Seismic Imaging Based on Spectral-Element & Adjoint Methods

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CSCS User Day 2011

Seismic Wave Propagation

("Forward" Problem)

Equation of motion: $\rho\,\partial_t^2 \mathbf{s} - \boldsymbol{\nabla}\cdot\mathbf{T} = \mathbf{f}$

Boundary condition: $\hat{\mathbf{n}}\cdot\mathbf{T} = \mathbf{0}$

Initial conditions: $\mathbf{s}(\mathbf{x},0) = \mathbf{0}$

$\partial_t\mathbf{s}(\mathbf{x},0) = \mathbf{0}$

Earthquake source:

$$\mathbf{f} = -\mathbf{M}\cdot\boldsymbol{\nabla}\delta(\mathbf{x}-\mathbf{x}_s)S(t)$$

Spectral-Element Method

Weak form:

$$\int_\Omega \rho\, \mathbf{w} \cdot \partial_t^2 \mathbf{s}\, \mathrm{d}^3\mathbf{x} = -\int_\Omega \boldsymbol{\nabla}\mathbf{w} : \mathbf{T}\, \mathrm{d}^3\mathbf{x} + \mathbf{M} : \boldsymbol{\nabla}\mathbf{w}(\mathbf{x}_s) S(t)$$

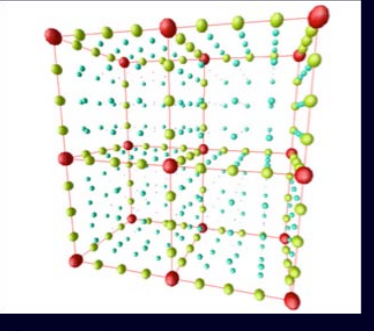
- implicitly accounts for free-surface boundary condition
- fluid-solid coupling terms may be explicitly added

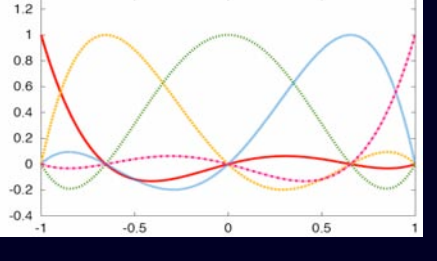
Spectral-Element Method

Finite-elements:

- hexahedral elements
- Gauss-Lobatto-Legrendre quadrature
- diagonal mass matrix
- explicit time-marching scheme

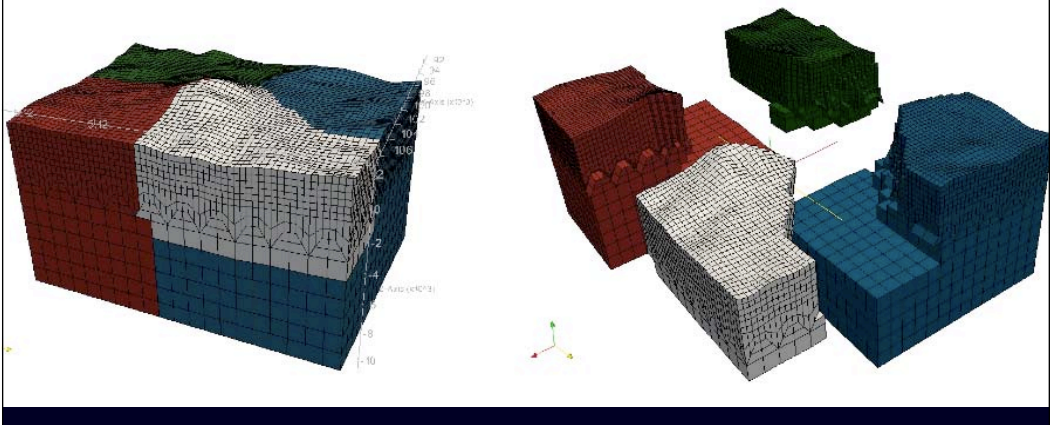
$$M\ddot{U} = -KU + F$$





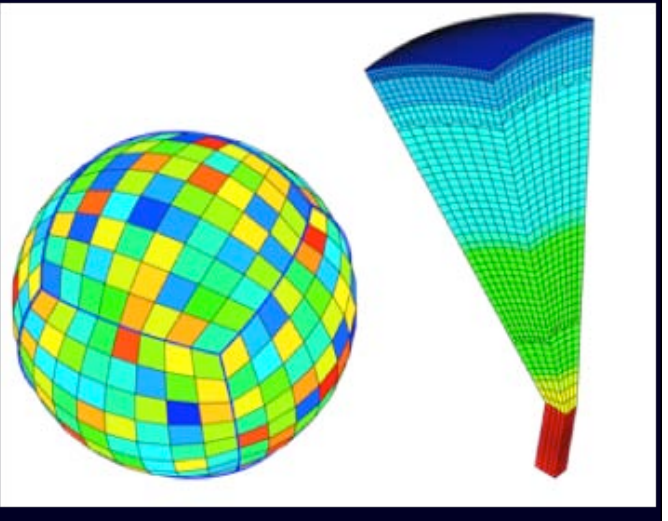
Parallel Implementation

Regional mesh partitioning



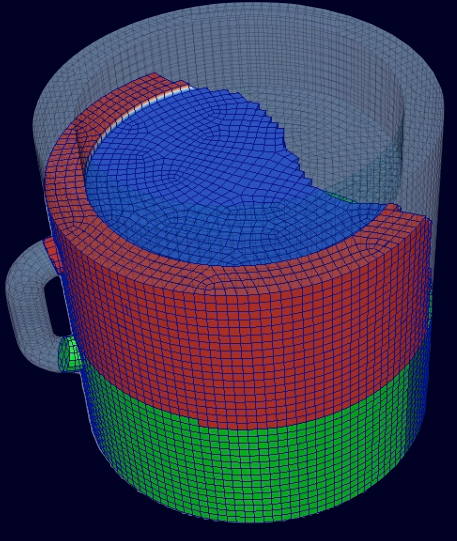
Parallel Implementation

Global mesh partitioning



Cubed Sphere: 6 n^2 mesh slices

Coffee Cup Simulation



SPECFEM3D_SESAME

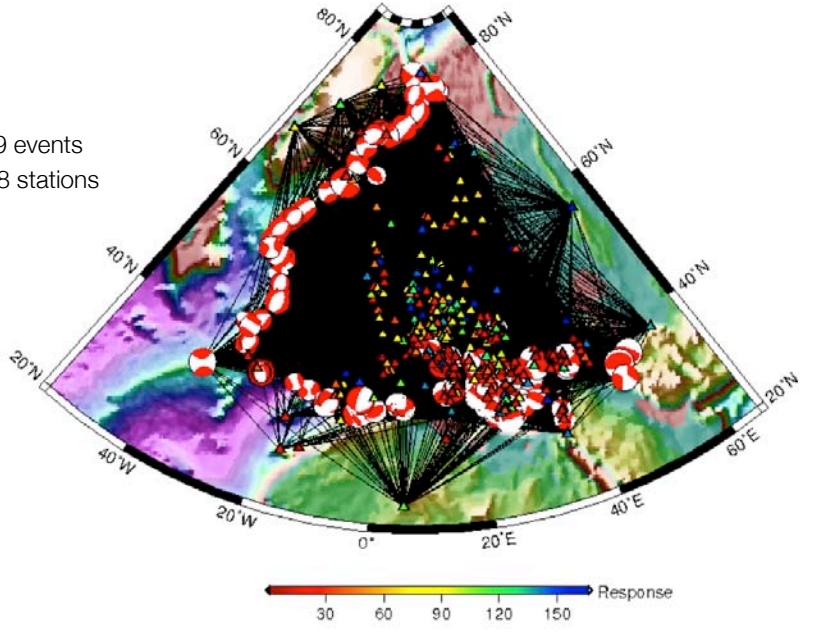
Soon: GPU version

Daniel Peter, Max Riethman, Dimitri Komatitsch, Olaf Schenk, Tarje Nissen-Meyer, Piero Basini, Lapo Boschi

Adjoint Tomography of Europe

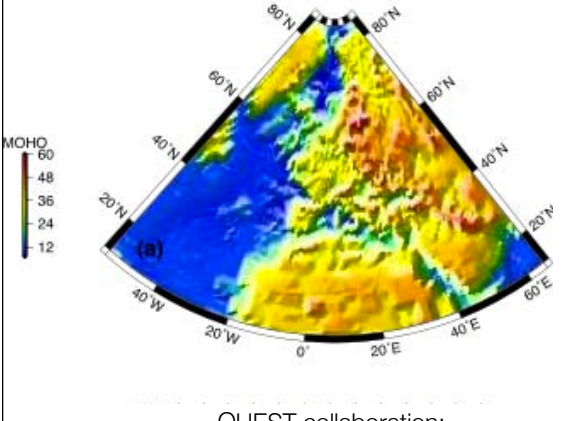
("Inverse" Problem)

159 events
338 stations

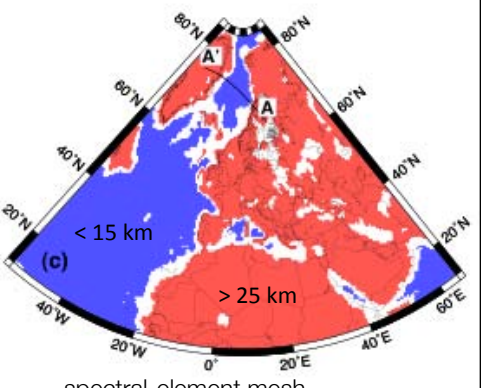


Hejun Zhu

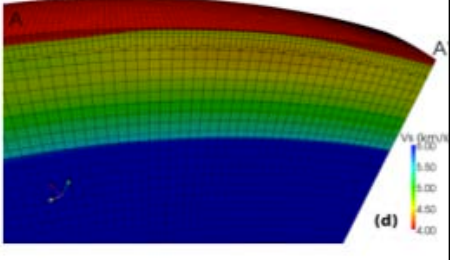
Starting 3D Crustal Model: EPCrust



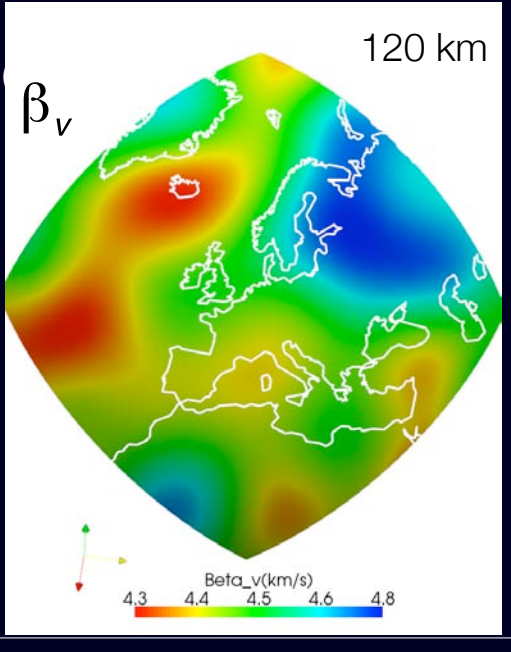
QUEST collaboration:
Irene Molinari

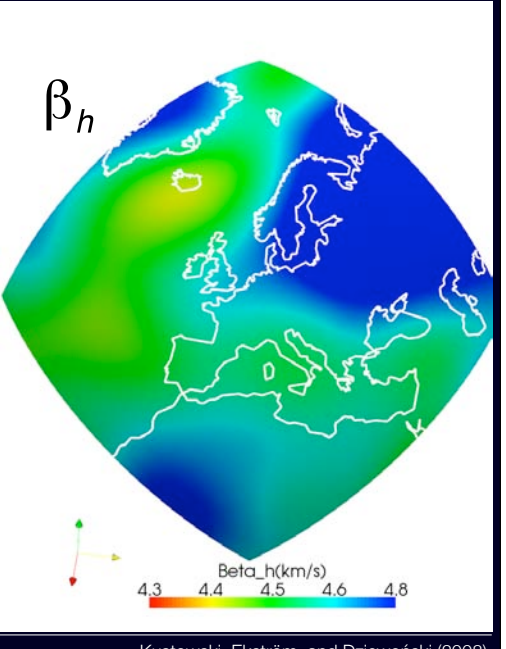


spectral-element mesh



Starting 3D Mantle Model: S362ANI

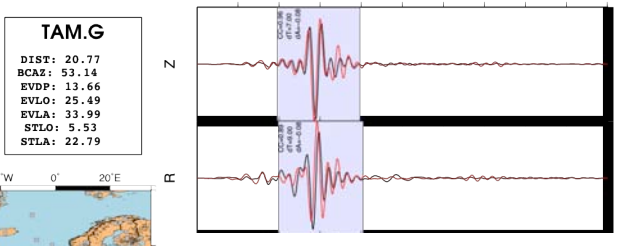




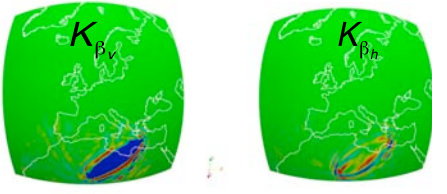
Kustowski, Ekström, and Dziewoński (2008)

Model Parameterization: Radial Anisotropy

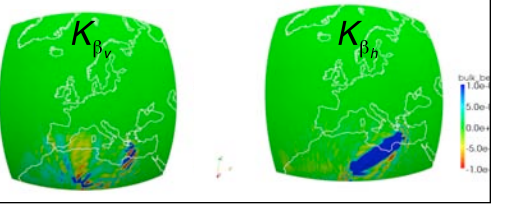
(Transverse Isotropy)



Rayleigh wave



Love wave



Misfit Function

$$\chi(\mathbf{m}) = \frac{1}{6}\sum_{Z,R,T}\frac{1}{N_s}\sum_{s}\frac{1}{N_p}\sum_{i=1}^{p}\left(\frac{\Delta T_i}{\sigma_i}\right)^2 + \frac{1}{6}\sum_{Z,R,T}\frac{1}{N_s}\sum_{s}\frac{1}{N_p}\sum_{i=1}^{p}\int W_i\left[\frac{\Delta\tau(\omega)_i}{\sigma(\omega)_i}\right]^2 d\omega$$

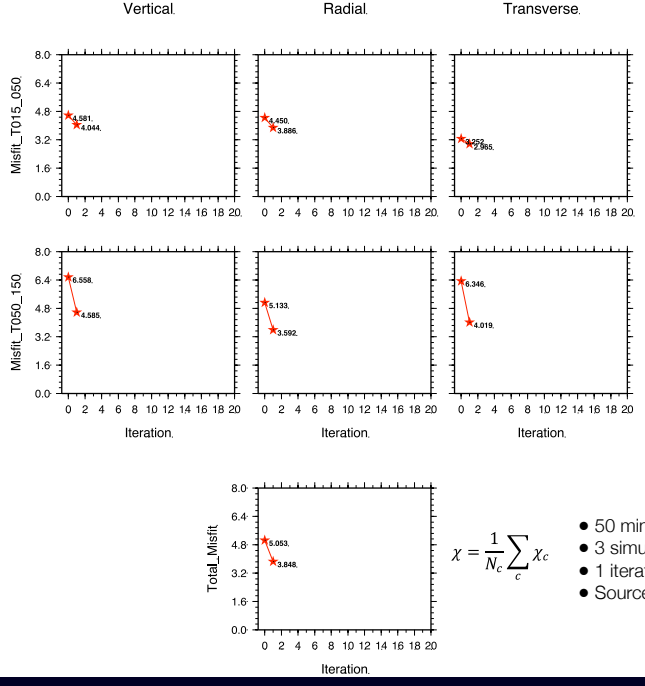
Body-wave cross correlation/multitaper
15-40 s band pass
(1) P-SV (Vertical)
(2) P-SV(Radial)
(3) SH (Transverse)

Surface-wave multitaper
25-150 s band pass
(4) Rayleigh (Vertical)
(5) Rayleigh (Radial)
(6) Love (Transverse)

Adjoint source = SP(body-wave measurement) + LP (surface-wave measurement)

$$\delta\chi^{TI} = \int K_c\,\delta\ln c + K_{\beta_v}\delta\ln\beta_v + K_{\beta_h}\delta\ln\beta_h + K_\eta\delta\ln\eta + K_\rho\delta\ln\rho\, dV$$

Reduction in Misfit: First Iteration



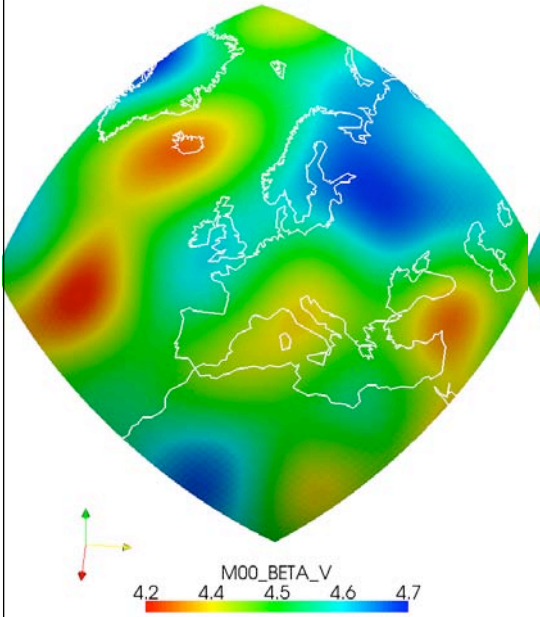
$$\chi_c = \frac{1}{N_s}\sum_s \frac{1}{N_p}\sum_p \left(\frac{\Delta T_p}{\sigma_p}\right)^2$$

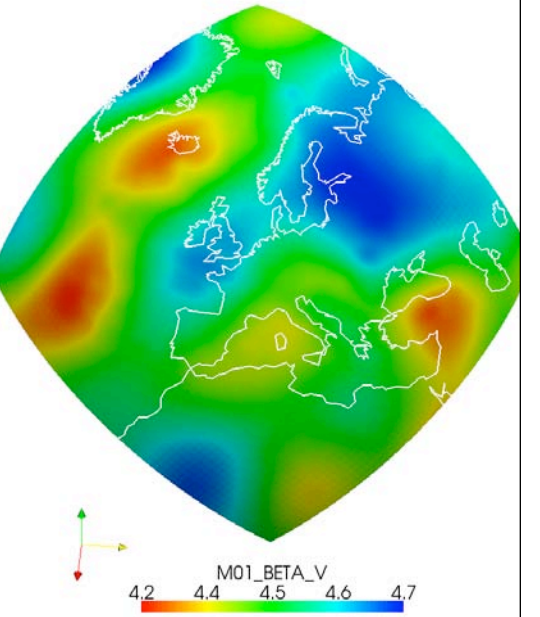
$$\chi_c = \frac{1}{N_s}\sum_s \frac{1}{N_p}\sum_p \int W_p \left(\frac{\Delta \tau_p(\omega)}{\sigma_p(\omega)}\right)^2 d\omega$$

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

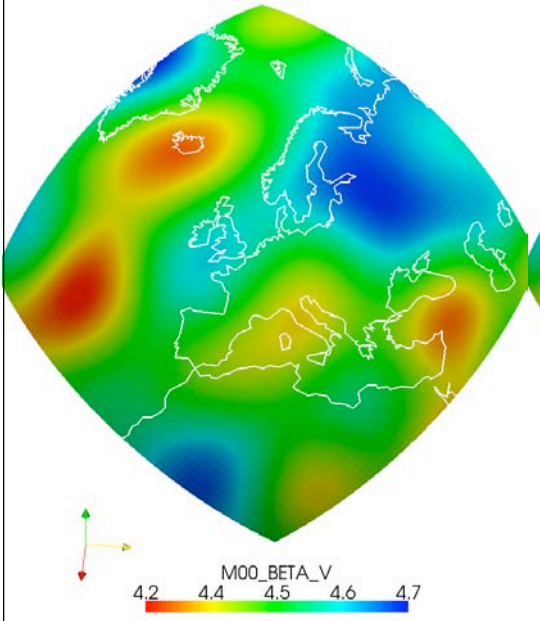
- 50 minutes per simulation (168 cores)
- 3 simulations per event per iteration
- 1 iteration ~1 day
- Source + structure inversion: ~1.5M CPU hours

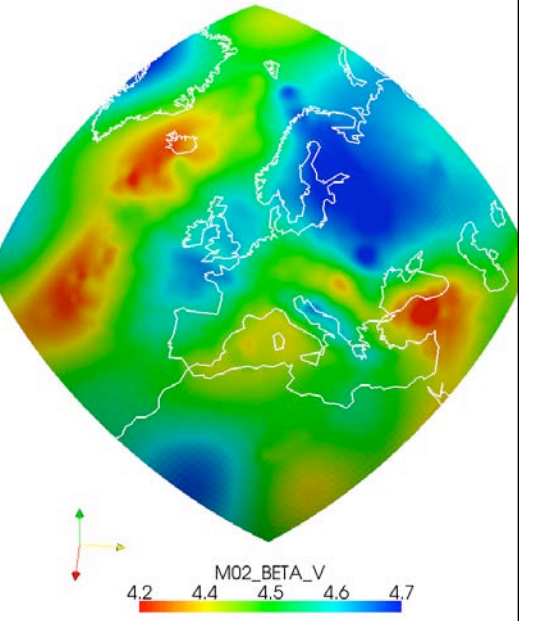
Depth 75 km





Depth 75 km





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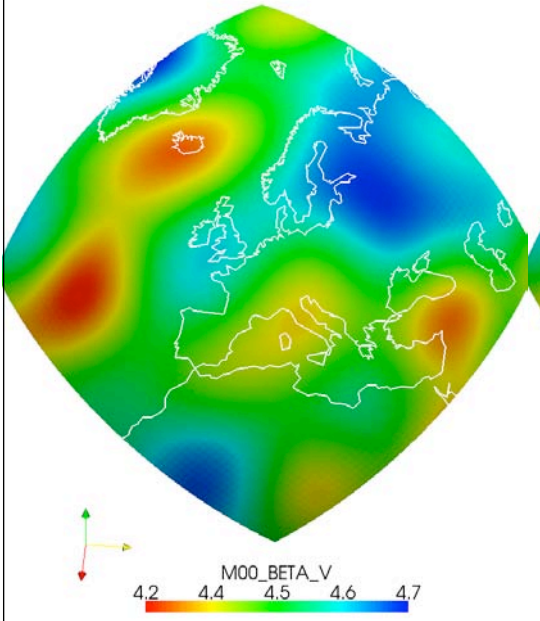

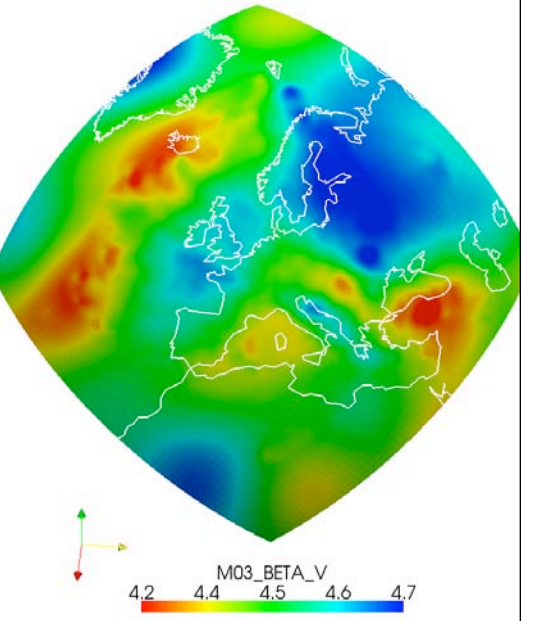

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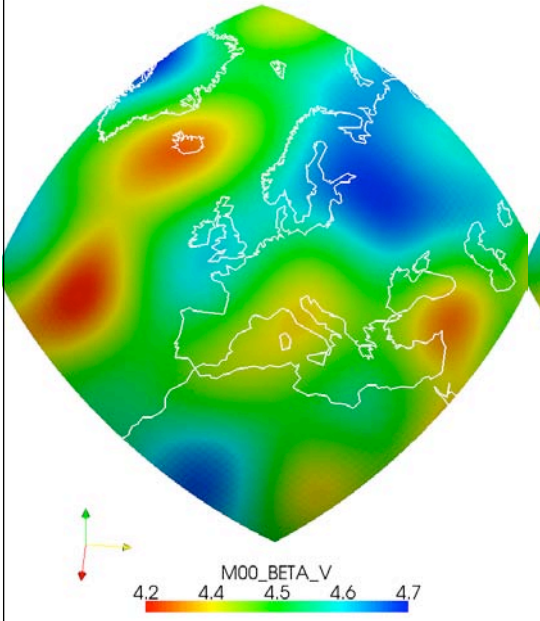

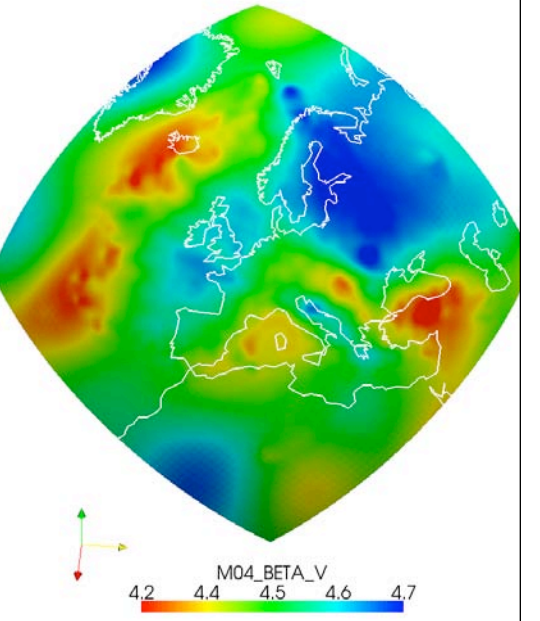

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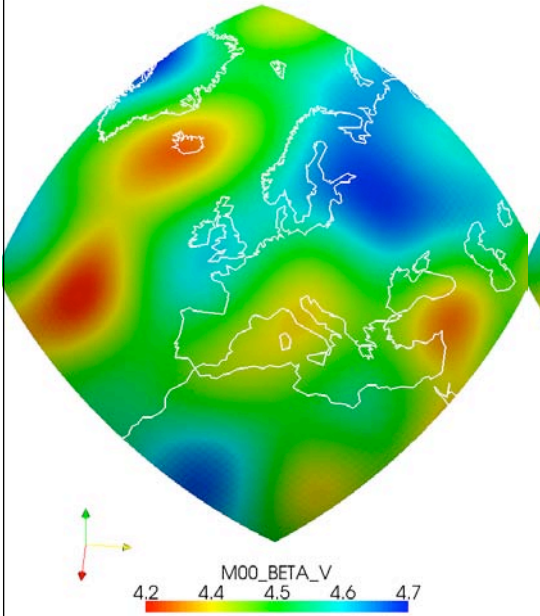

