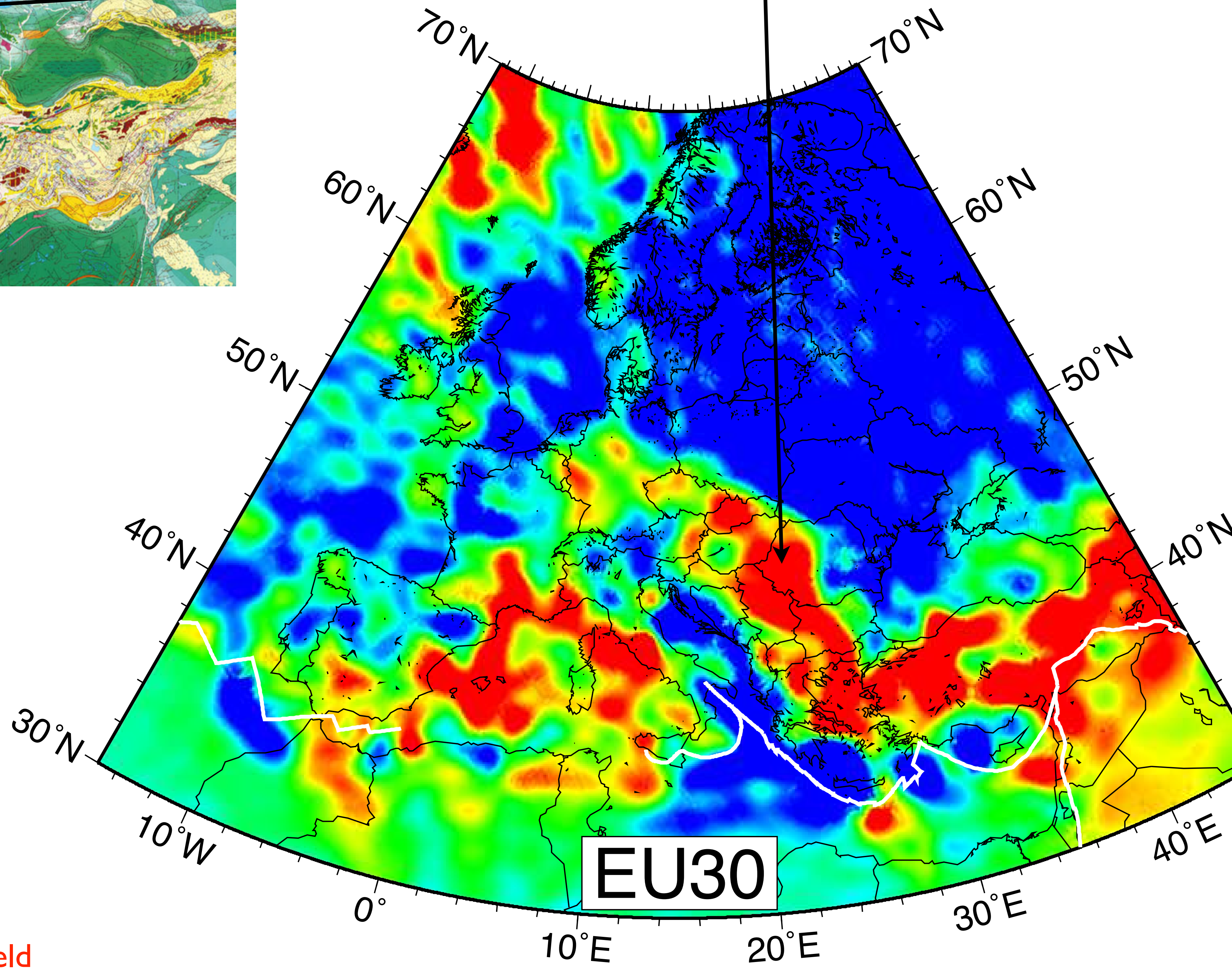
Triple junction	Bohemian massif
Cyprus arc	CSVF



★ CSVF: Central Slovakian Volcanic Field

Geological features of EU30 at 75 km

Pannonian basin



Tornquist-Teisseyre Zone

Central graben	Tyrrhenian sea
Armorican massif	Massif Central
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Adria plate	Harz hotspot
Triple junction	Bohemian massif
Cyprus arc	CSVF

★ CSVF: Central Slovakian Volcanic Field

Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Central graben	Tyrrhenian sea
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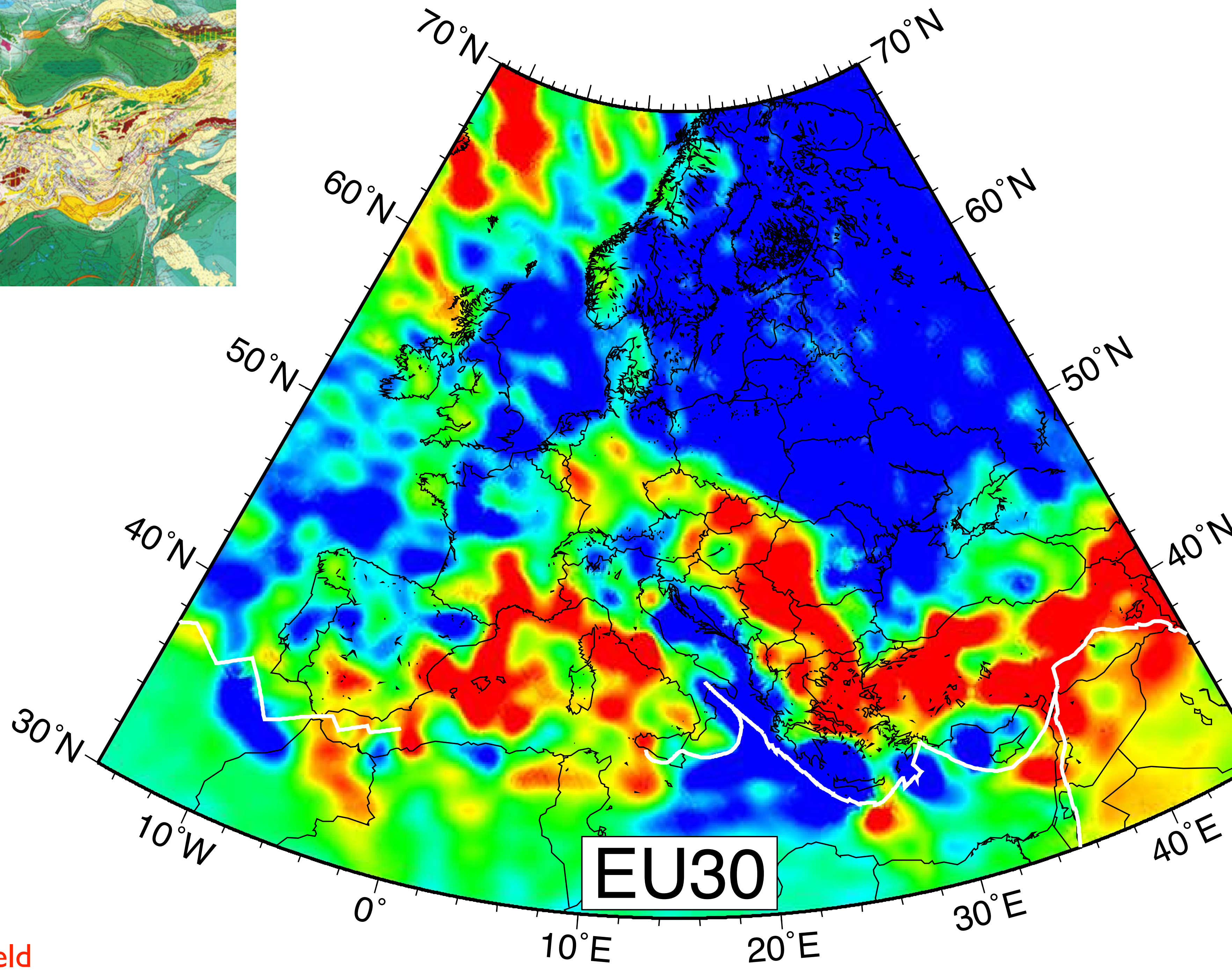
Triple junction	Bohemian massif
Cyprus arc	CSVF
	Pannonian basin



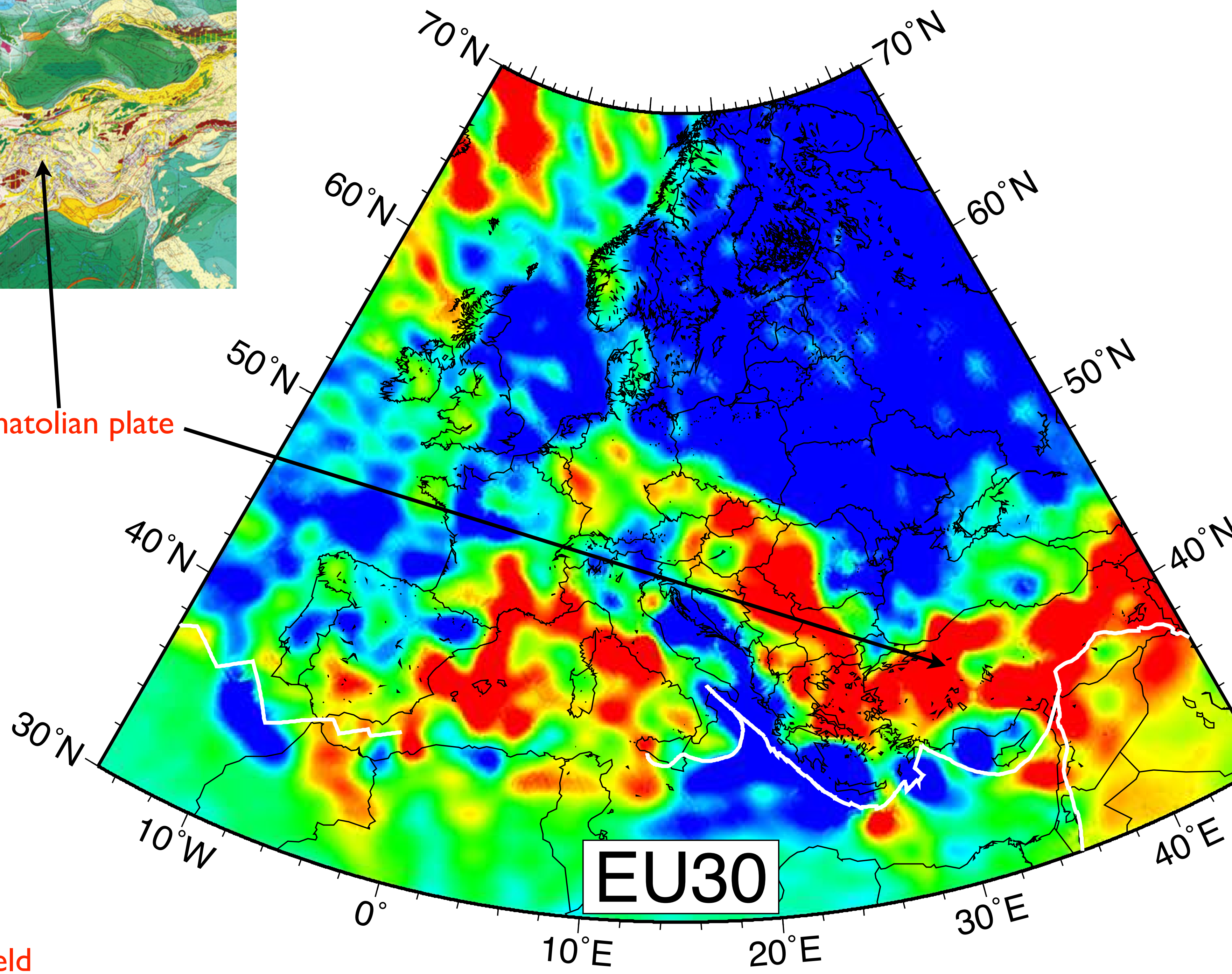
★ CSVF: Central Slovakian Volcanic Field

Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

Anatolian plate

Central graben	Tyrrhenian sea
Armorican massif	Massif Central
Pyrenees	Rhine graben
Adria plate	Harz hotspot
Triple junction	Bohemian massif
Cyprus arc	CSVF
	Pannonian basin



★ CSVF: Central Slovakian Volcanic Field

Geological features of EU30 at 75 km

Tornquist-Teisseyre Zone

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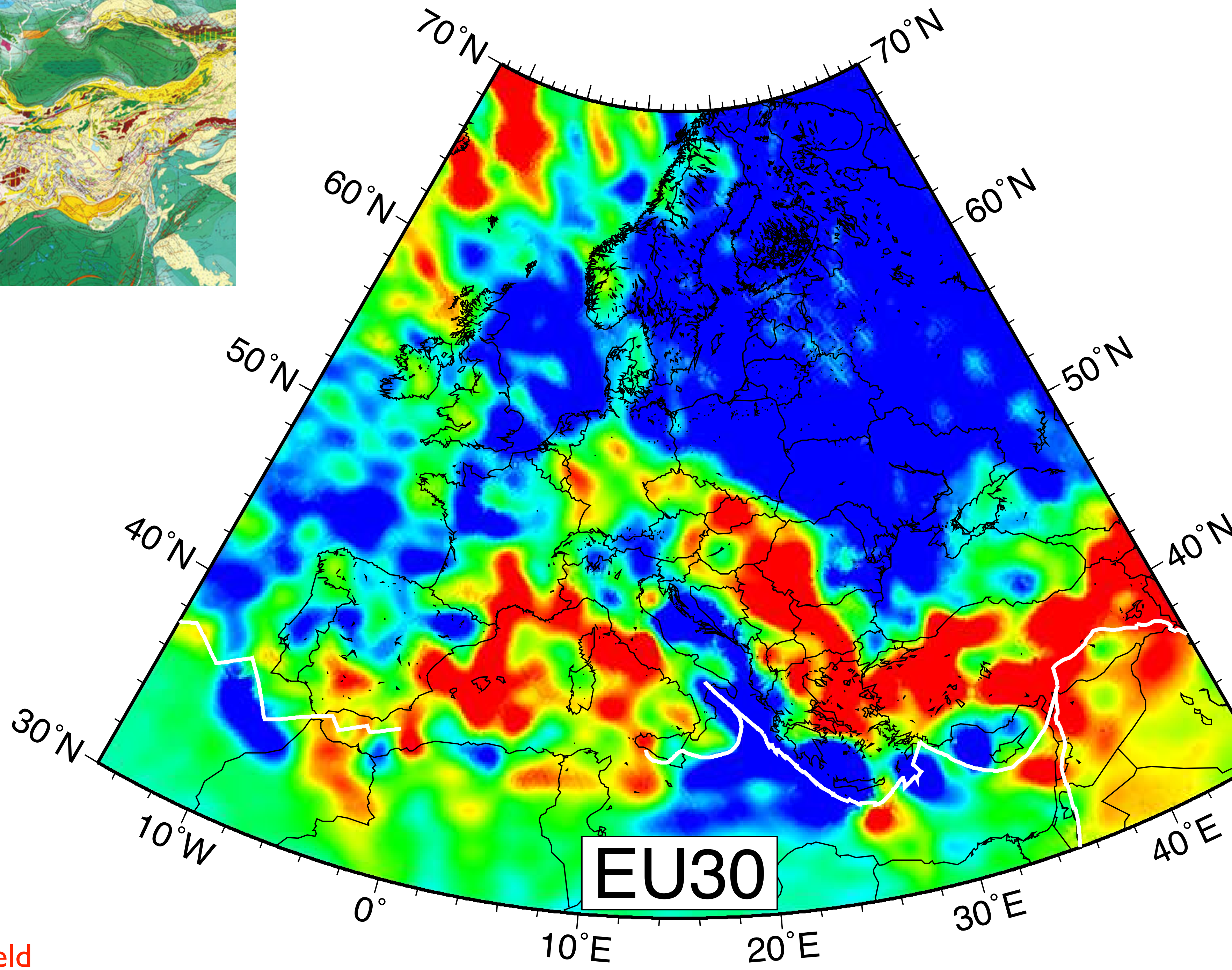
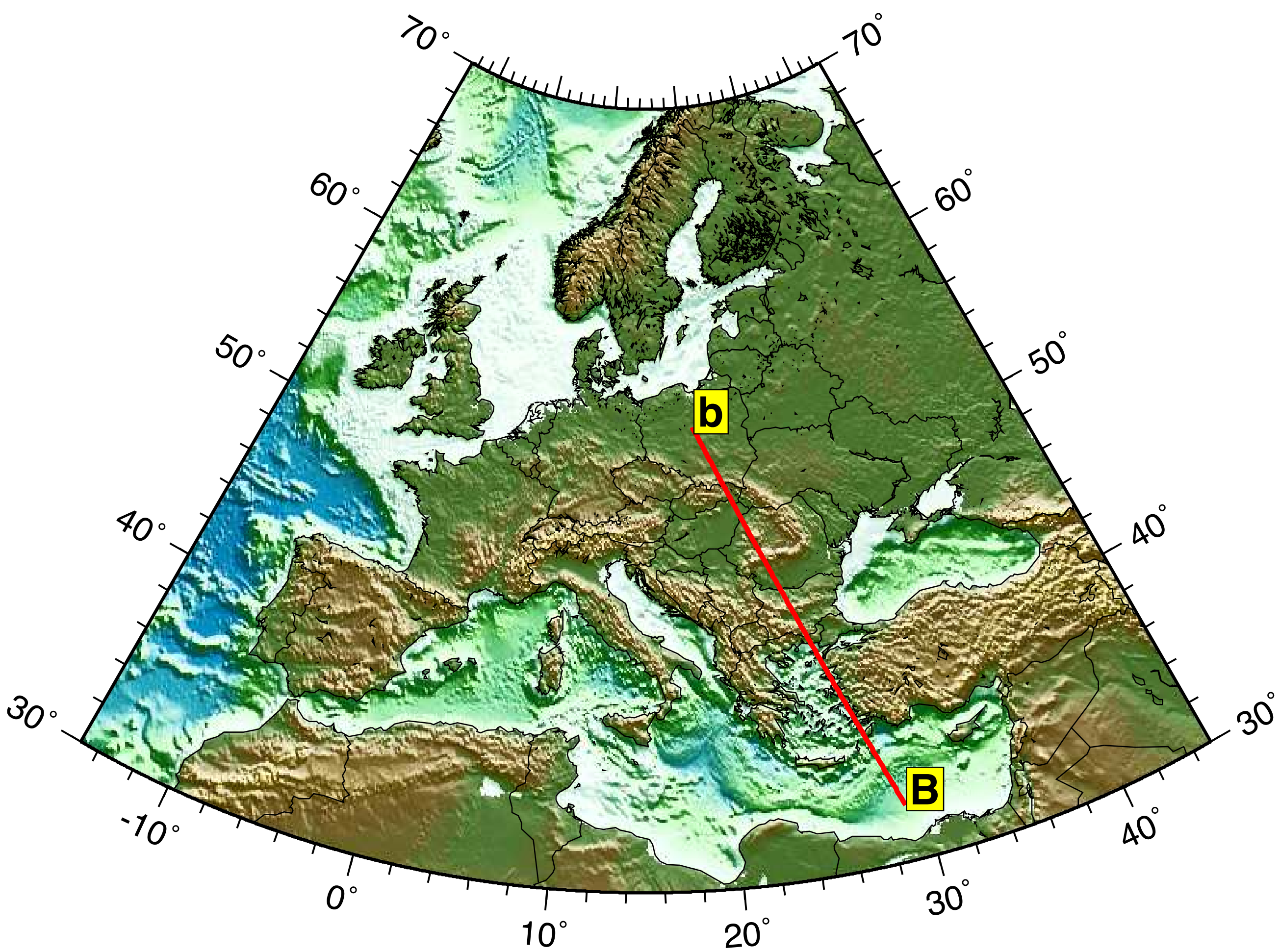
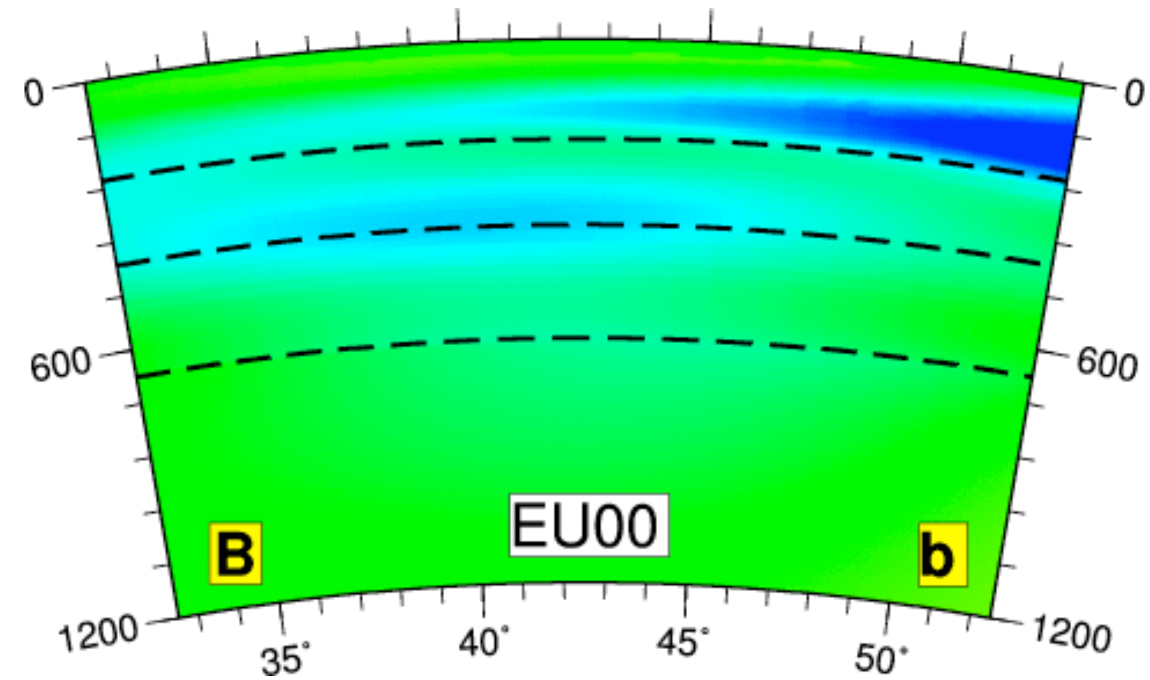
Cyprus arc	CSVF
	Pannonian basin
	Anatolian plate



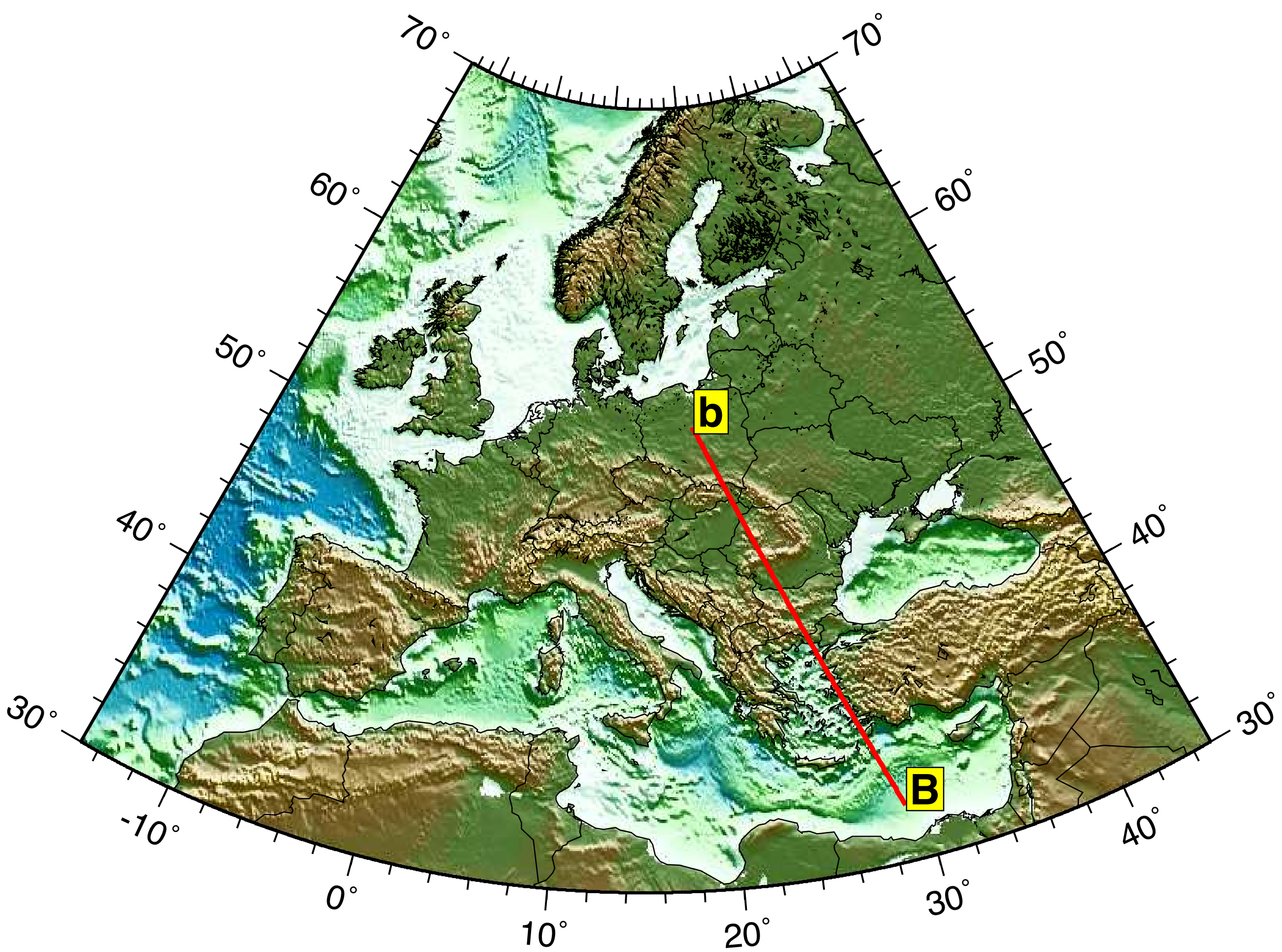
★ CSVF: Central Slovakian Volcanic Field