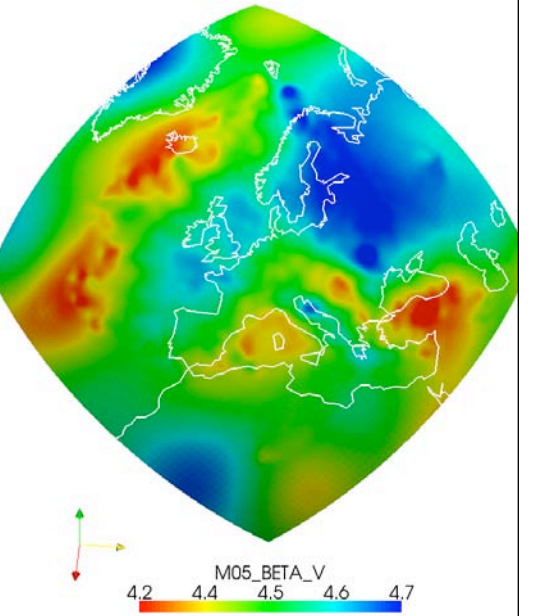

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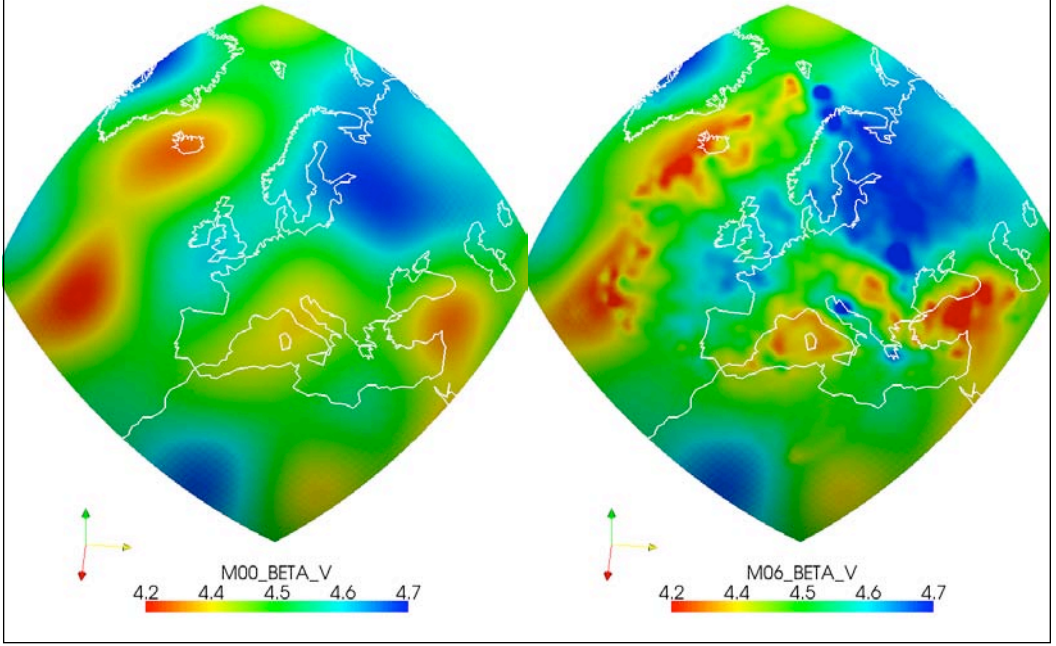

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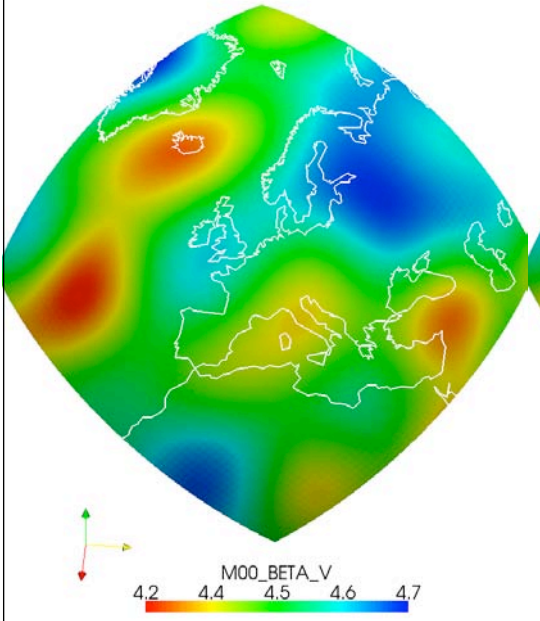

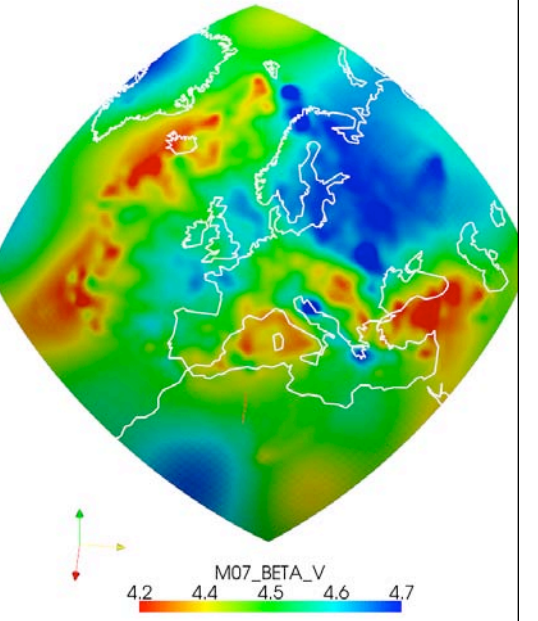

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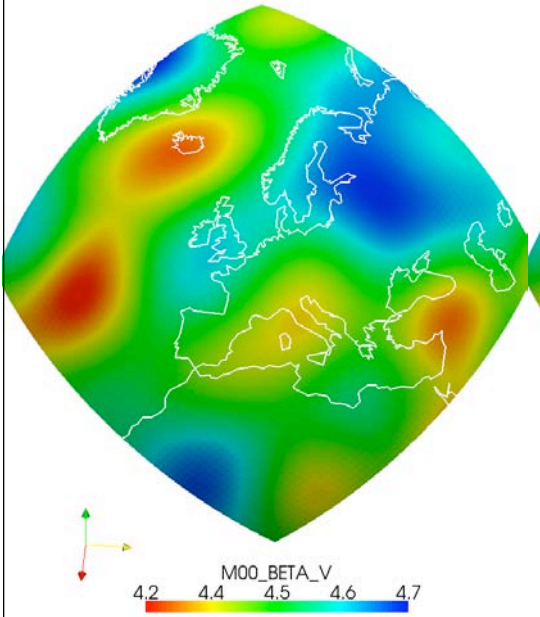

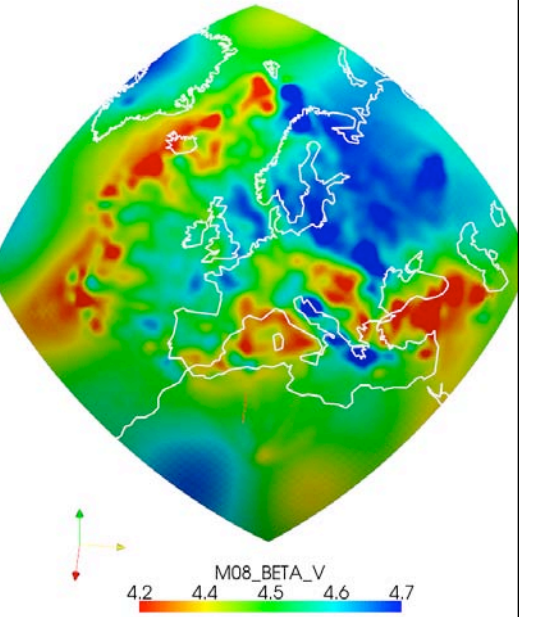

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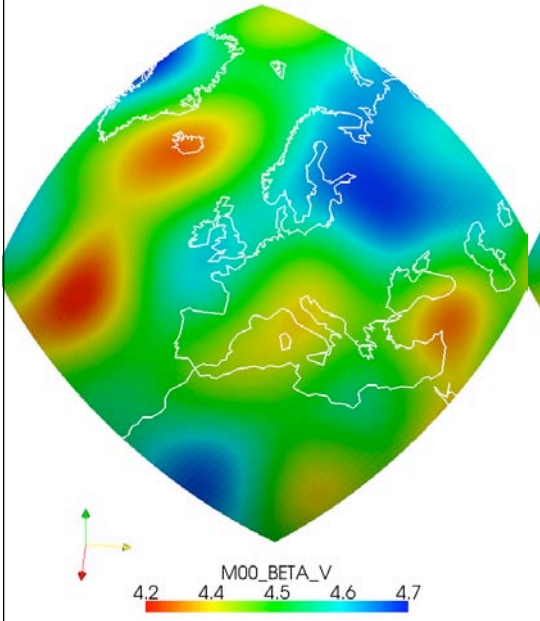

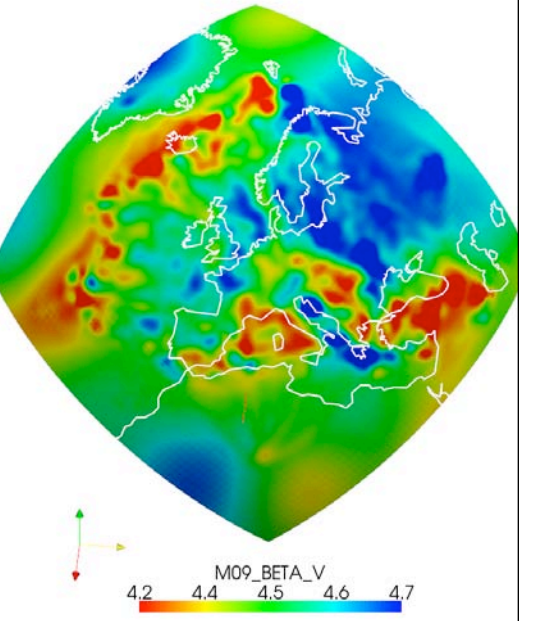

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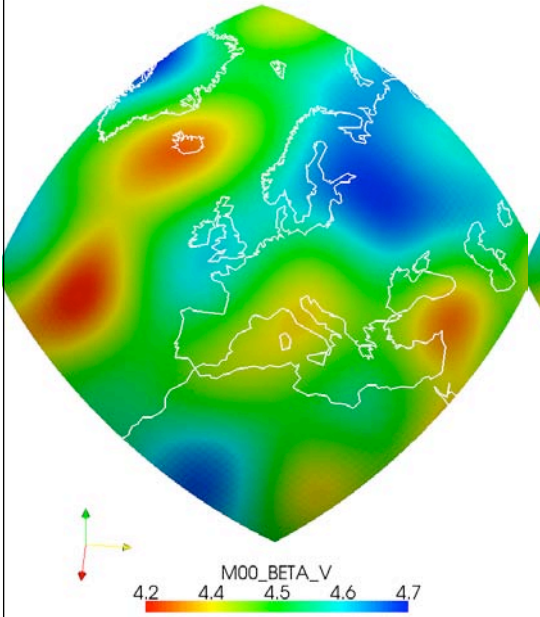

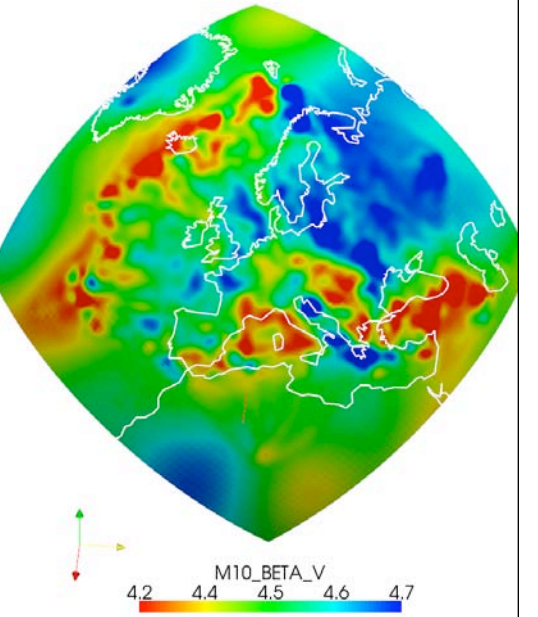

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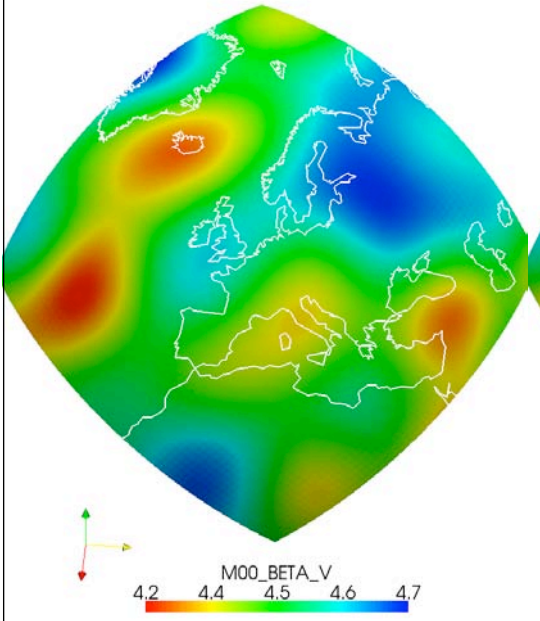

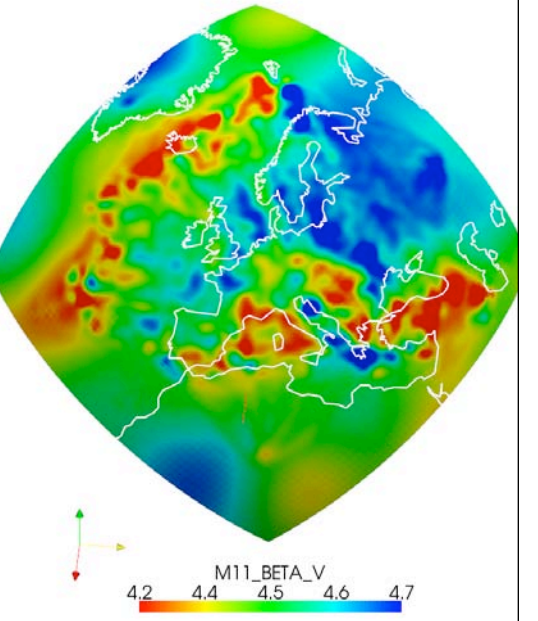

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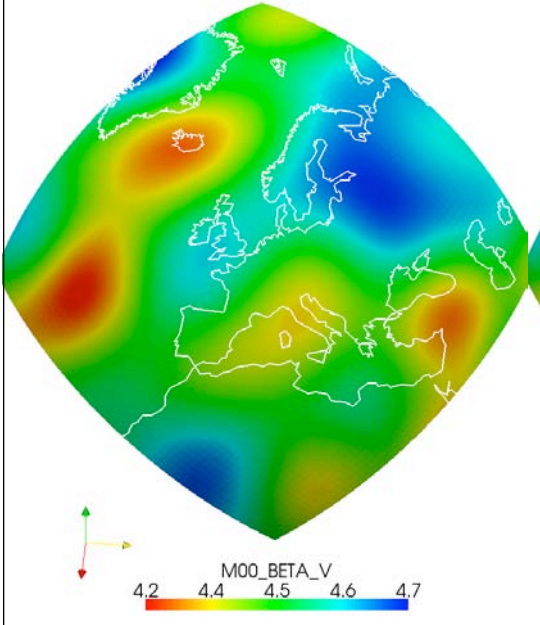

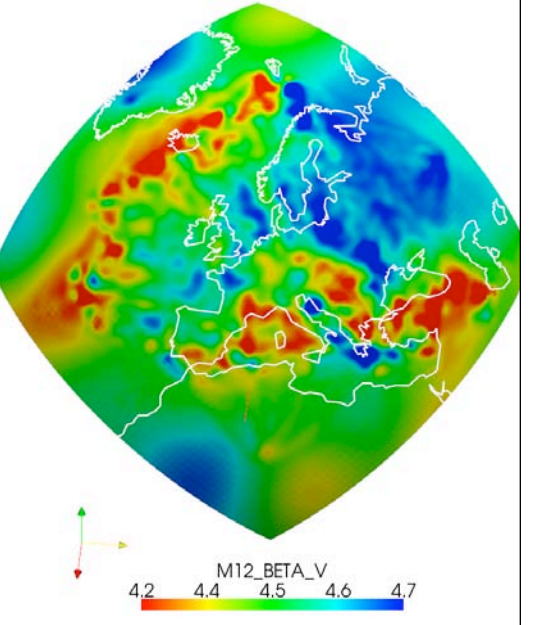

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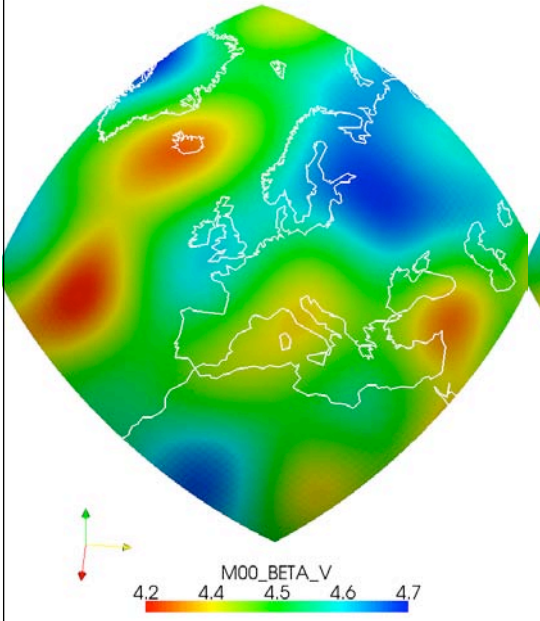

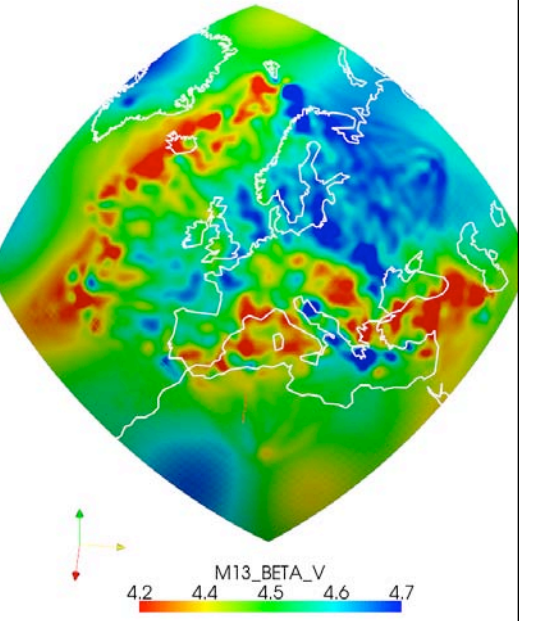

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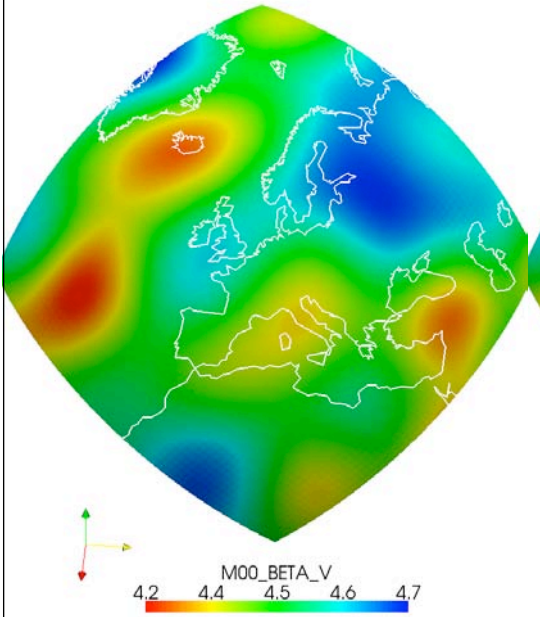

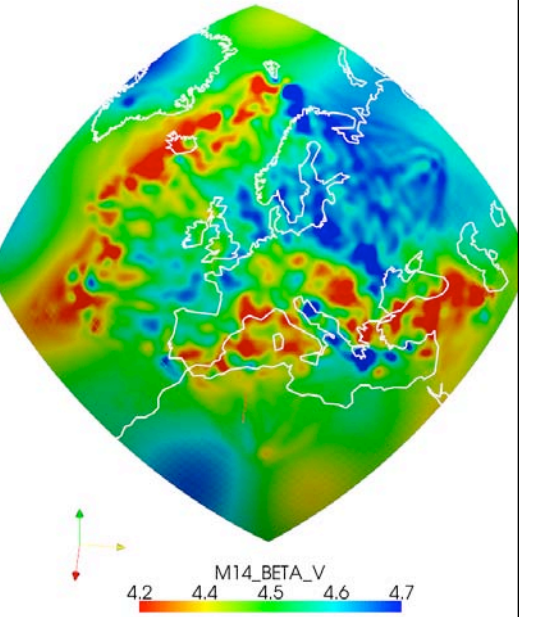

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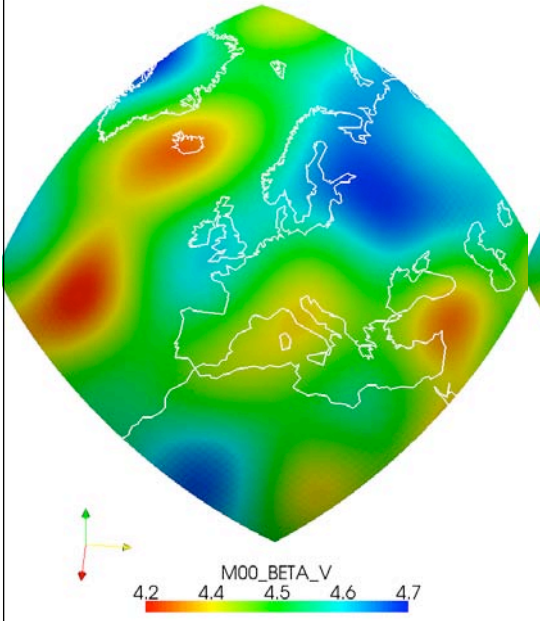

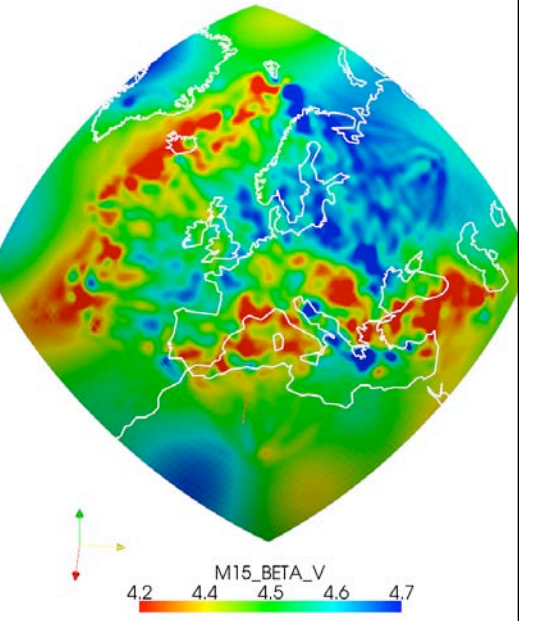

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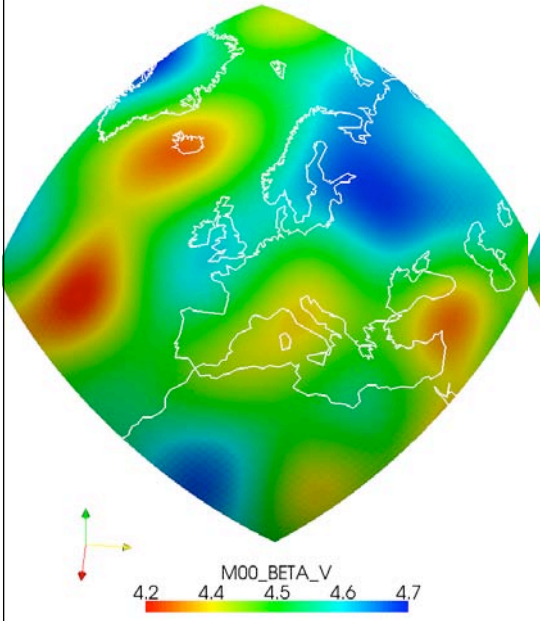

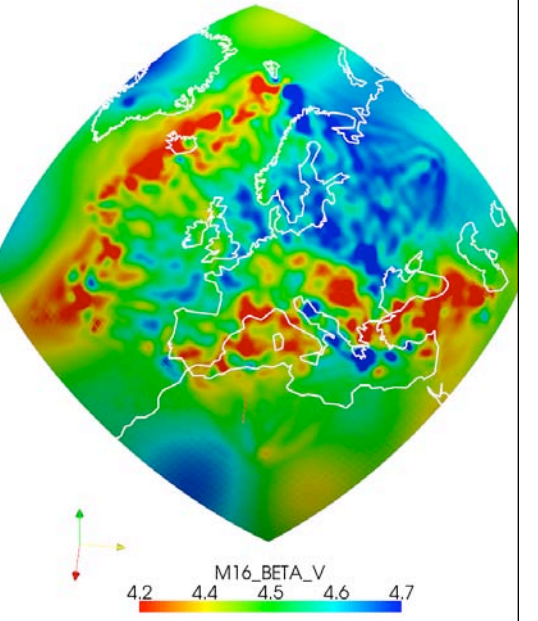

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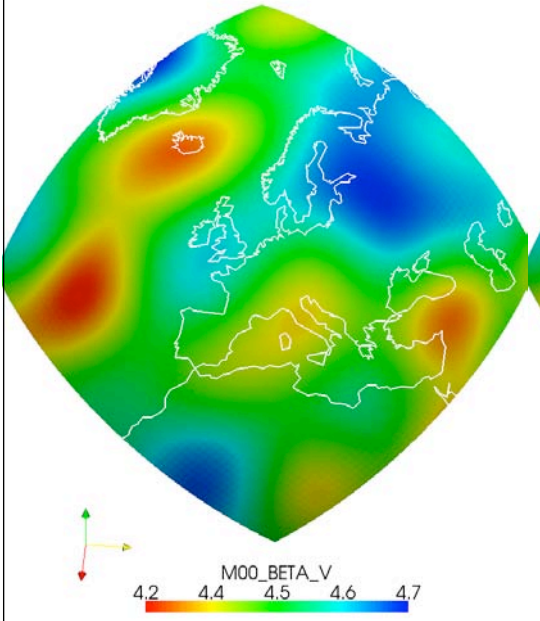

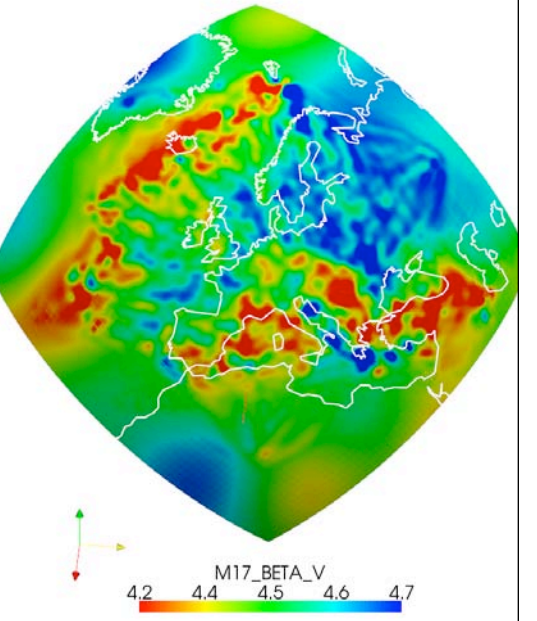

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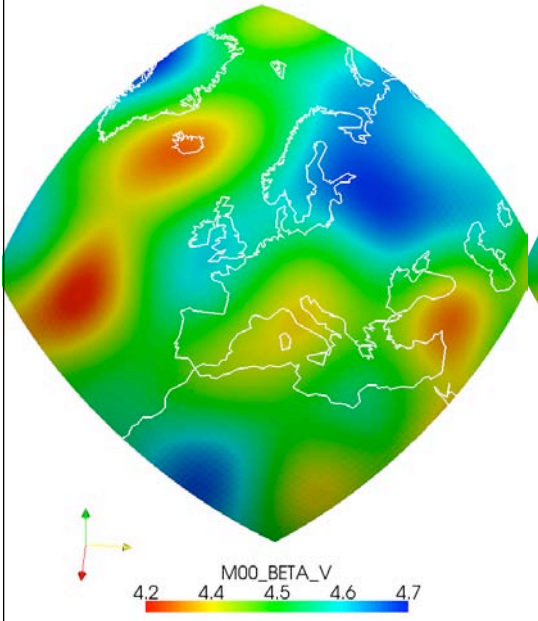
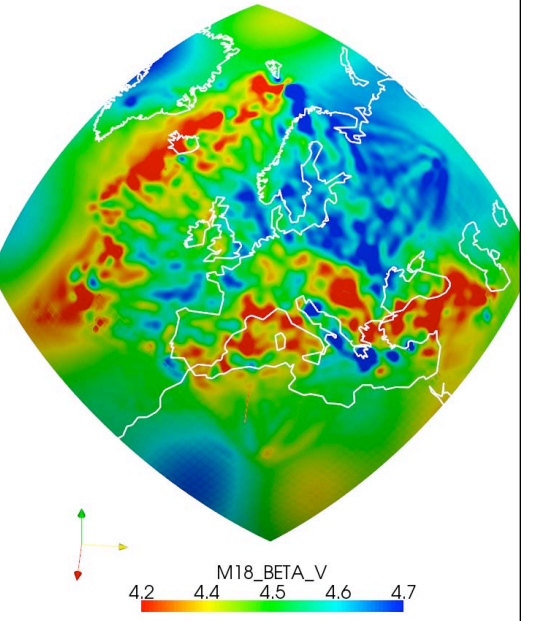
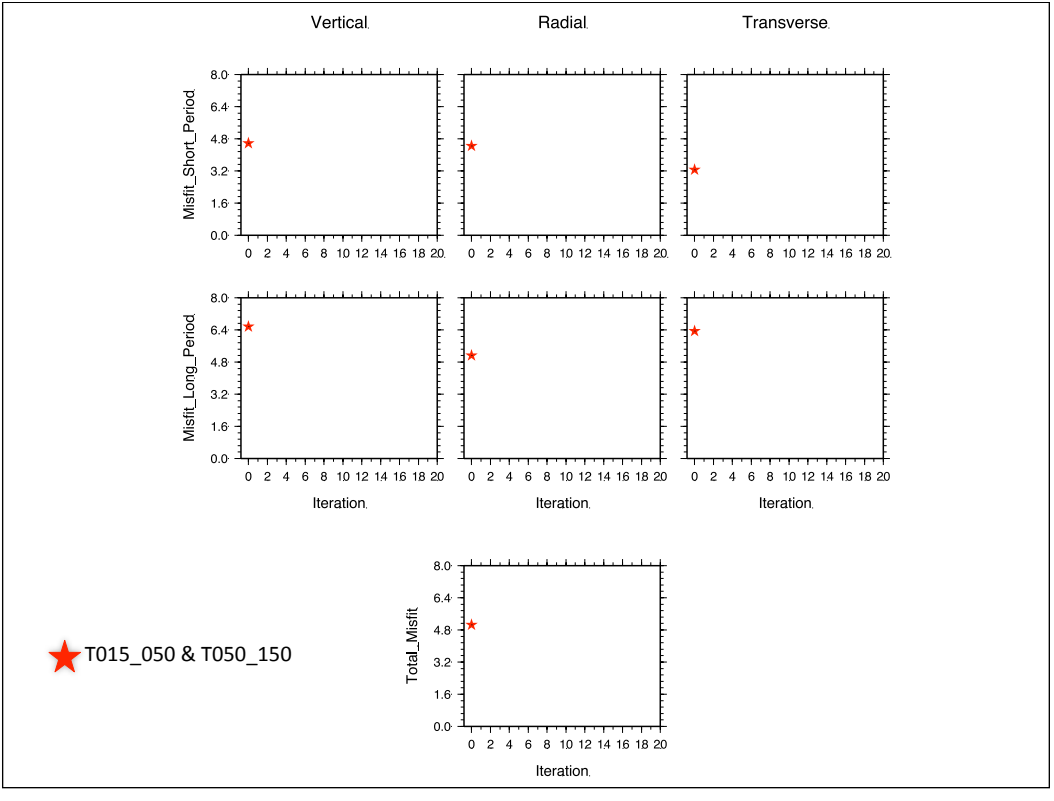
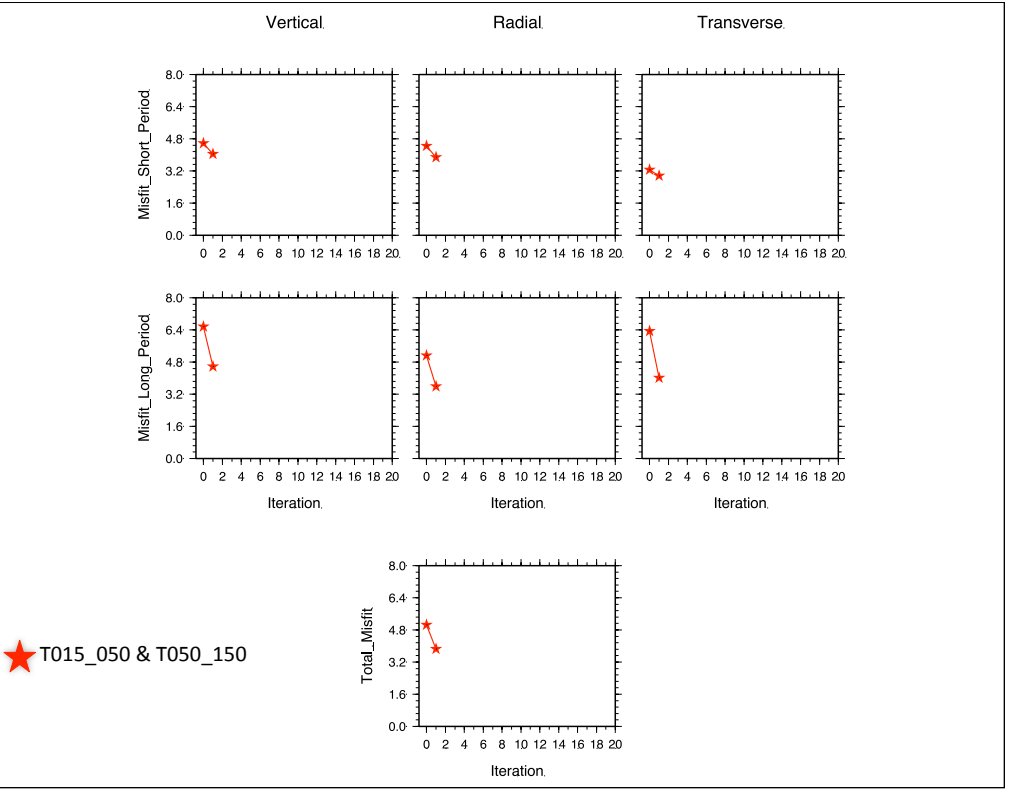





Vertical
Radial
Transverse
Misfit_Short_Period
Misfit_Long_Period
Total_Misfit
Iteration
0.0
1.6
3.2
4.8
6.4
8.0
0 2 4 6 8 10 12 14 16 18 20
T015_050 & T050_150