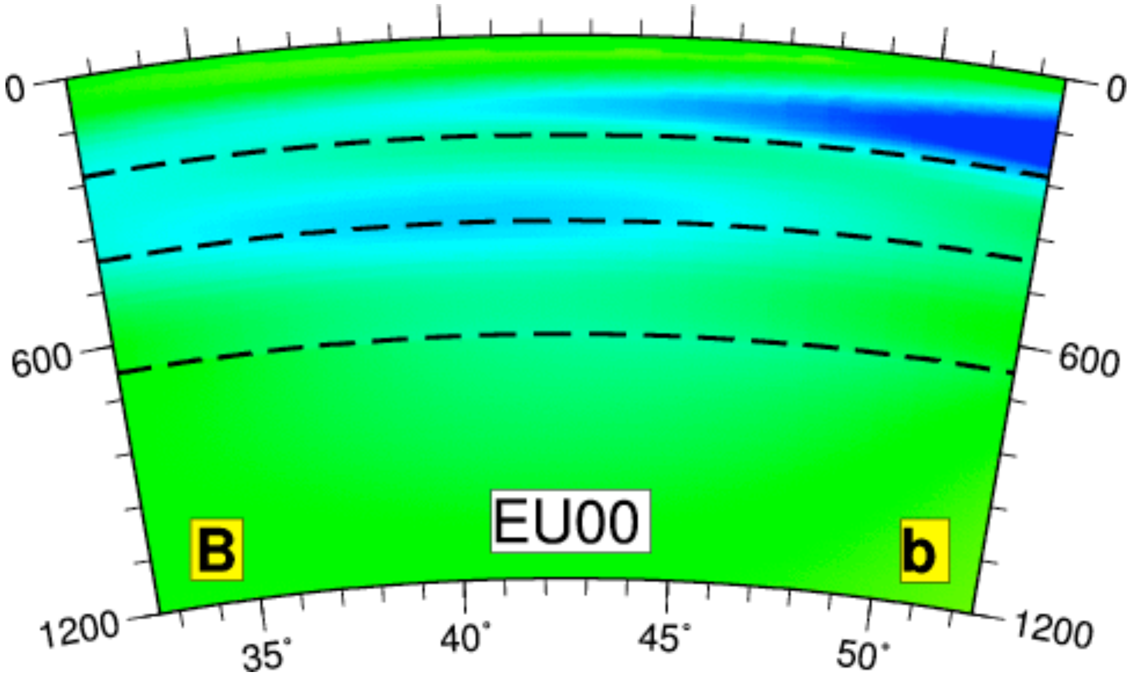
Hellenic arc

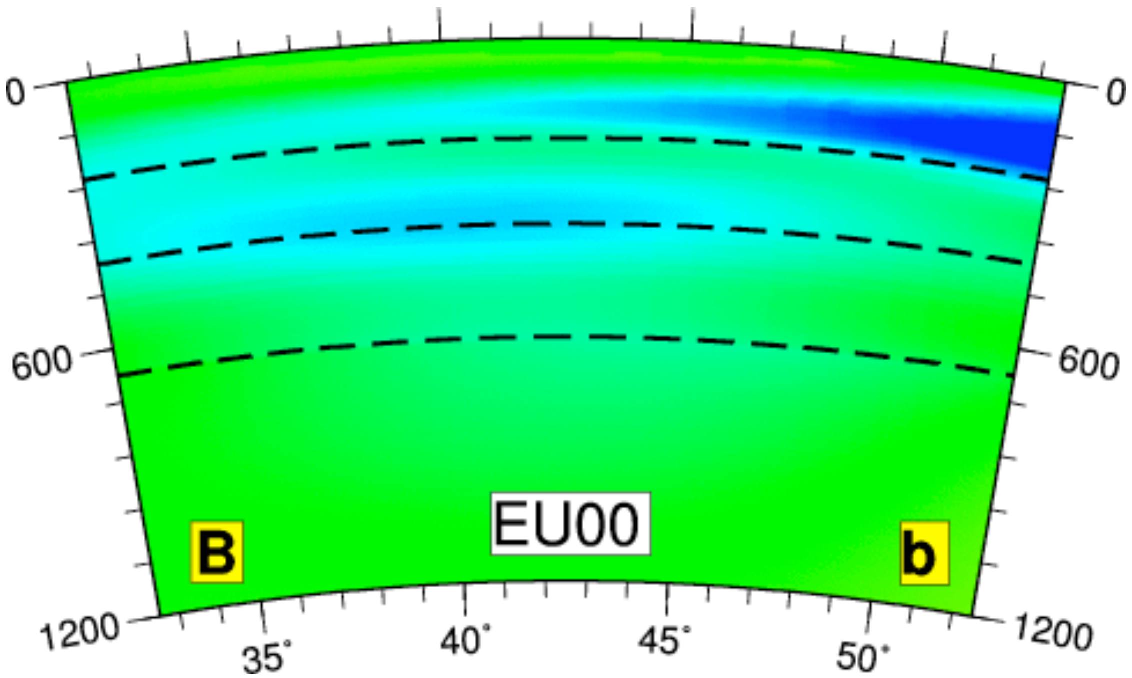




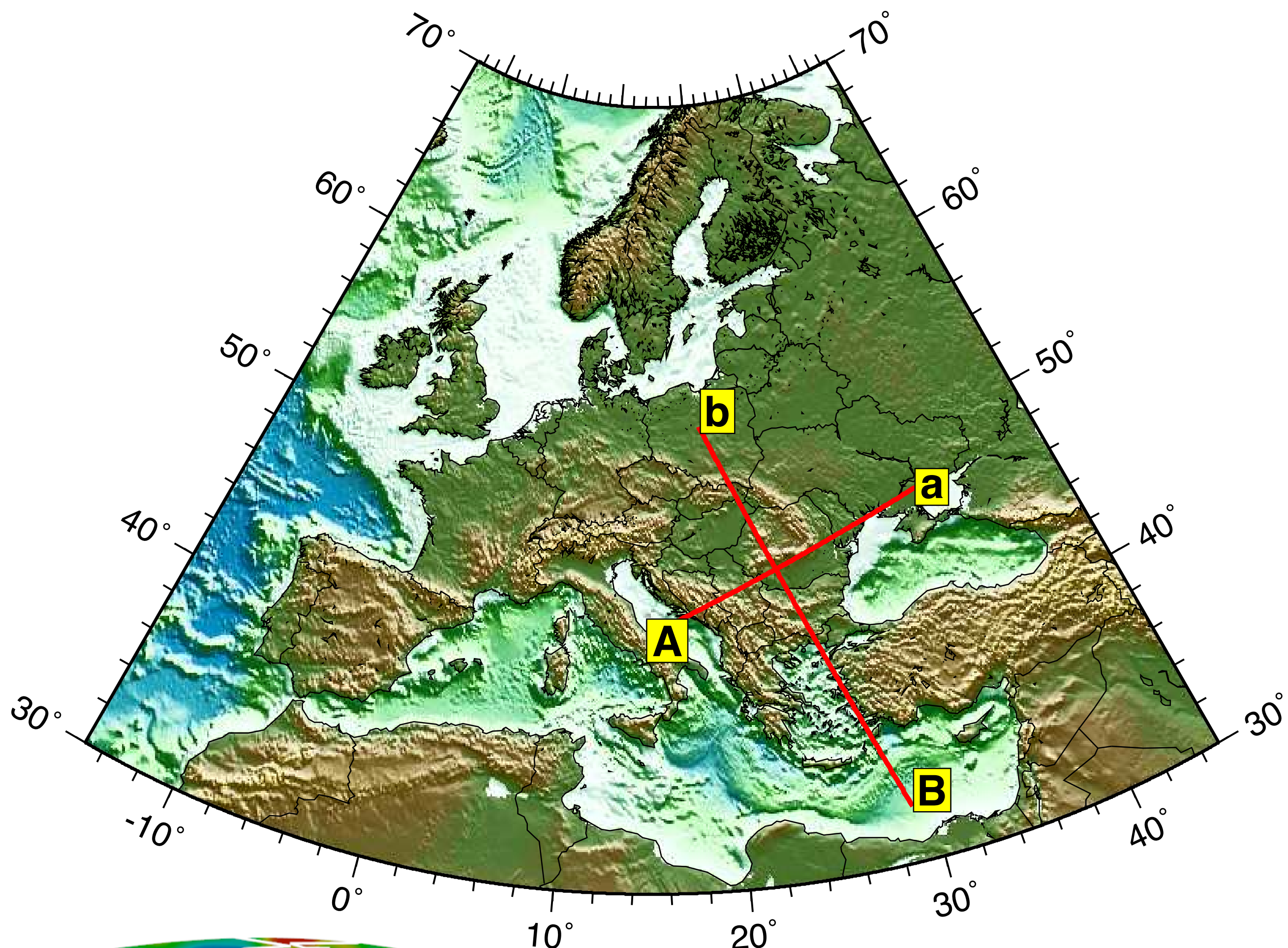
Hellenic arc

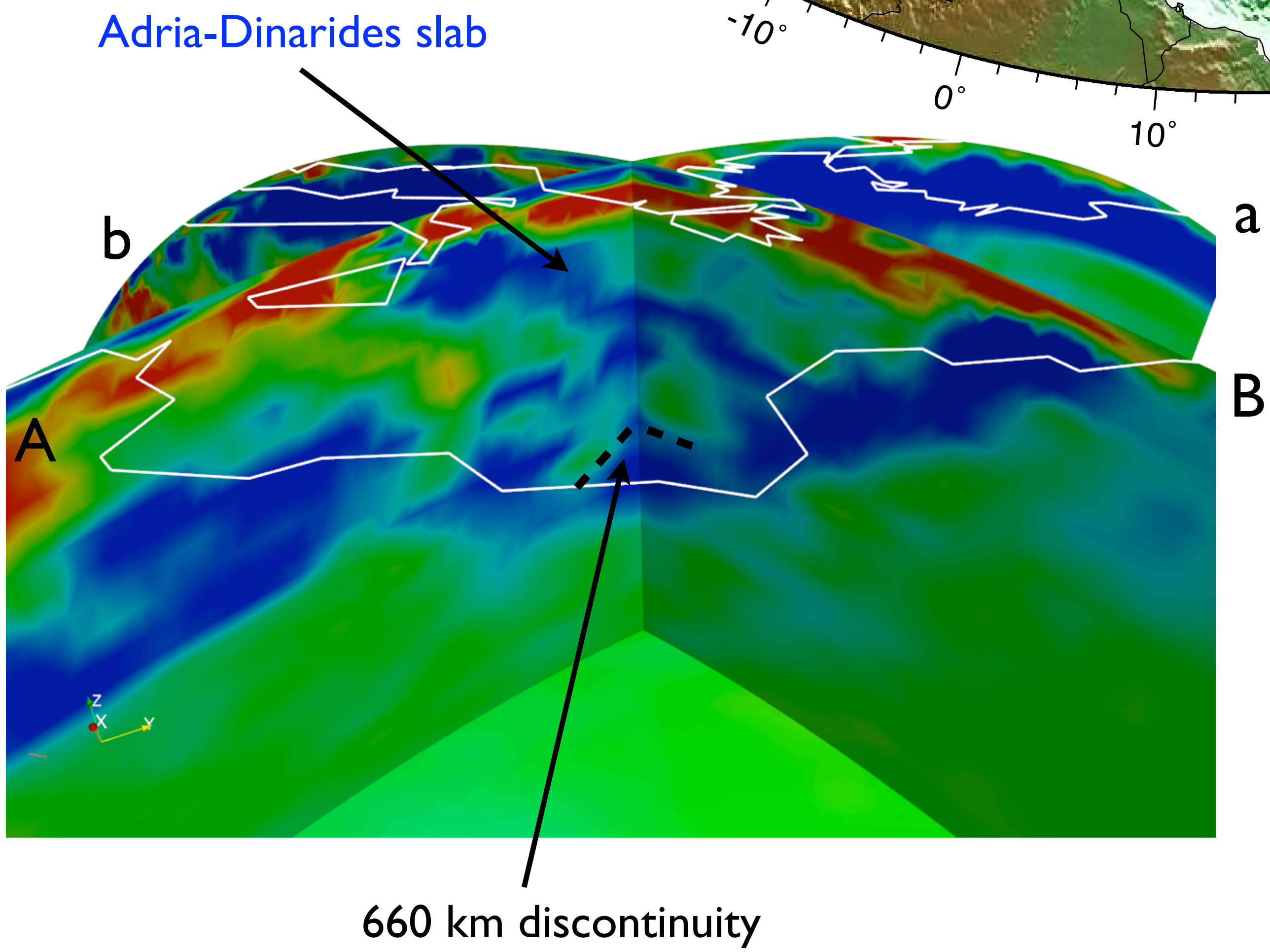




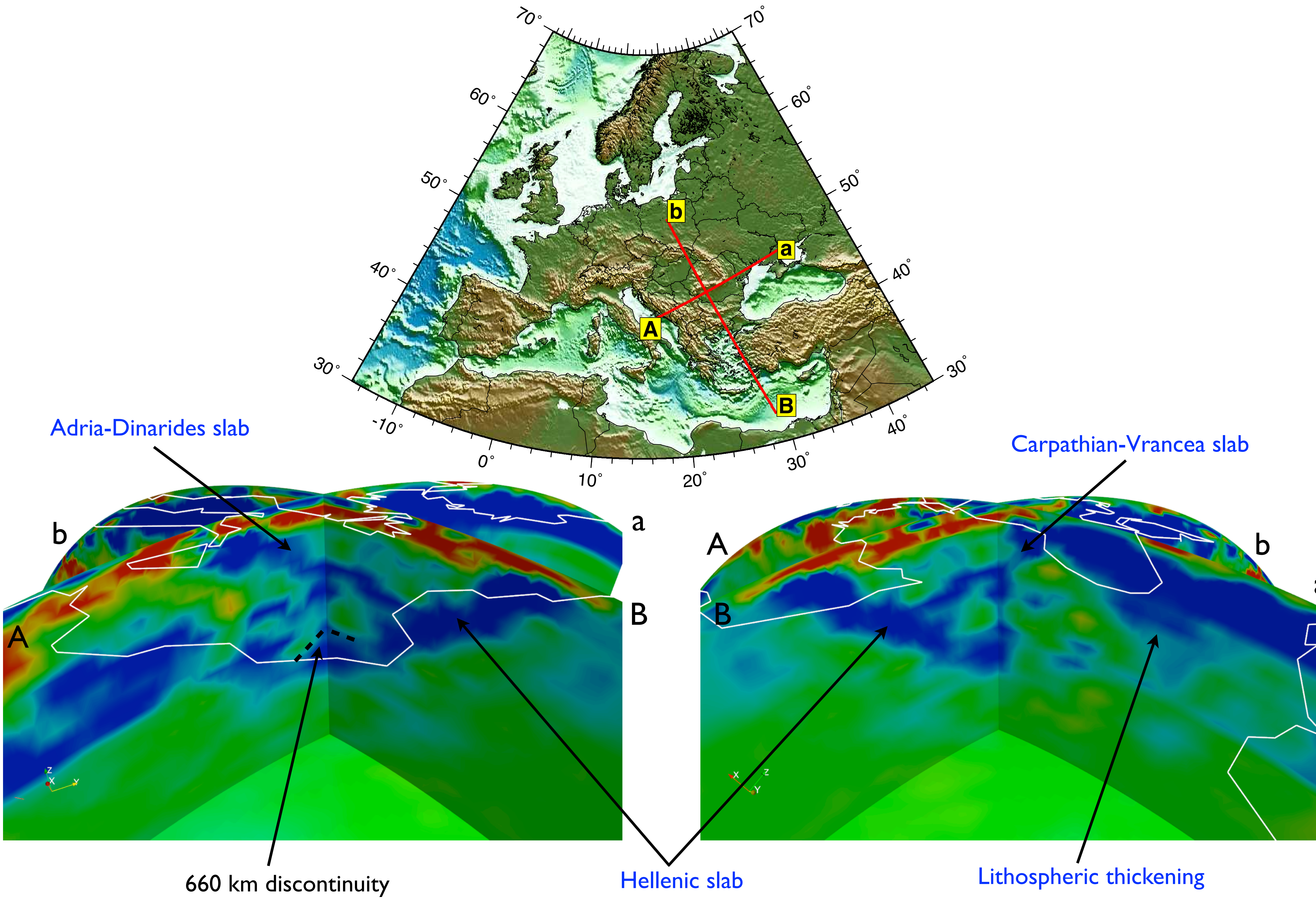


Complicated triple slab structures

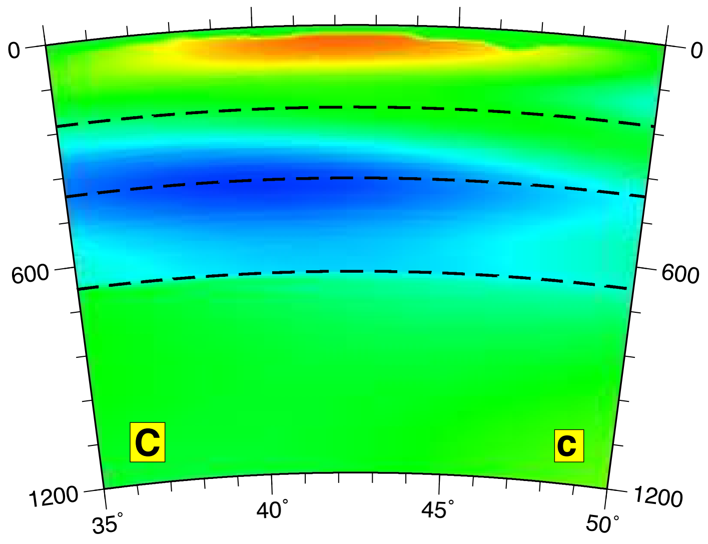


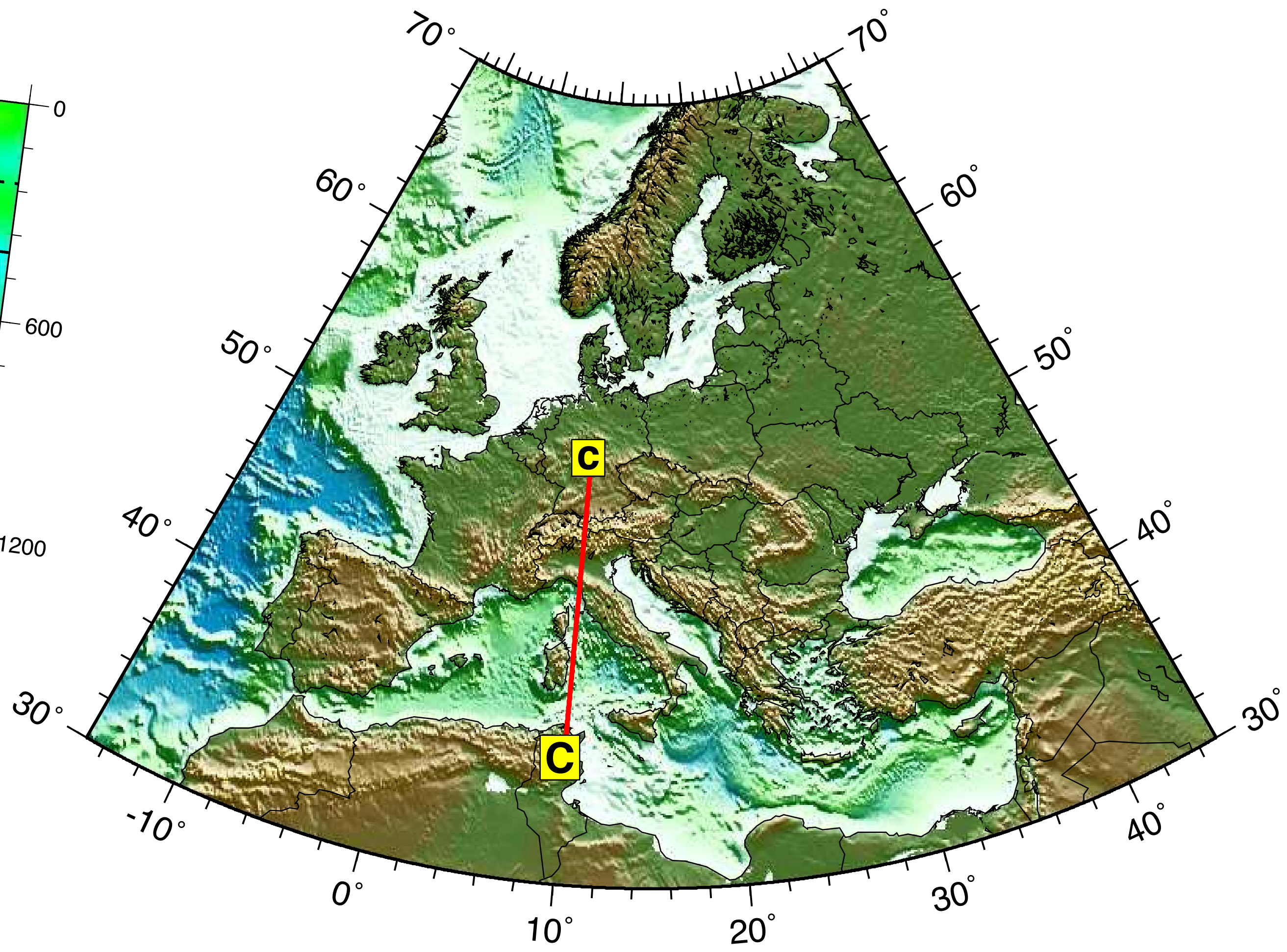


Complicated triple slab structures



More cross sections





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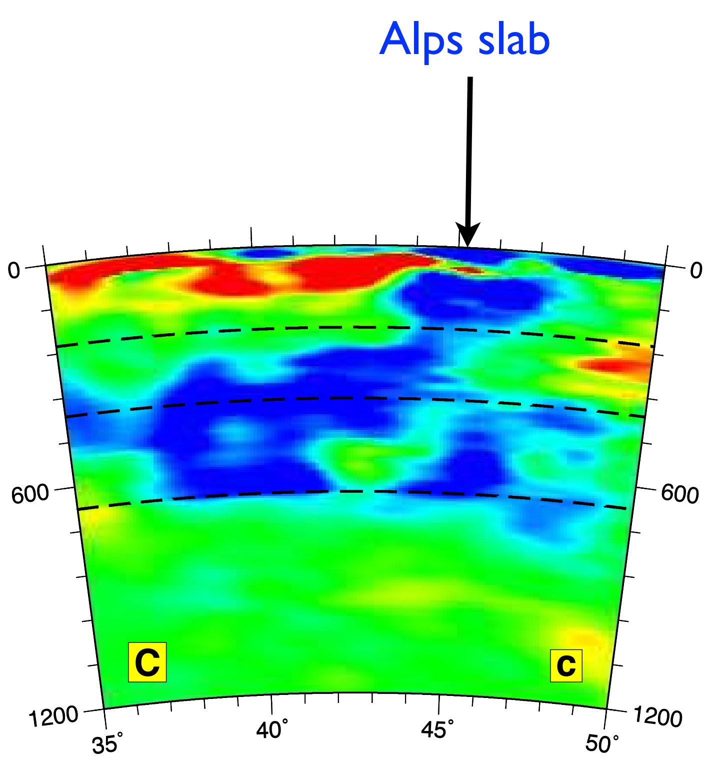