Vertical
Radial
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Iteration
0.0
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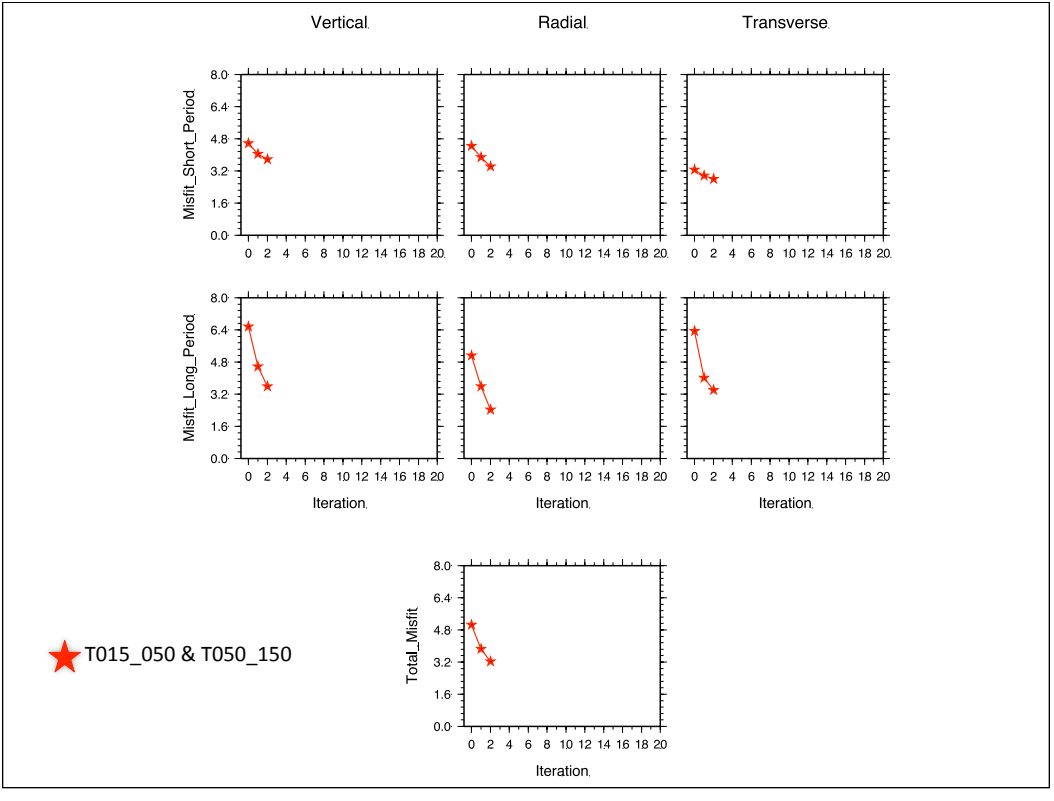
0 2 4 6 8 10 12 14 16 18 20
T015_050 & T050_150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Radial
Transverse
Misfit_Short_Period
Misfit_Long_Period
Total_Misfit
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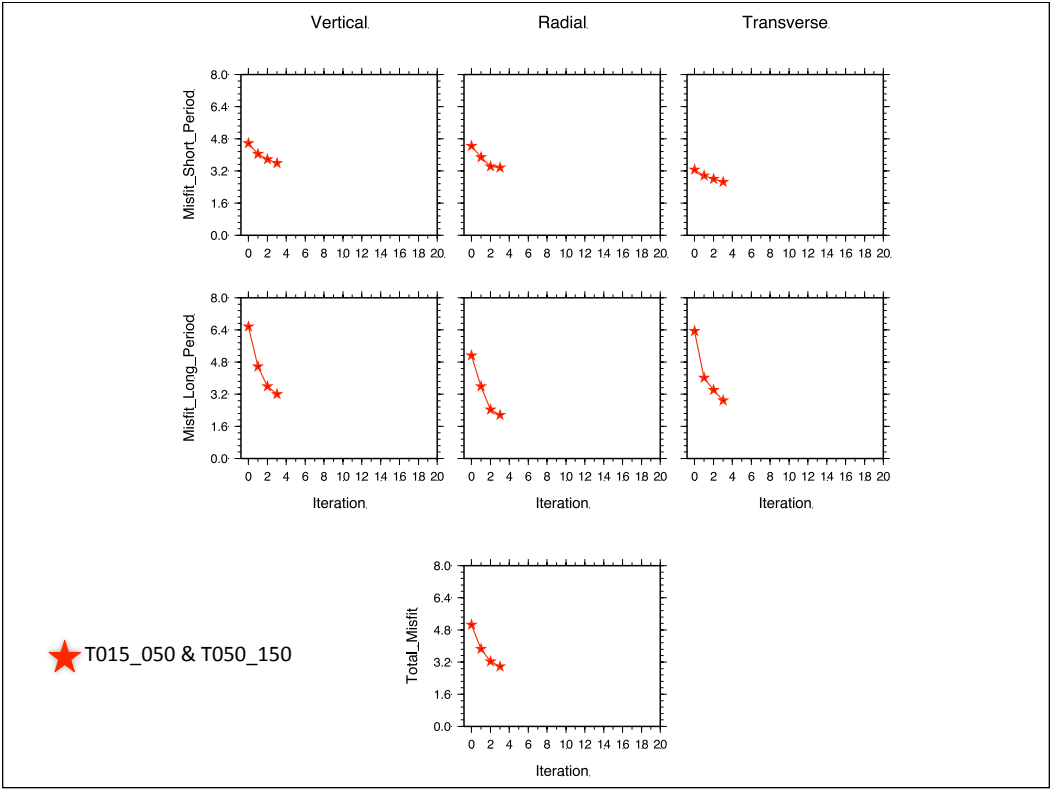
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Transverse
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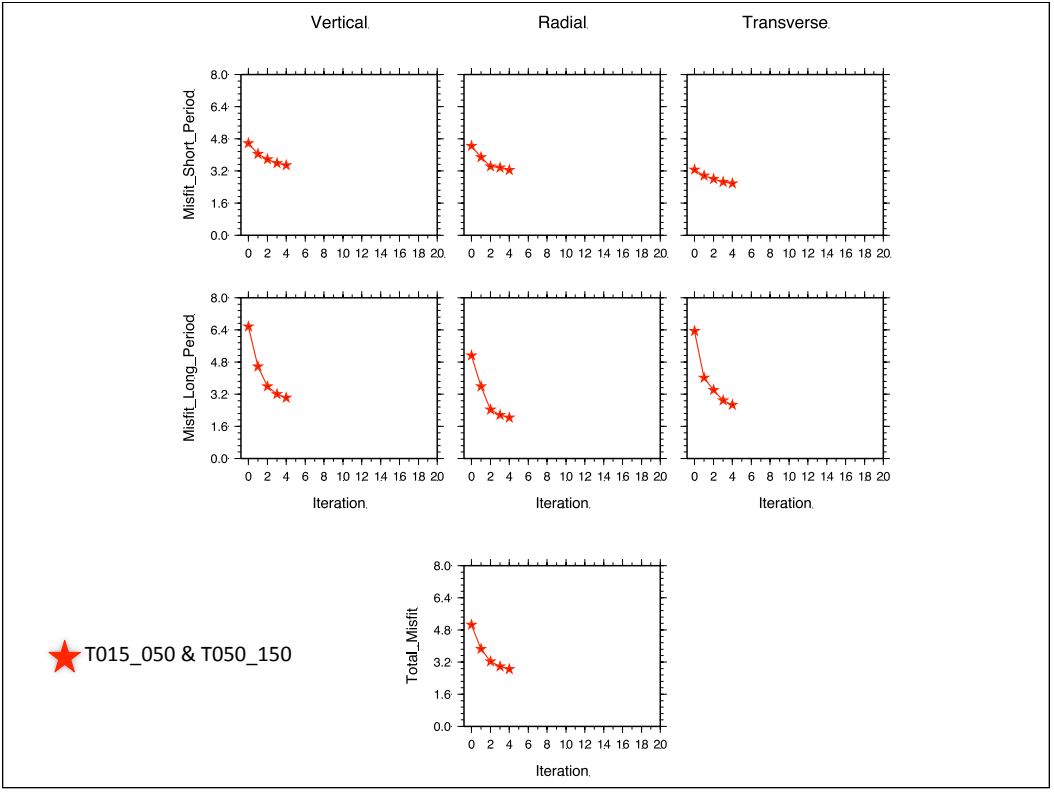
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Transverse
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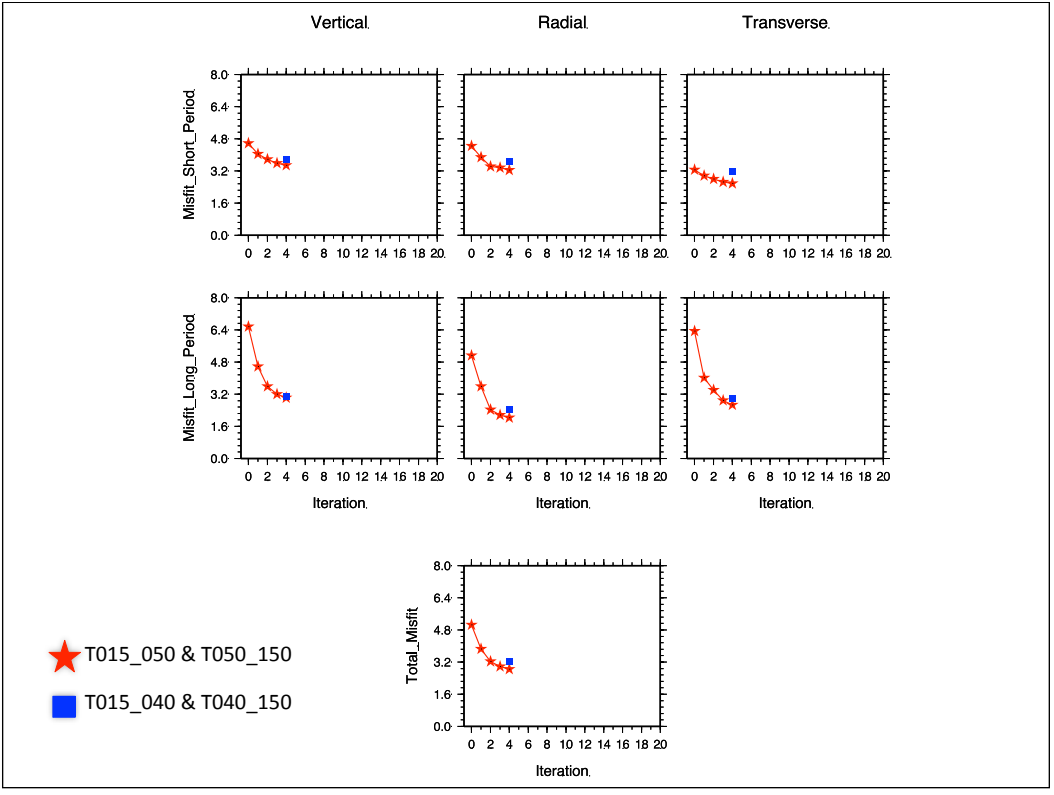
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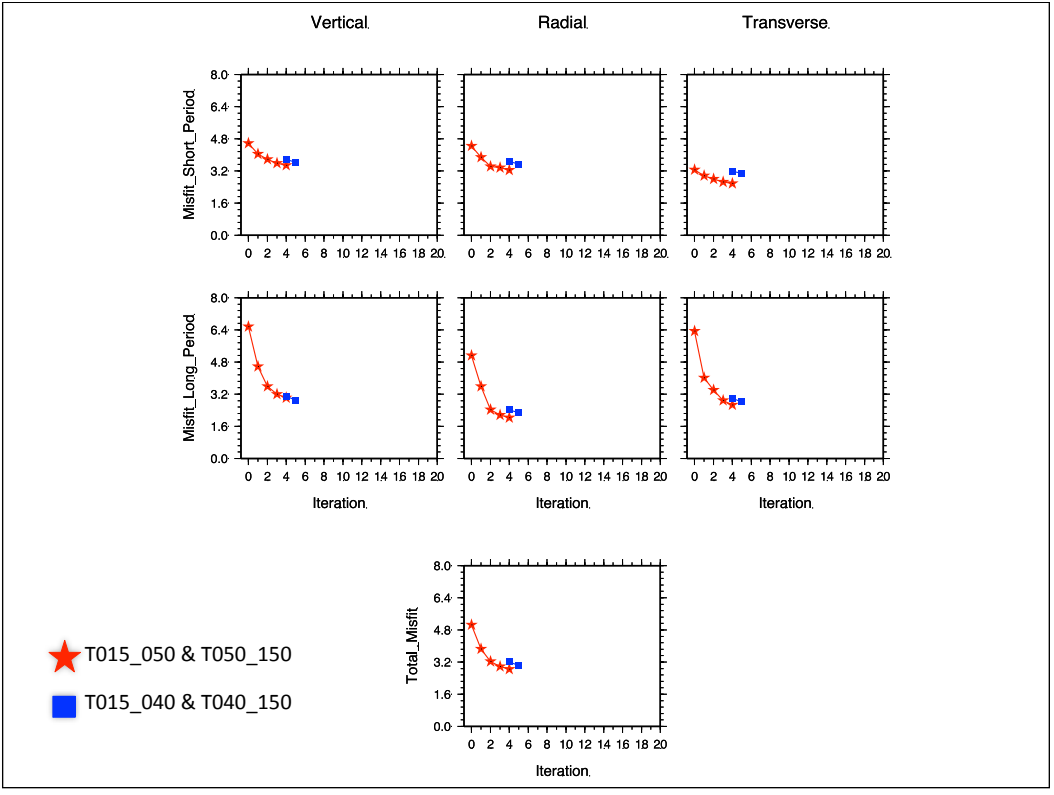
T015_040 & T040_150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Transverse
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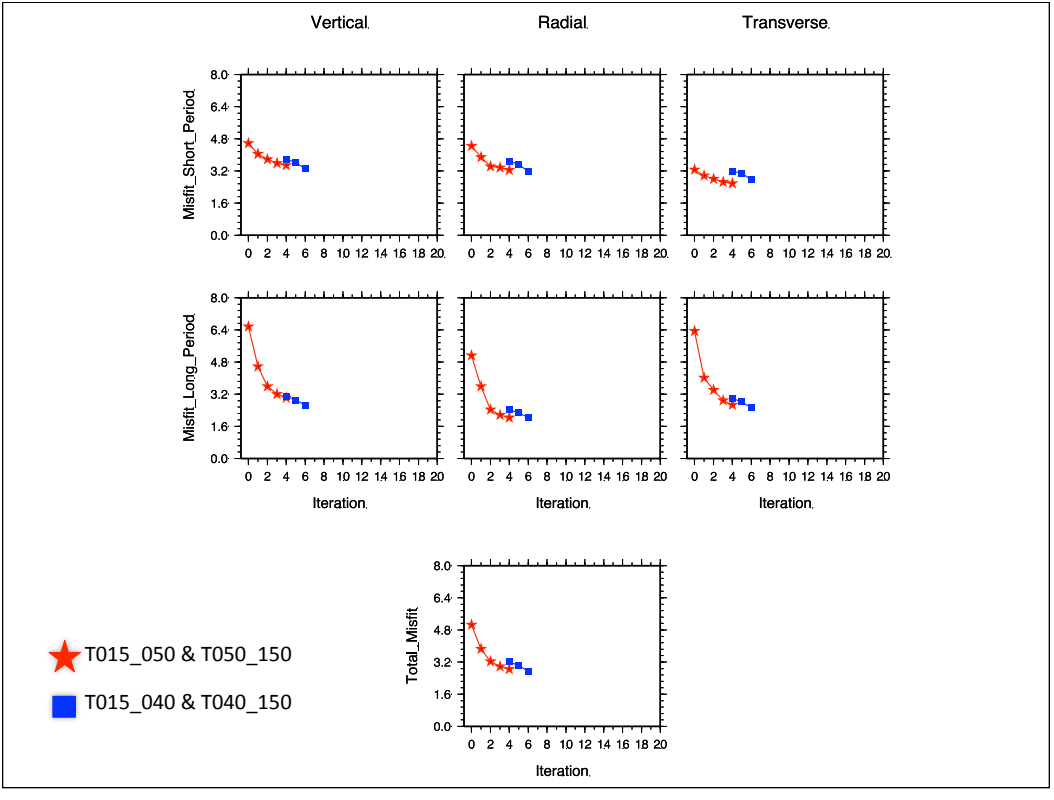
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Transverse
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Misfit_Long_Period
Total_Misfit
Iteration
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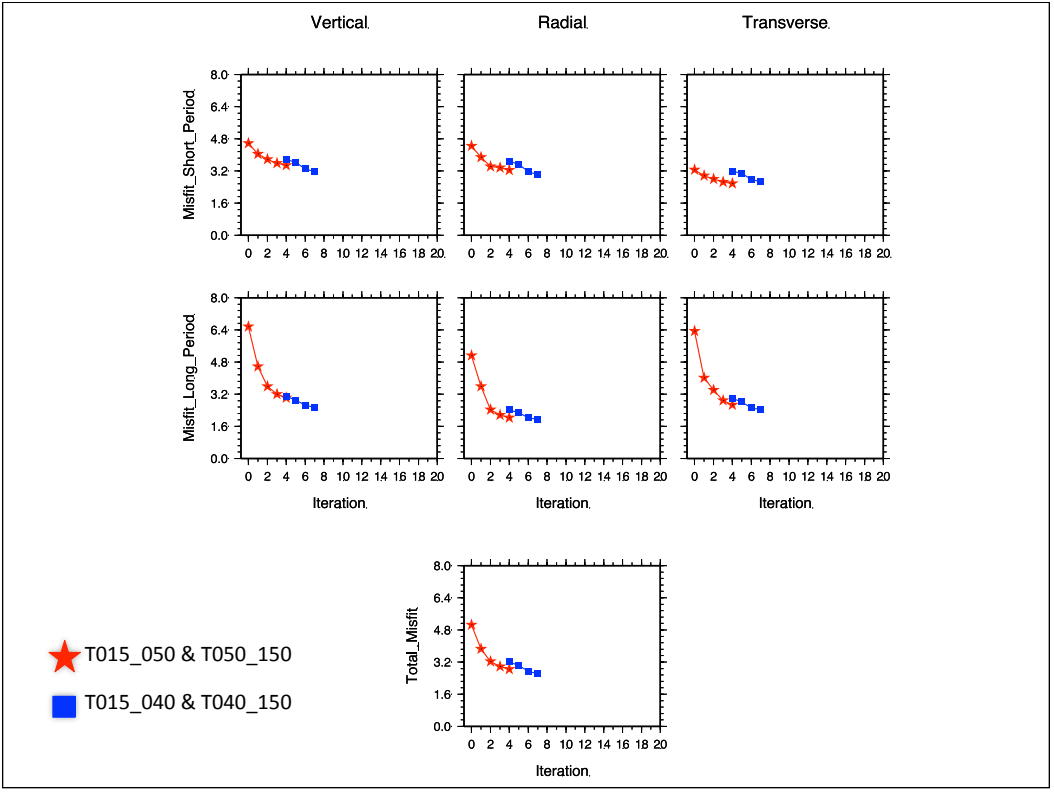
T015_040 & T040_150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Iteration
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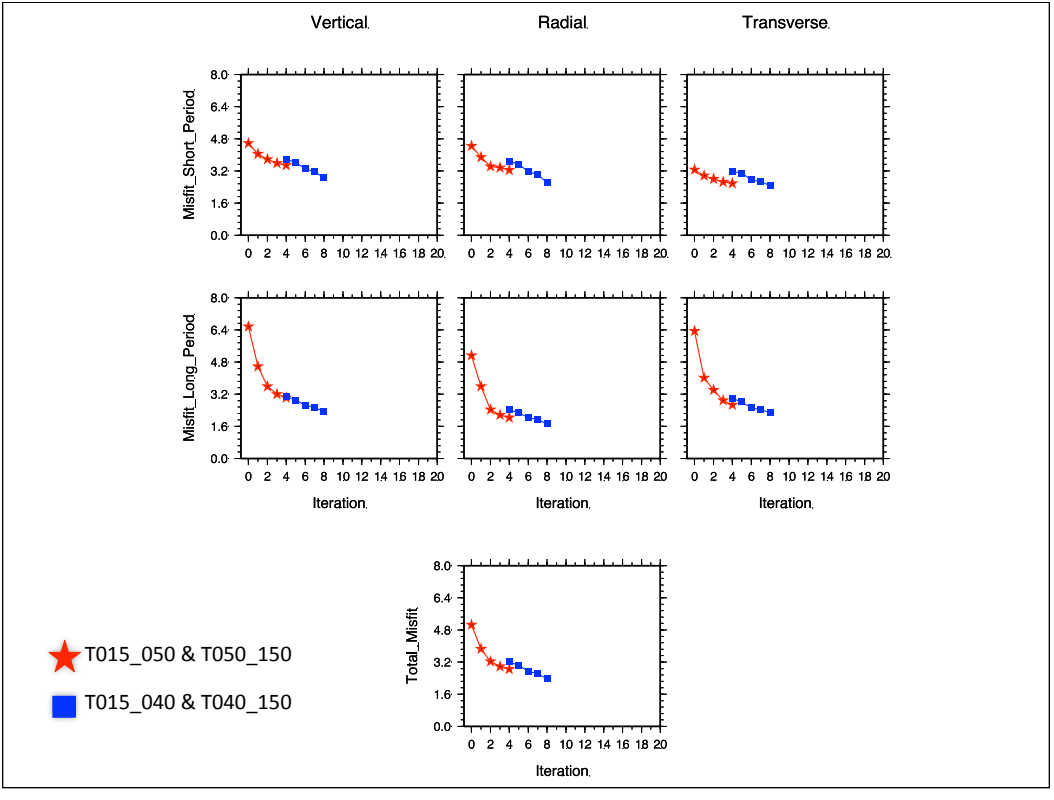
T015_040 & T040_150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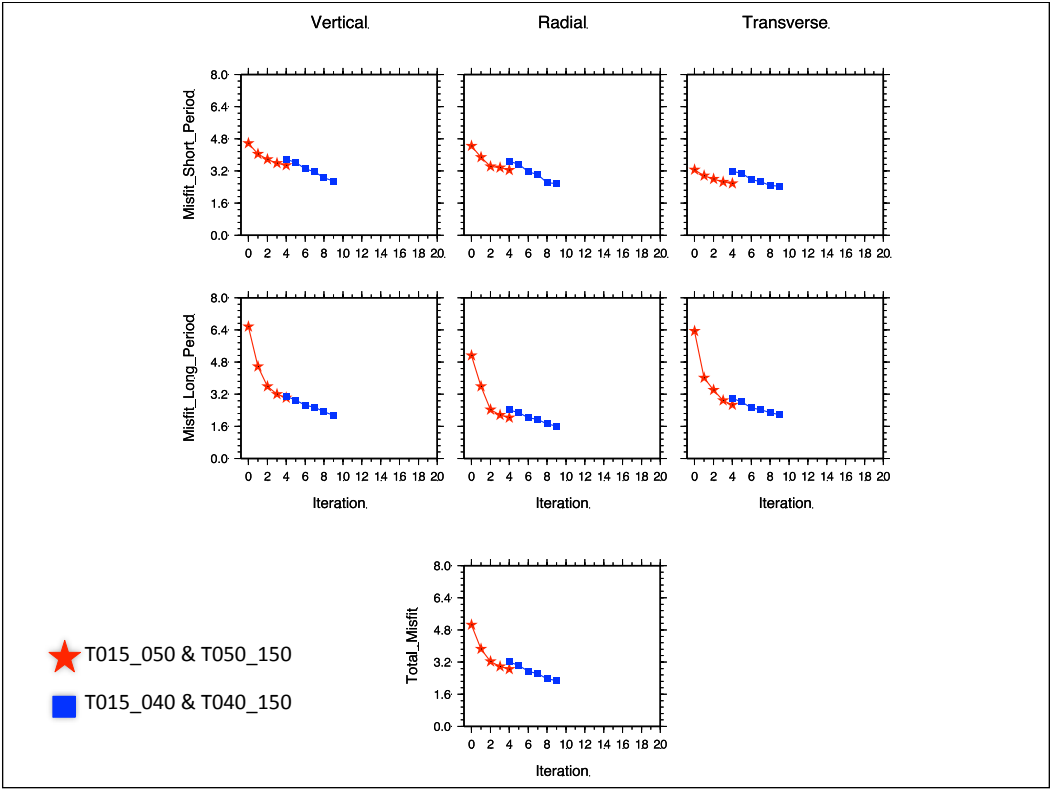
T015_040 & T040_150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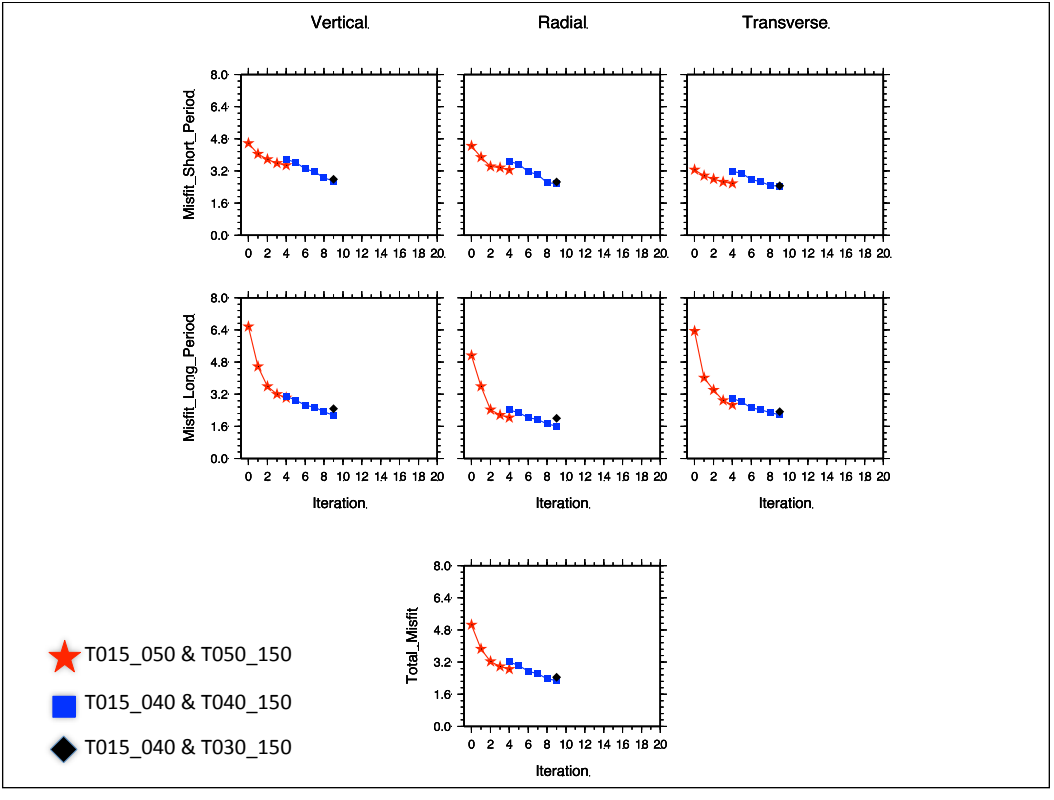
T015_040 & T040_150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Transverse.
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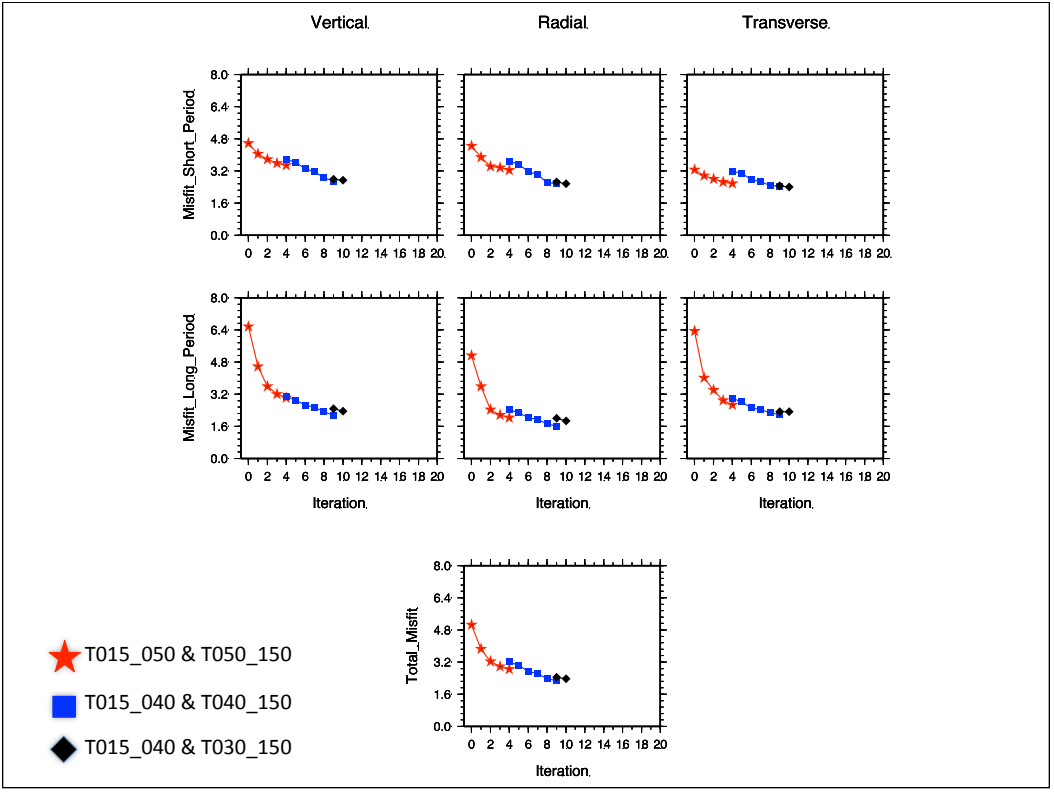
Misfit_Long_Period.
Total_Misfit
Iteration.
T015_050 & T050_150
T015_040 & T040_150
T015_040 & T030_150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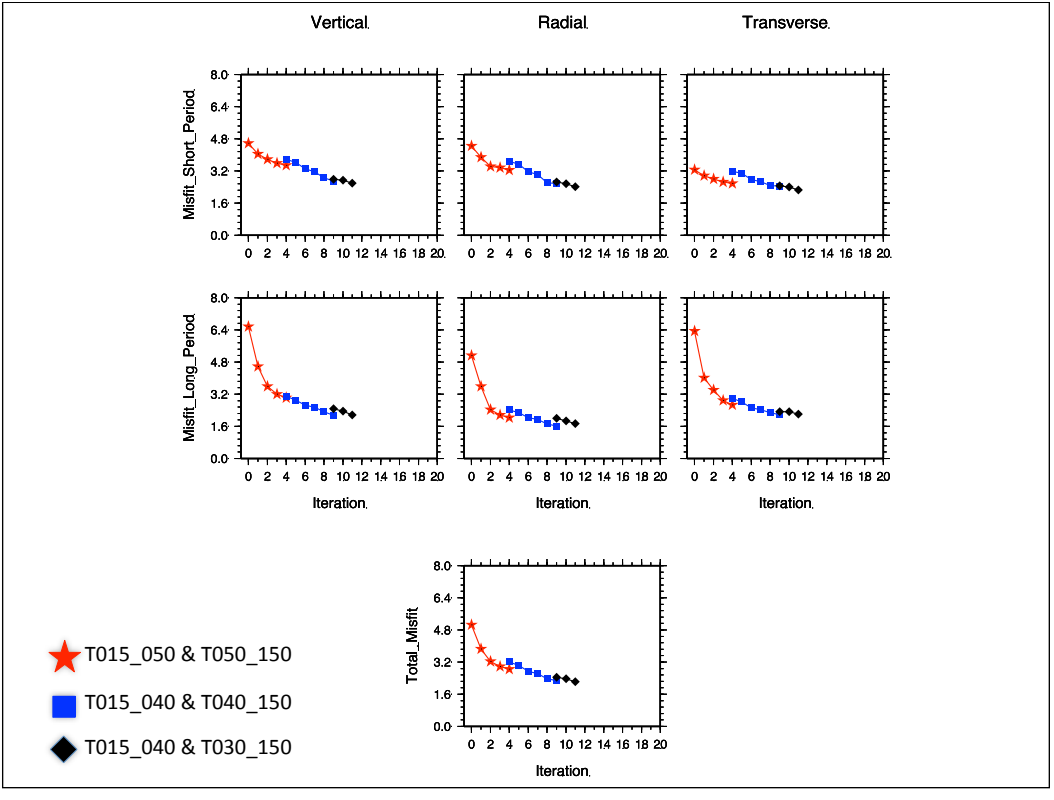
T015_040 & T040_150
T015_040 & T030_150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T015_050 & T050_150
T015_040 & T040_150
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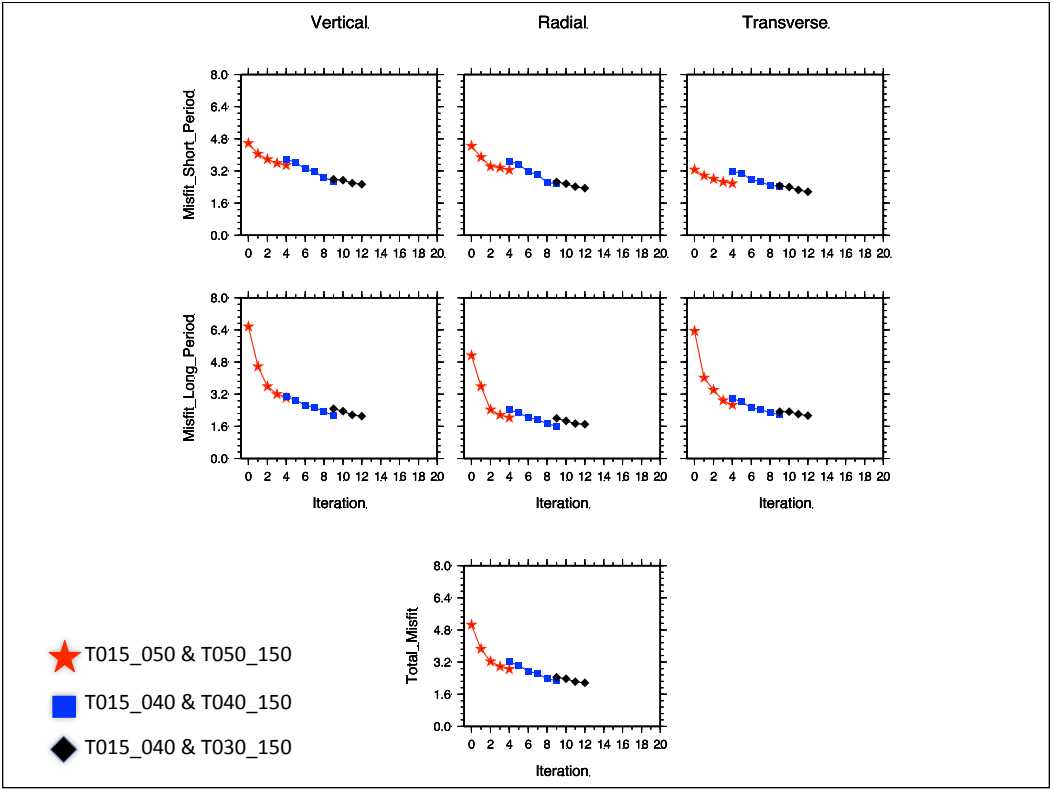
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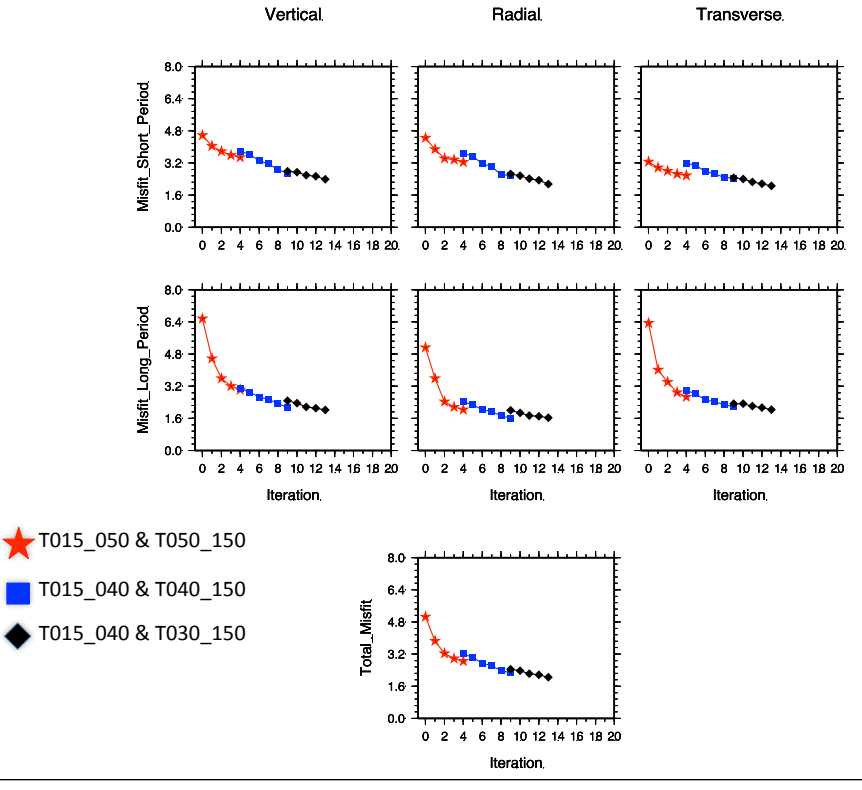
T015_050 & T050_150
T015_040 & T040_150
T015_040 & T030_150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Transverse.
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Iteration.
Total_Misfit
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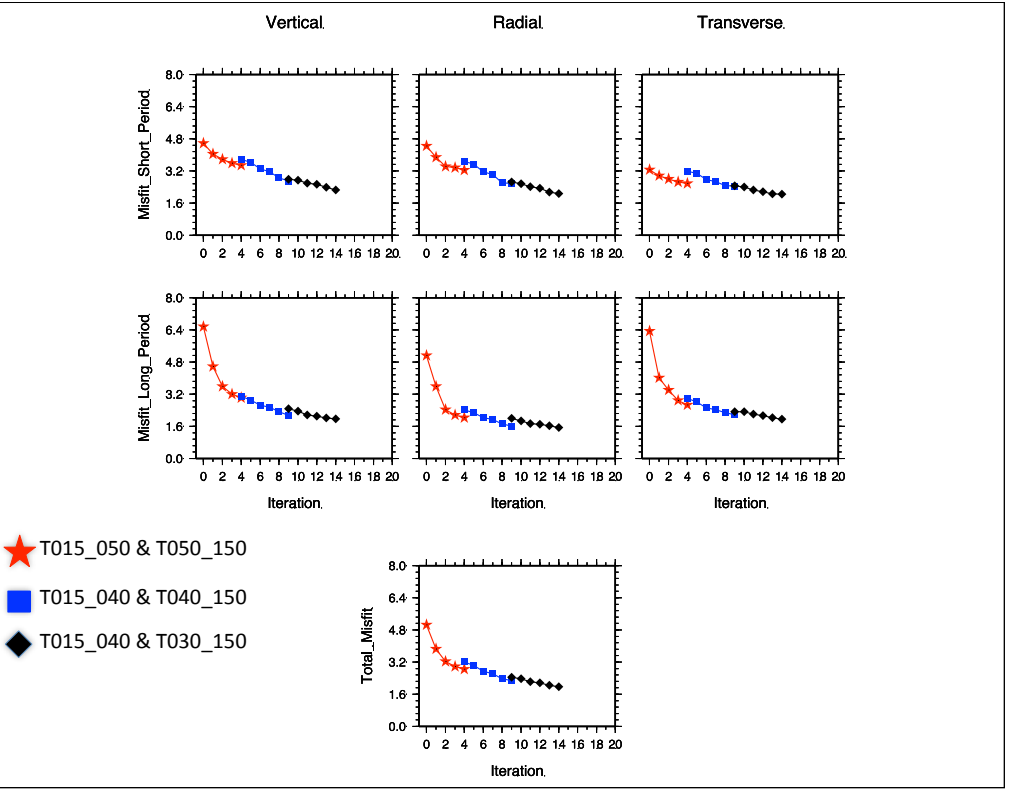
T015_040 & T040_150
T015_040 & T030_150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Radial
Transverse
Misfit_Short_Period
Misfit_Long_Period
Total_Misfit
Iteration
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T015_050 & T050_150
T015_040 & T040_150
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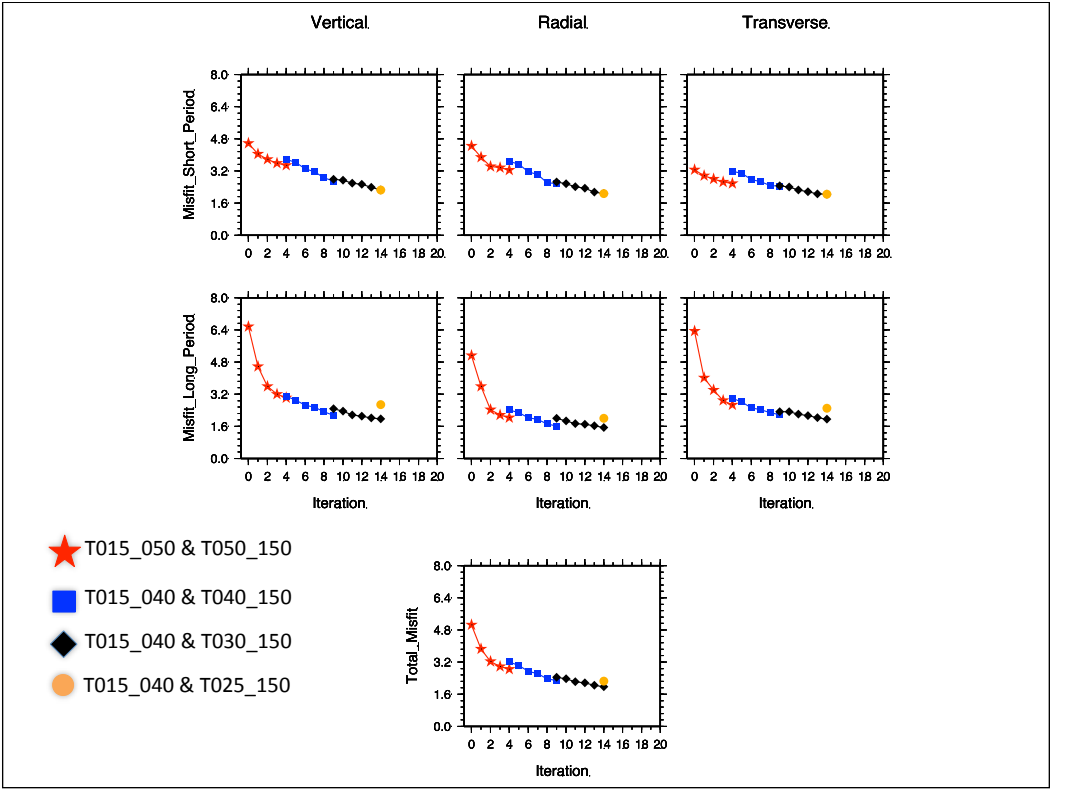
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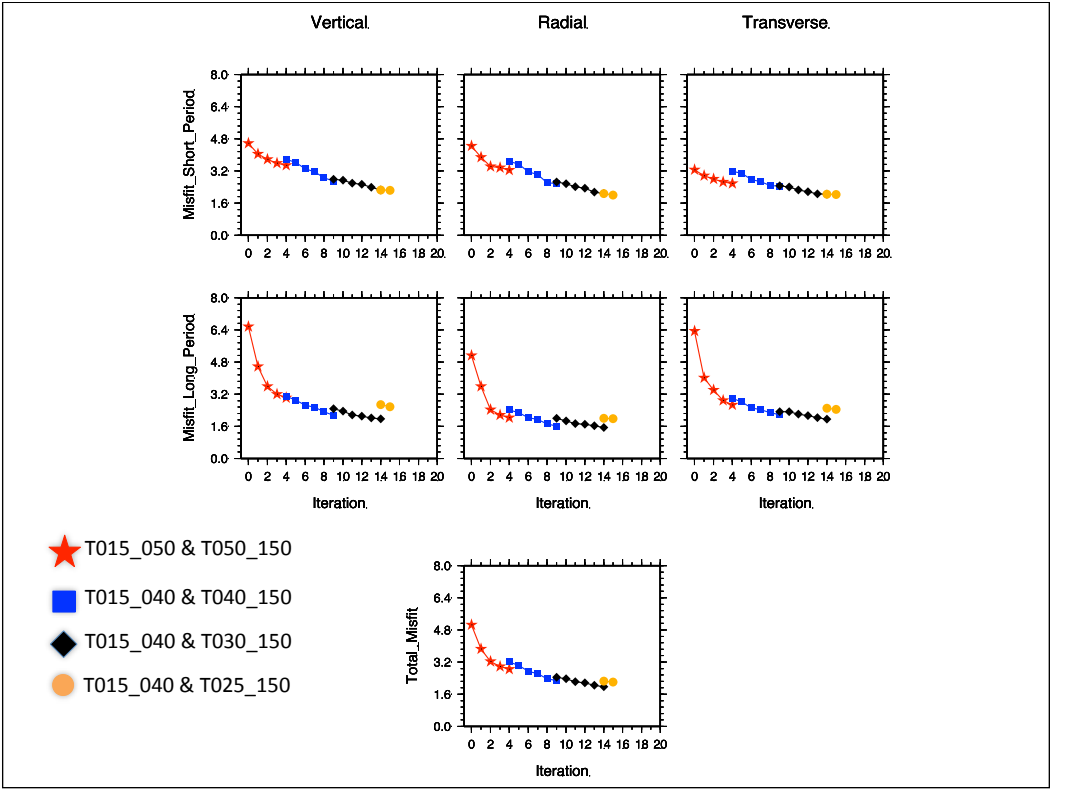
T015_050 & T050_150
T015_040 & T040_150
T015_040 & T030_150
T015_040 & T025_150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Total_Misfit
Iteration.
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T015_050 & T050_150
T015_040 & T040_150
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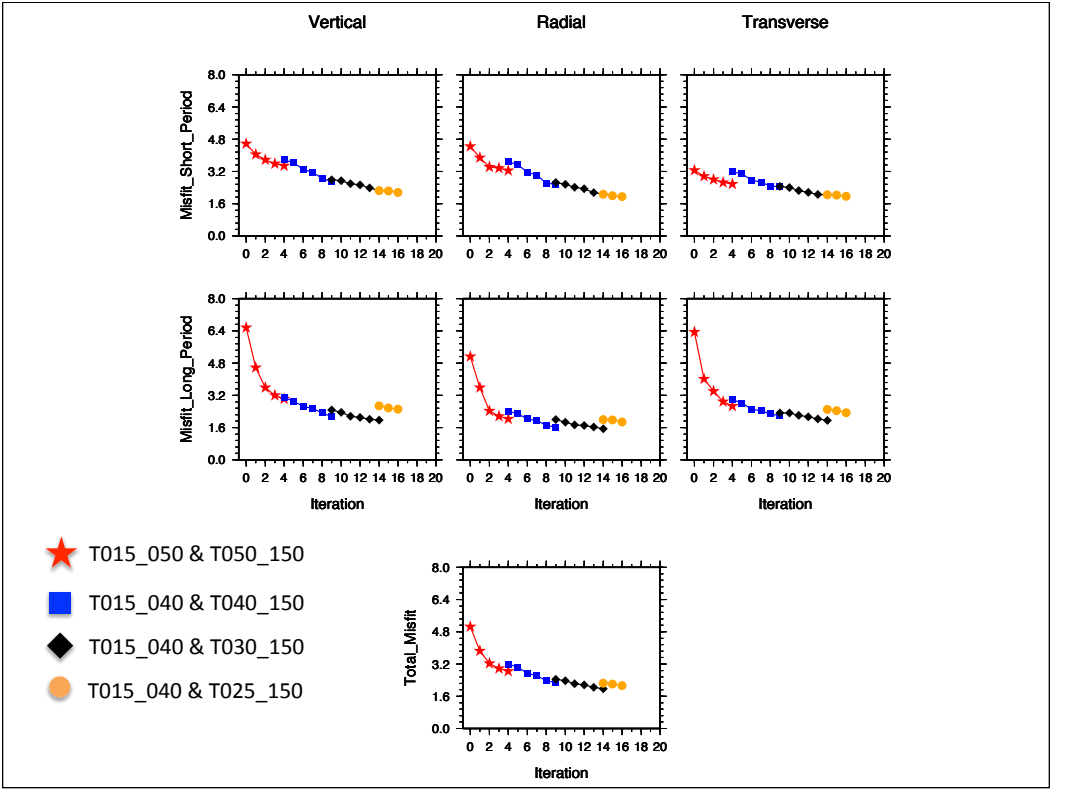
Vertical
Radial
Transverse
Misfit_Short_Period
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Total_Misfit
Iteration
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T015_050 & T050_150
T015_040 & T040_150
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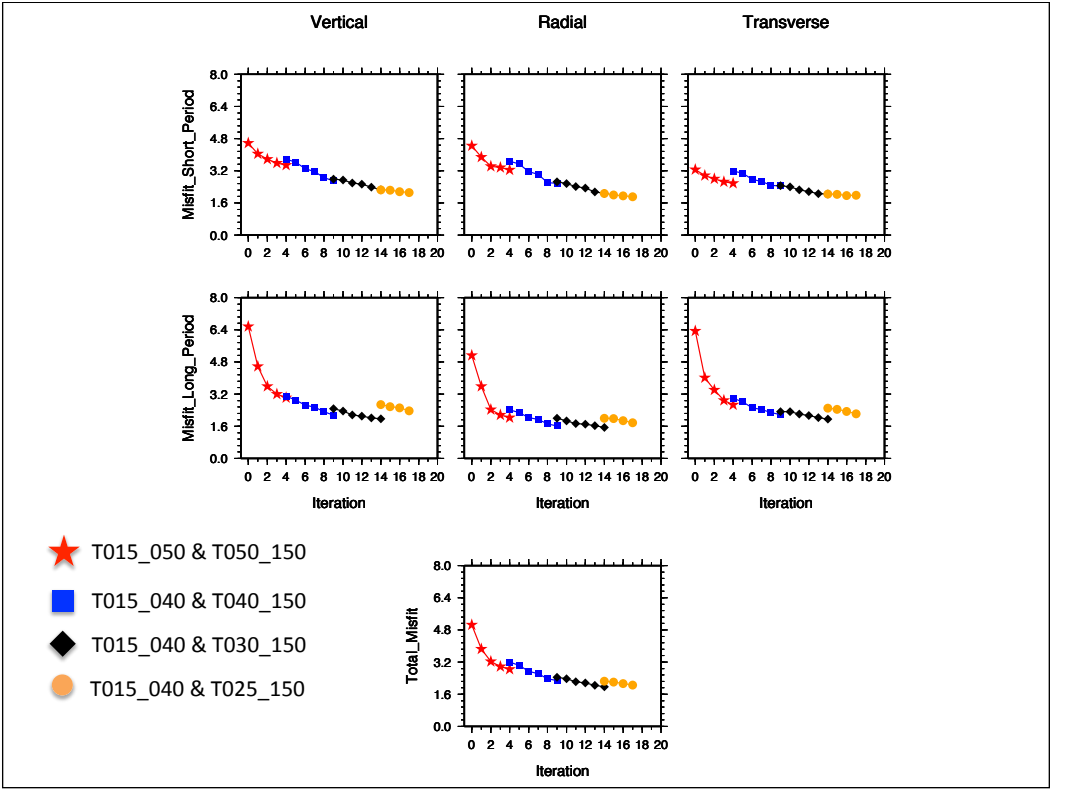
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Radial
Transverse
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T015_050 & T050_150
T015_040 & T040_150
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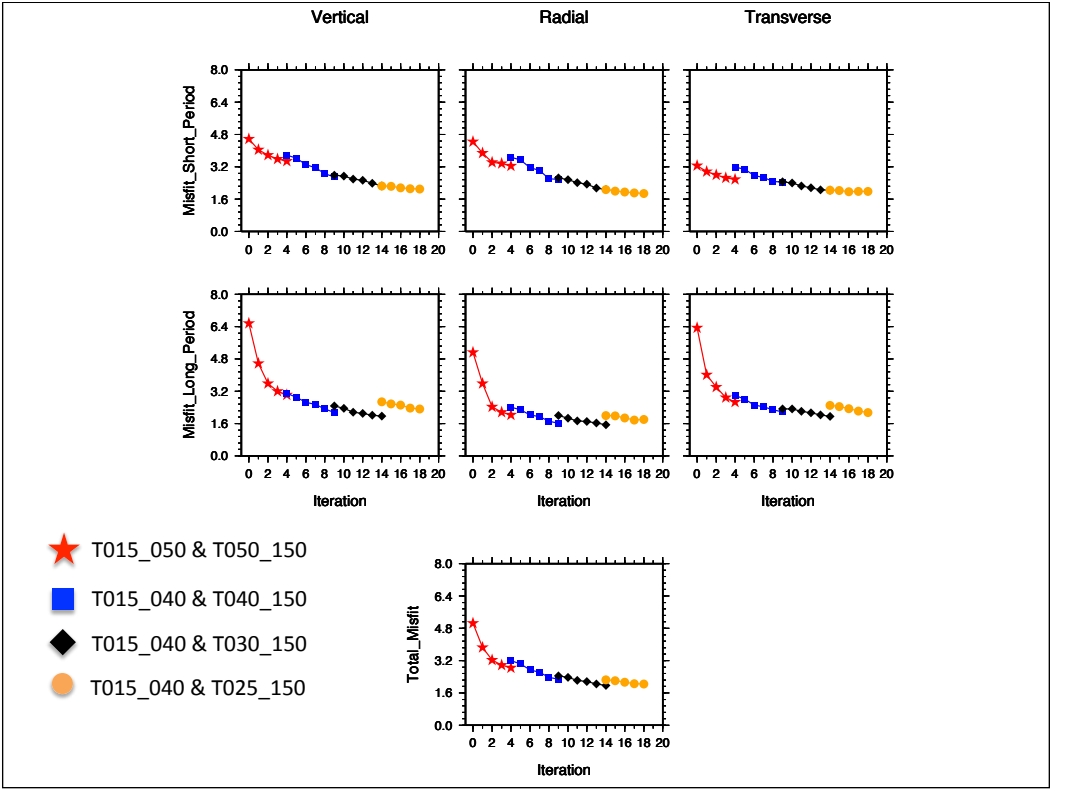
Vertical
Radial
Transverse
Misfit_Short_Period
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Iteration
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T015_050 & T050_150
T015_040 & T040_150
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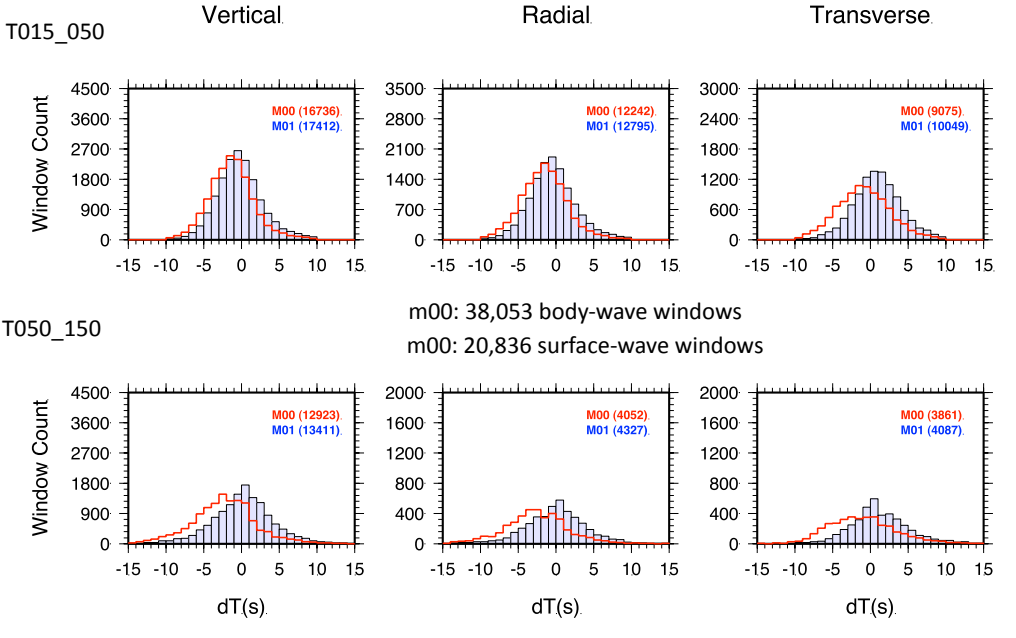
T015_050
Vertical
Radial
Transverse
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M01 (10049)
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m00: 20,836 surface-wave windows
T050_150
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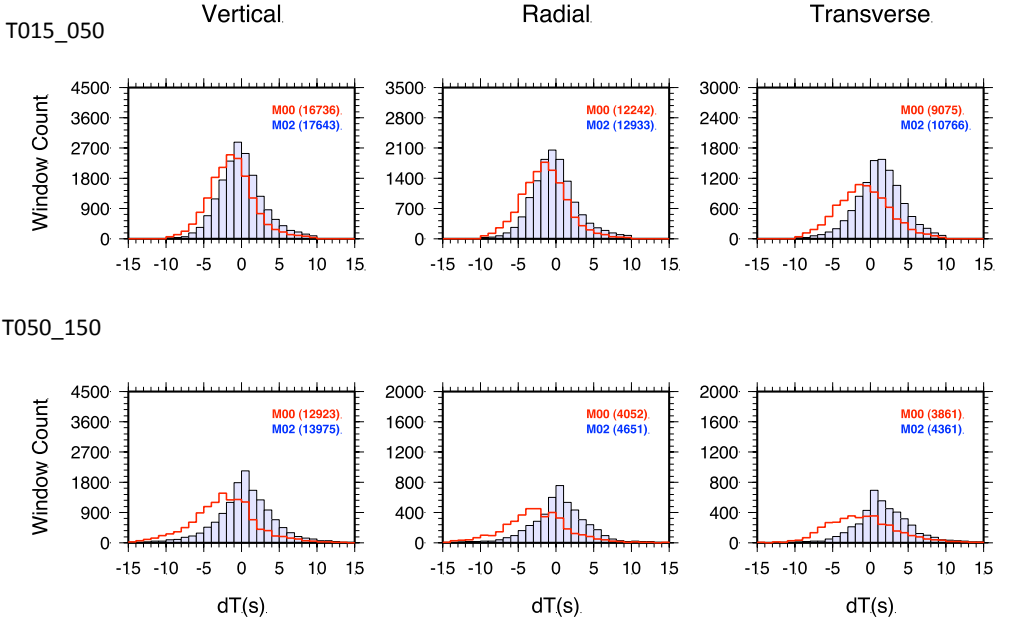
dT(s)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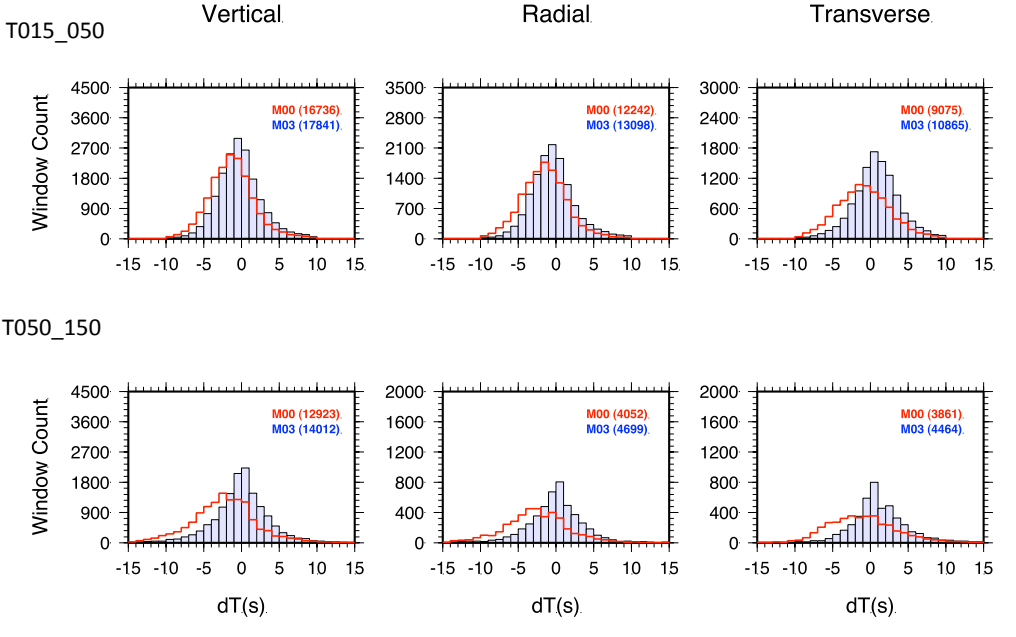
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Transverse
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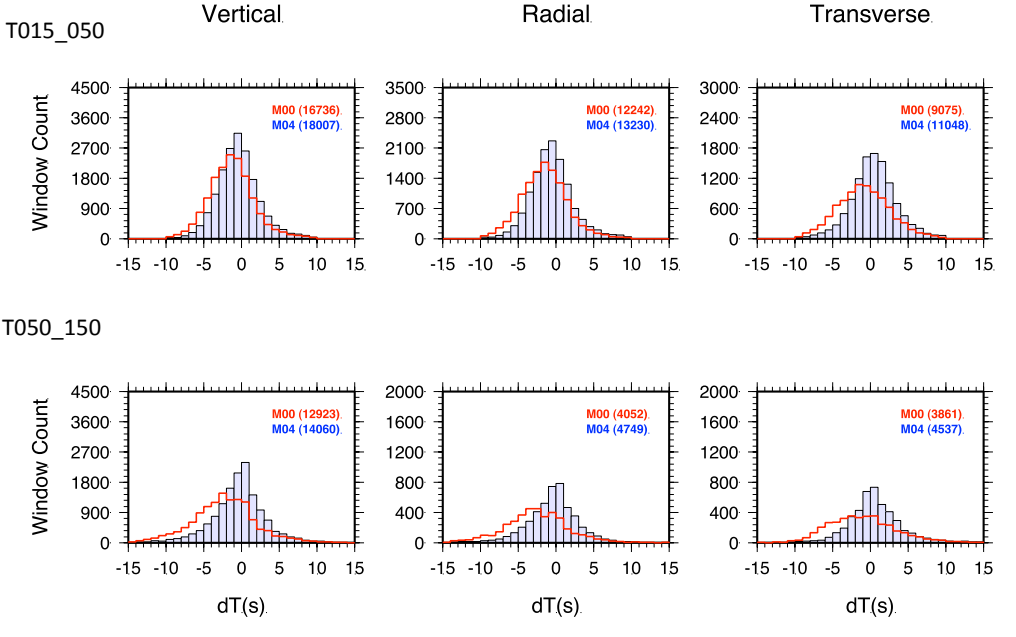
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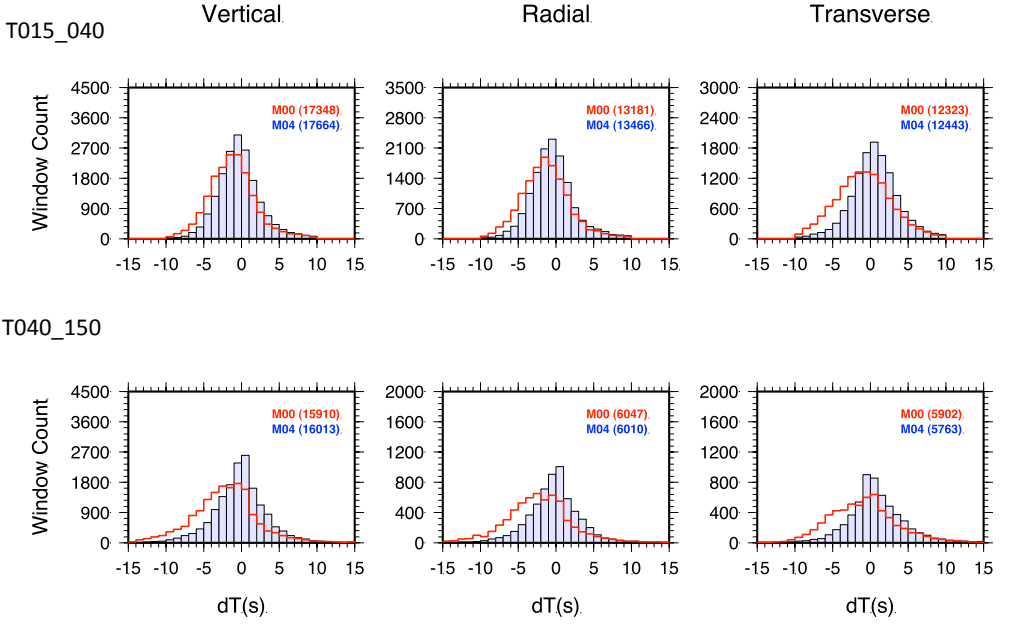
dT(s)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Transverse
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M04 (12443)
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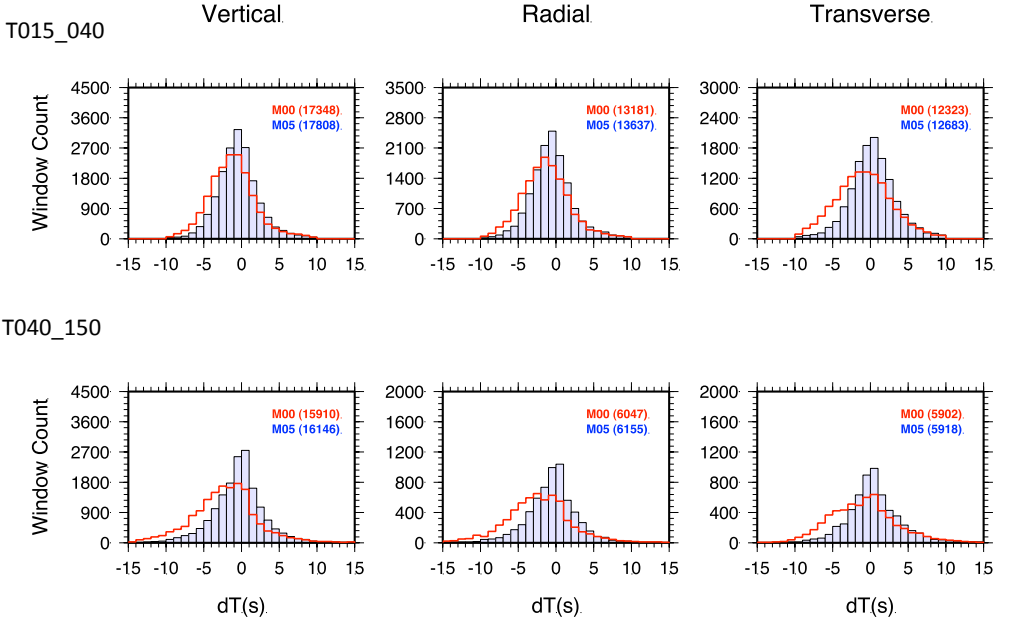
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Transverse
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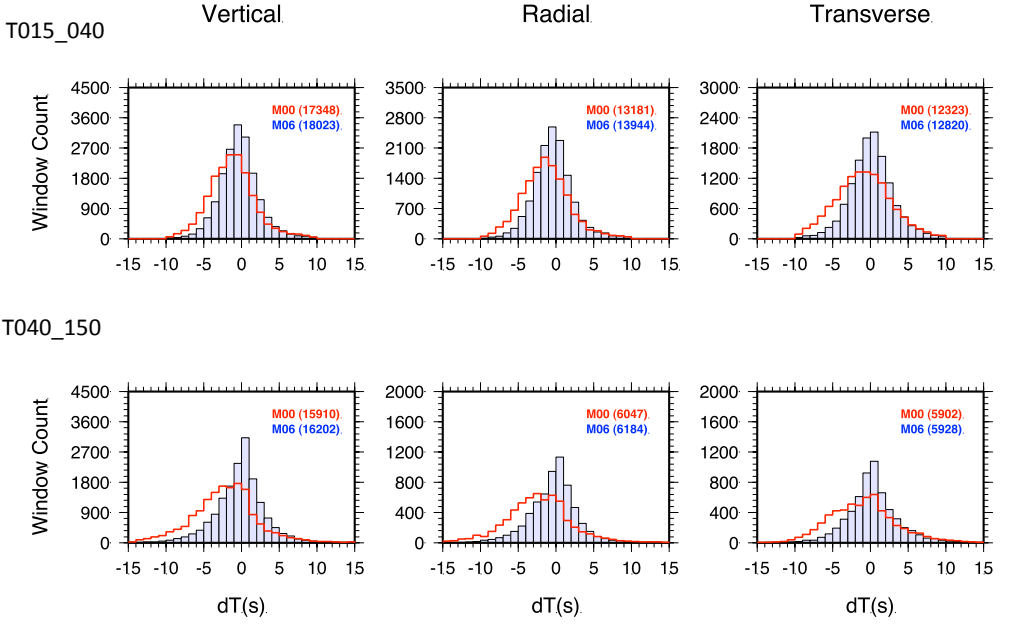
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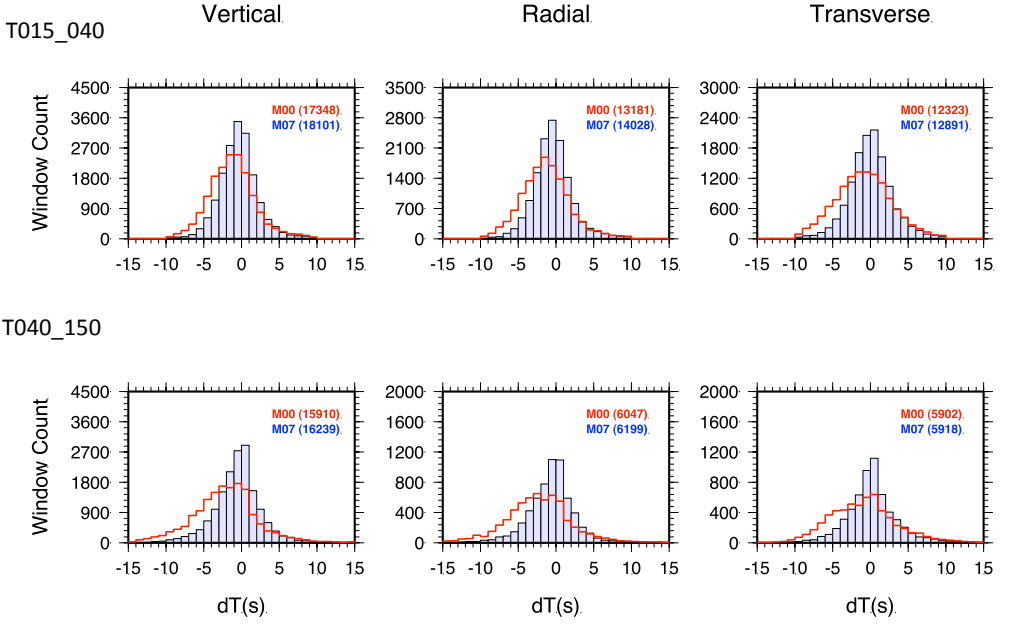
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Radial
Transverse
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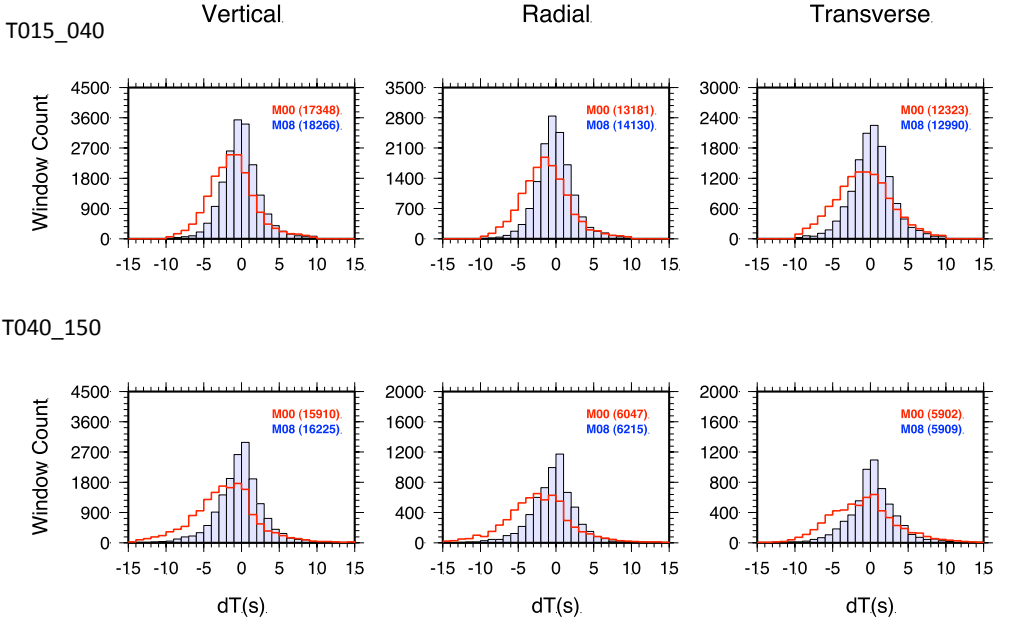
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Transverse
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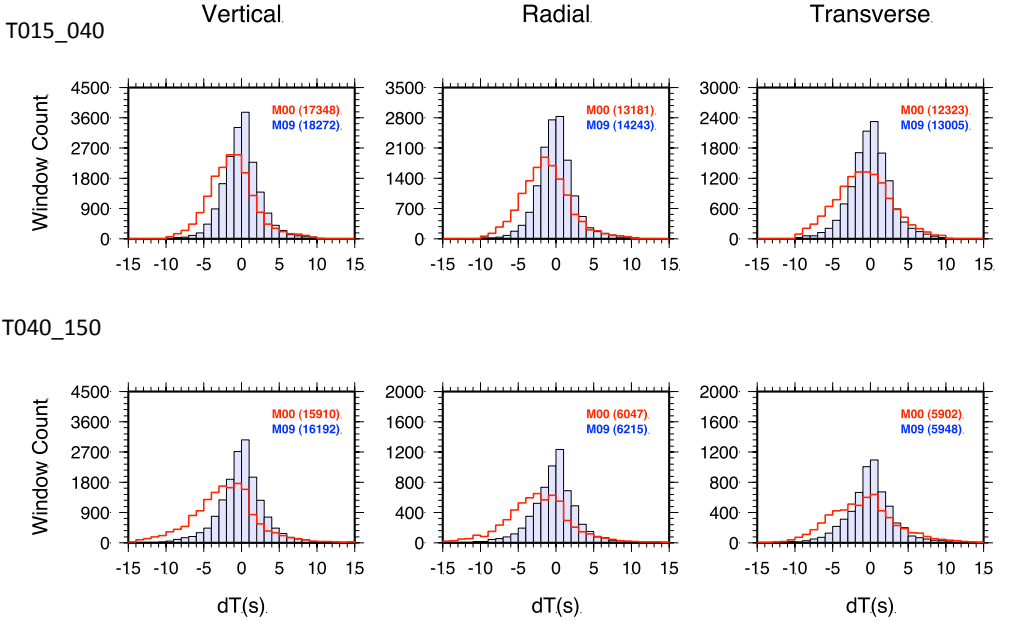
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Radial
Transverse
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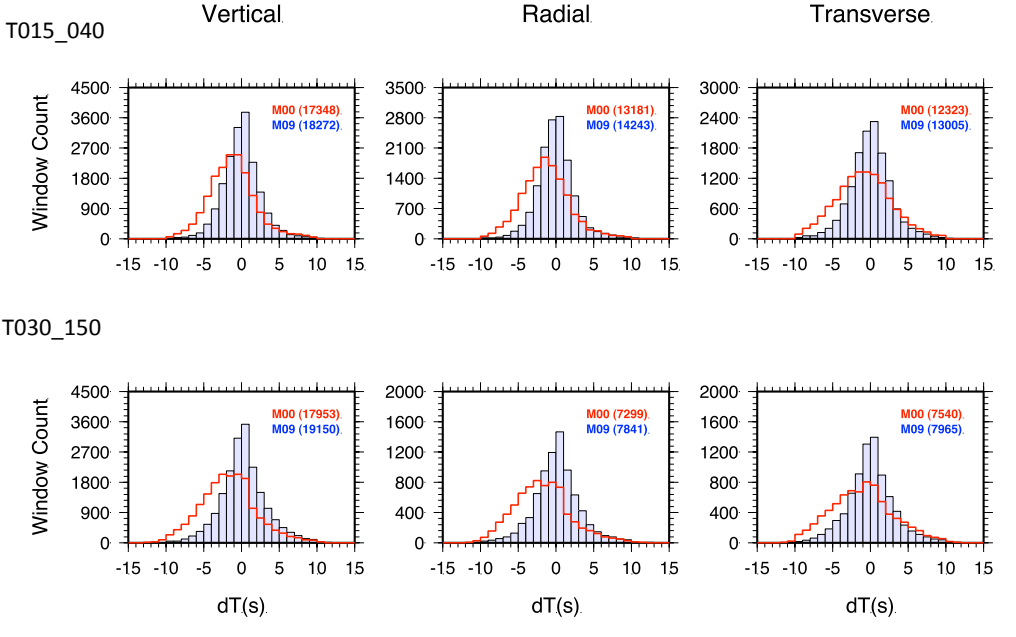
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Vertical
Radial
Transverse
Window Count
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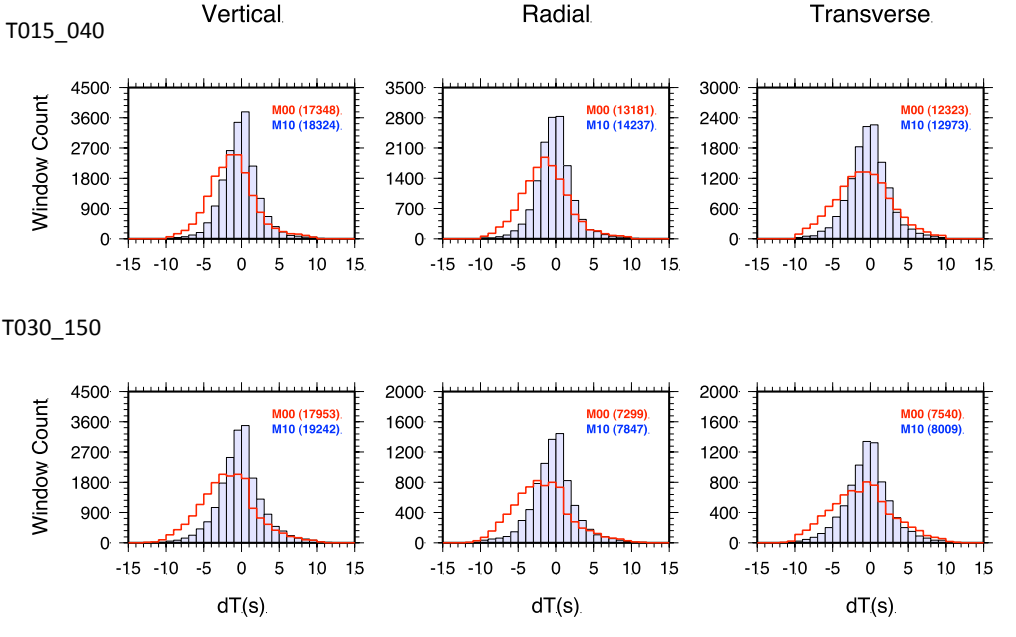
dT(s)


T015_040
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Radial
Transverse
Window Count
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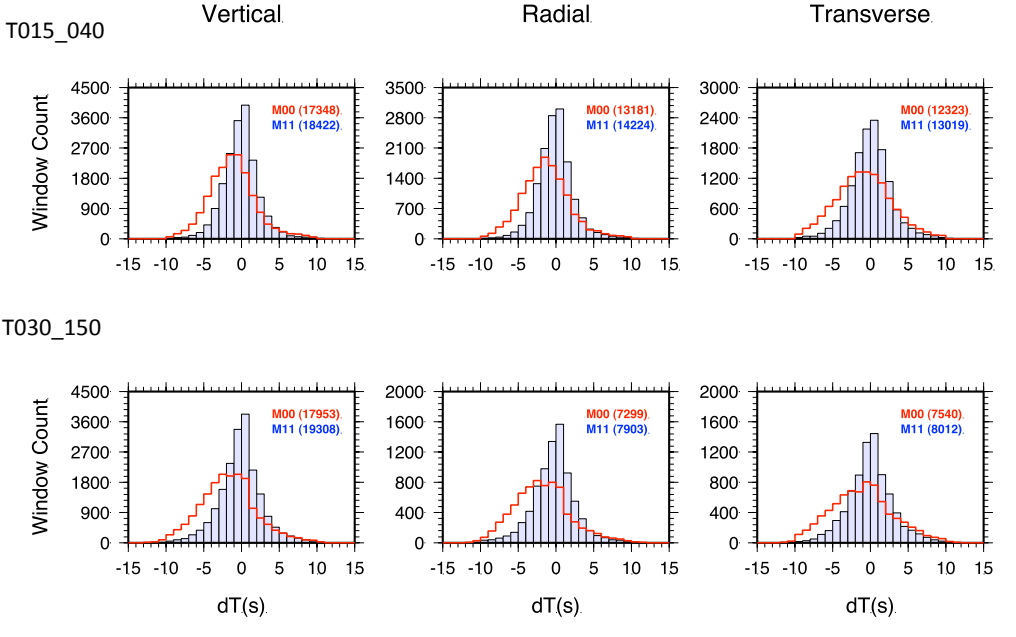
dT(s)
dT(s)