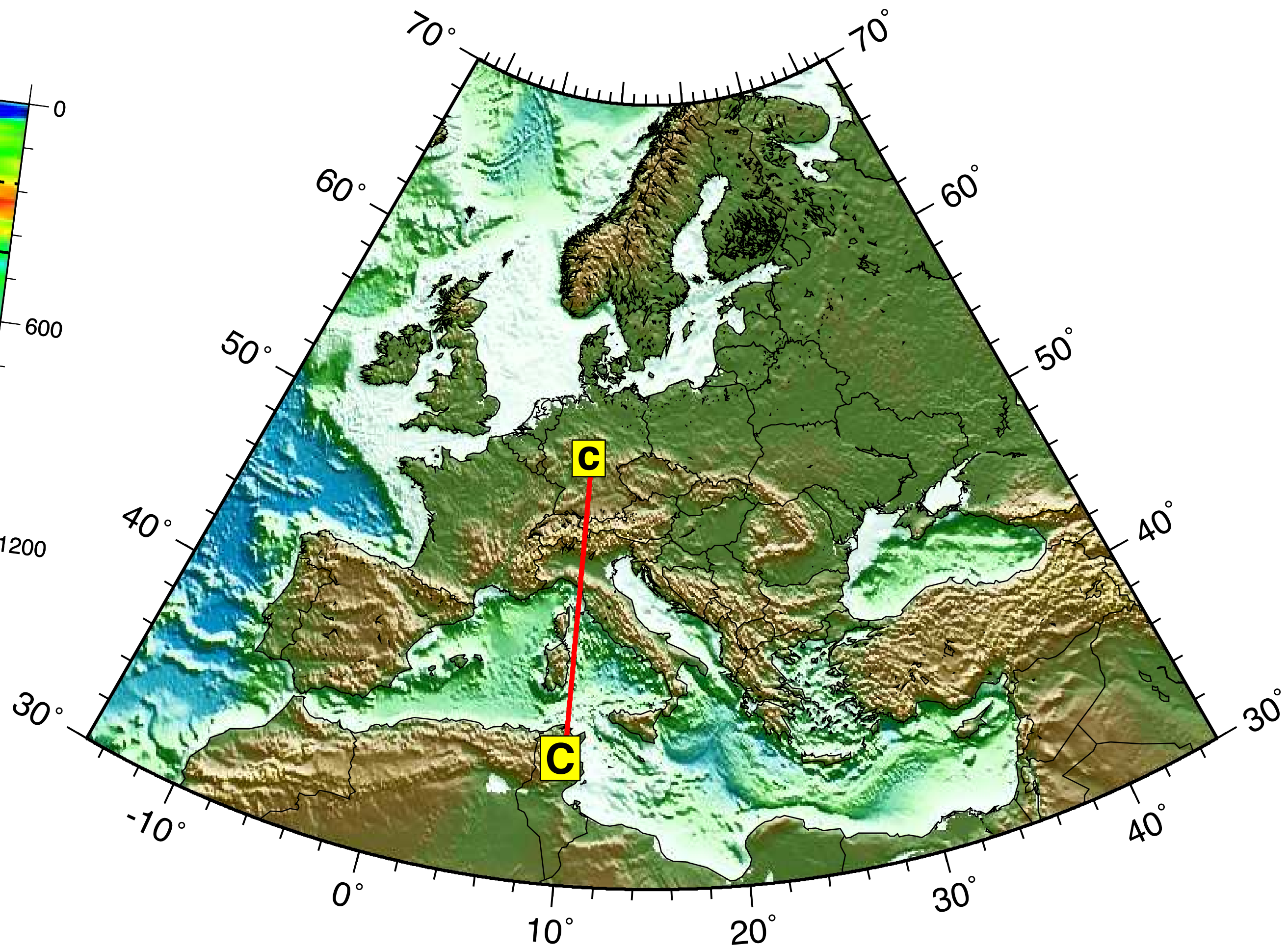

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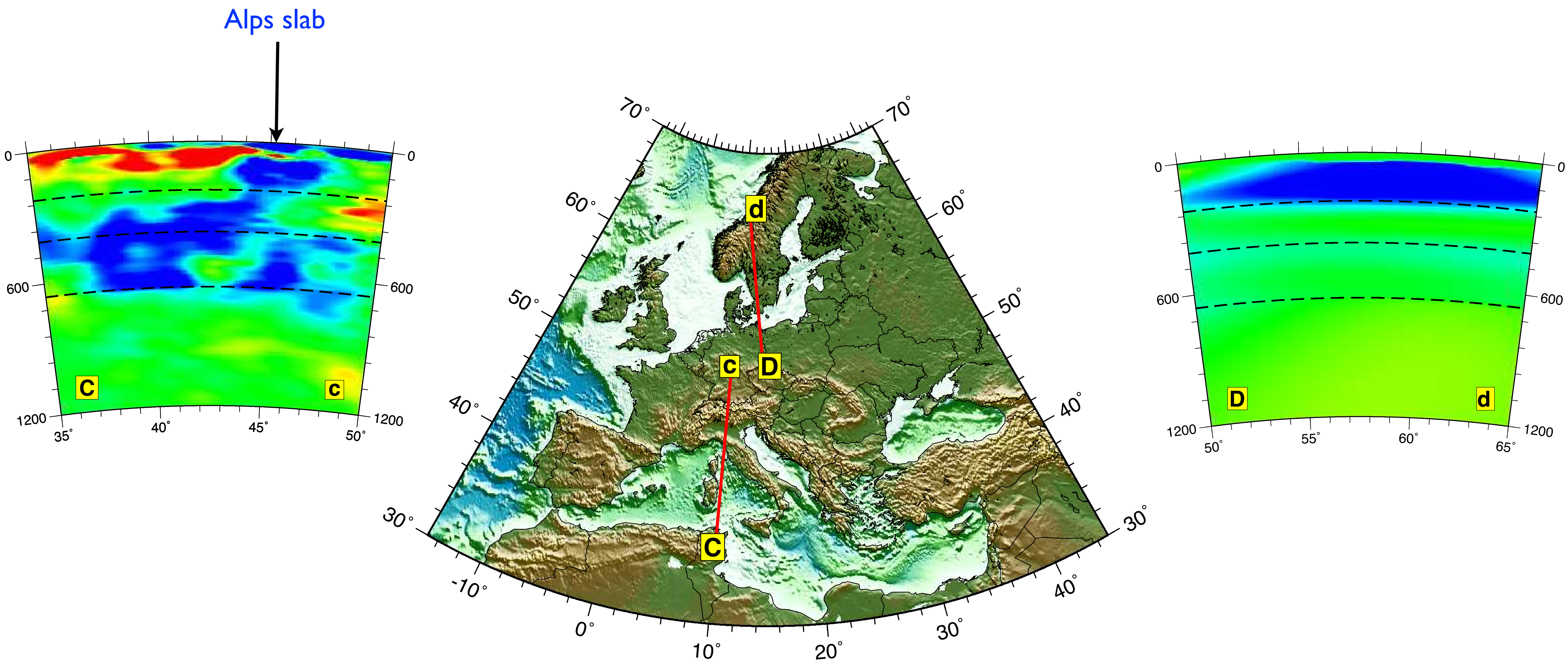

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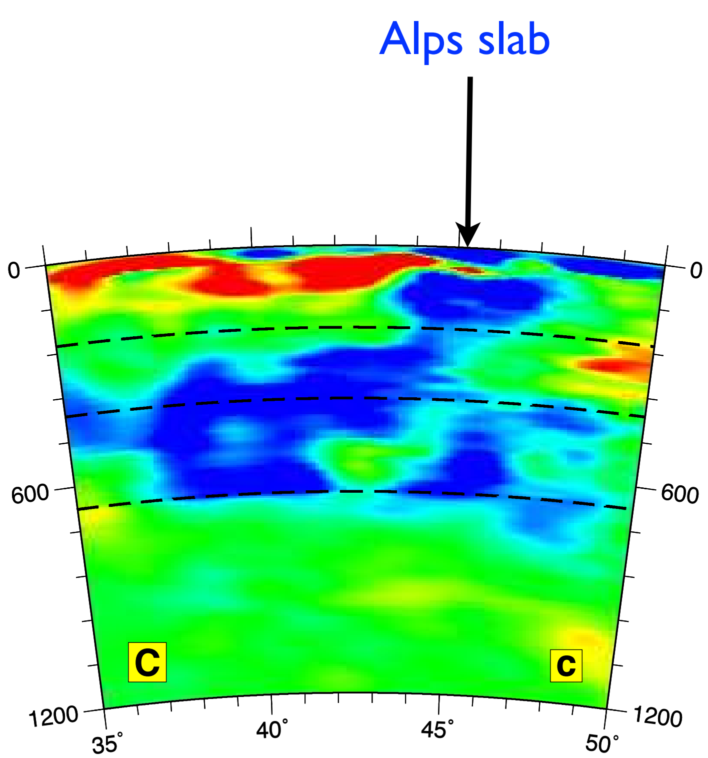

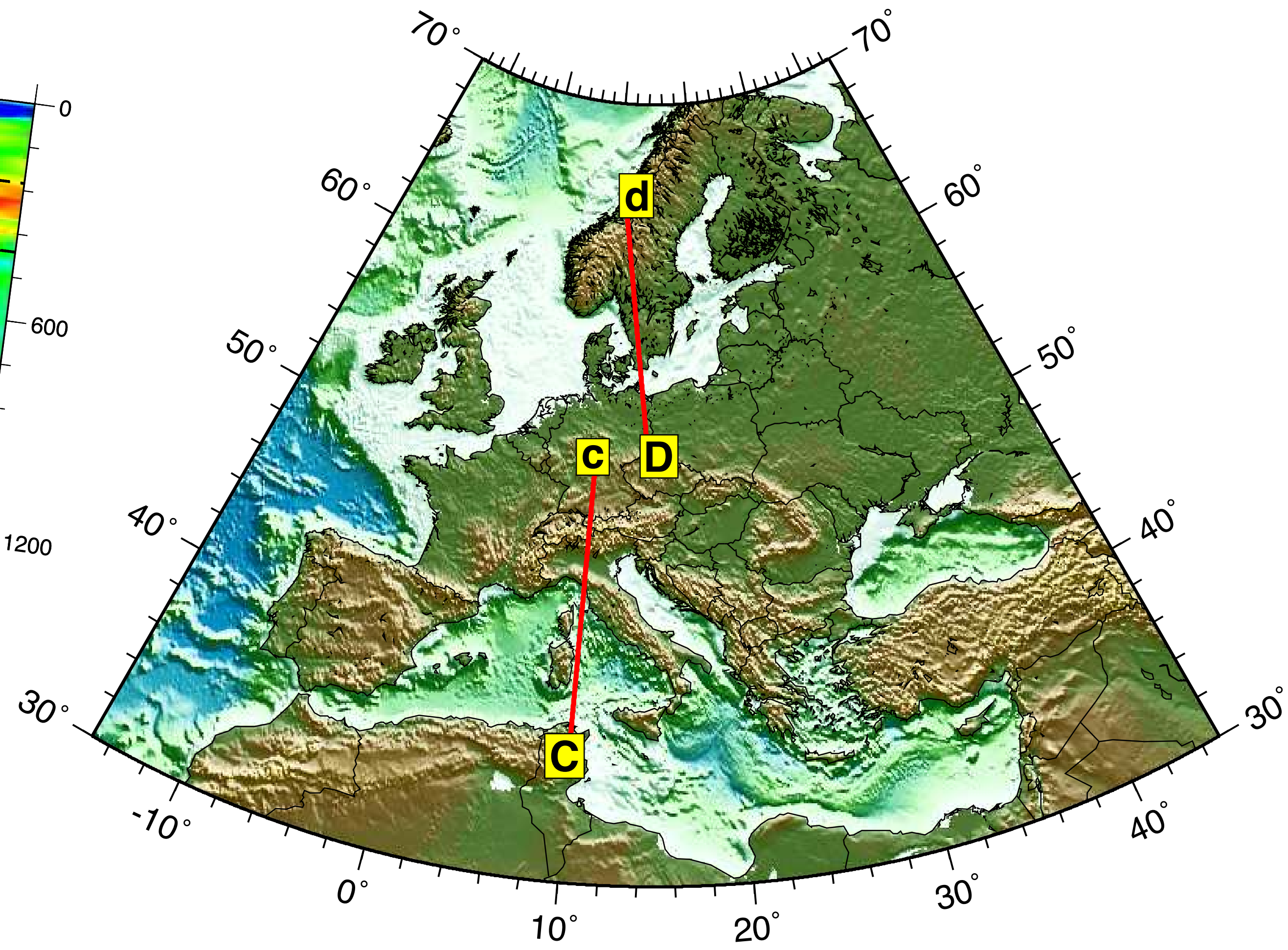

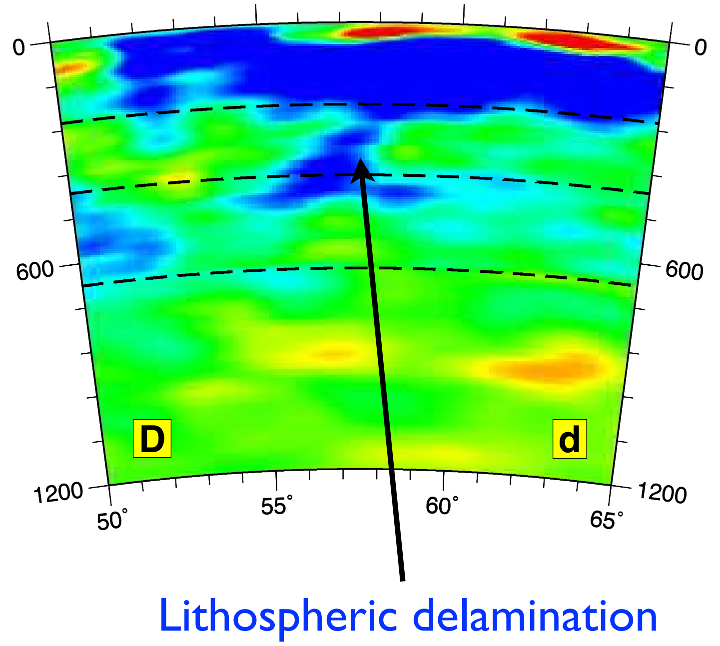

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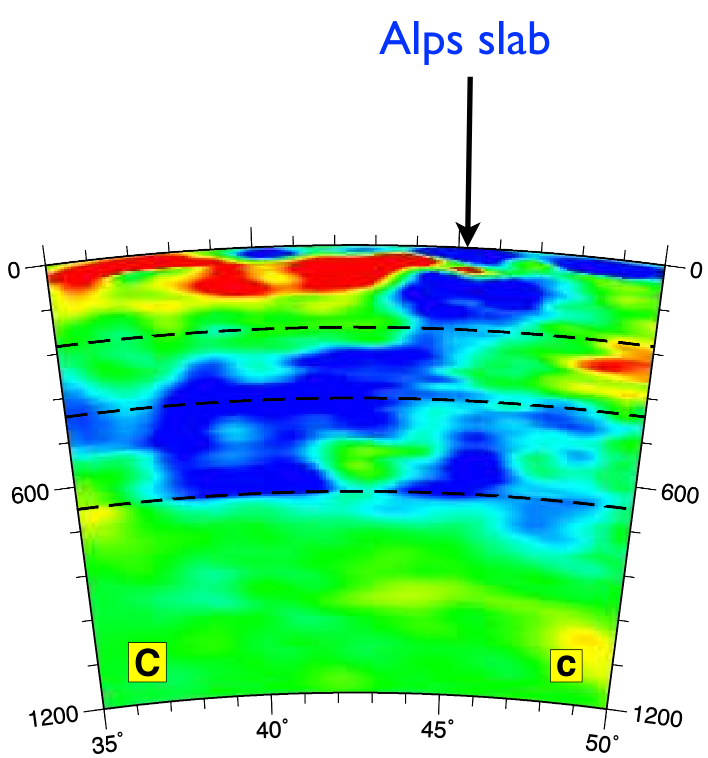

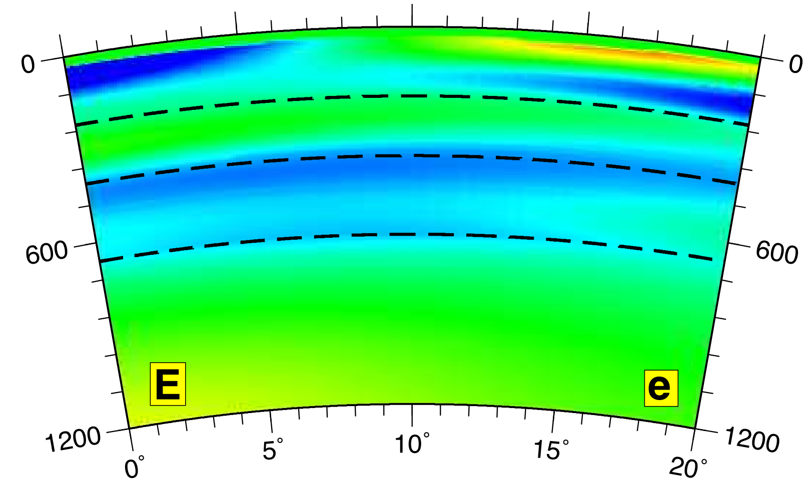

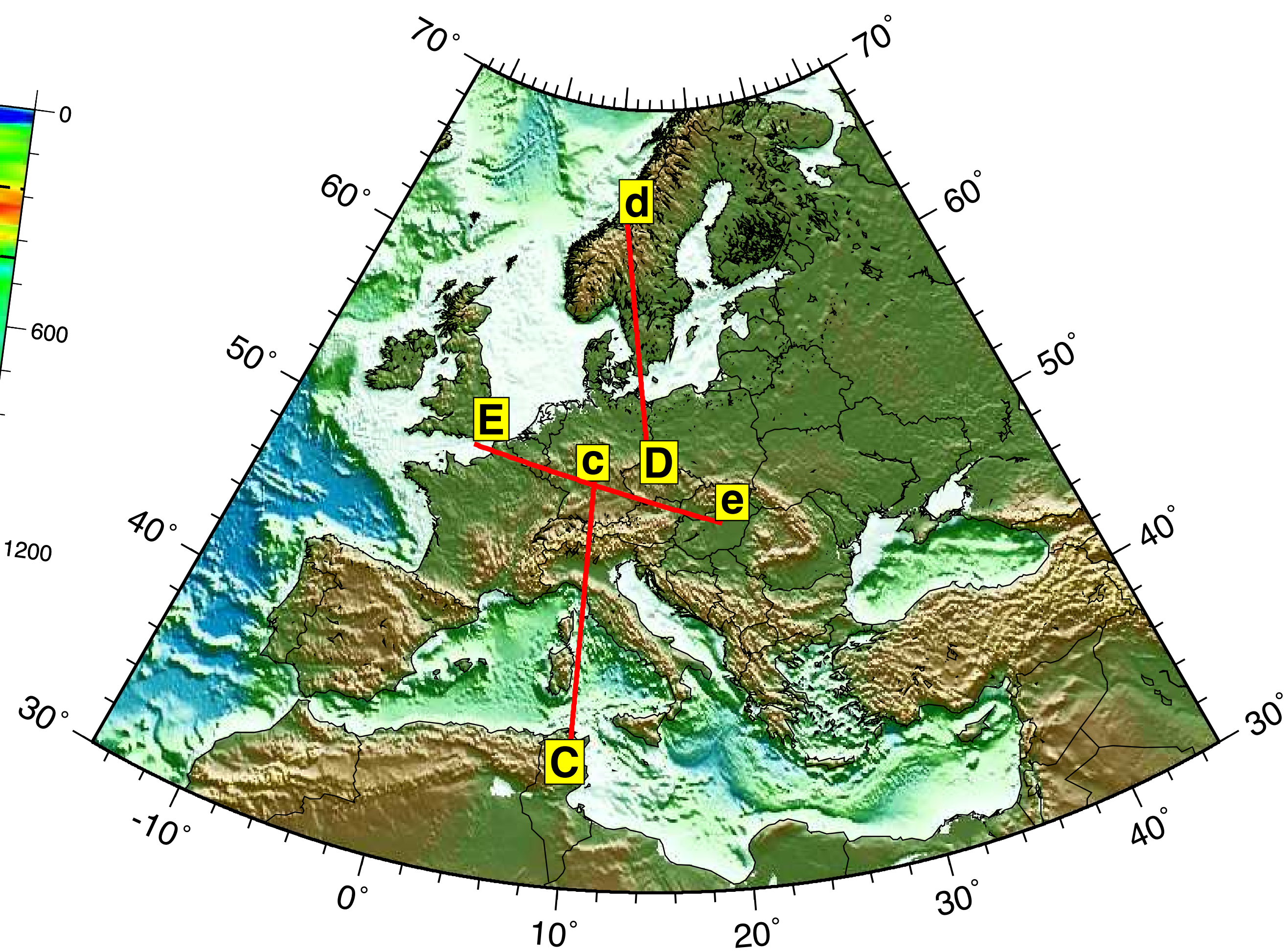

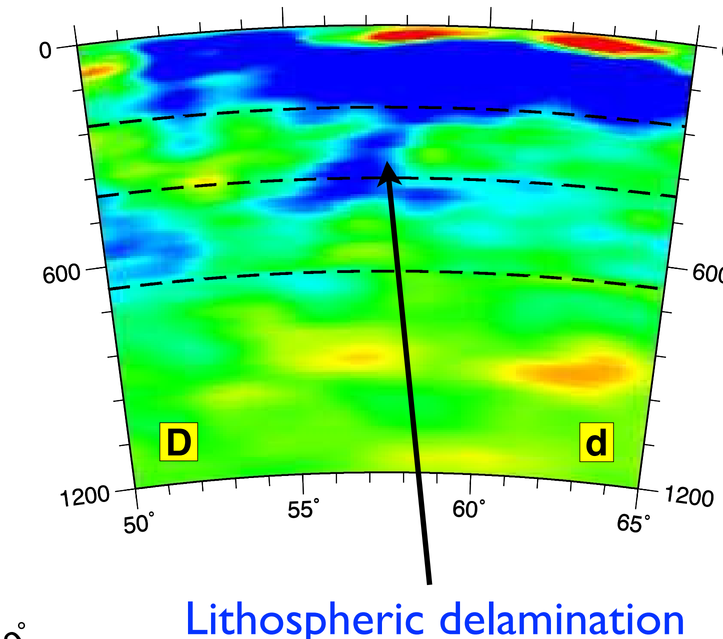

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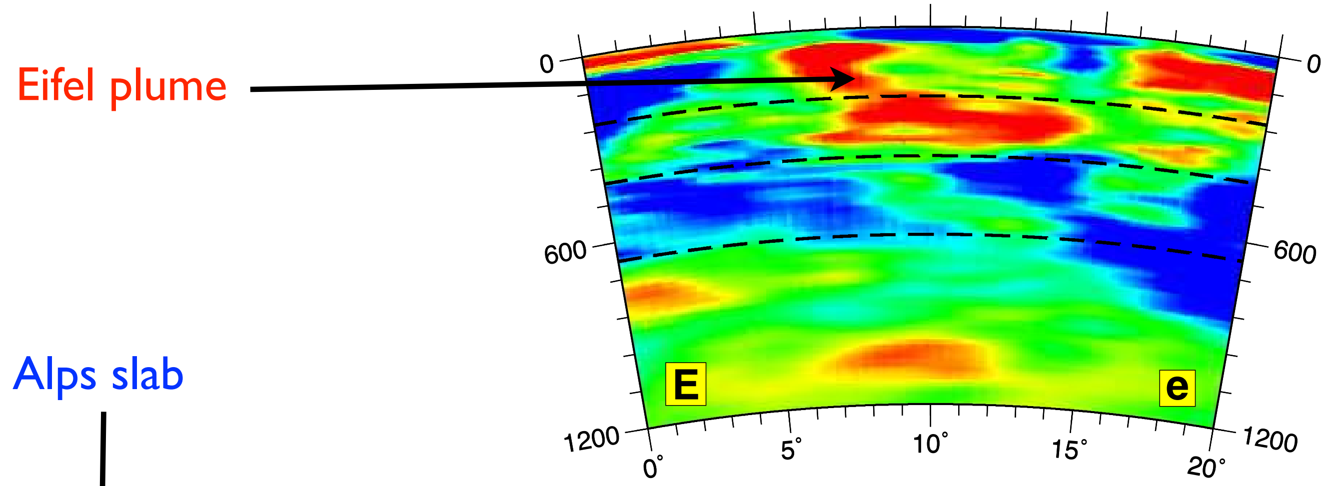