T015_040
Vertical
Radial
Transverse
Window Count
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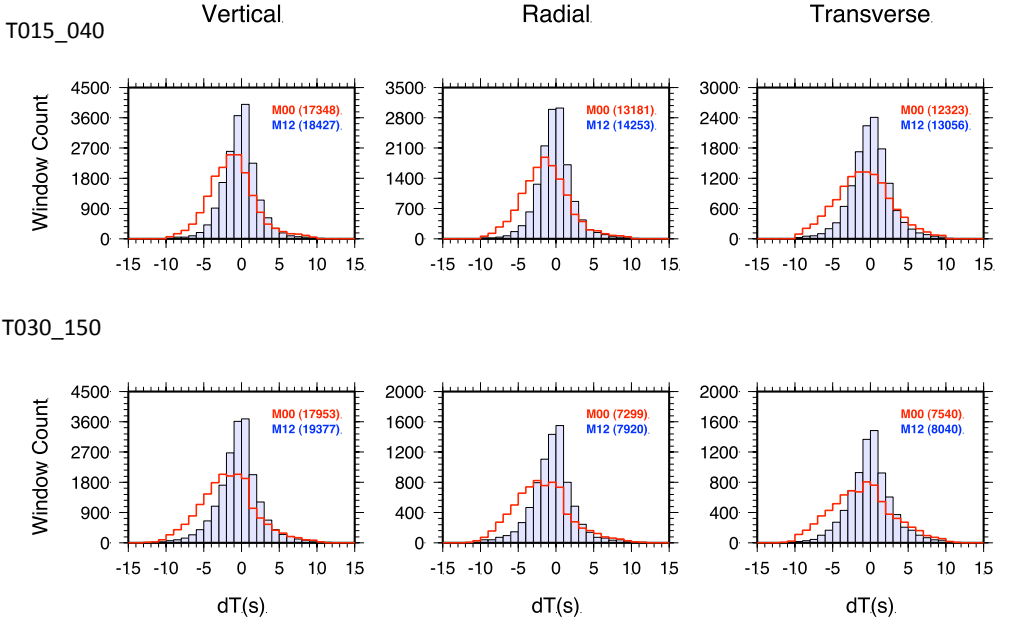
M11 (18422)
M00 (13181)
M11 (14224)
M00 (12323)
M11 (13019)
T030_150
M00 (17953)
M11 (19308)
M00 (7299)
M11 (7903)
M00 (7540)
M11 (8012)
dT(s)
dT(s)
dT(s)


T015_040
Vertical
Radial
Transverse
Window Count
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M12 (13056)
T030_150
M00 (17953)
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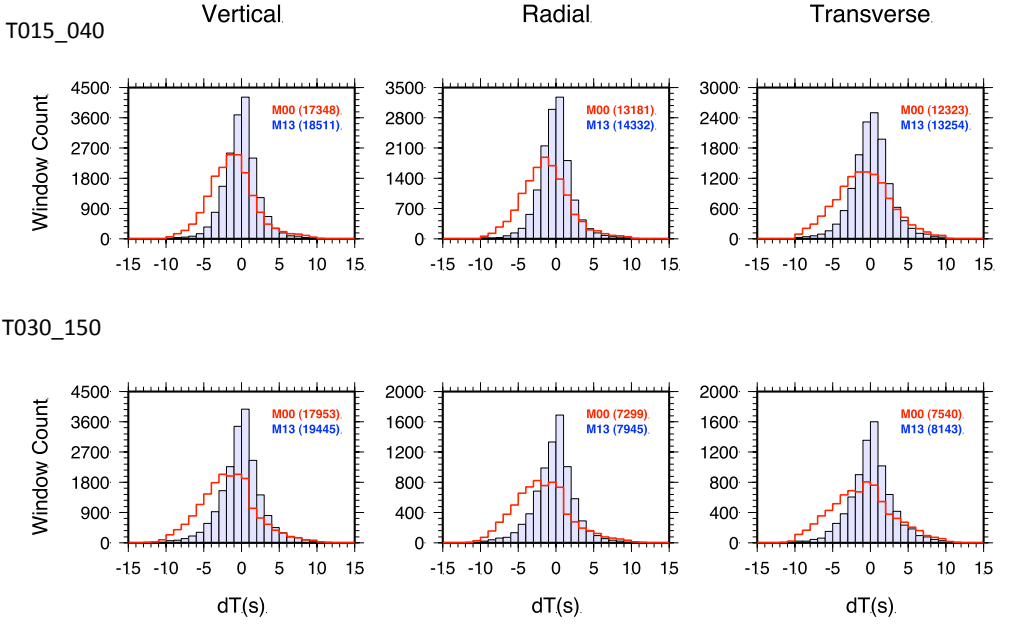
M00 (7540)
M12 (8040)
dT(s)
dT(s)
dT(s)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Transverse
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T030_150
M00 (17953)
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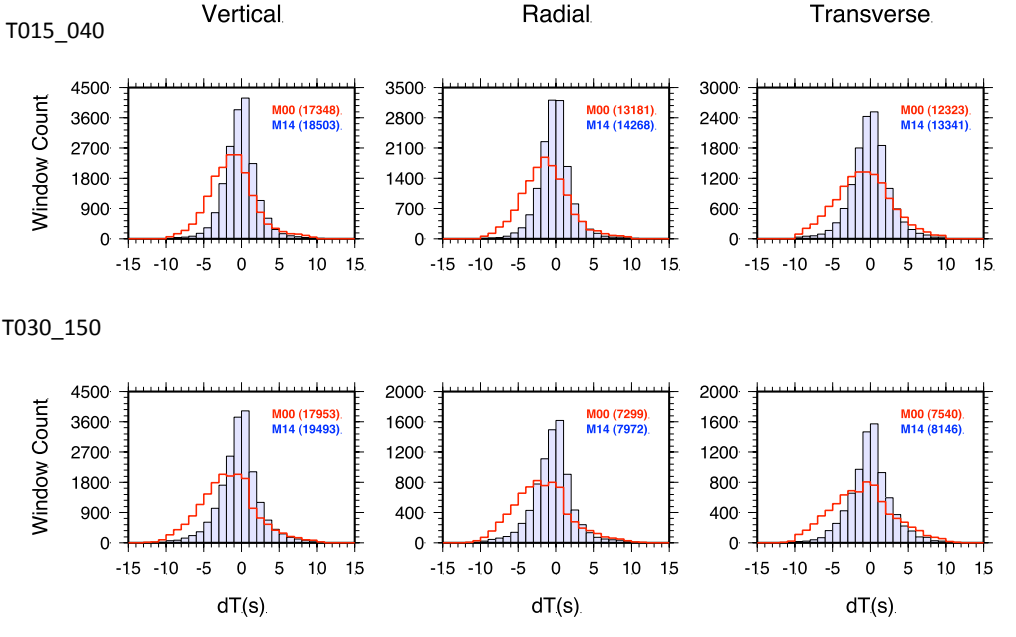
M13 (7945)
M00 (7540)
M13 (8143)
dT(s)
dT(s)
dT(s)


T015_040
Vertical
Radial
Transverse
Window Count
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M14 (18503)
M00 (13181)
M14 (14268)
M00 (12323)
M14 (13341)
T030_150
M00 (17953)
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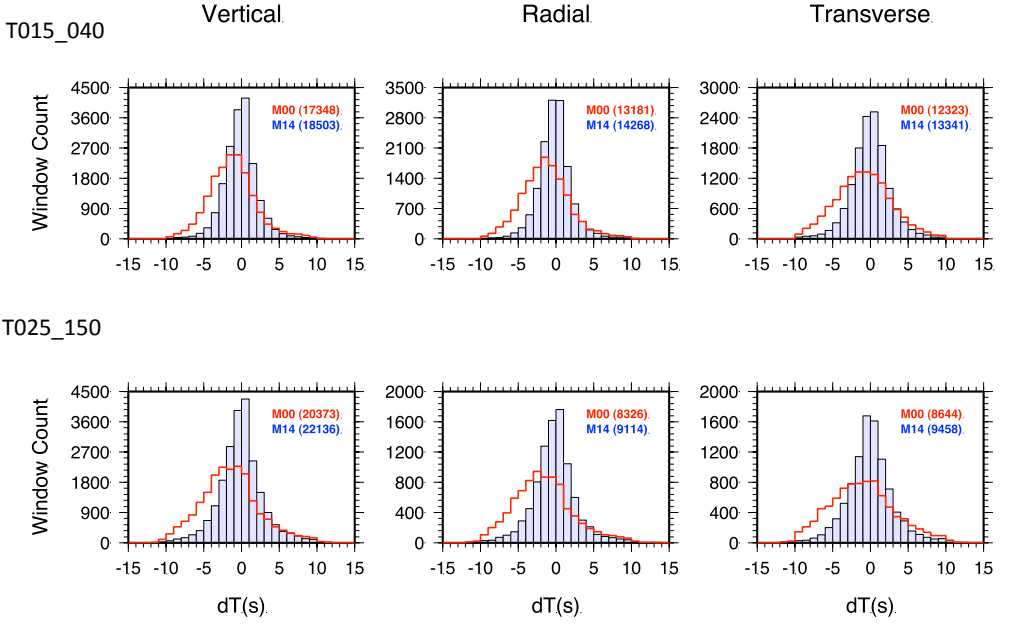
M00 (7299)
M14 (7972)
M00 (7540)
M14 (8146)
dT(s)
dT(s)
dT(s)


Vertical
Radial
Transverse
T015_040
Window Count
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M14 (18503)
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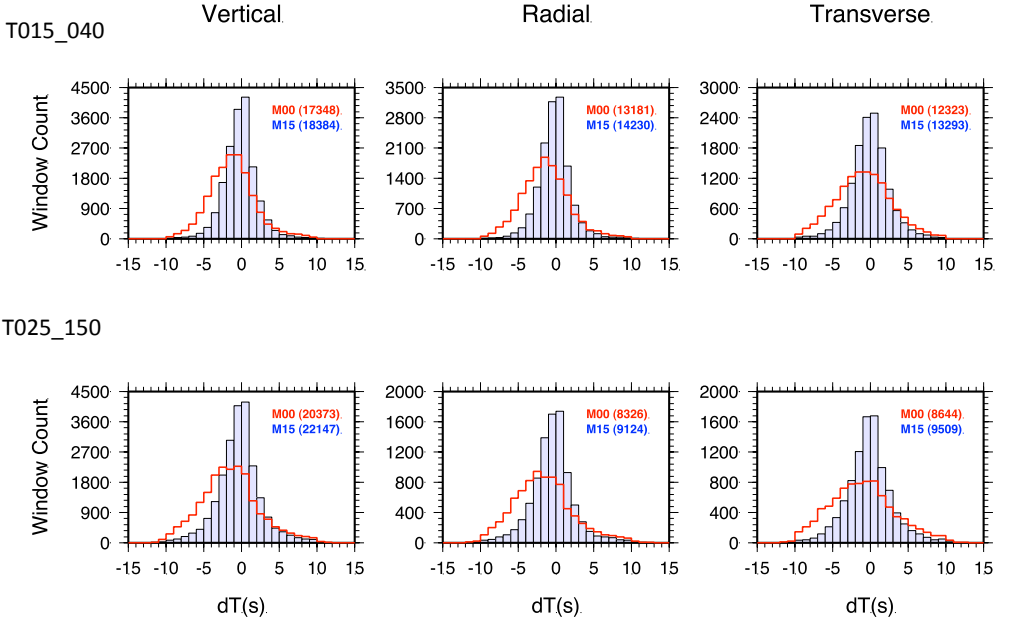
M14 (13341)
T025_150
M00 (20373)
M14 (22136)
M00 (8326)
M14 (9114)
M00 (8644)
M14 (9458)
dT(s)


T015_040
Vertical
Radial
Transverse
Window Count
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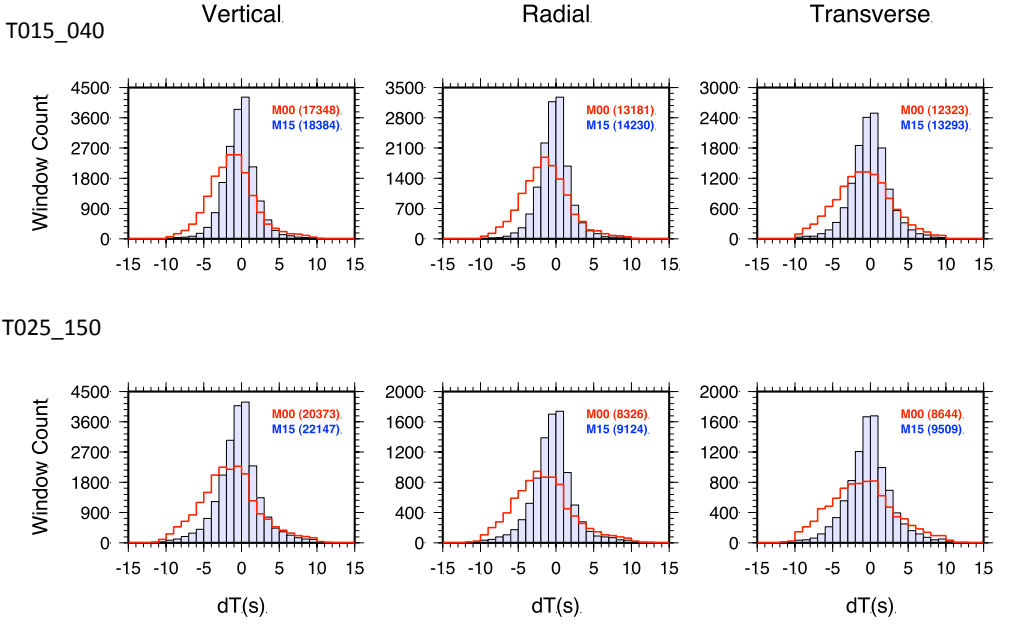
M00 (13181)
M15 (14230)
M00 (12323)
M15 (13293)
T025_150
M00 (20373)
M15 (22147)
M00 (8326)
M15 (9124)
M00 (8644)
M15 (9509)
dT(s)
dT(s)
dT(s)


T015_040
Vertical
Radial
Transverse
Window Count
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M00 (13181)
M15 (14230)
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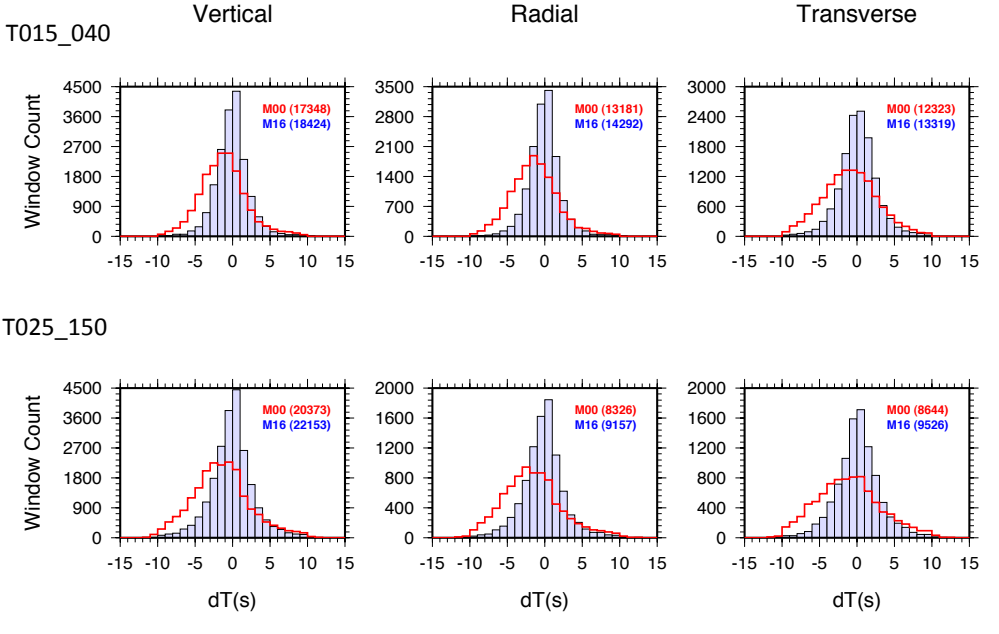
M15 (13293)
T025_150
M00 (20373)
M15 (22147)
M00 (8326)
M15 (9124)
M00 (8644)
M15 (9509)
dT(s)
dT(s)
dT(s)


Vertical
Radial
Transverse
T015_040
T025_150
Window Count
dT(s)
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M00 (12323)
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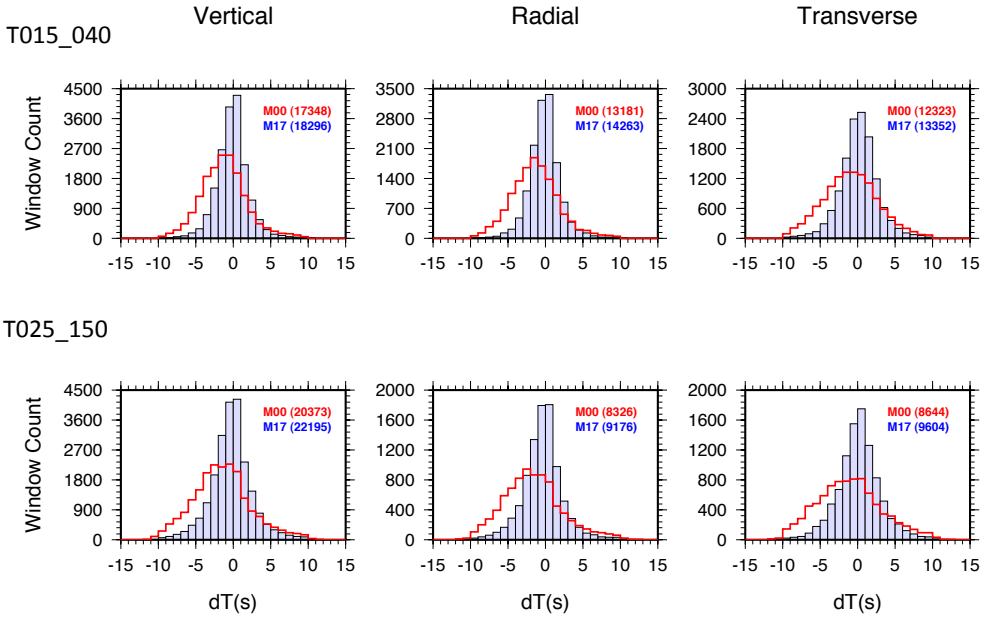
M00 (20373)
M16 (22153)
M00 (8326)
M16 (9157)
M00 (8644)
M16 (9526)


Vertical
Radial
Transverse
T015_040
Window Count
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M17 (13352)
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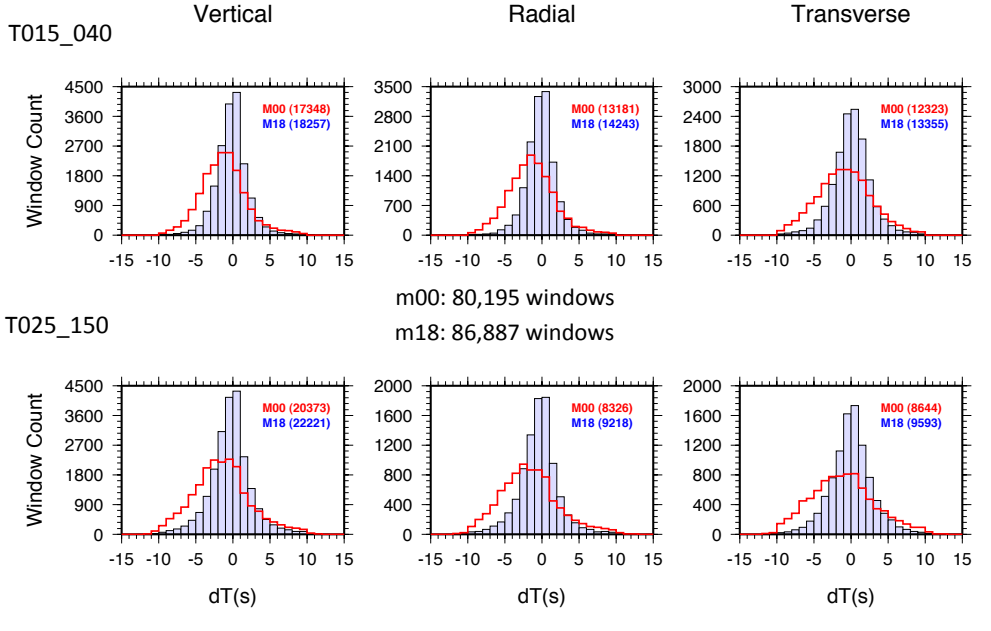
M00 (20373)
M17 (22195)
M00 (8326)
M17 (9176)
M00 (8644)
M17 (9604)
dT(s)