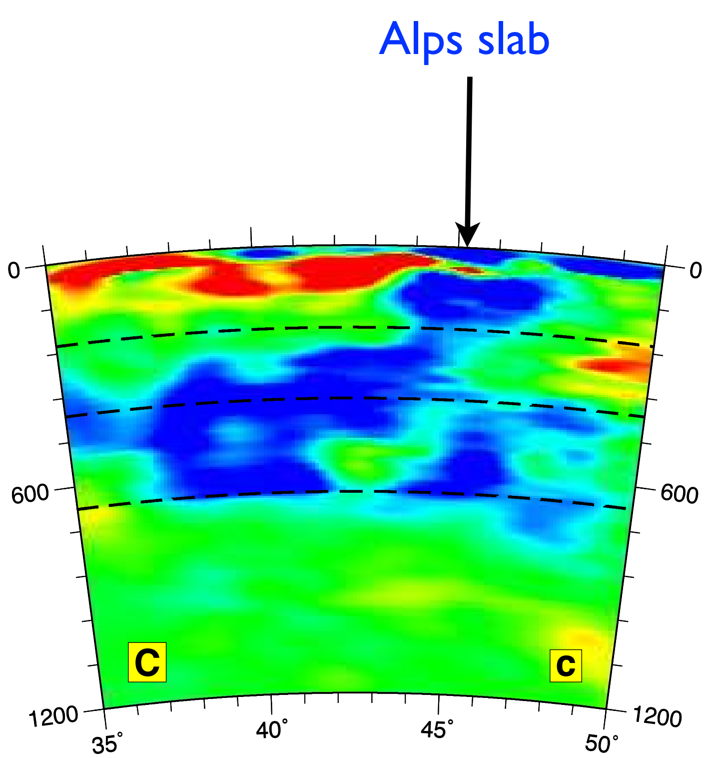

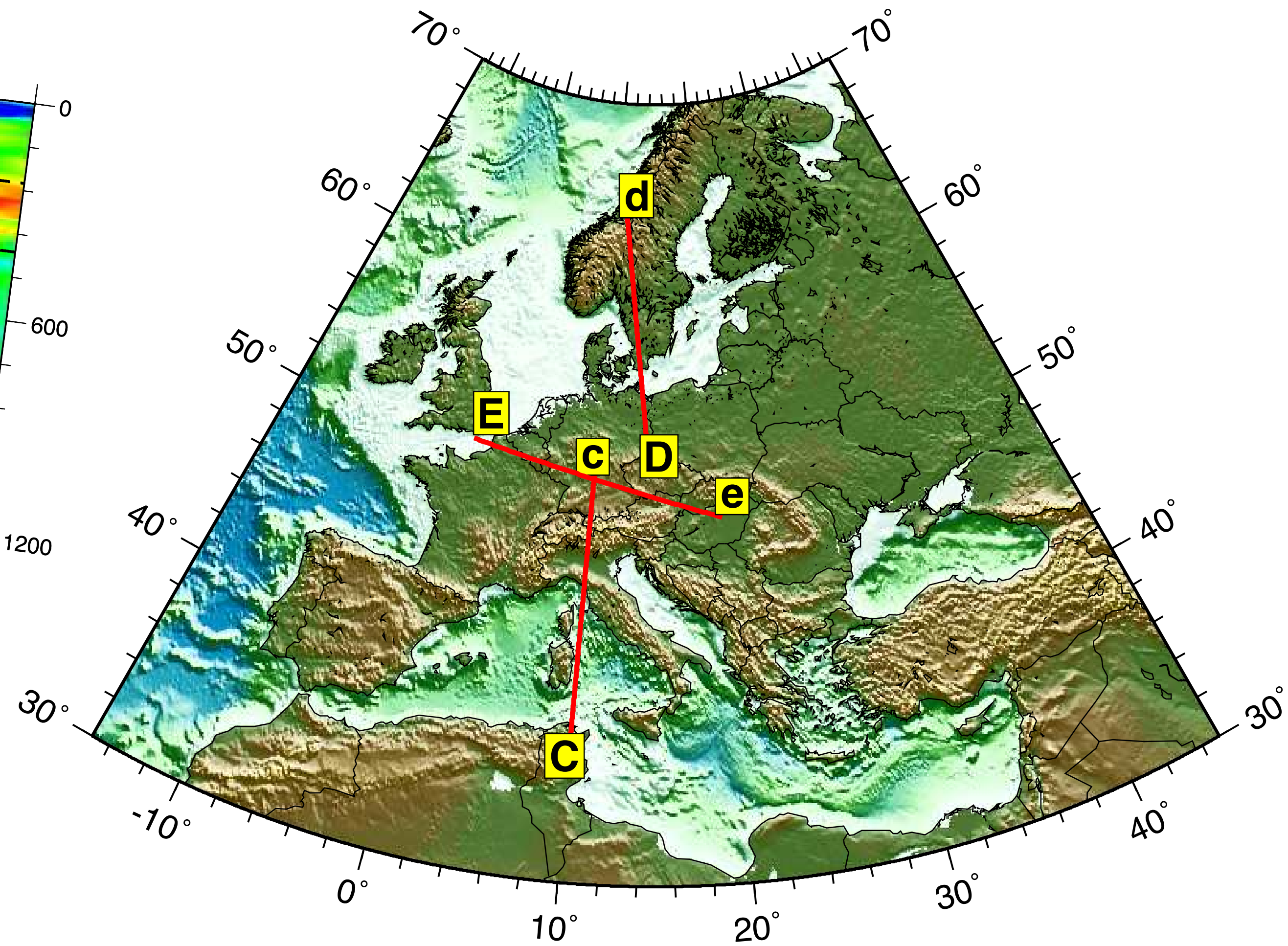

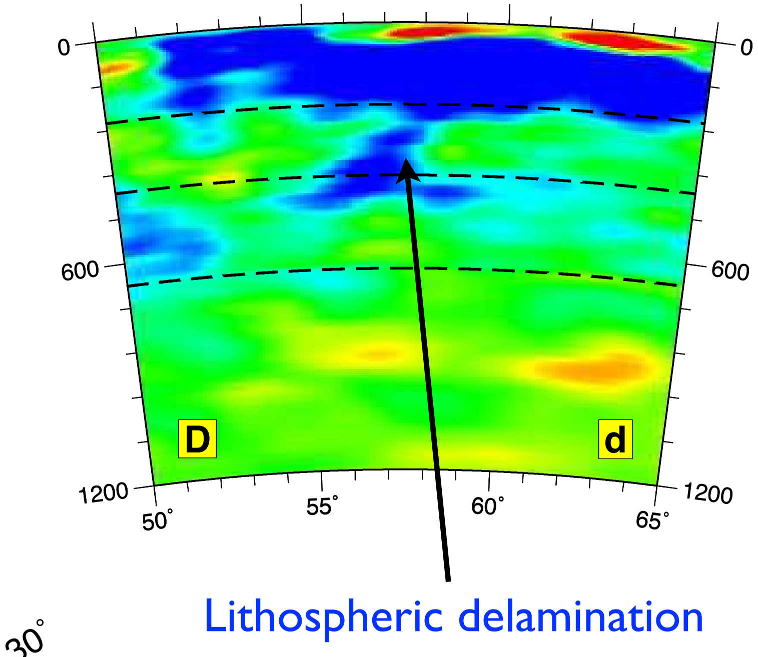

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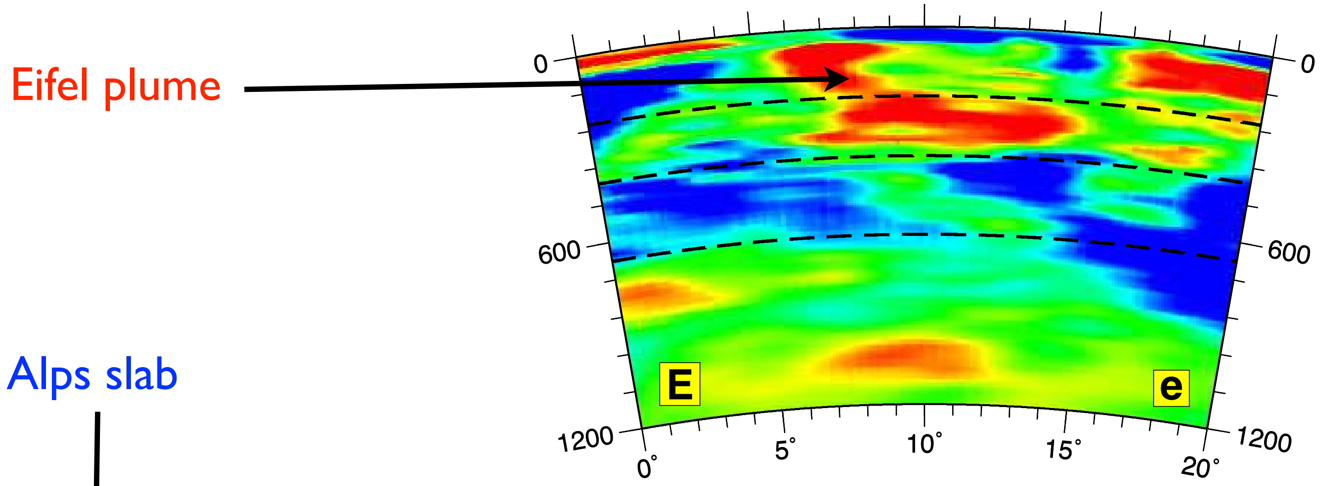
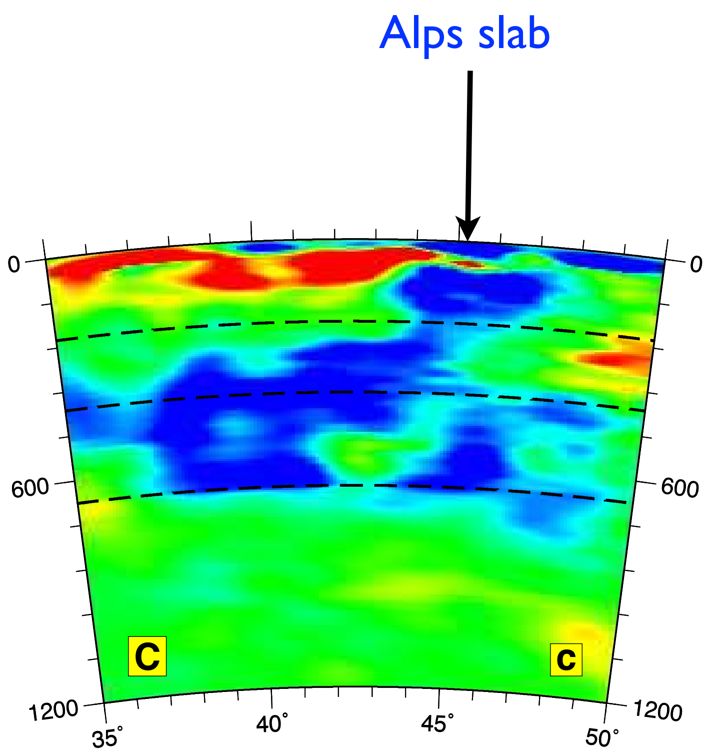
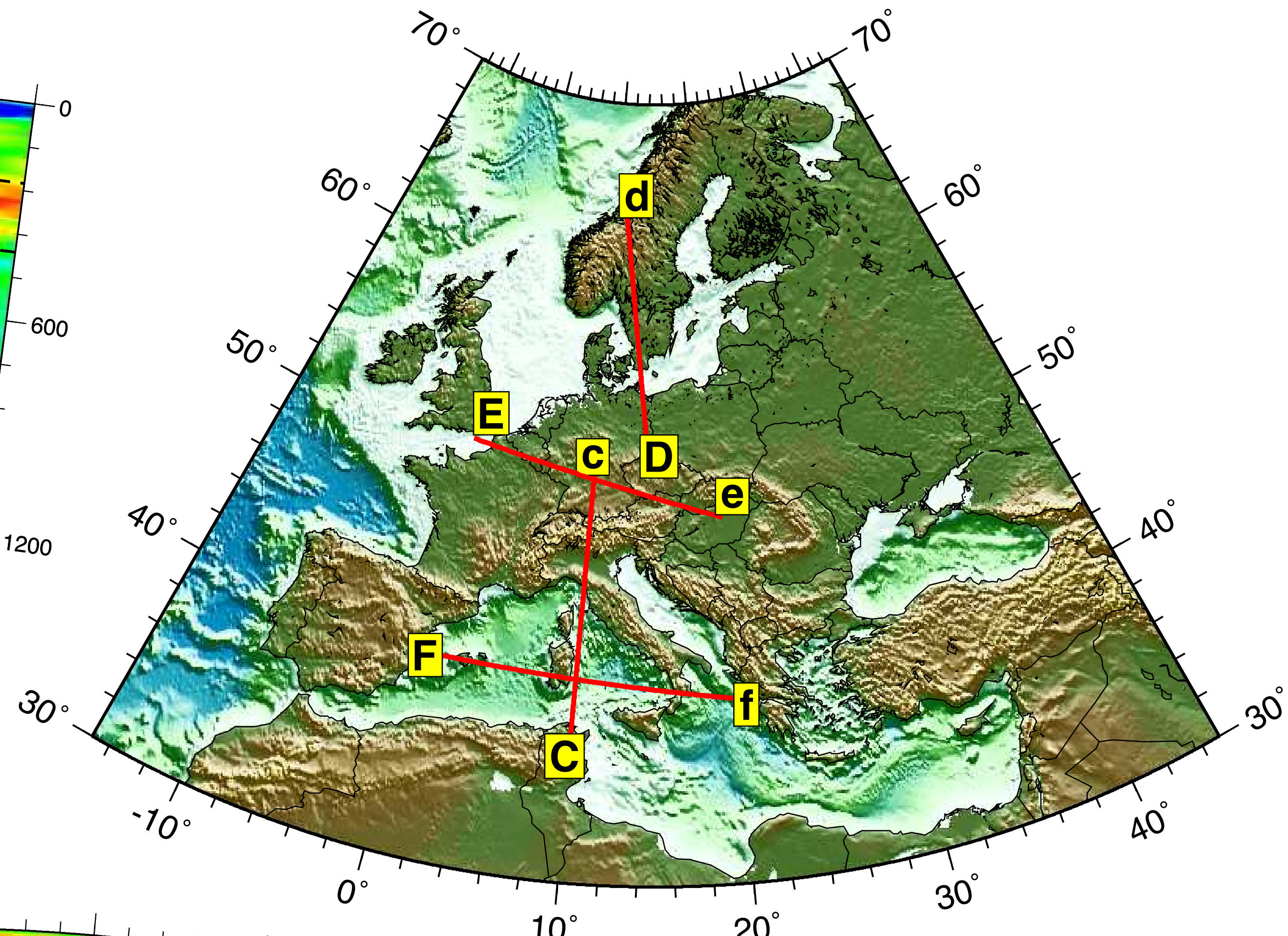
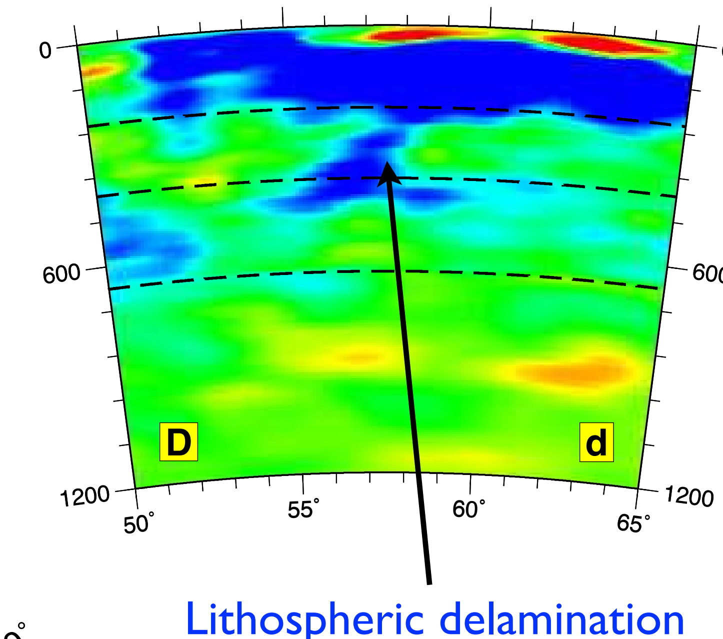
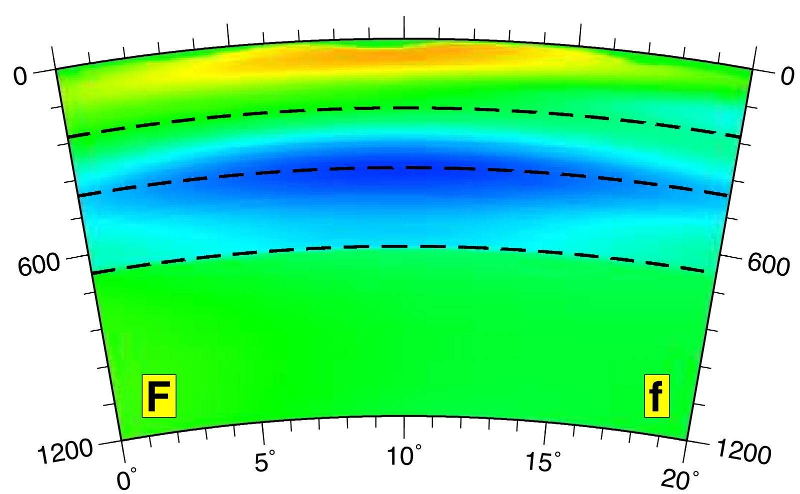


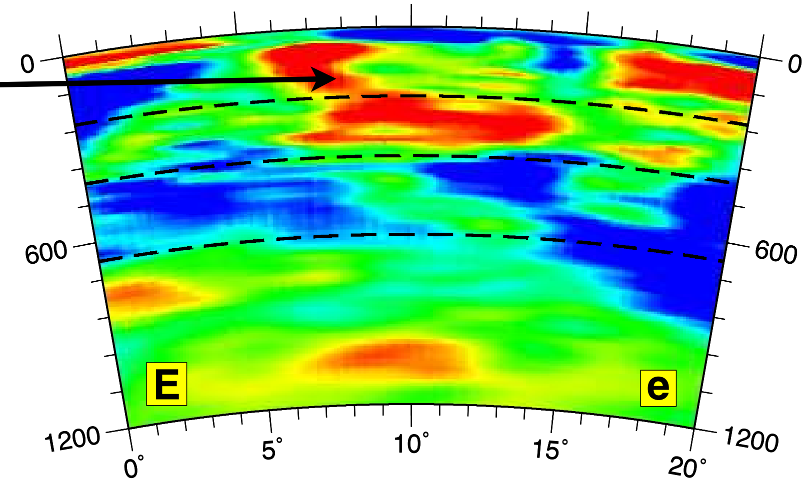


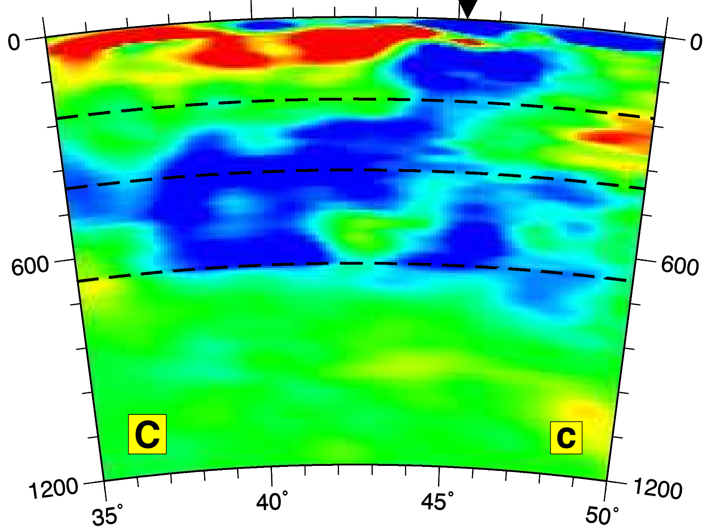


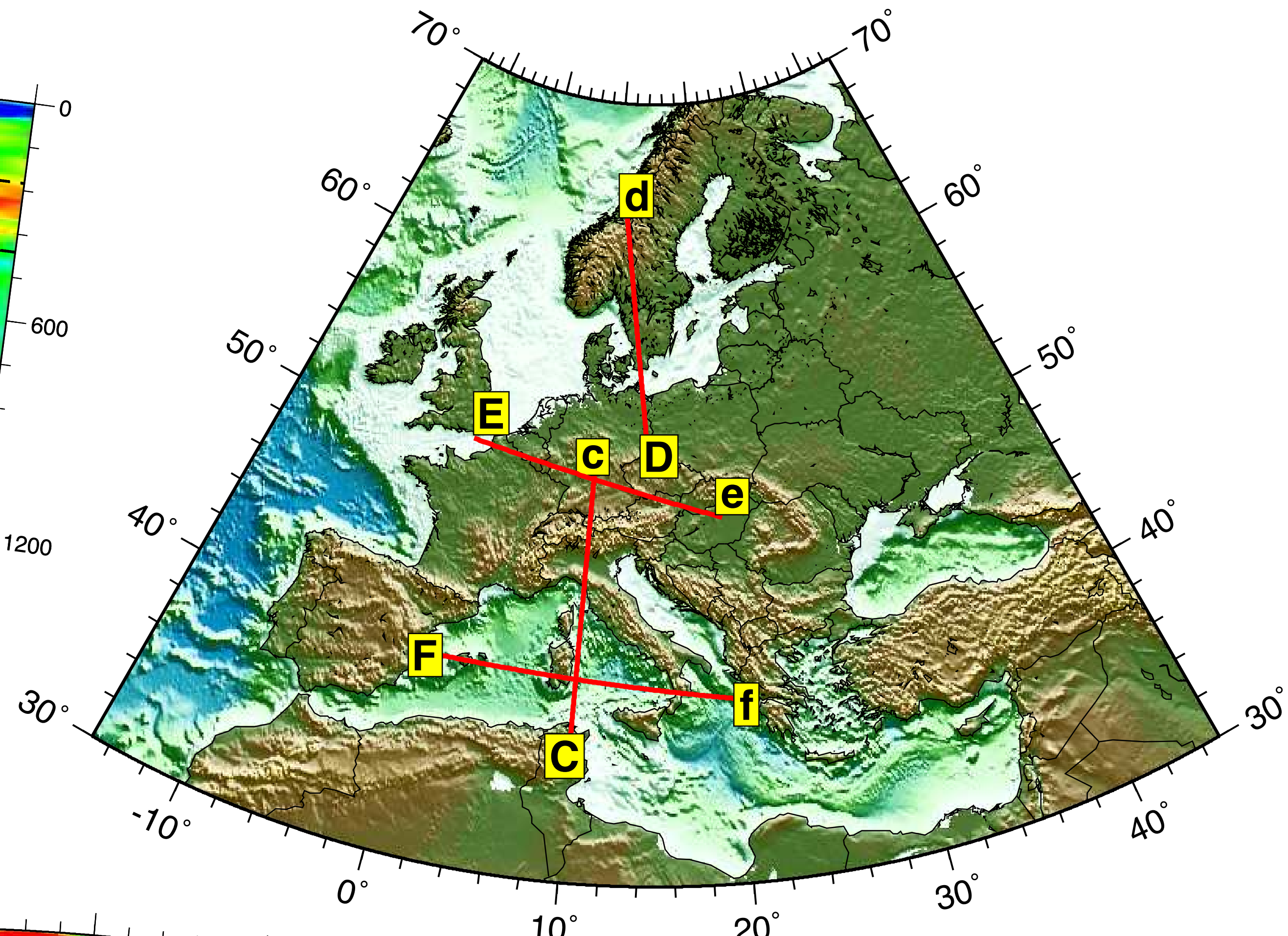


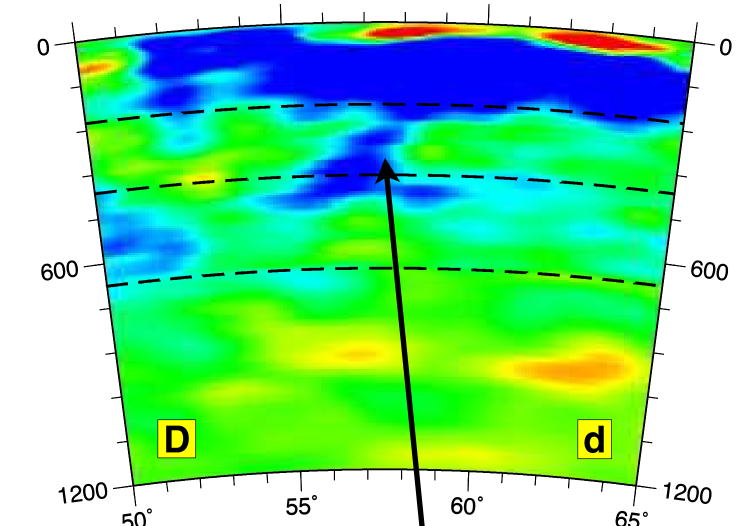


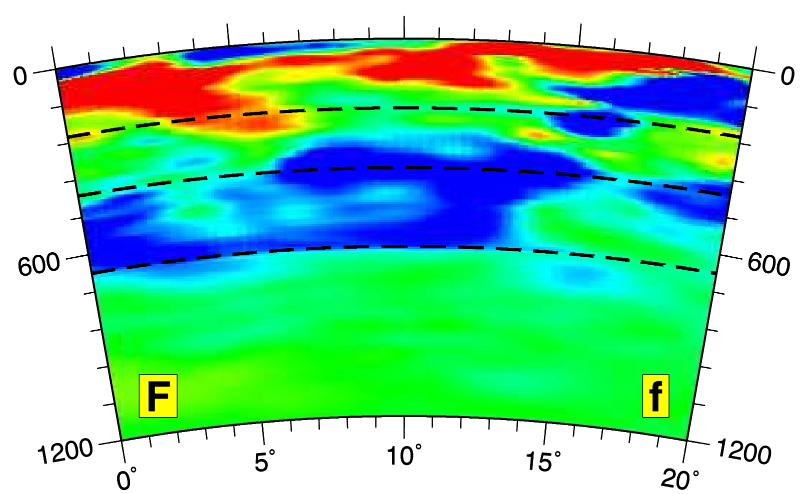
More cross sections











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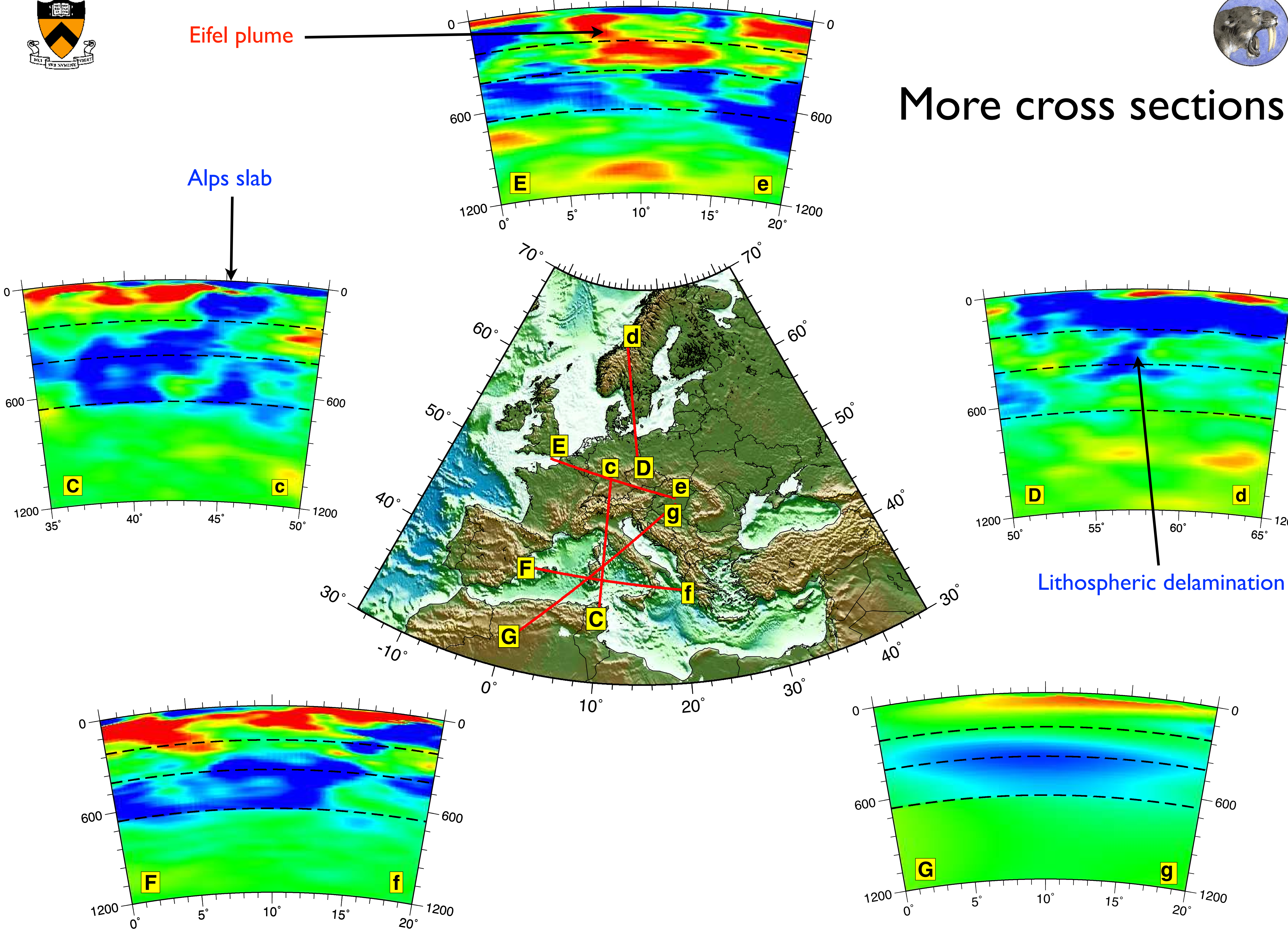