Vertical
Radial
Transverse
T015_040
Window Count
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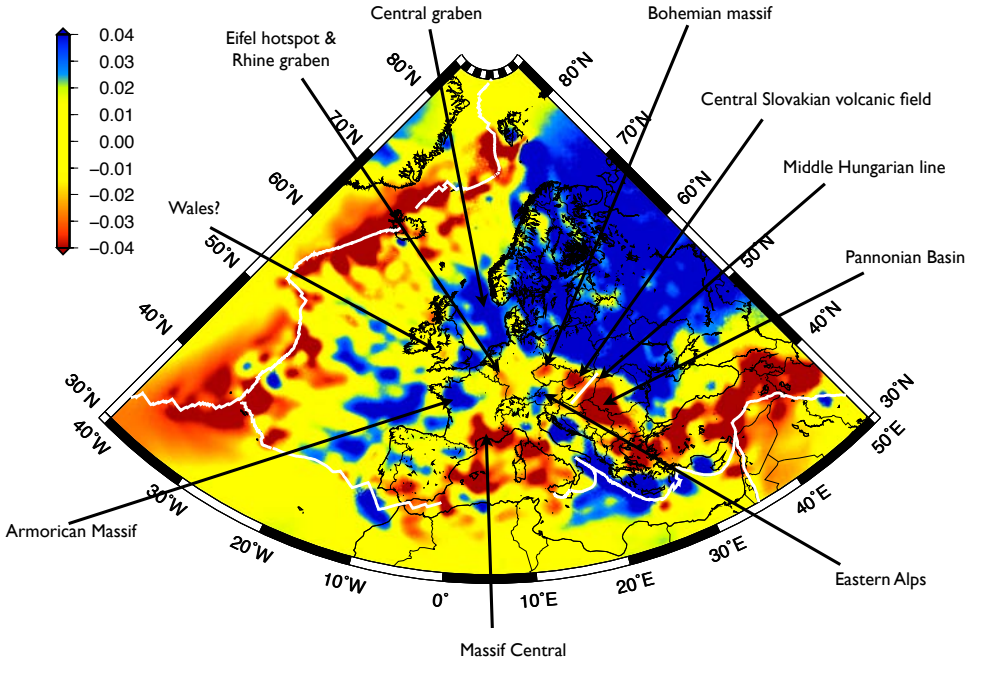
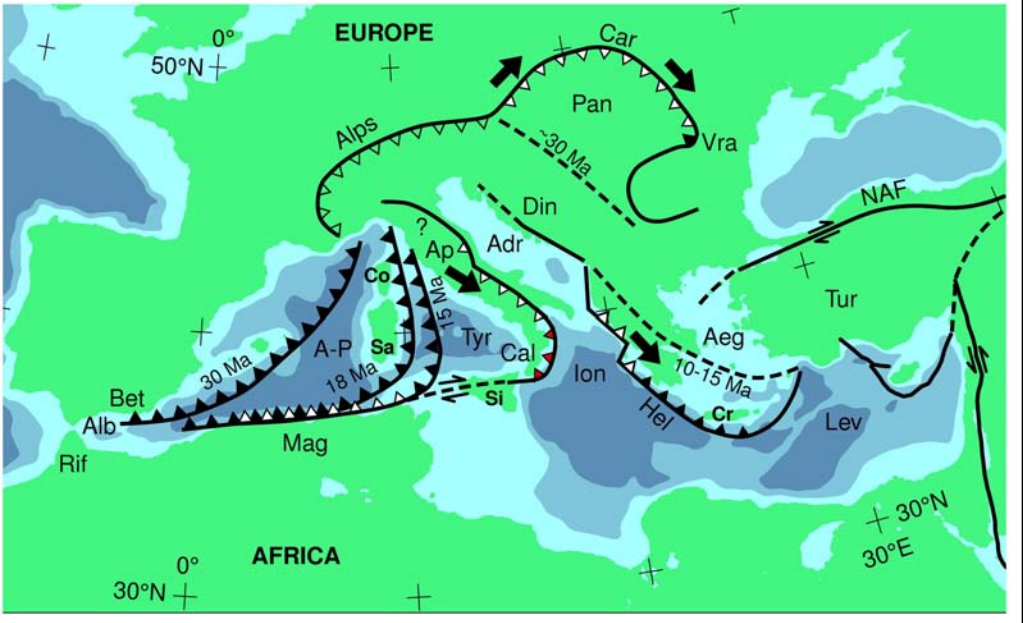
M18 (18257)
M00 (13181)
M18 (14243)
M00 (12323)
M18 (13355)
m00: 80,195 windows
m18: 86,887 windows
T025_150
M00 (20373)
M18 (22221)
M00 (8326)
M18 (9218)
M00 (8644)
M18 (9593)
dT(s)
dT(s)
dT(s)

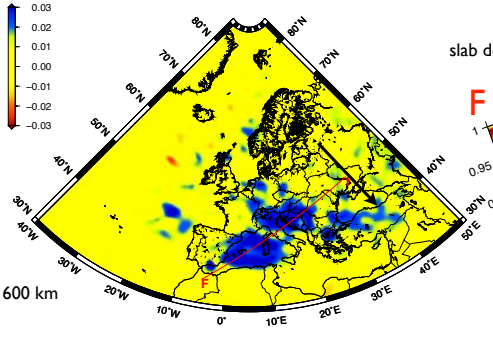
Depth 75 km

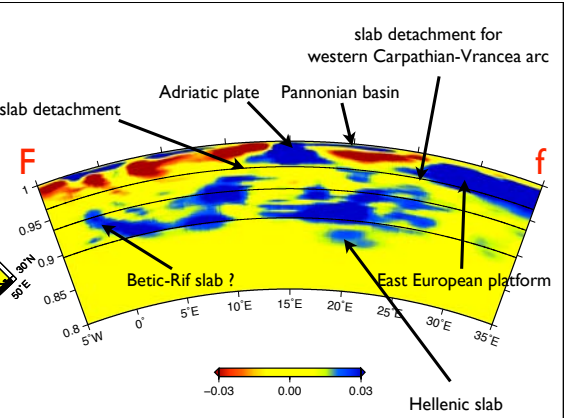

0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
Central graben
Bohemian massif
Eifel hotspot &
Rhine graben
Central Slovakian volcanic field
Middle Hungarian line
Wales?
Pannonian Basin
Armorican Massif
Eastern Alps
Massif Central
80°N
70°N
60°N
50°N
40°N
30°N
40°W
30°W
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E

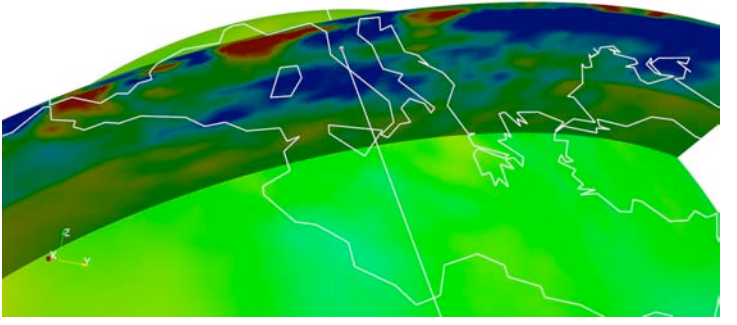
Mediterranean-Calabria Paleotectonics

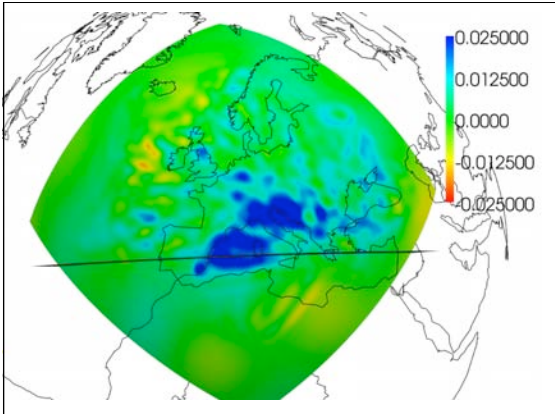


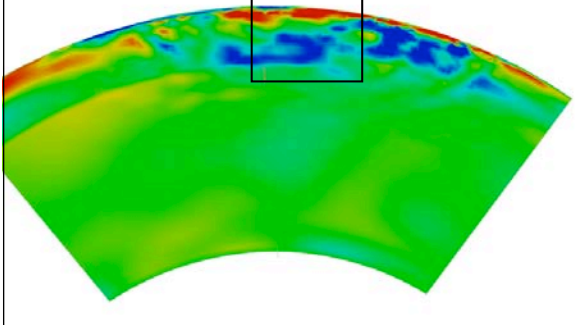
Wortel & Spakman (2000)

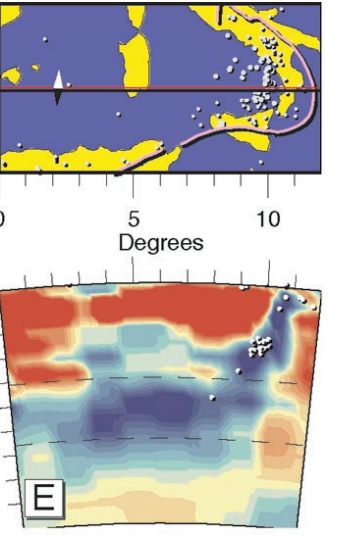

0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
80°N
70°N
60°N
50°N
40°N
30°N
40°W
30°W
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
F
600 km


slab detachment for
western Carpathian-Vrancea arc
Adriatic plate
Pannonian basin
slab detachment
F
f
1
0.95
0.9
0.85
0.8
5°W
0°
5°E
10°E
15°E
20°E
25°E
30°E
35°E
Betic-Rif slab ?
East European platform
Hellenic slab
−0.03
0.00
0.03

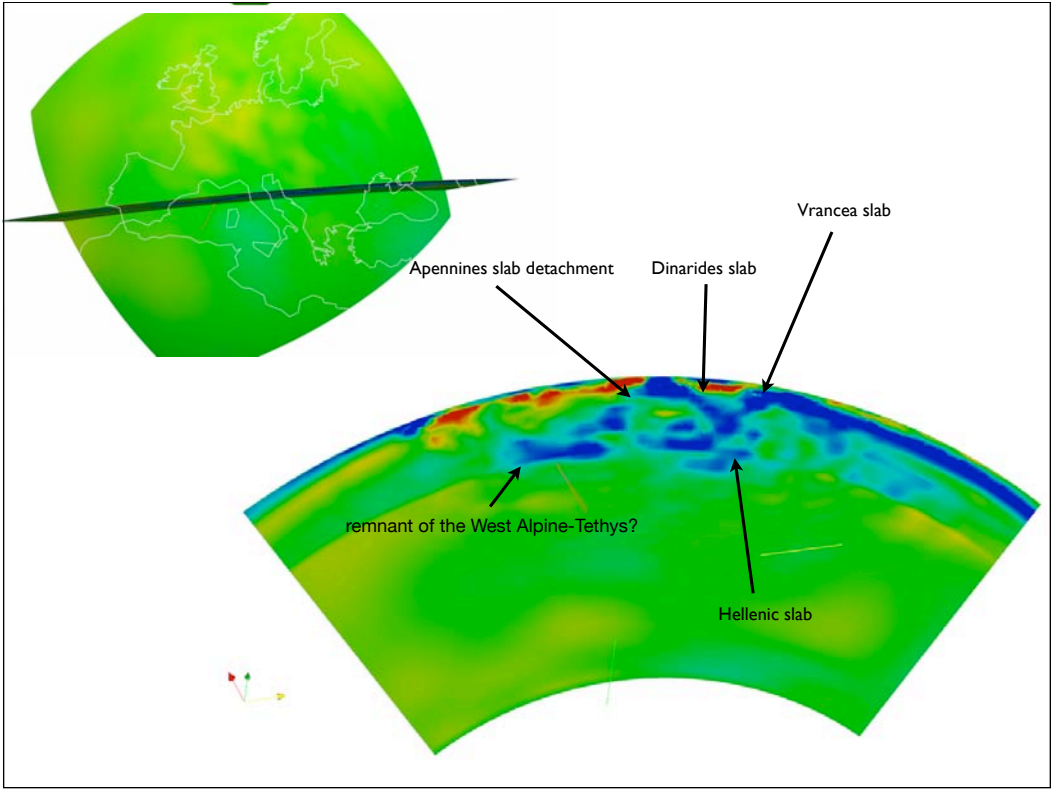




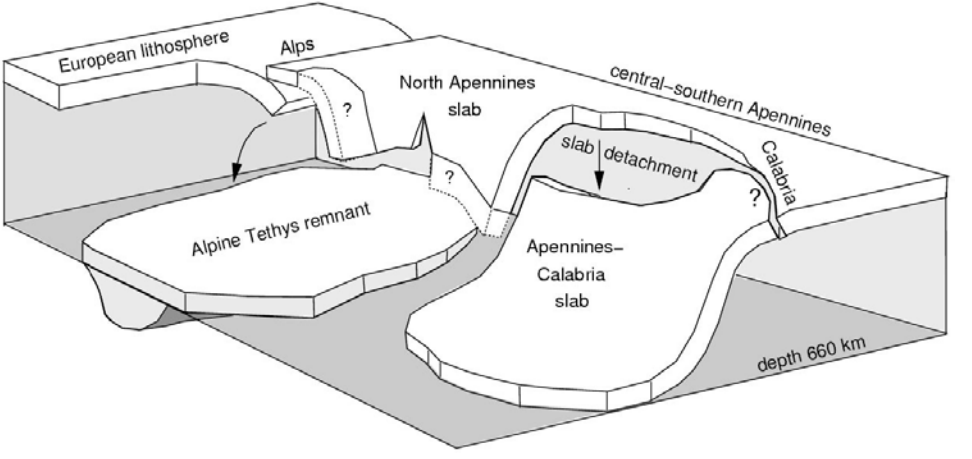




Wortel & Spakman (2000)

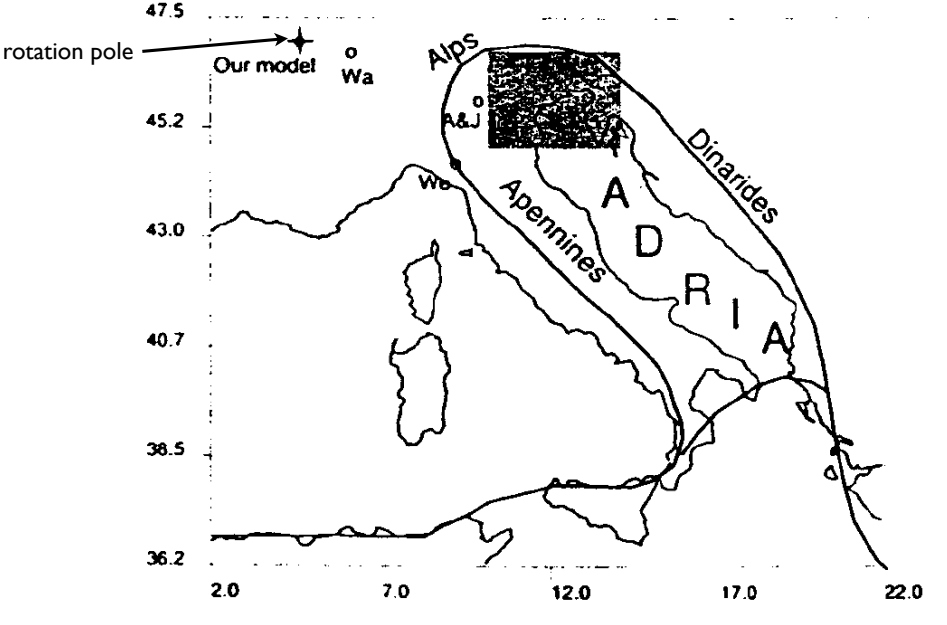

Vrancea slab
Apennines slab detachment
Dinarides slab
remnant of the West Alpine-Tethys?
Hellenic slab

Apennines-Calabria

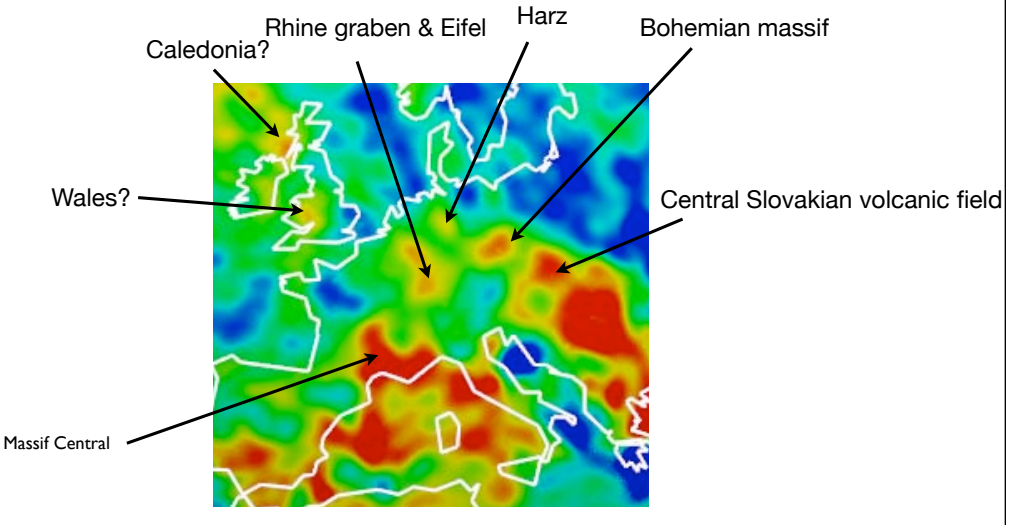


Spakman & Wortel (2004)

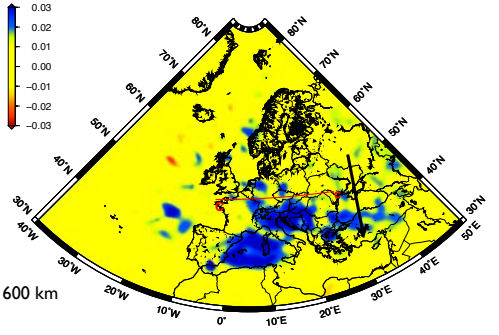
Adria Plate

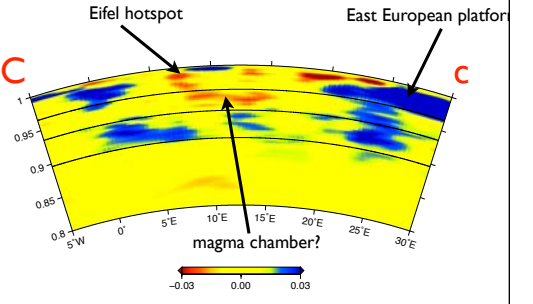


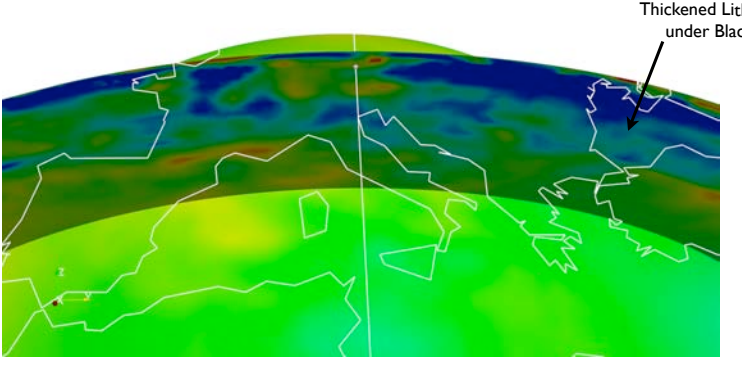
Rossi et al. (1997)


Caledonia?
Rhine graben & Eifel
Harz
Bohemian massif
Wales?
Central Slovakian volcanic field
Massif Central

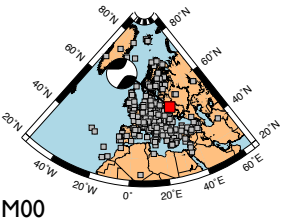
Depth 75 km


0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
80°N
70°N
60°N
50°N
40°N
30°N
40°W
30°W
20°W
10°W
0°
10°E
20°E
30°E
40°E
50°E
600 km


Eifel hotspot
East European platfor
C
C
1
0.95
0.9
0.85
0.8
5°W
0°
5°E
10°E
15°E
20°E
25°E
30°E
magma chamber?
−0.03
0.00
0.03

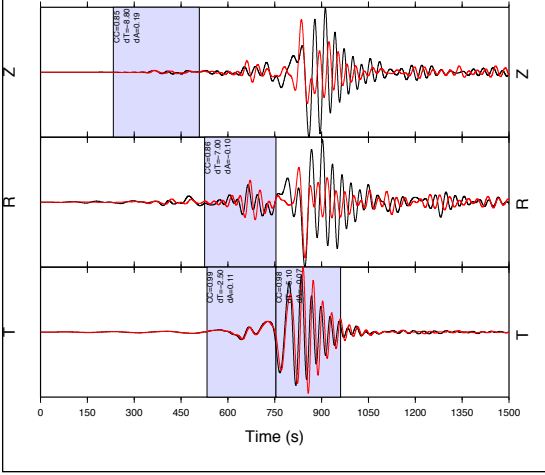

Thickened Lithosphere
under Black Sea

IU.KIEV
DIST: 29.37
BCAZ: 316.05
EVDP: 8.70
EVLO: −21.17
EVLA: 63.93
STLO: 29.22
STLA: 50.70
MB: 6.0



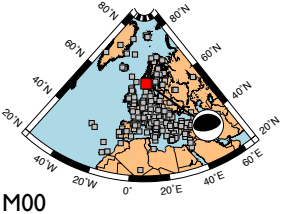
200805291546A

M00

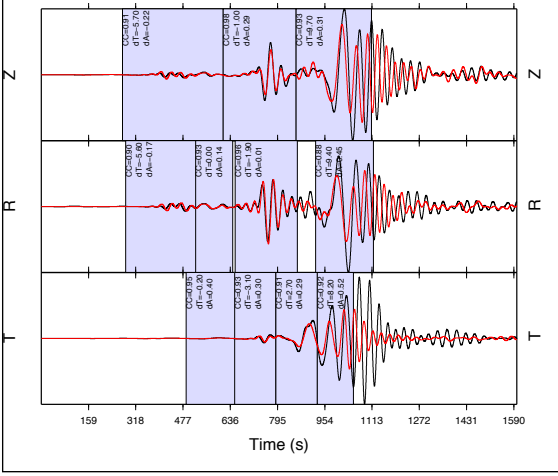


IU.KONO

DIST: 34.82
BCAZ: 115.45
EVDP: 10.27
EVLO: 48.97
EVLA: 35.82
STLO: 9.60
STLA: 59.65
MB: 6.2



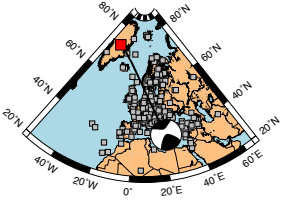
M00



062202B

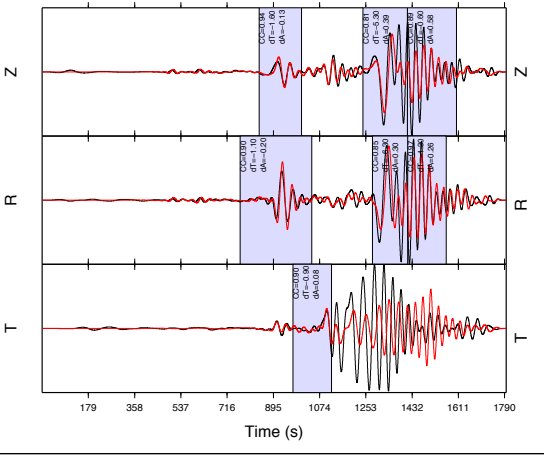
GE.SUMG

DIST: 45.37
BCAZ: 105.63
EVDP: 22.90
EVLO: 21.62
EVLA: 37.93
STLO: −38.45
STLA: 72.58
MB: 6.2



200806081225A

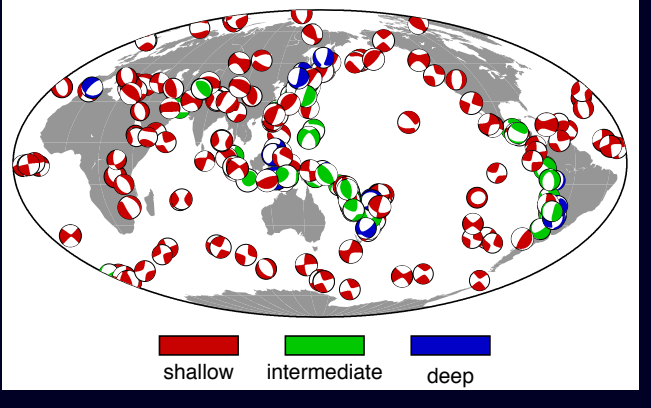
M00



Towards Global Adjoint Tomography

254 CMT events

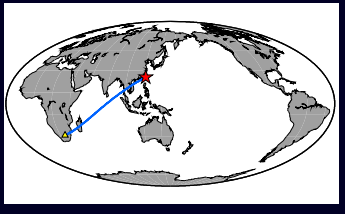
5.8 ≤ Mw ≤ 7



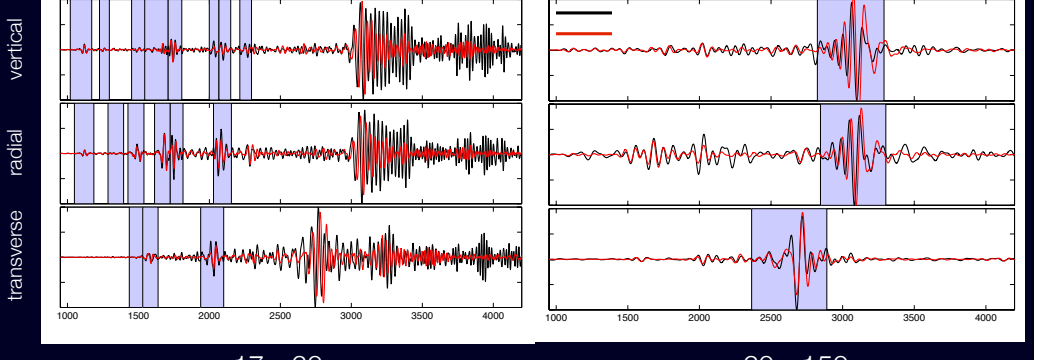
shallow: d≤ 50 km

intermediate: 50 km < d ≤ 300 km

deep: d > 300 km



Dec. 19, 2009, Taiwan
Mw=6.5, depth= 45.5 km
Station: BOSA



17 - 60 s
body waves

60 - 150 s
surface waves

Conclusions

- "Adjoint tomography" is feasible
  - Goal: whole seismogram (frequency-dependent phase & amplitude)
  - Europe (Hejun Zhu)
  - Middle East (Daniel Peter)
  - Entire globe! (Ebru Bozdag)
- Resolution Analysis

	# earthquakes	# simulations	CPU core hours
Europe	160	11,200	806,400
Globe (Phase 1)	250	17,500	14,437,400
Globe (Phase 2)	5,000	350,000	739,200,000

- Future extensions:
  - Include amplitudes
  - Shear attenuation
  - More general anisotropy