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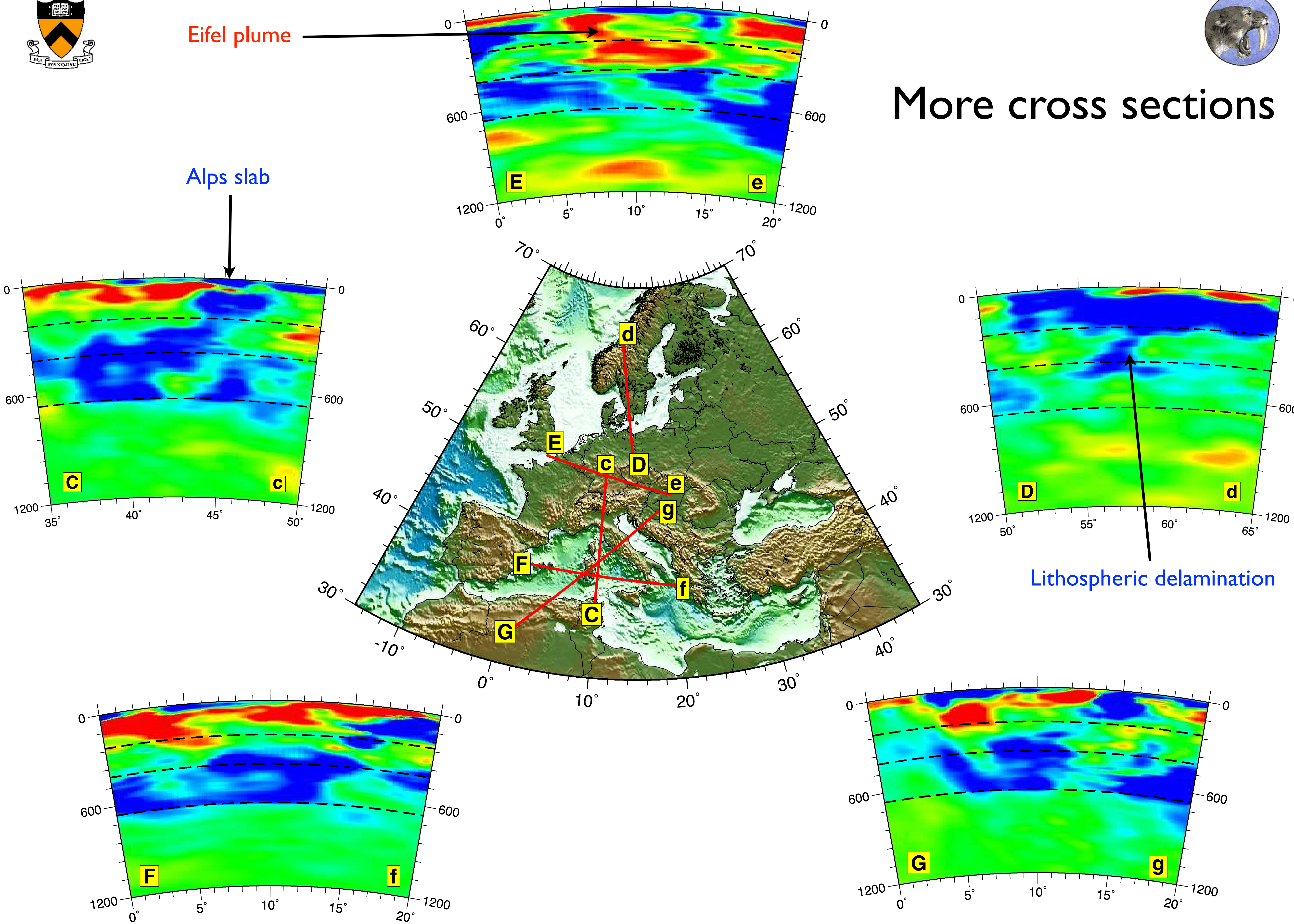

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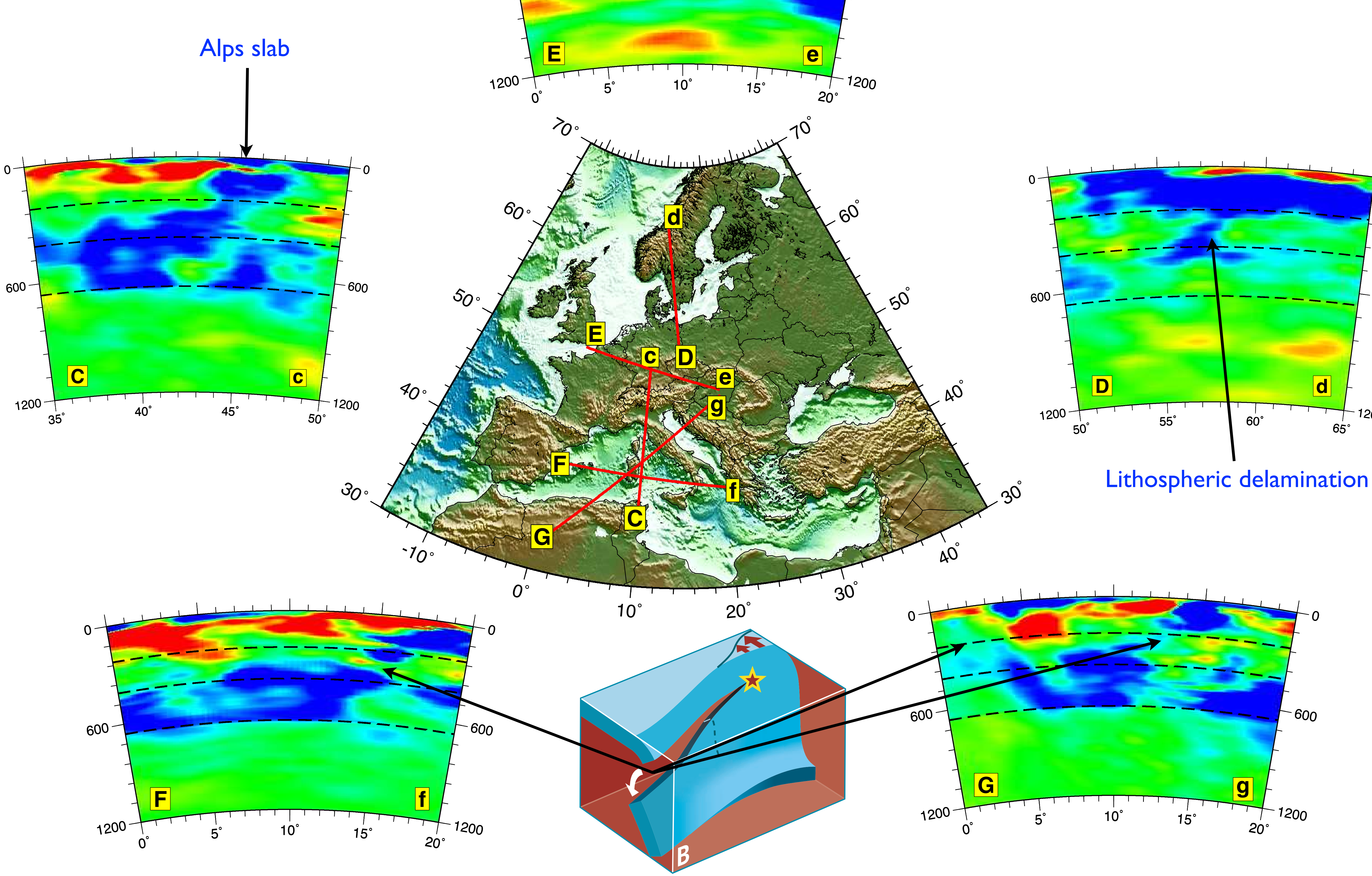
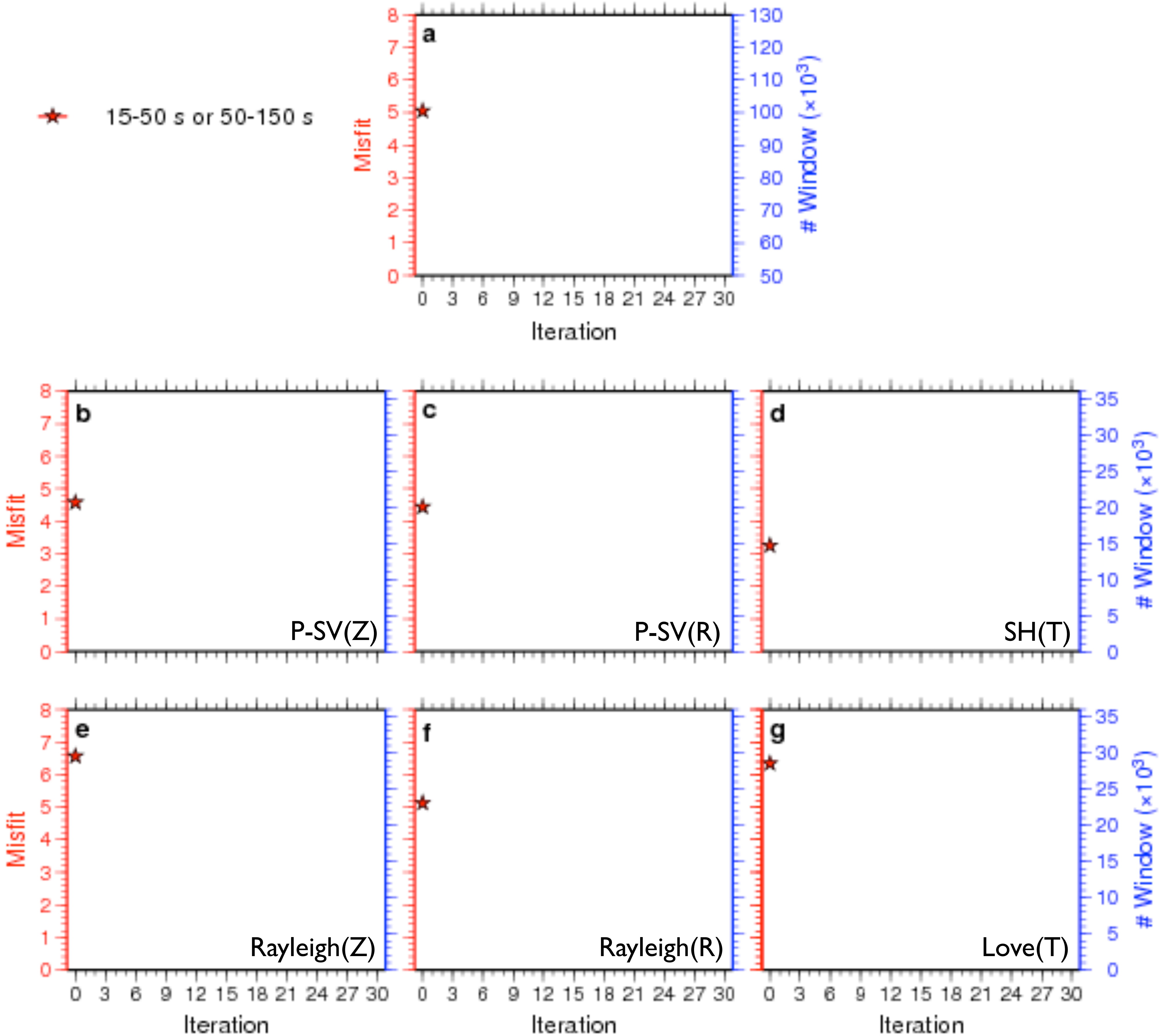
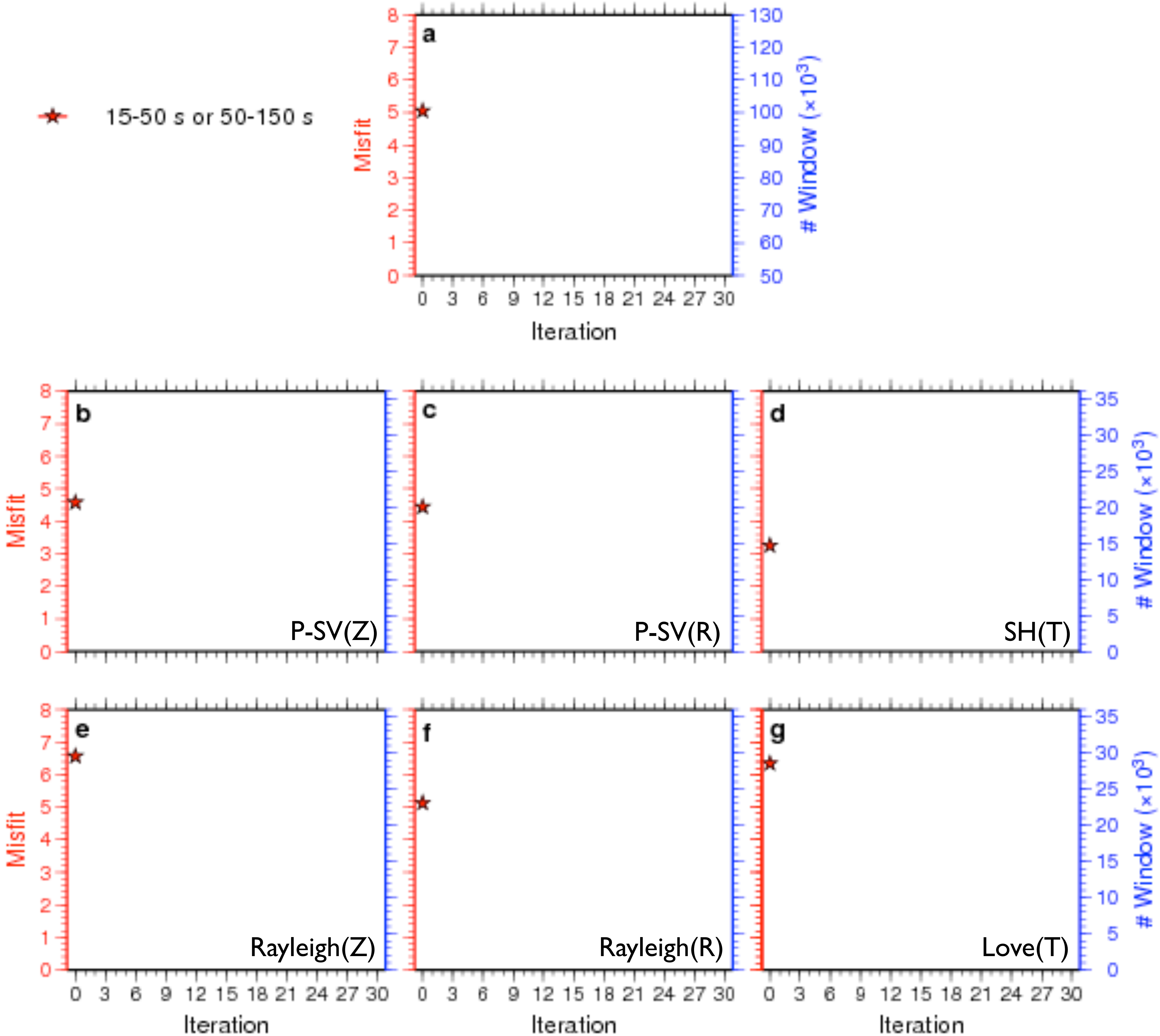


Misfit functions



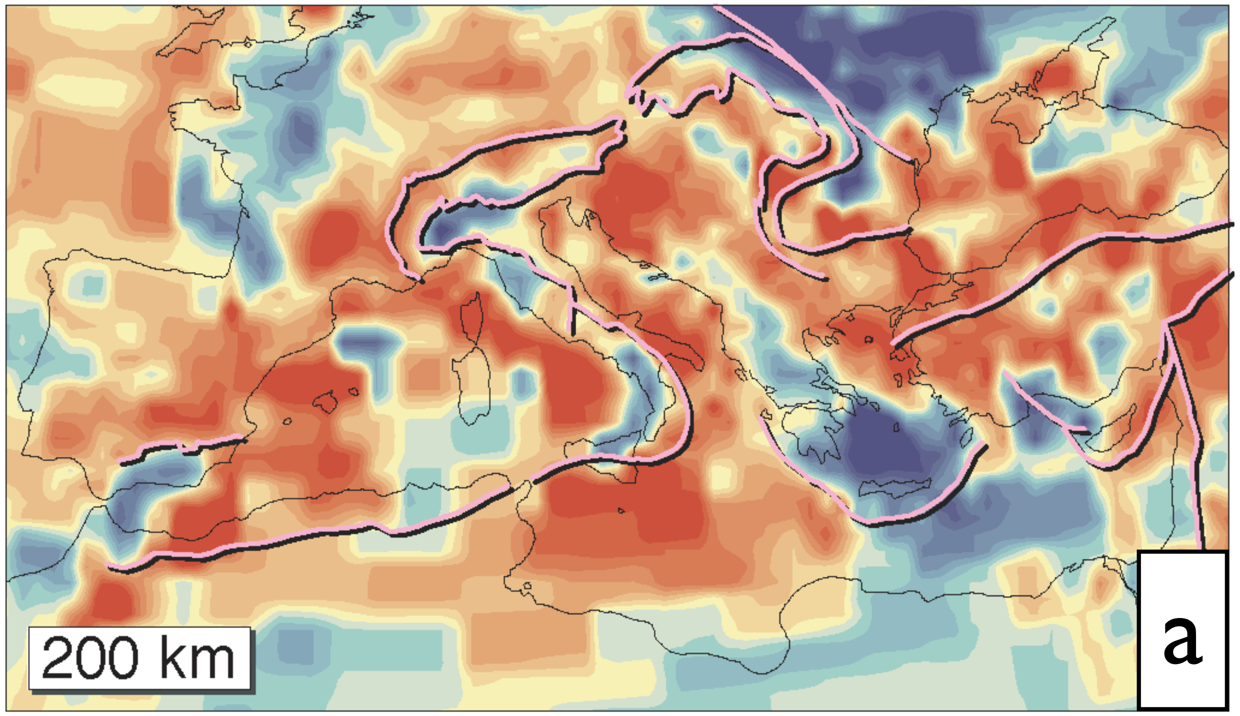
Misfit functions



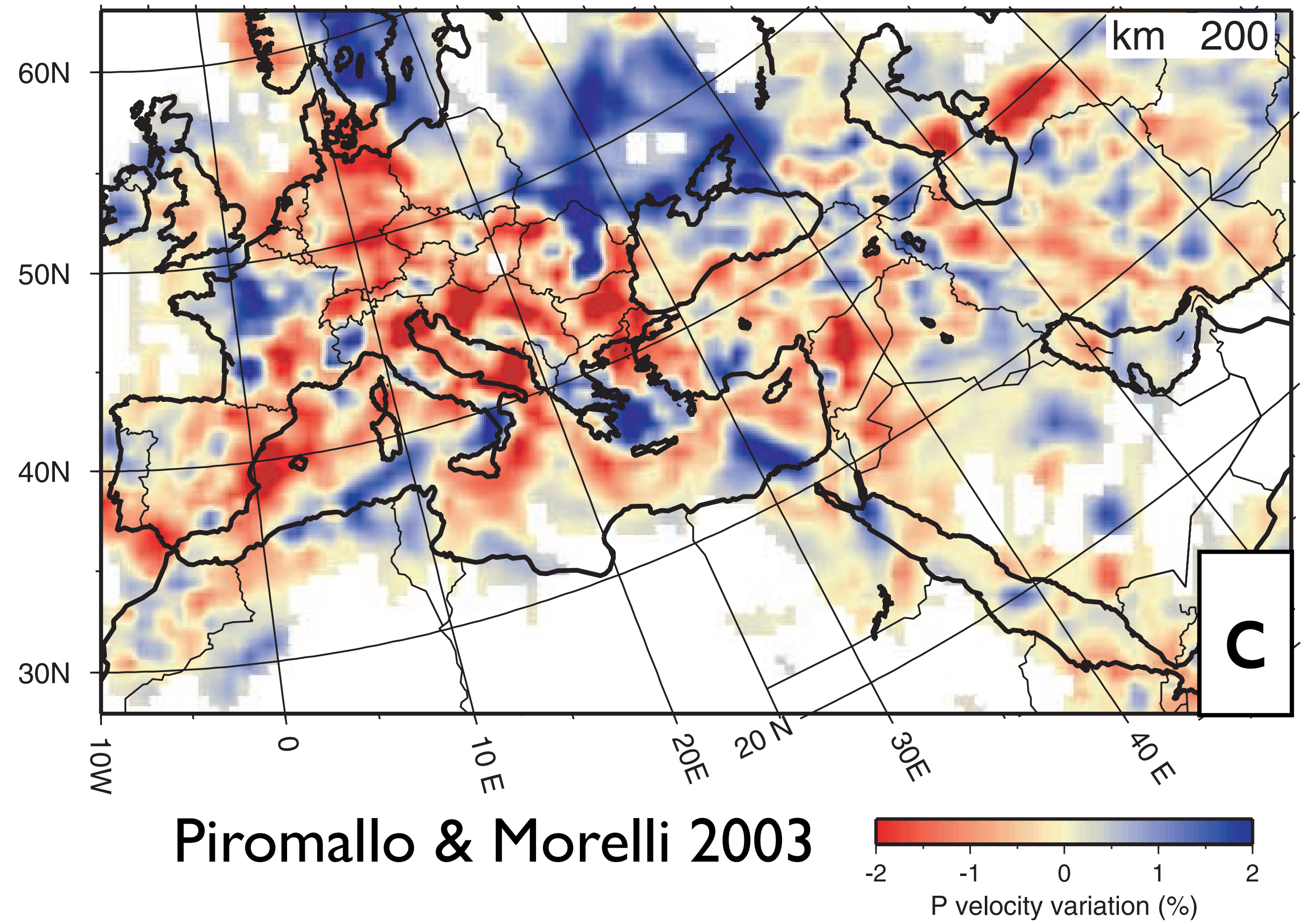
Model Comparisons, not easy !

1. Body waves versus Surface waves (blind men and an elephant)
2. 1D reference model (PREM versus IASP91 versus STW105)
3. Shear wave versus Compressional wave (apple versus orange)
4. Color scheme

Model Comparisons I (horizontal)

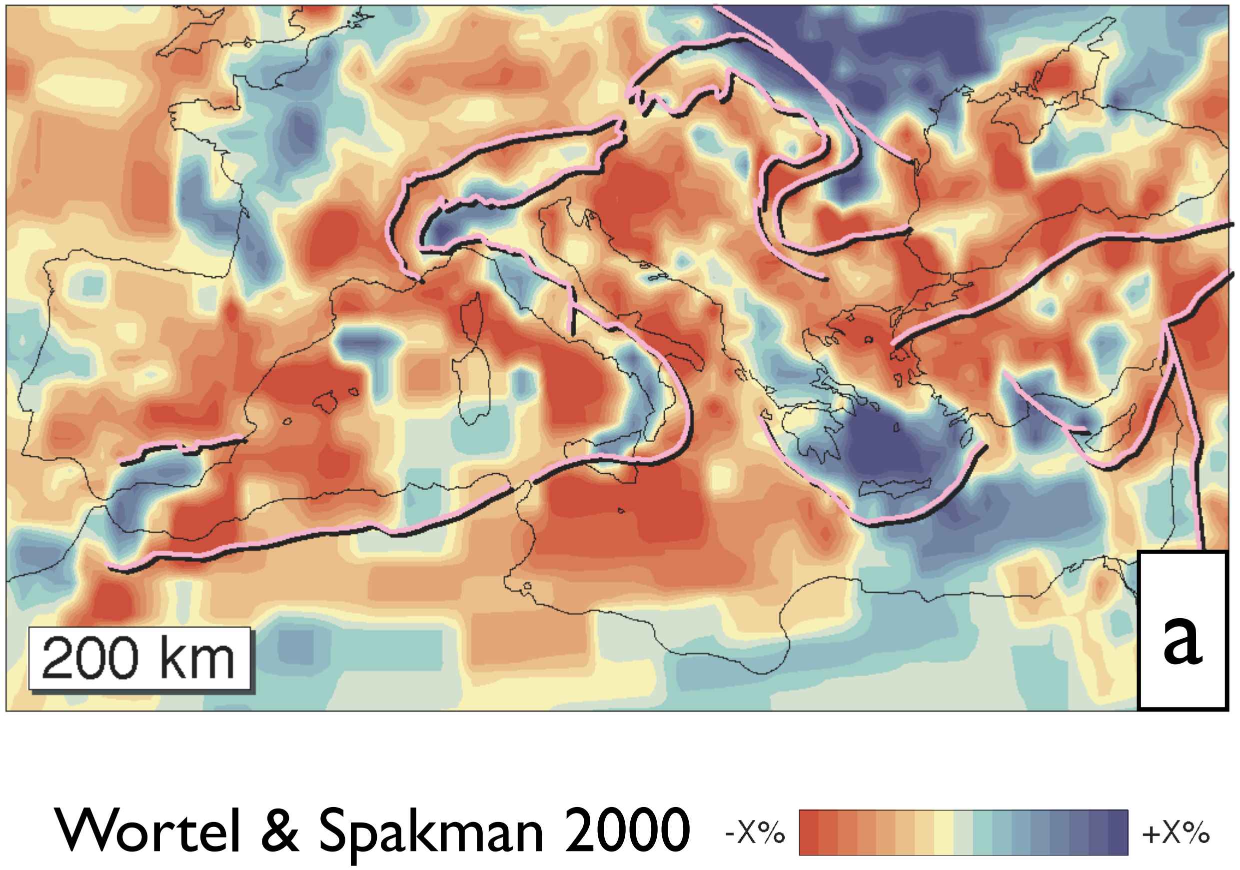


Wortel & Spakman 2000



Piromallo & Morelli 2003

Model Comparisons I (horizontal)



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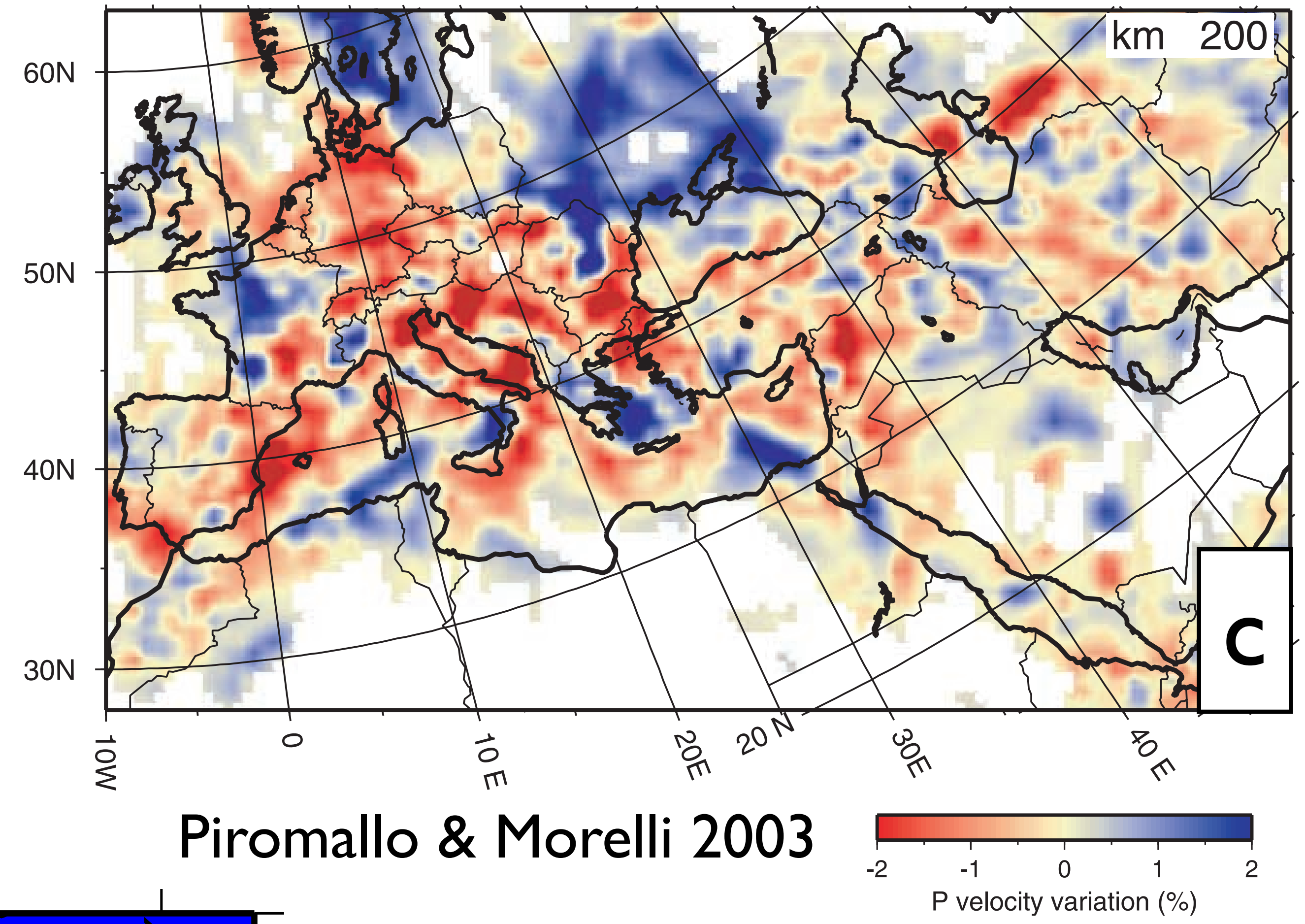
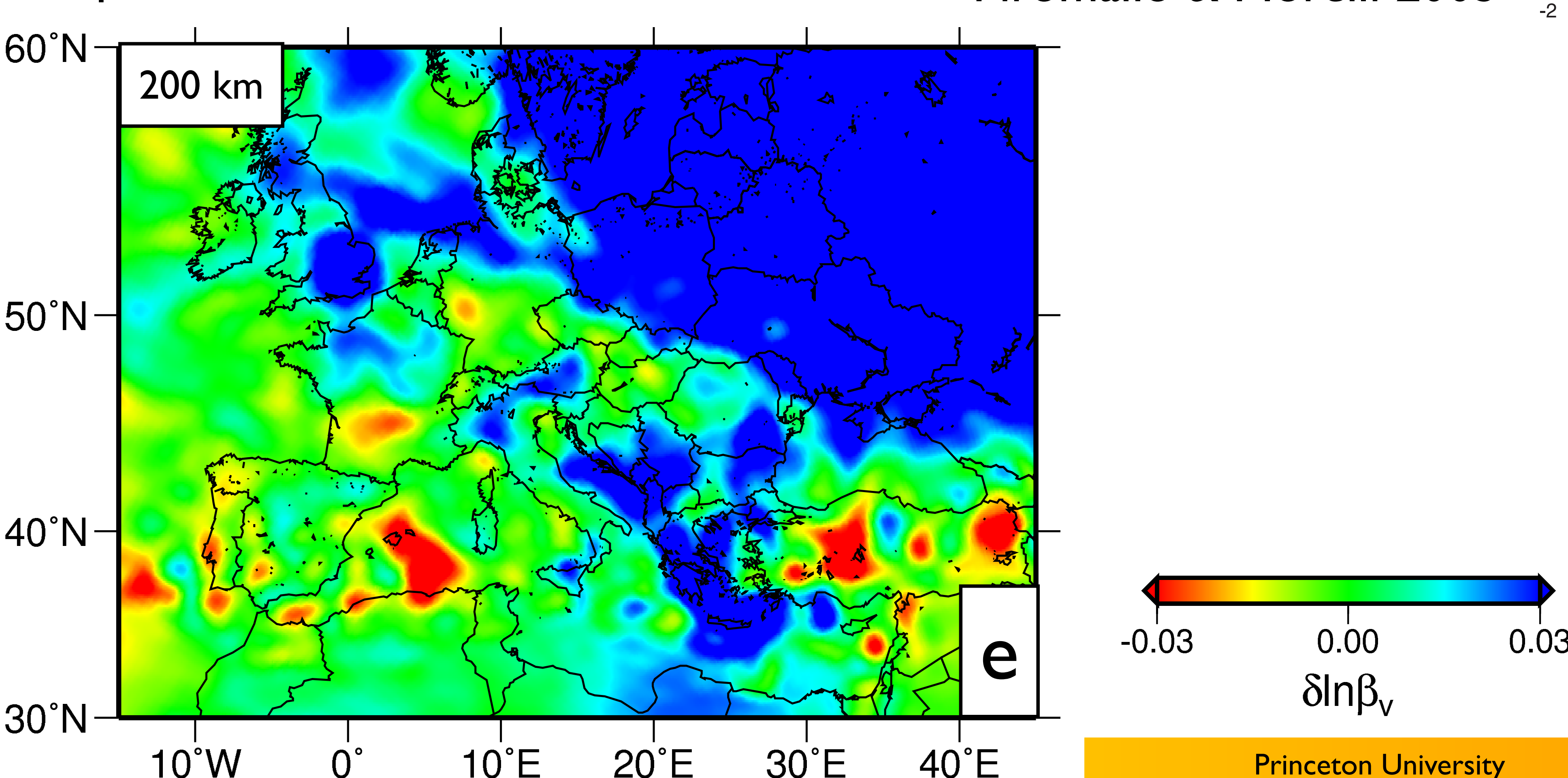


Piromallo & Morelli 2003



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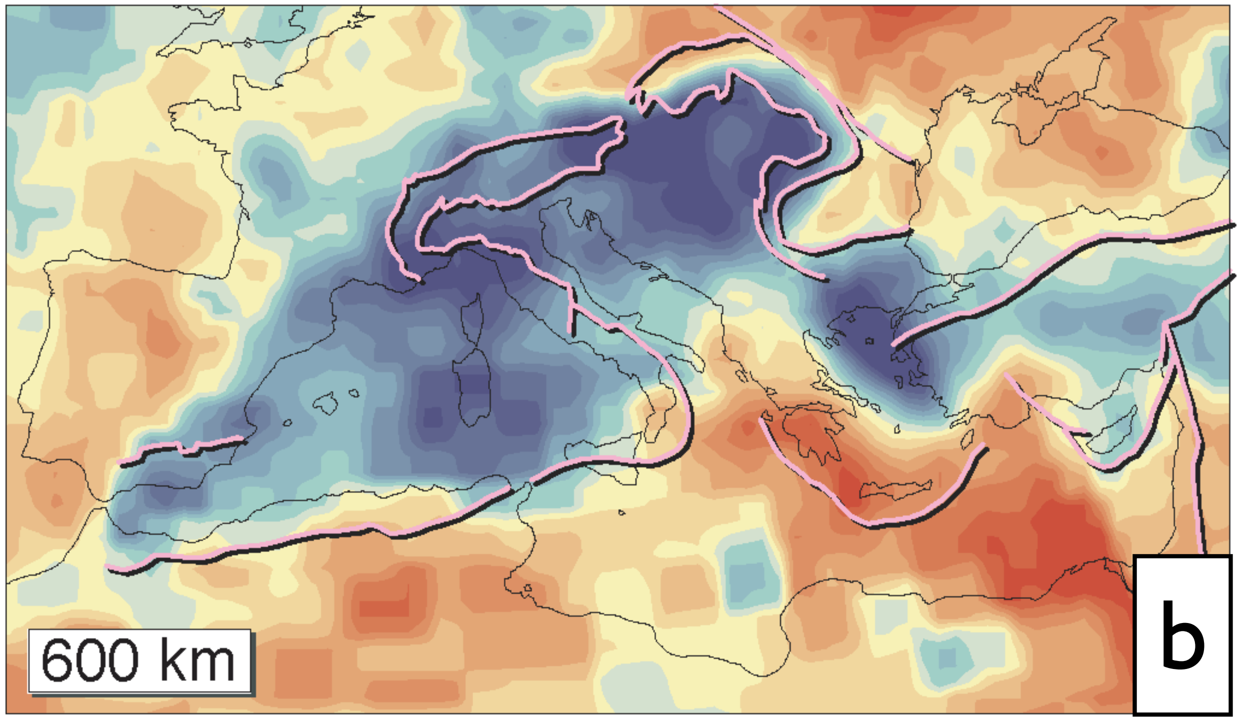

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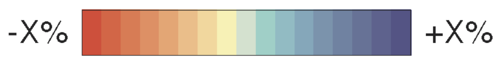
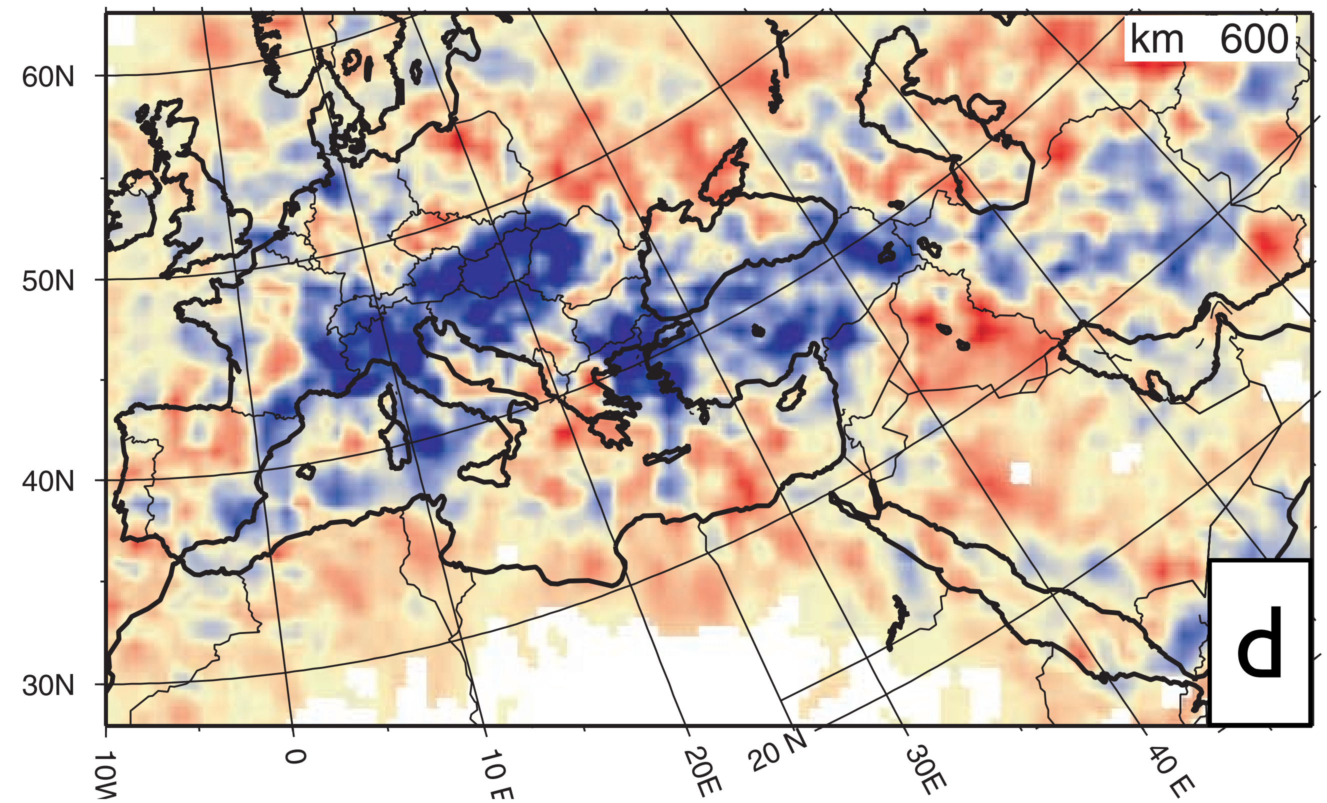
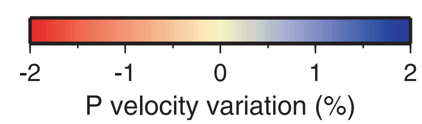
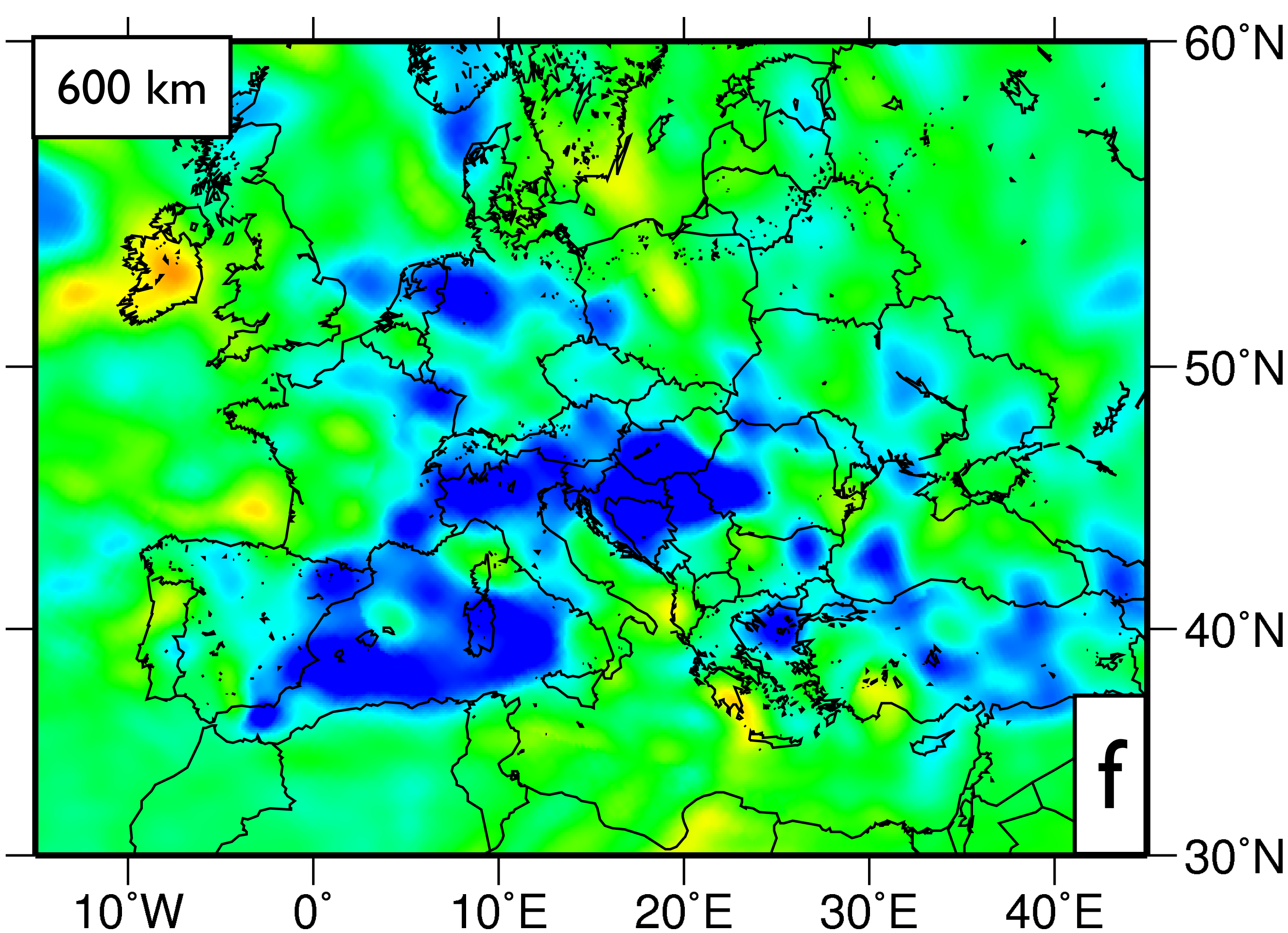
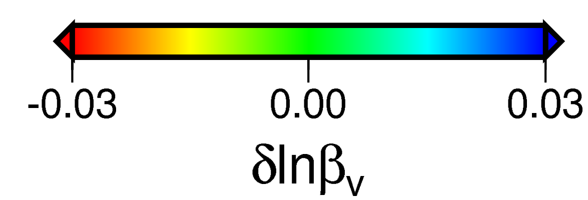




Piromallo & Morelli 2003

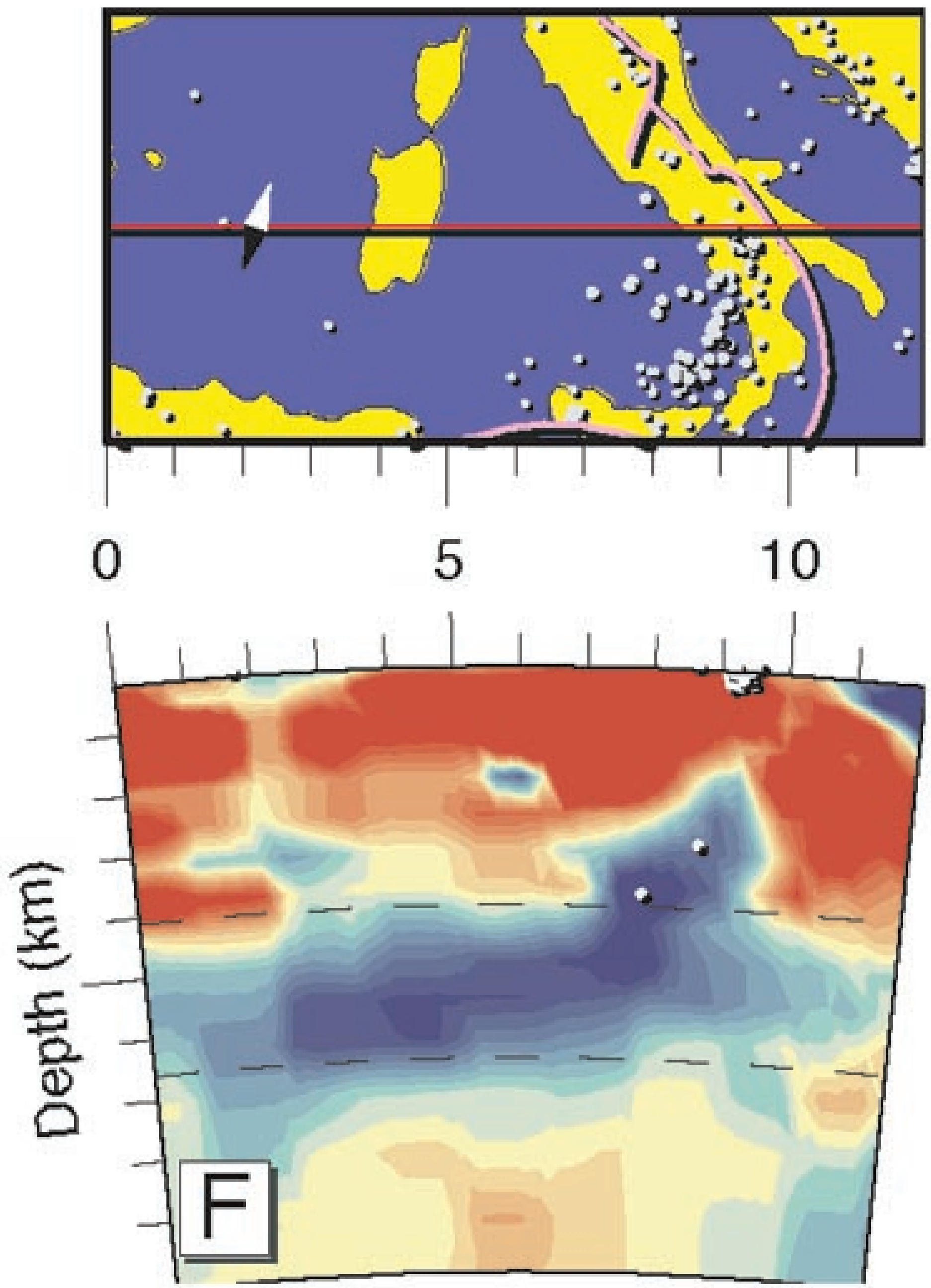


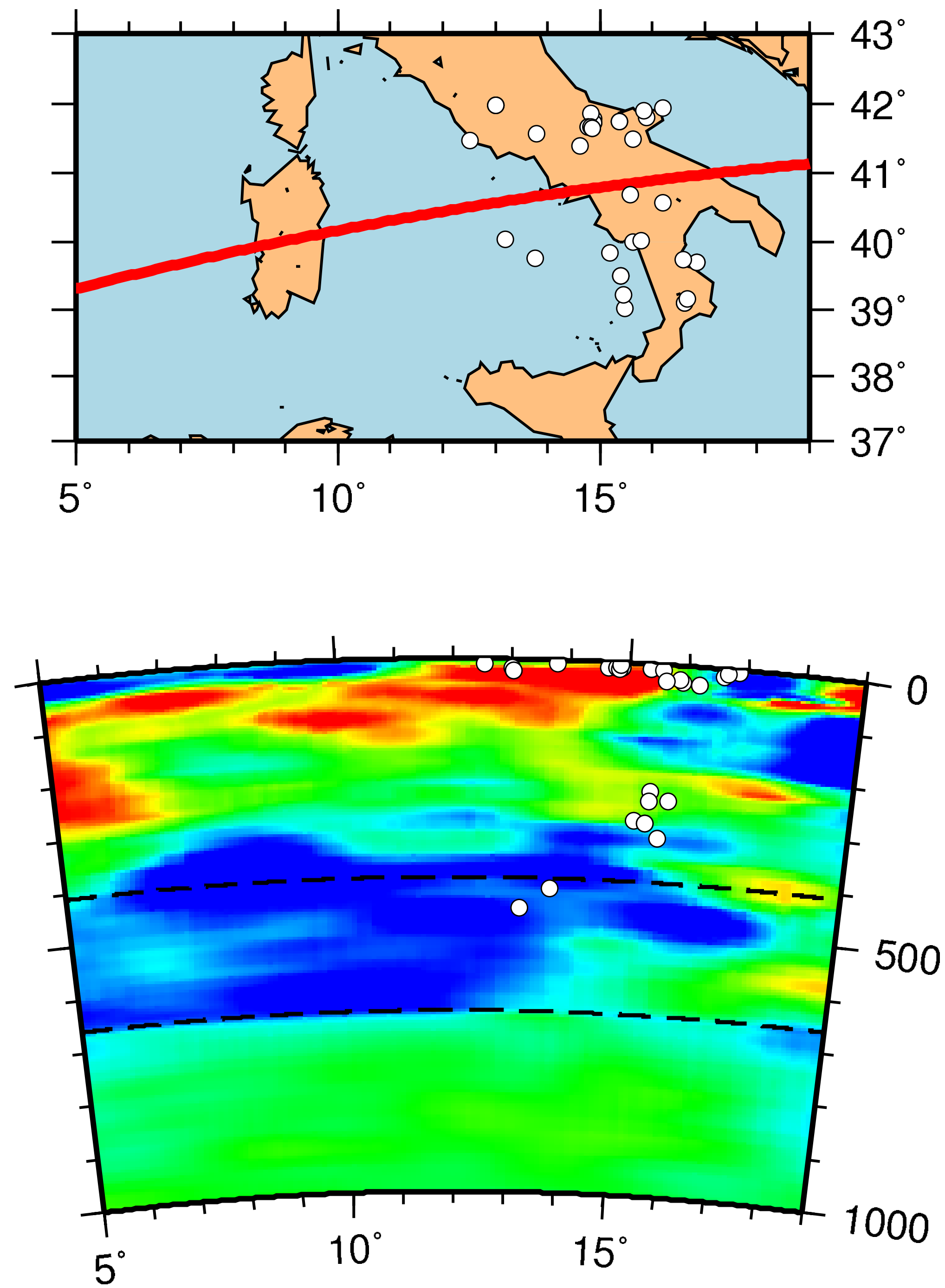




Model Comparisons II (slab detachment)

Wortel & Spakman 2000

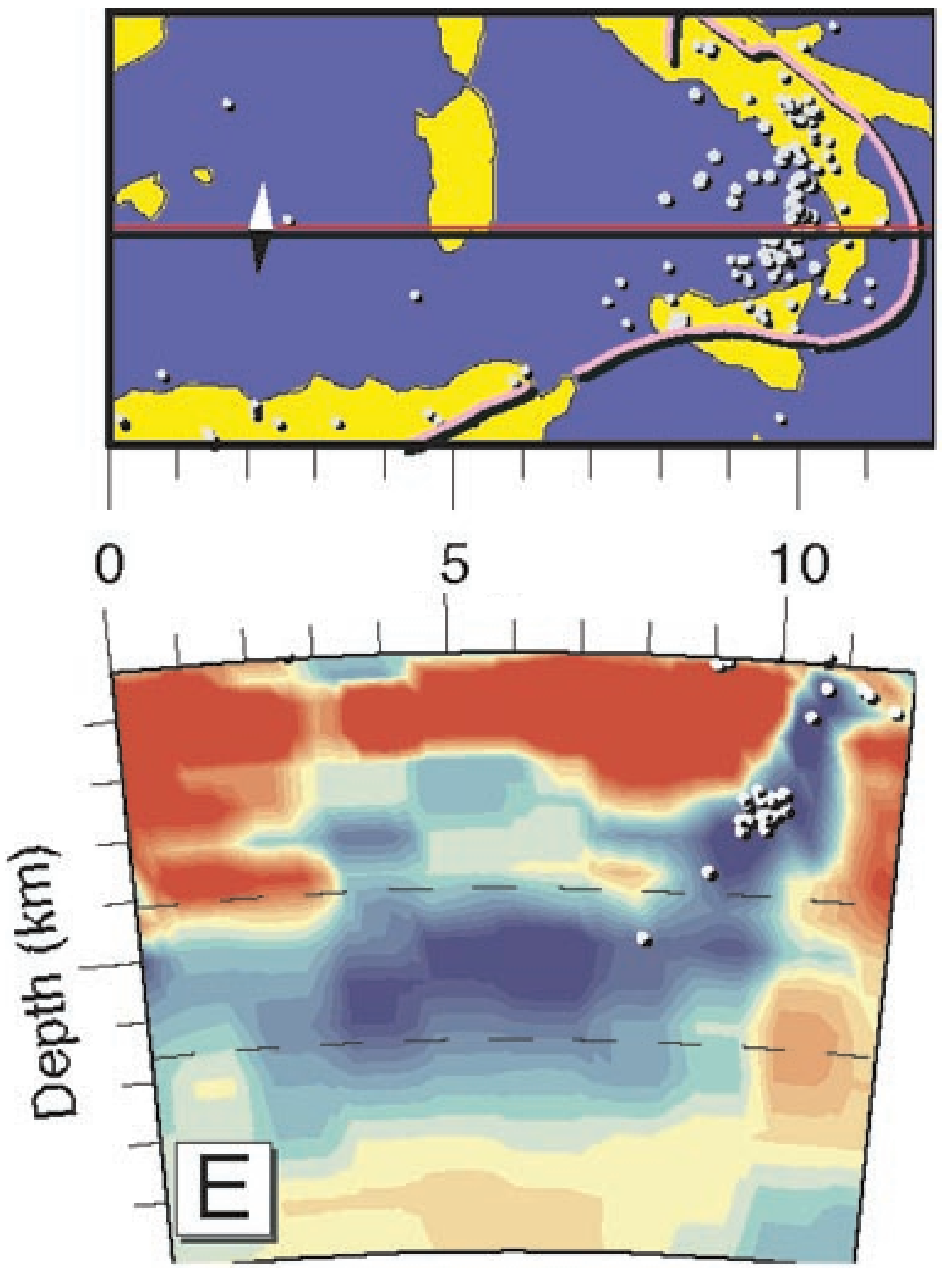


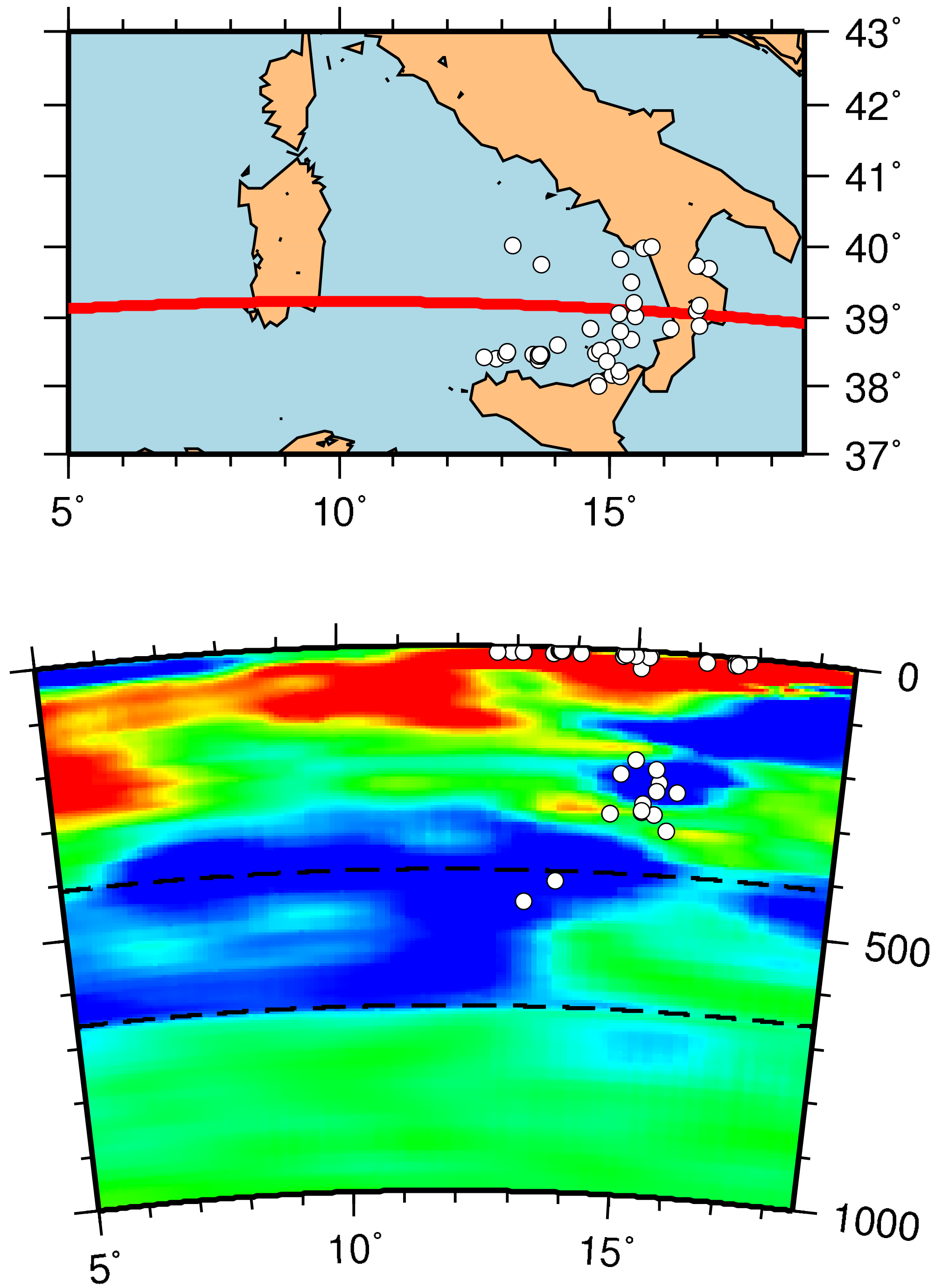


http://www.bo.ingv.it/RCMT/searchRCMT.html

Model Comparisons II (slab detachment)

Wortel & Spakman 2000





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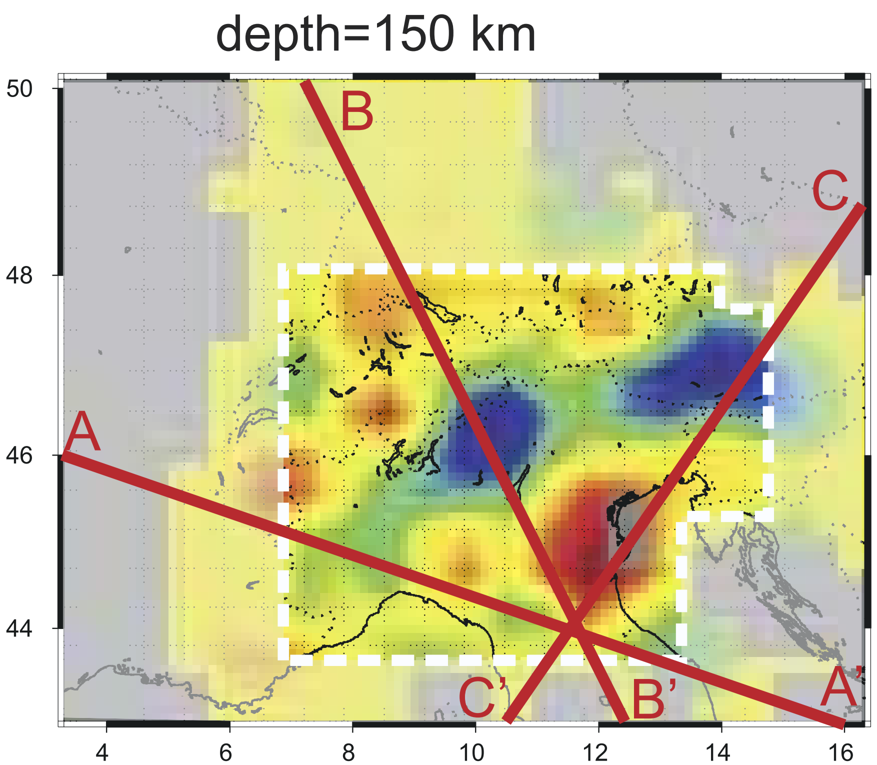
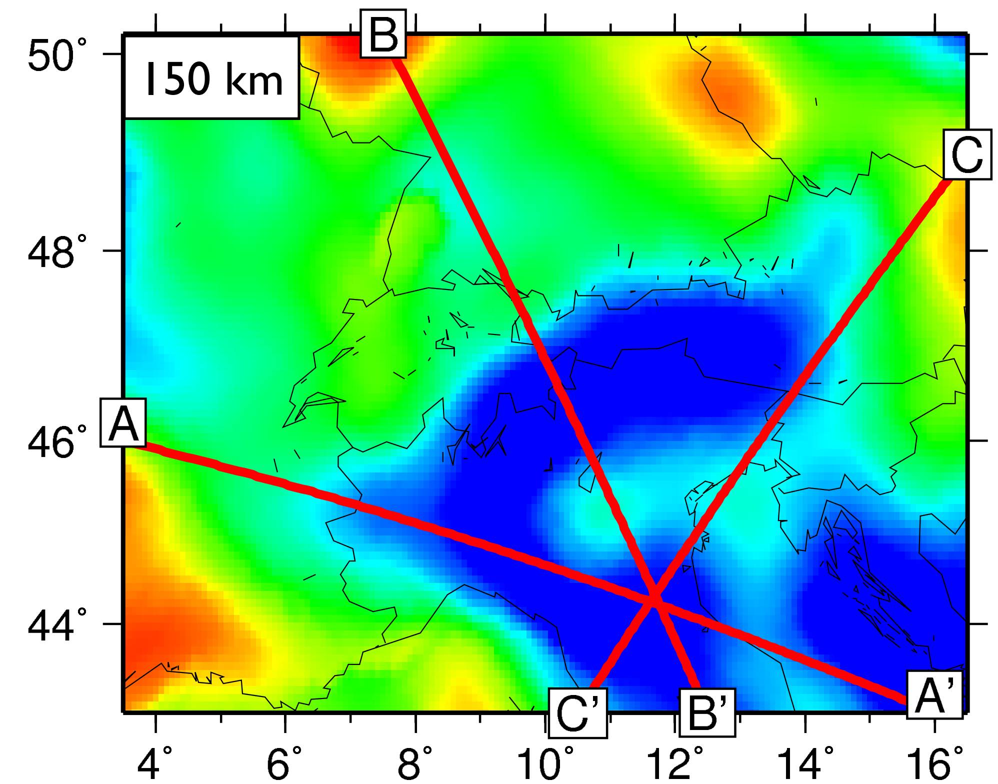
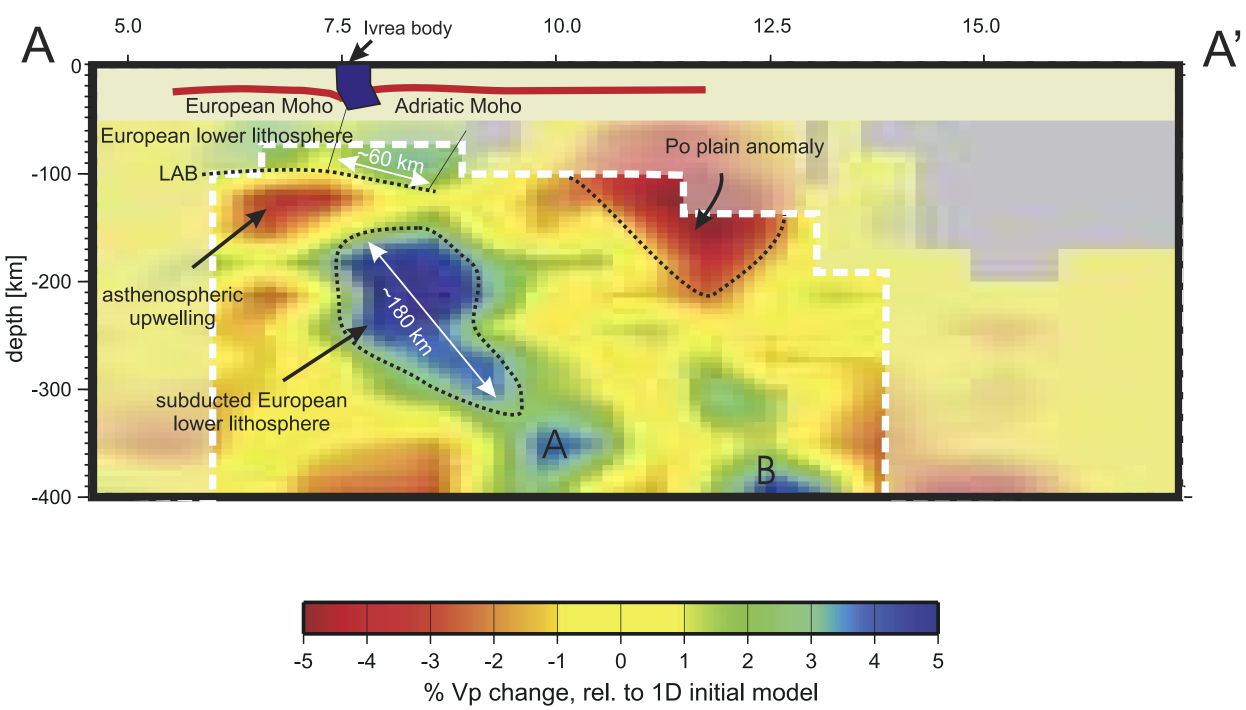
Model Comparisons III (Alps)

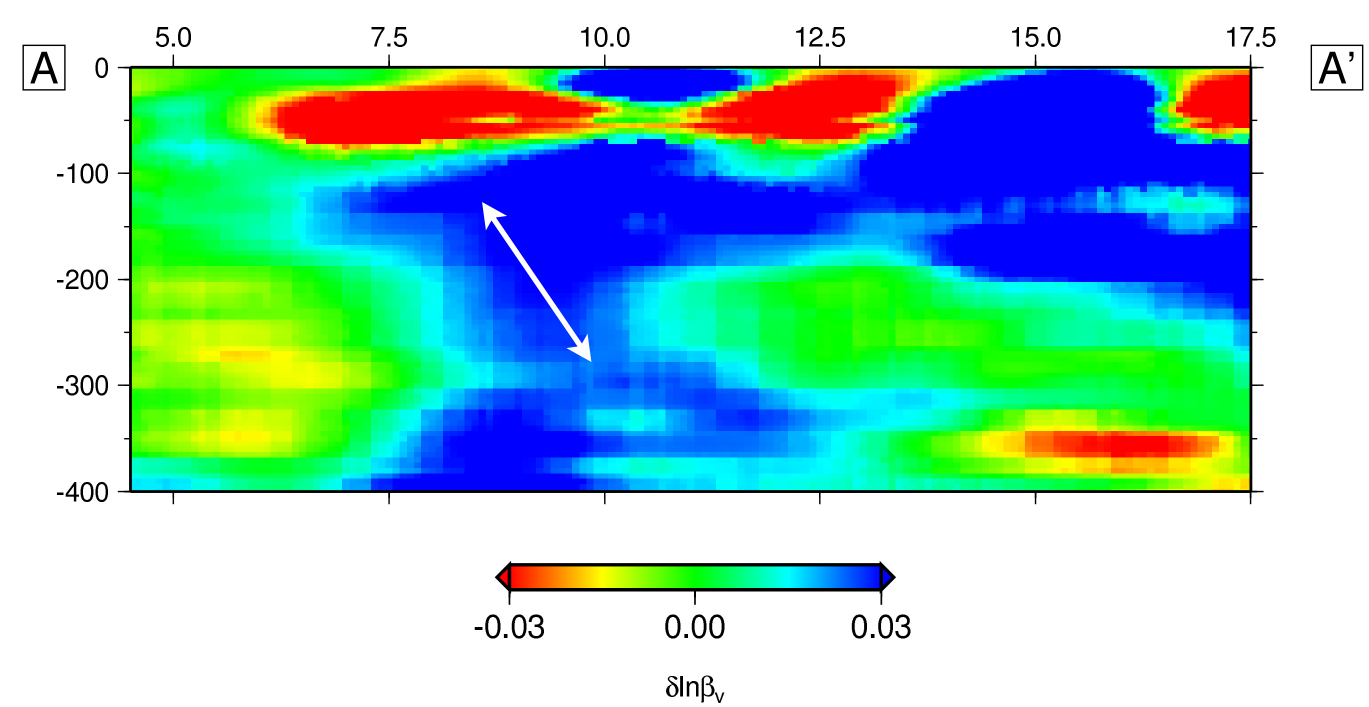
Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography

Regina Lippitsch, Edi Kissling, and Jörg Ansorge
Institute of Geophysics, Swiss Federal Institute of Technology, ETH Hönggerberg, Zürich, Switzerland









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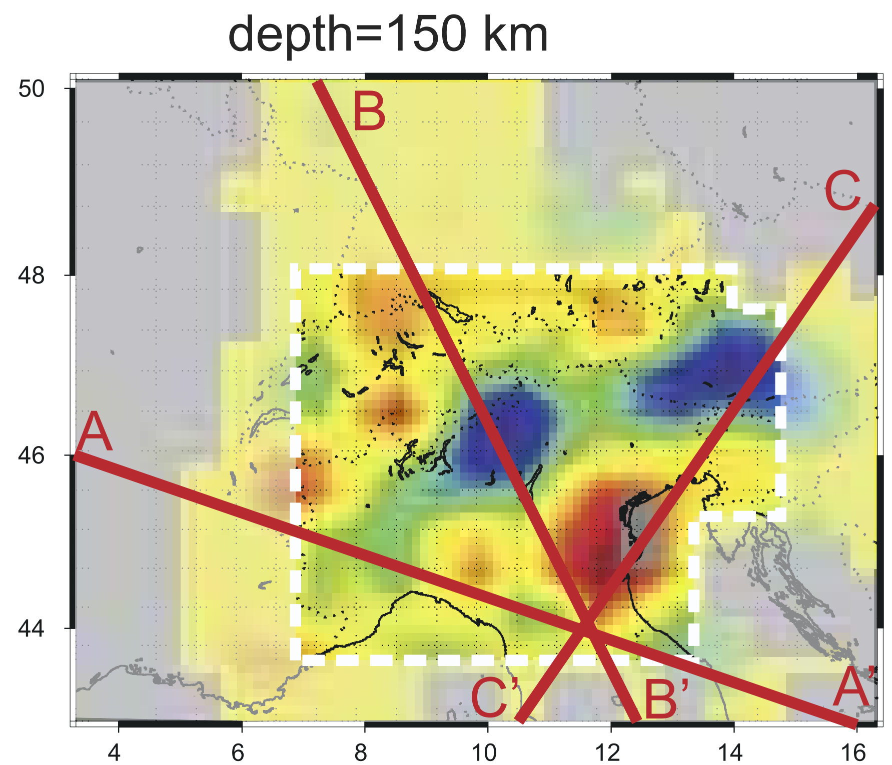

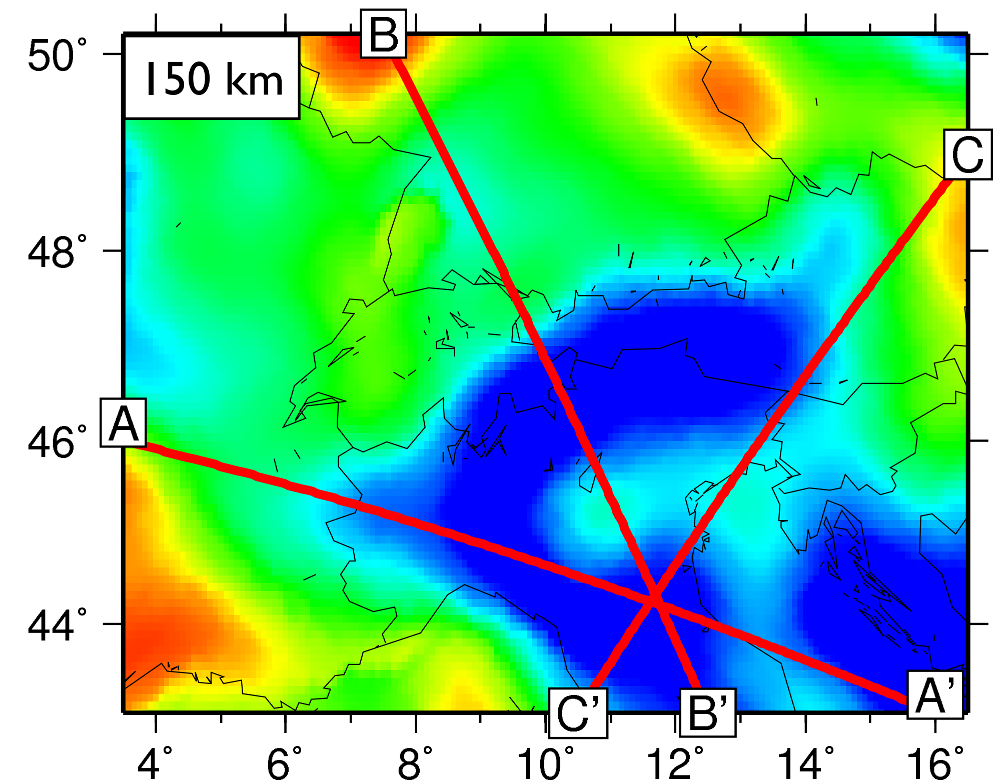

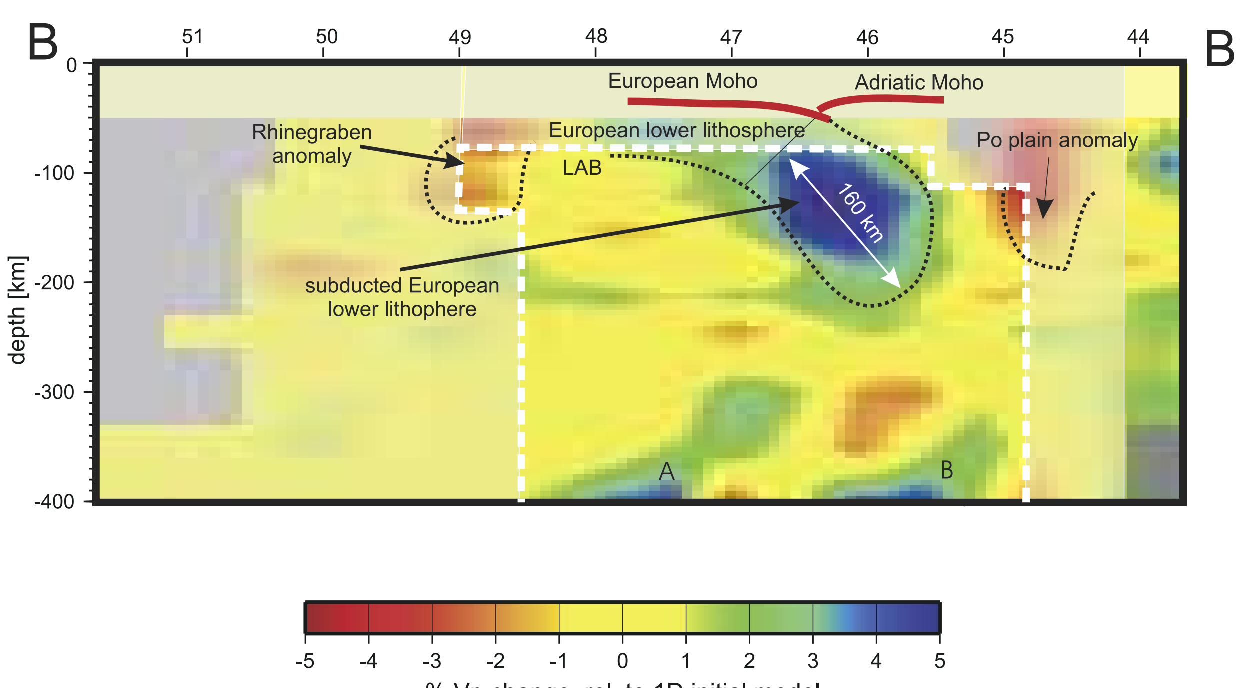

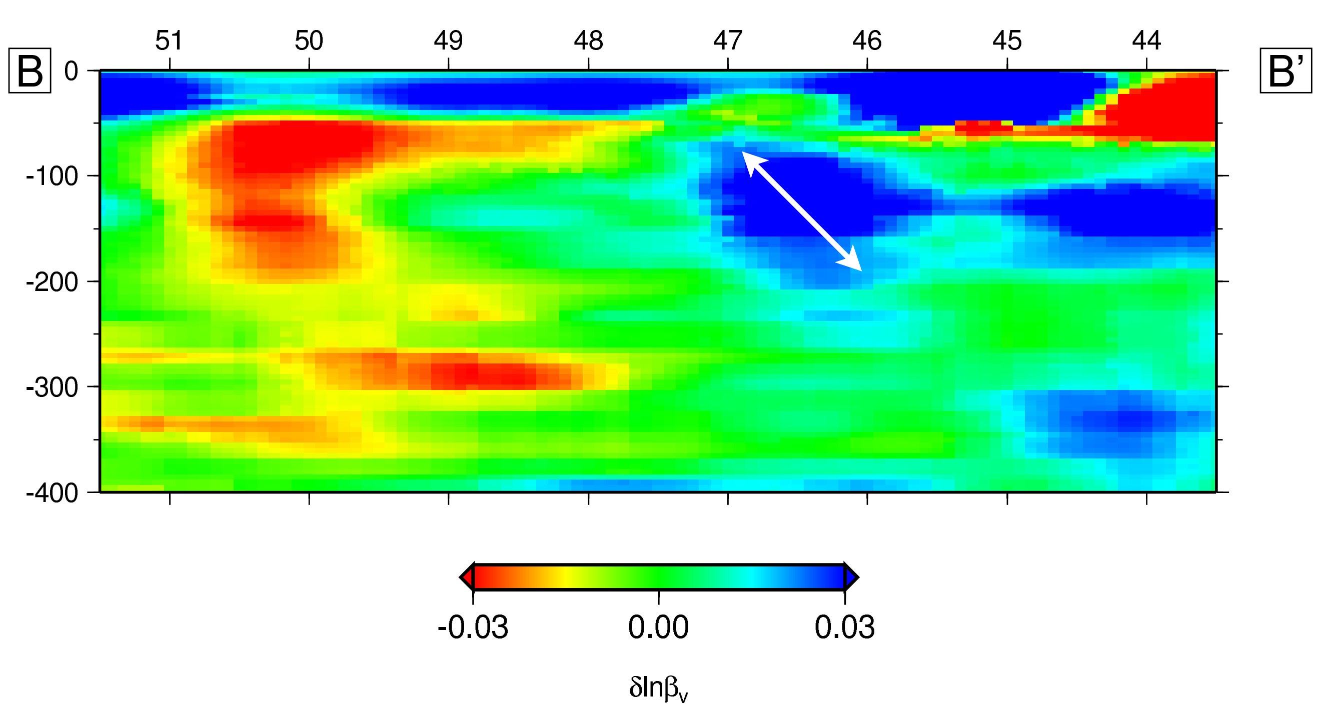

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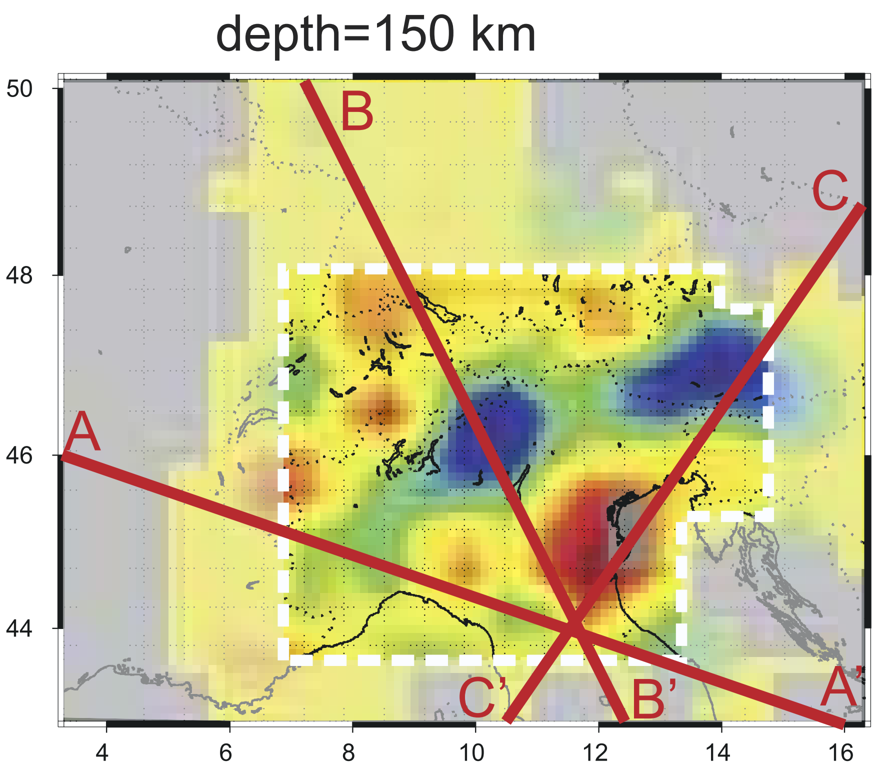
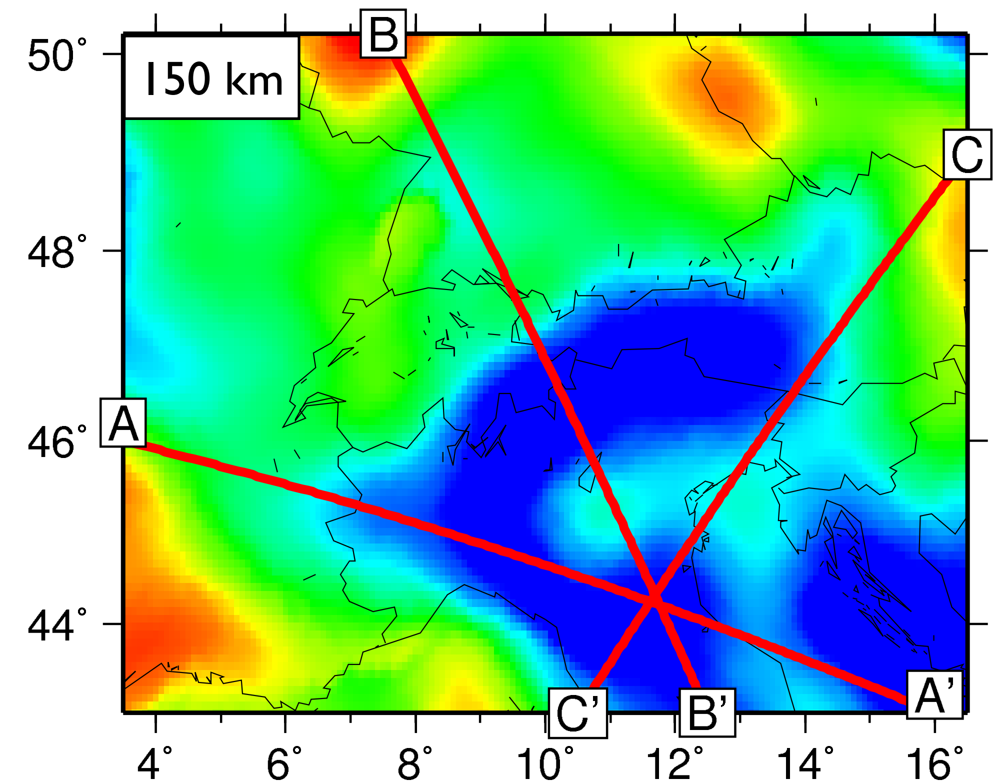
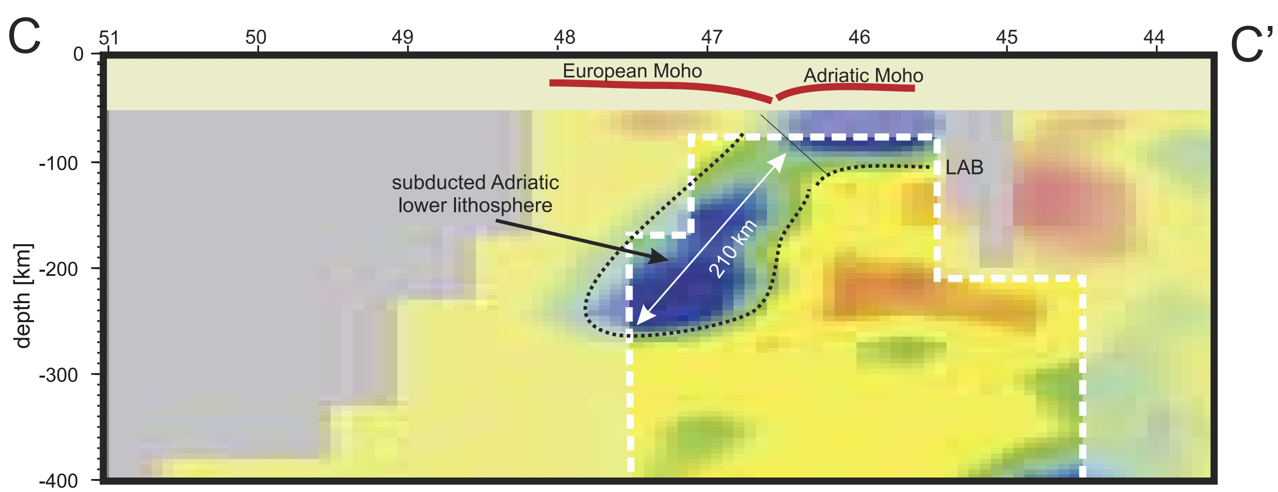
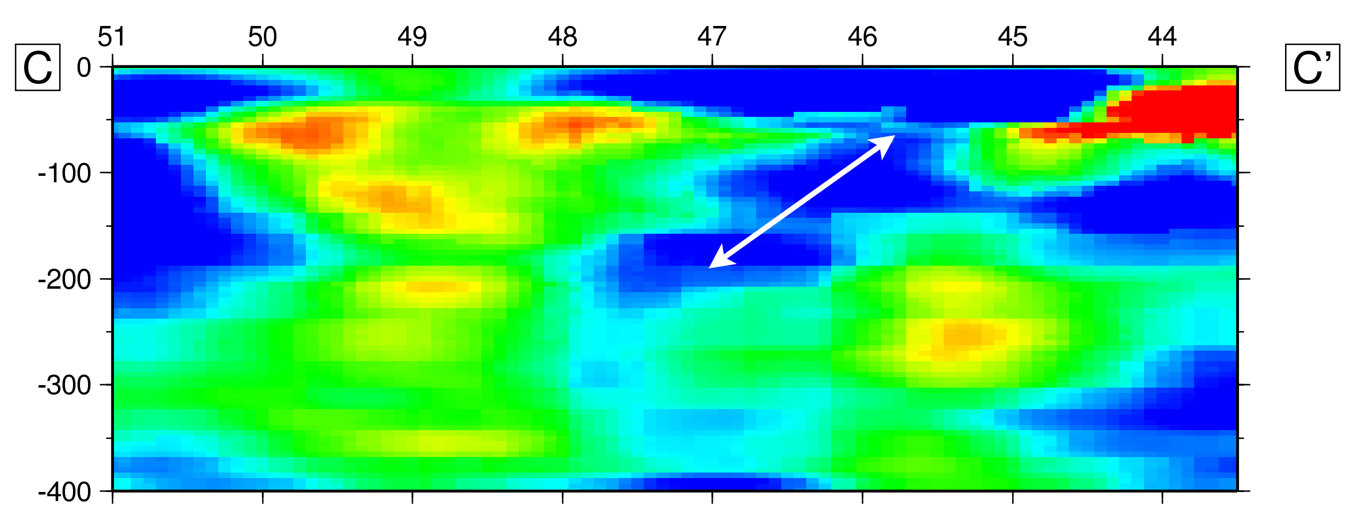
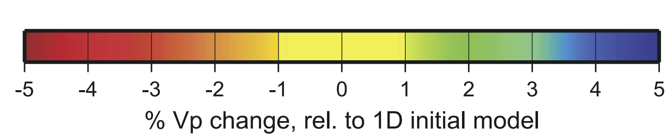
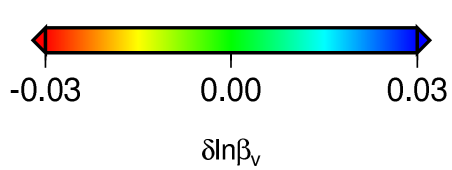








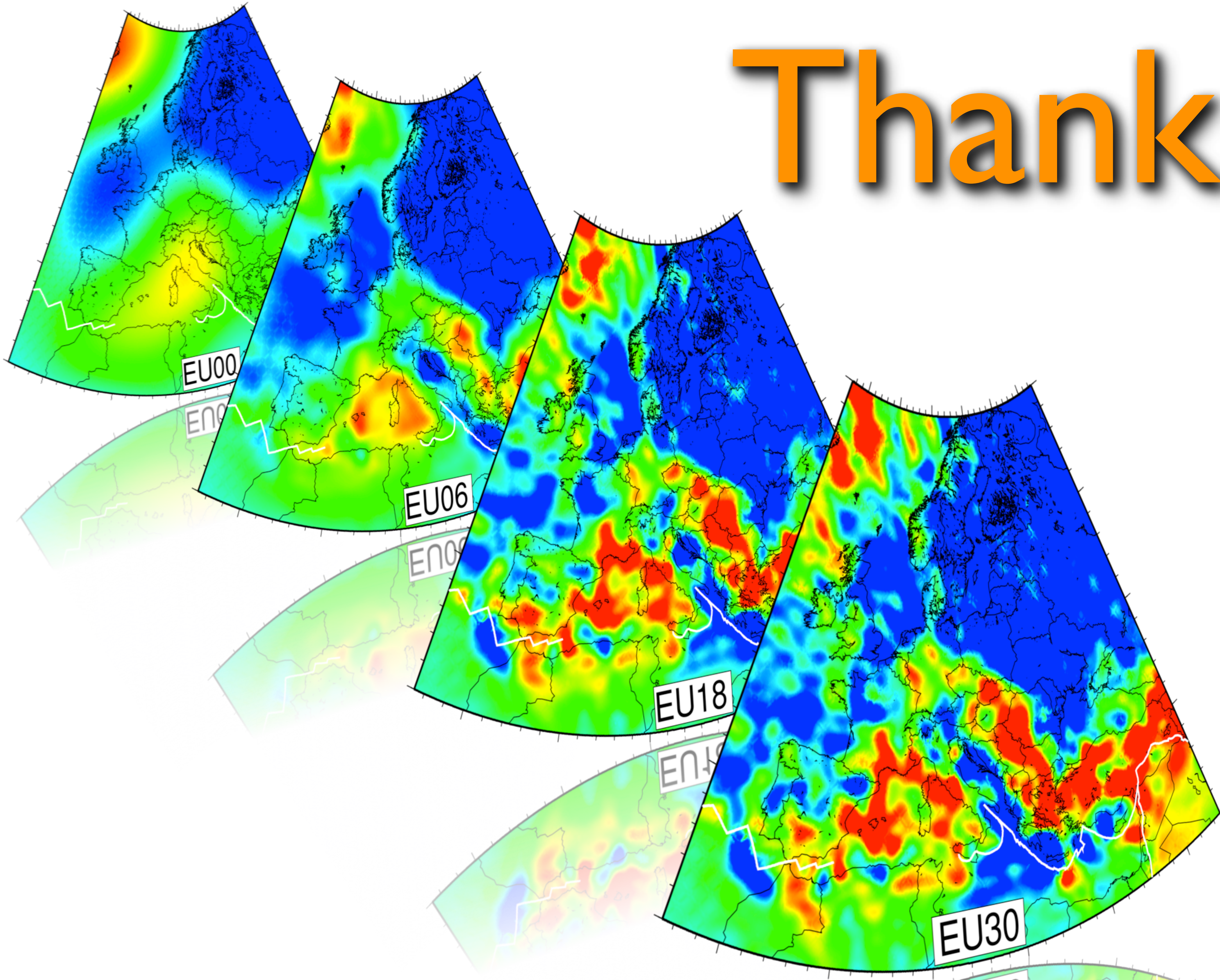




Conclusion

- ✓ 3D starting models + 3D forward simulations (Spectral-Element method) + 3D Fréchet derivatives (Adjoint method)
- ✓ Many interesting structures naturally emerge from the smooth background model
- ✓ Bridging the gap between high-resolution body-wave tomography and lower resolution inversions based on long period body waves, surface waves and free oscillations
- ✓ Model comparisons is challenging but satisfactory

Thanks!



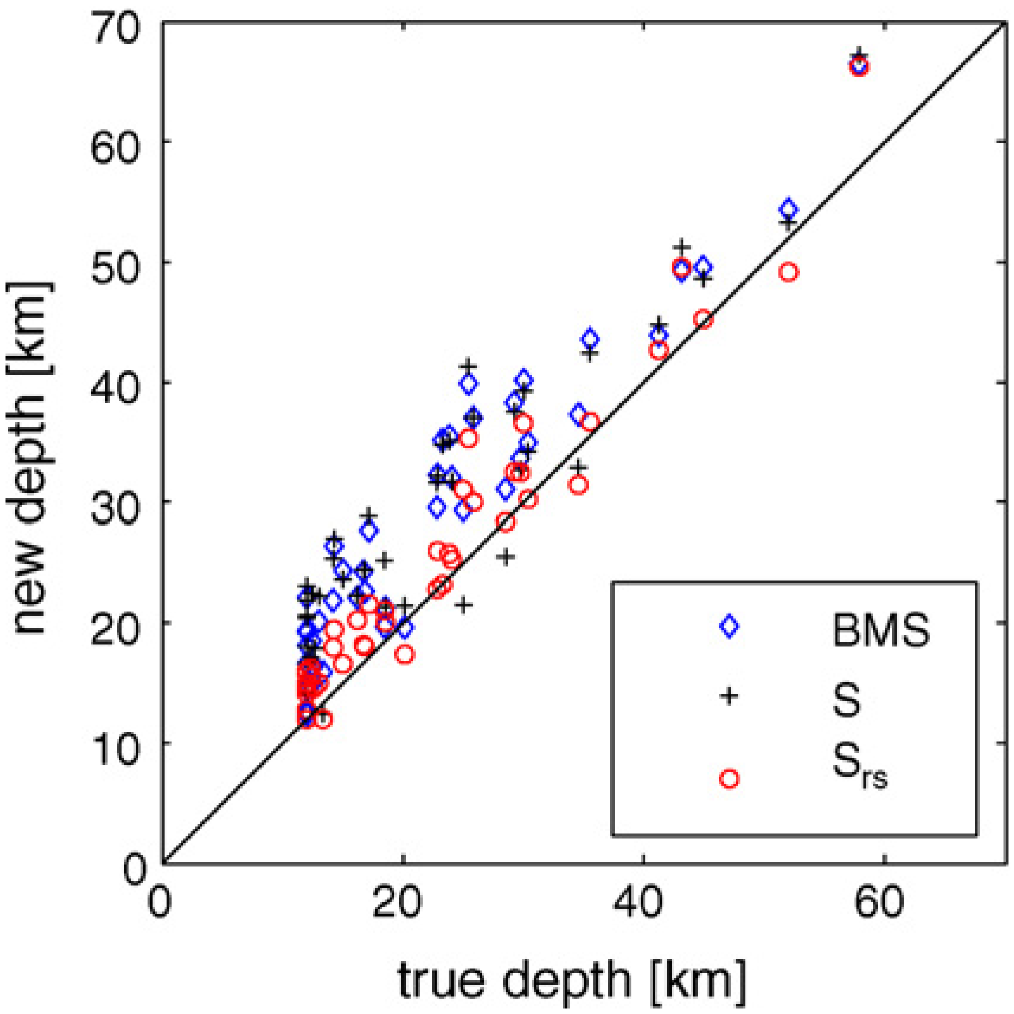
3D full waveform tomography era

Depth changes from source inversions

Effects of three-dimensional Earth structure on CMT earthquake parameters

Vala Hjörleifsdóttir*, Göran Ekström

Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, Palisades, NY 10964, USA



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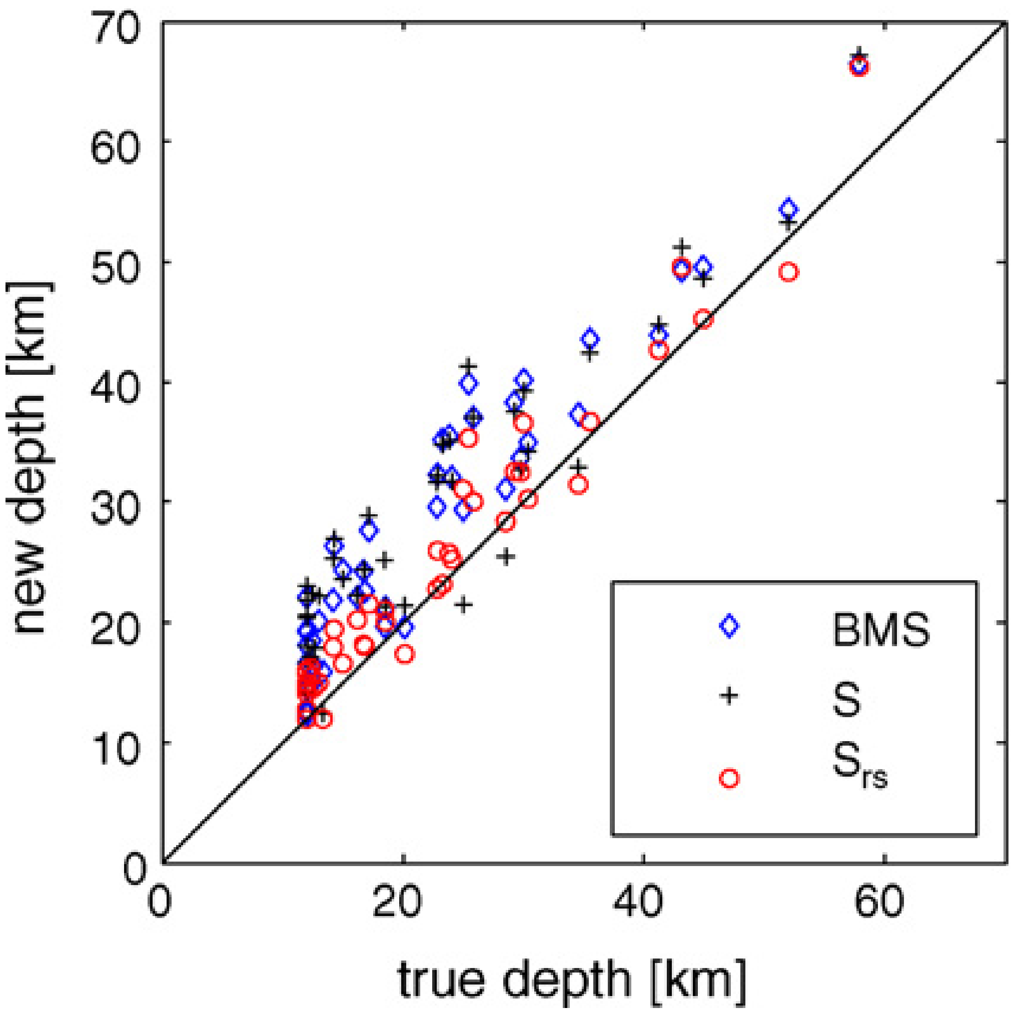

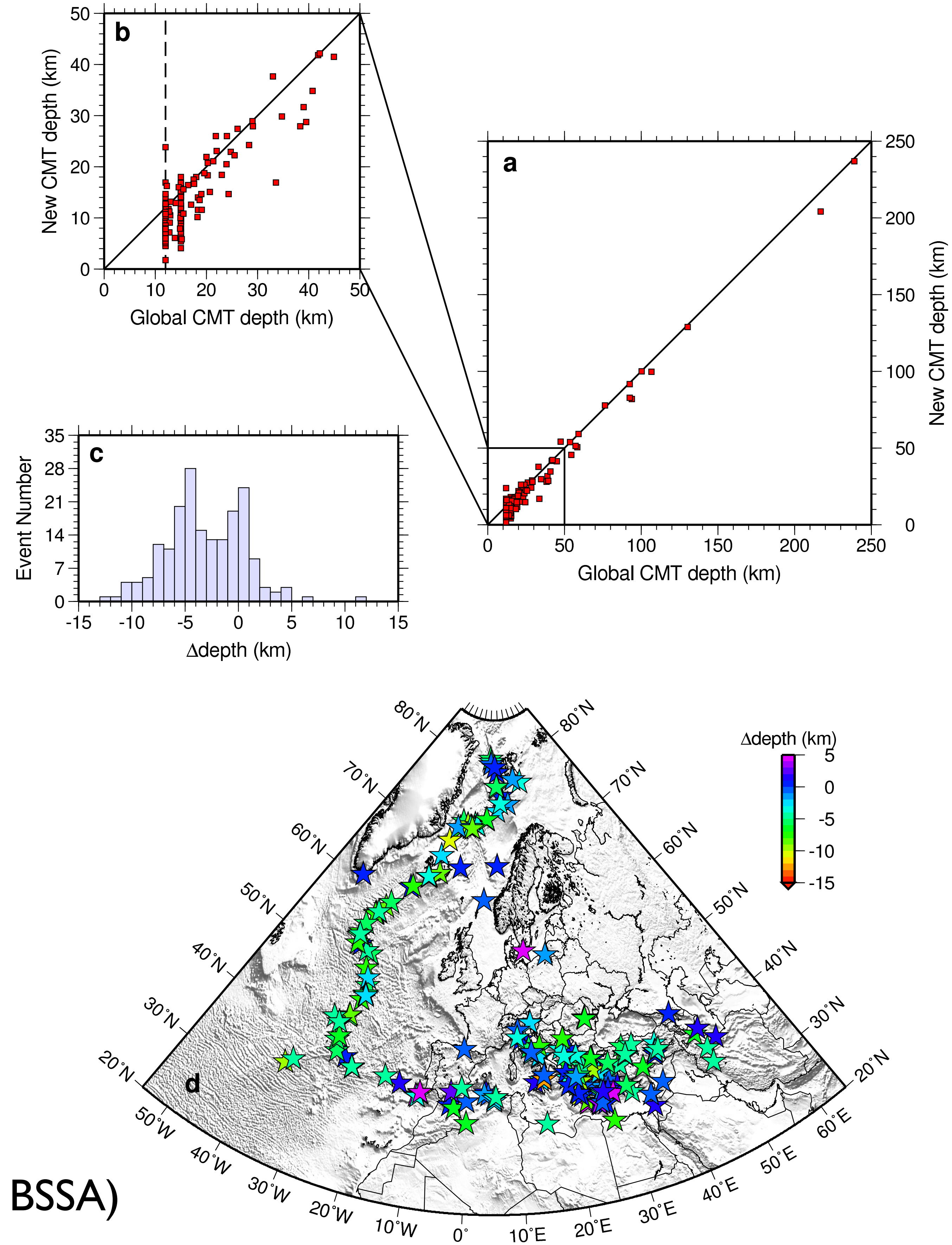

(Liu et al 2004 BSSA)