Depth 75 km

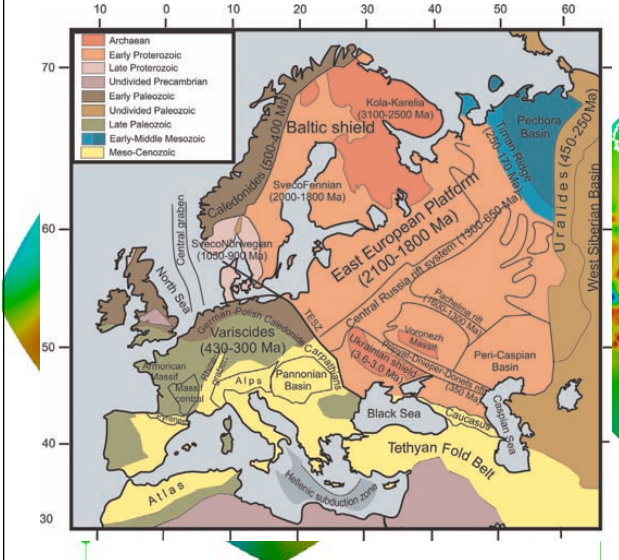
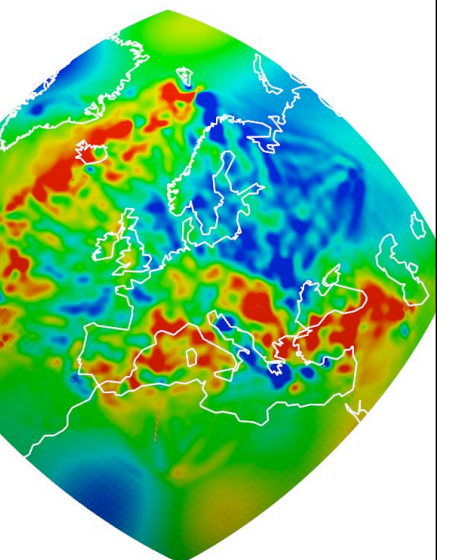
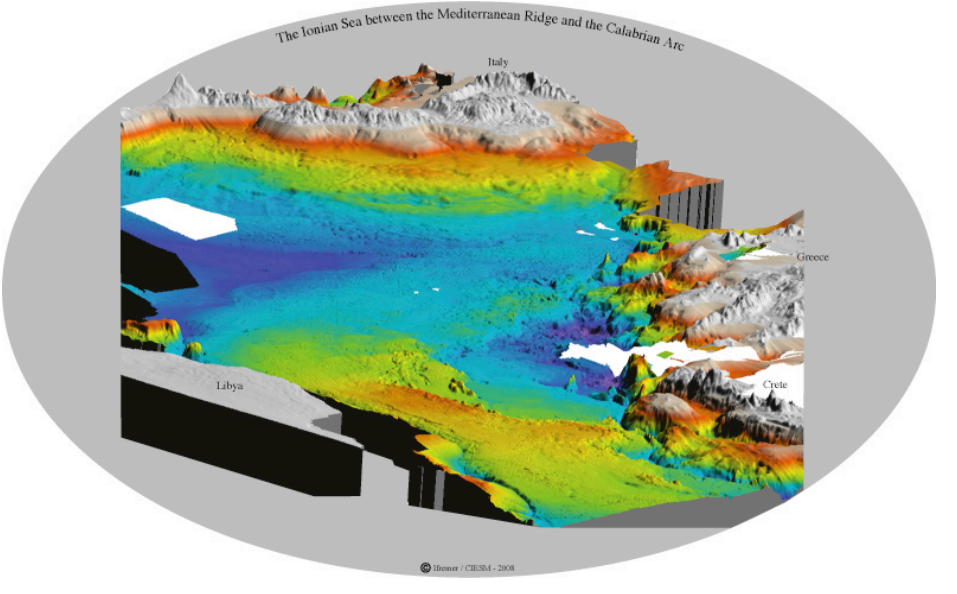
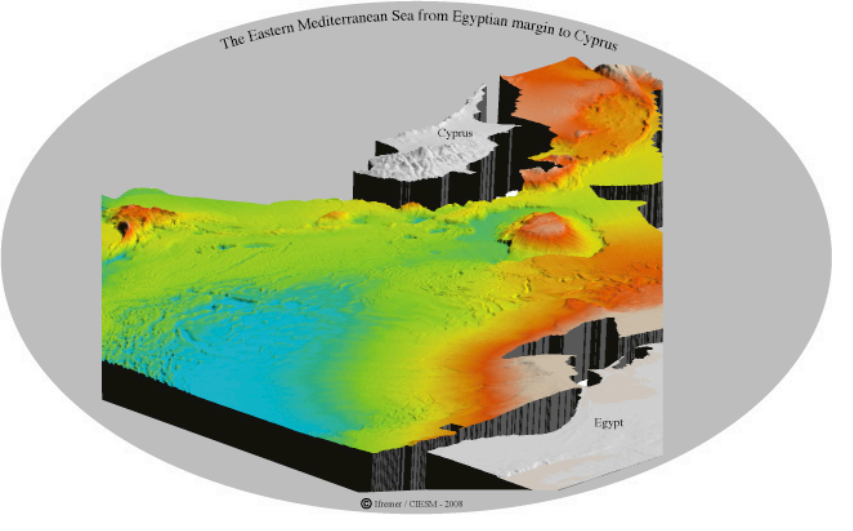


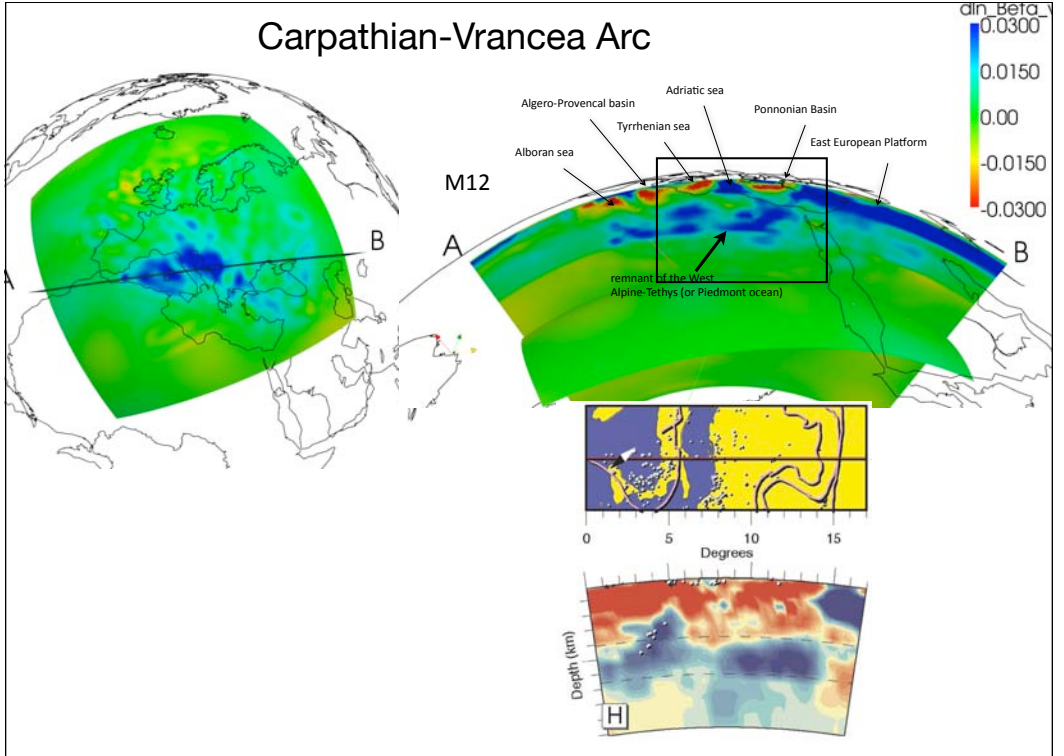
Fig. 1. Simplified tectonic map of Europe. TESZ, Trans-European Suture Zone.

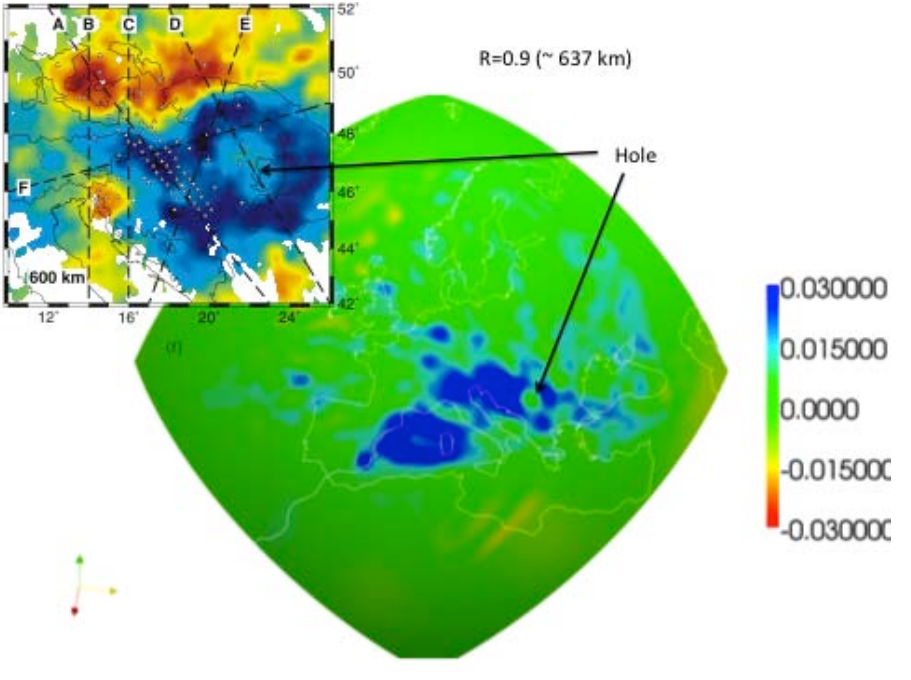



The Ionian Sea between the Mediterranean Ridge and the Calabrian Arc
Italy
Greece
Crete
Libya
© Ifremer / CIESM - 2008

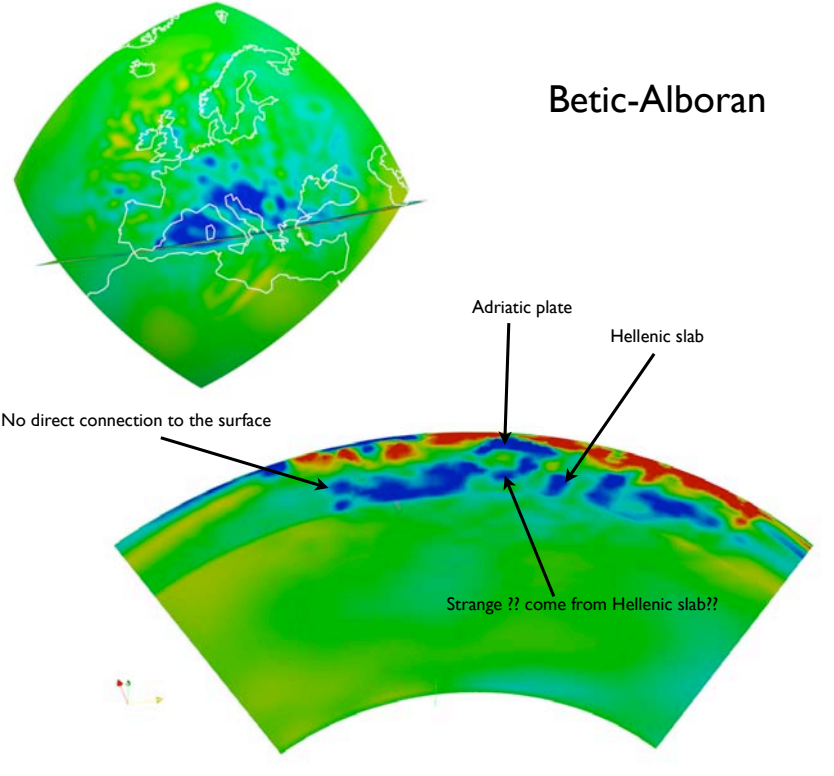

The Eastern Mediterranean Sea from Egyptian margin to Cyprus
Cyprus
Egypt
Ifremer / CIESM - 2008

Carpathian-Vrancea Arc

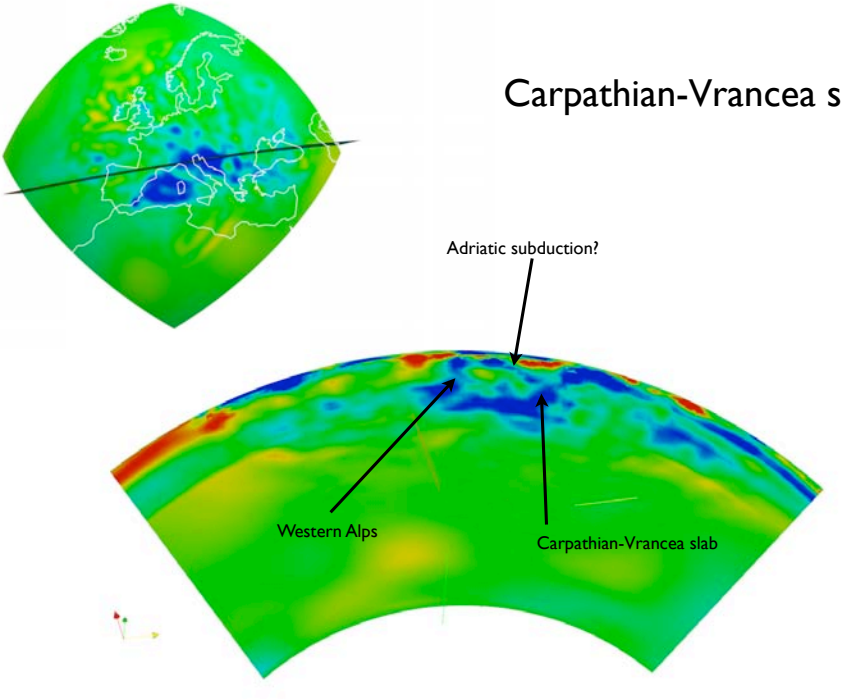


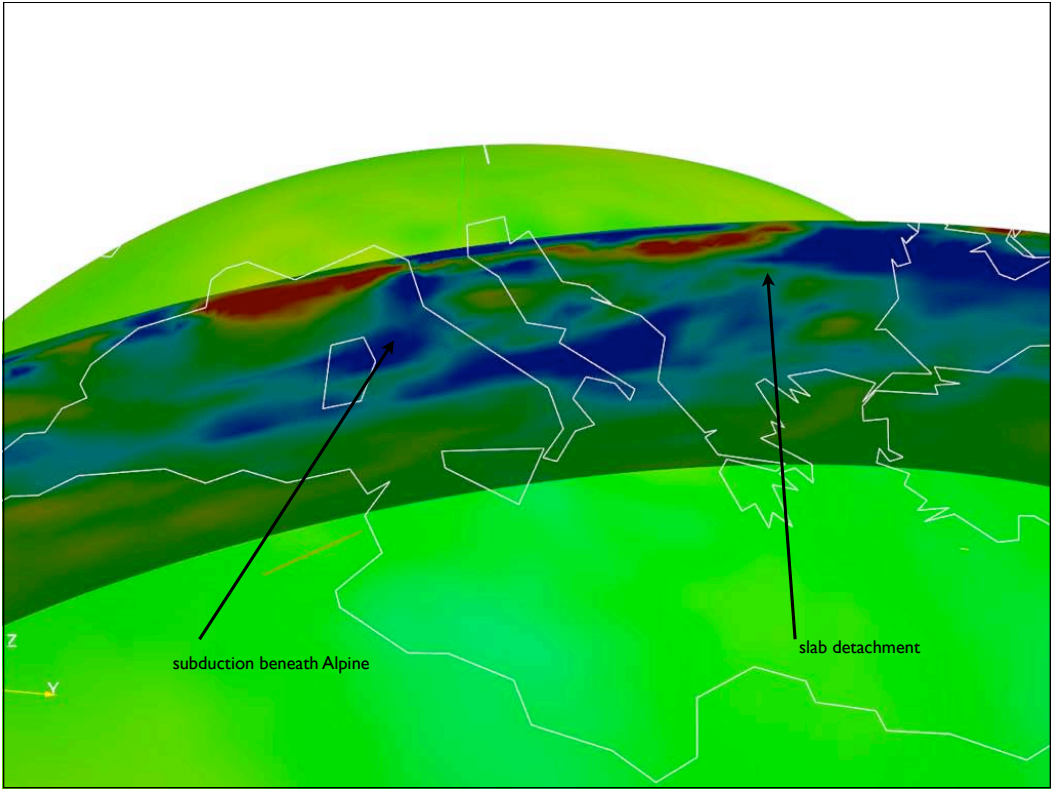

A
B
C
D
E
F
600 km
52°
50°
48°
46°
44°
42°
12°
16°
20°
24°
R=0.9 (~ 637 km)
Hole
0.030000
0.015000
0.0000
-0.015000
-0.030000

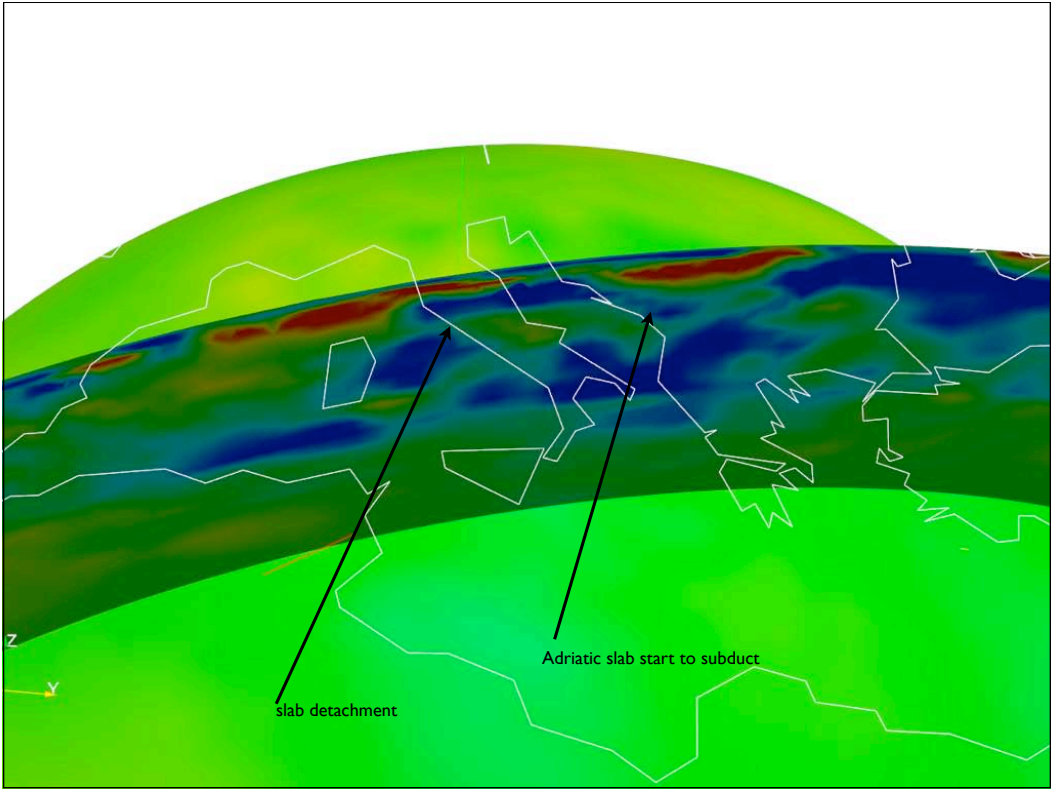
Betic-Alboran

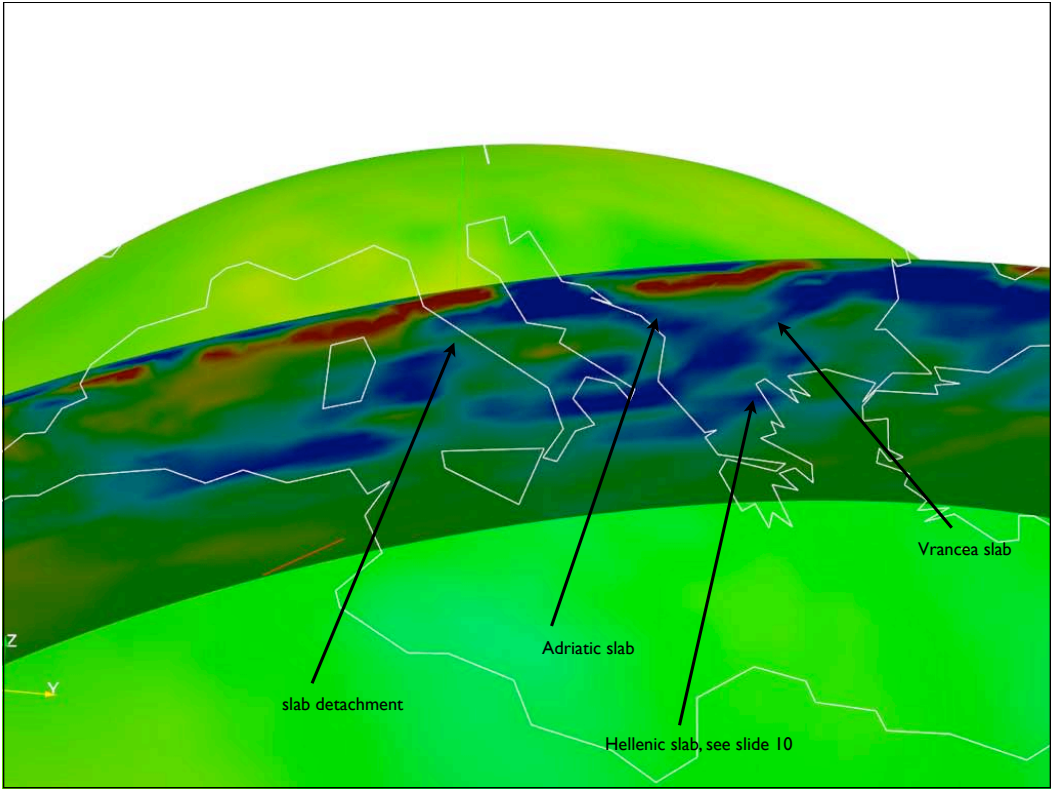


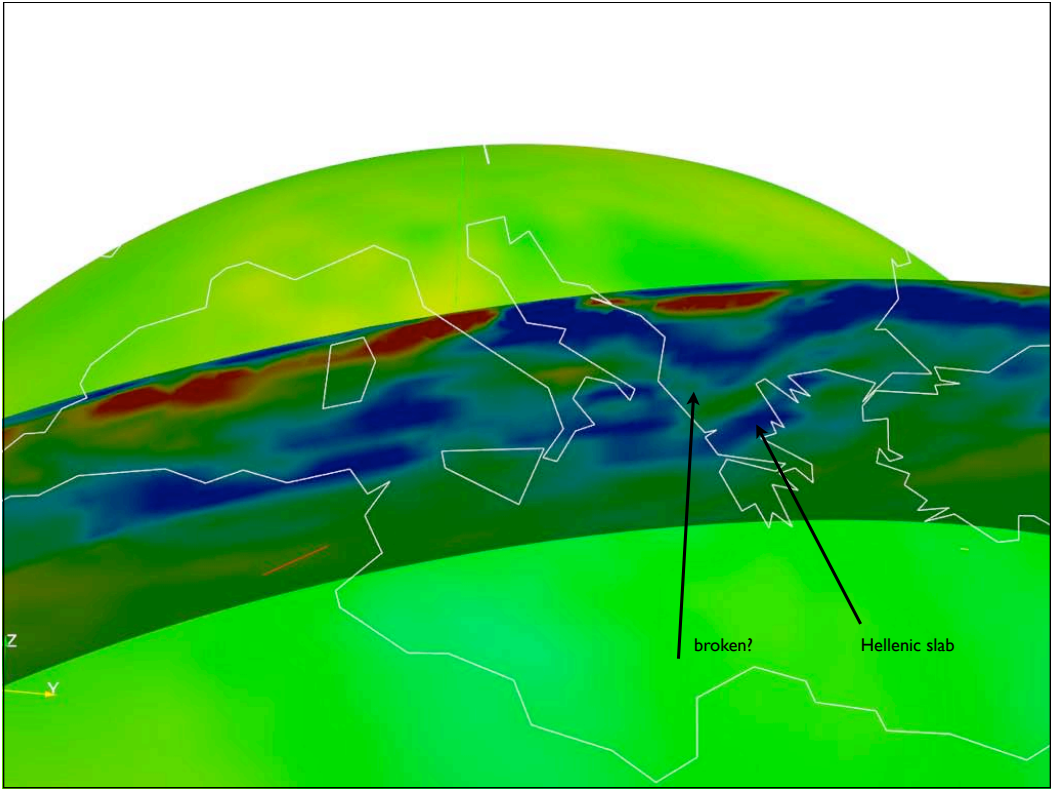
Carpathian-Vrancea slab

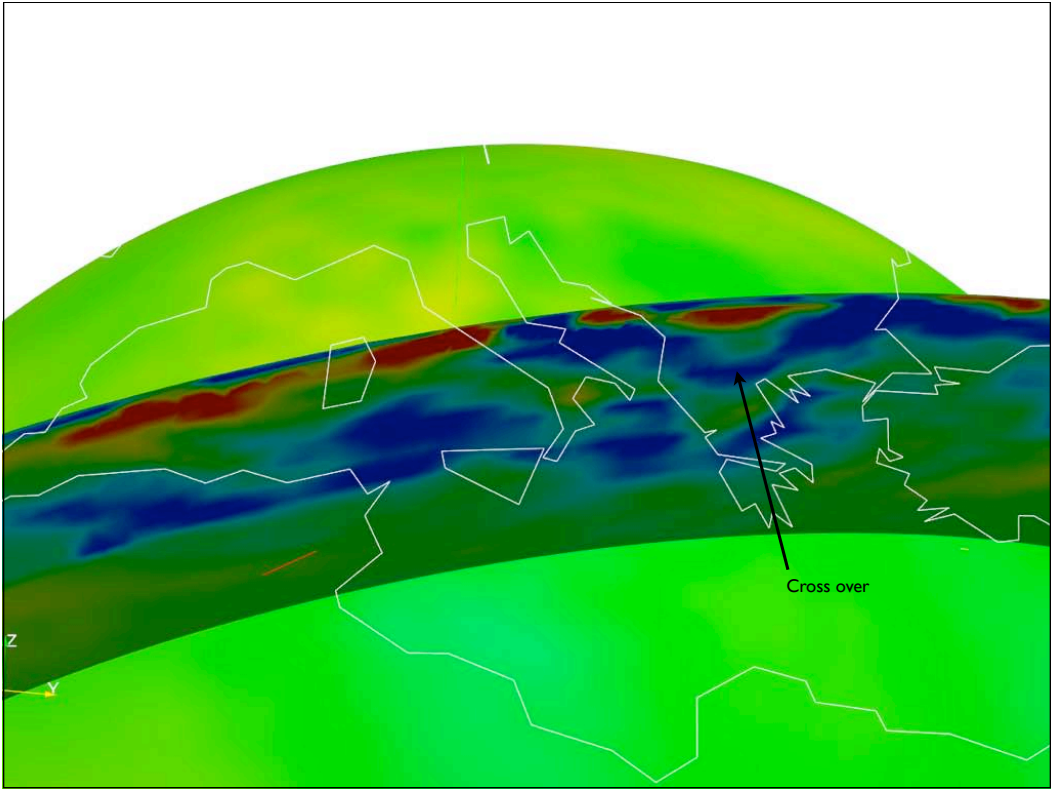


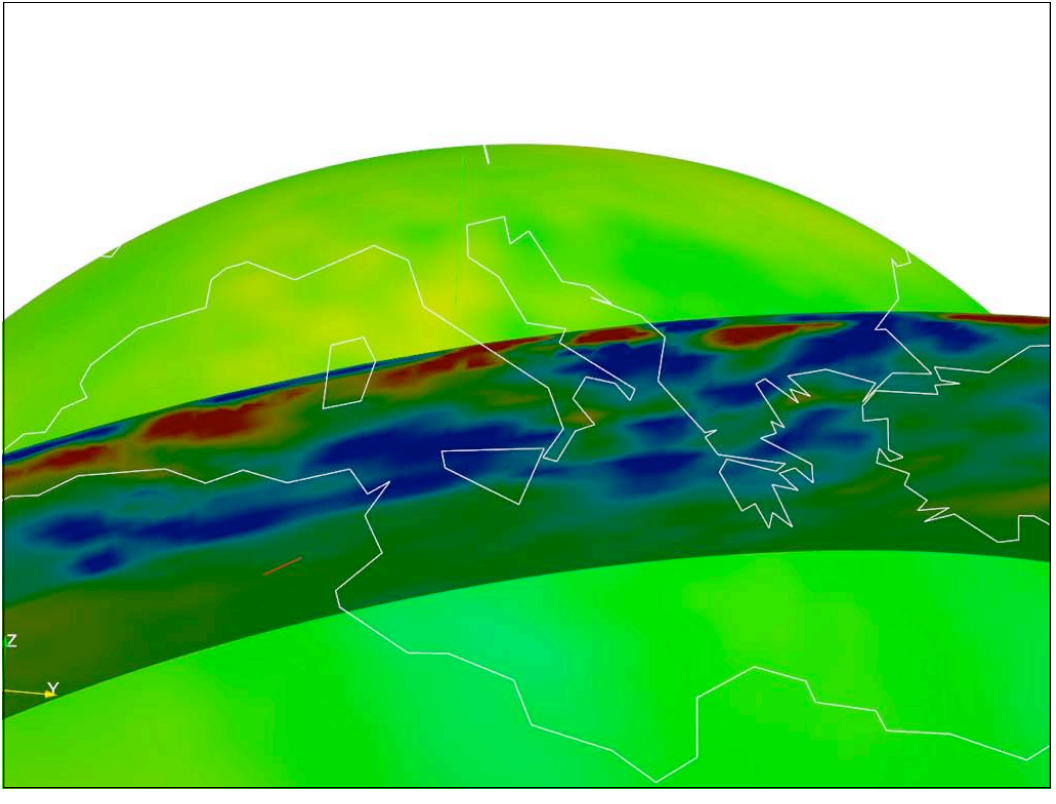

subduction beneath Alpine
slab detachment
Z
Y

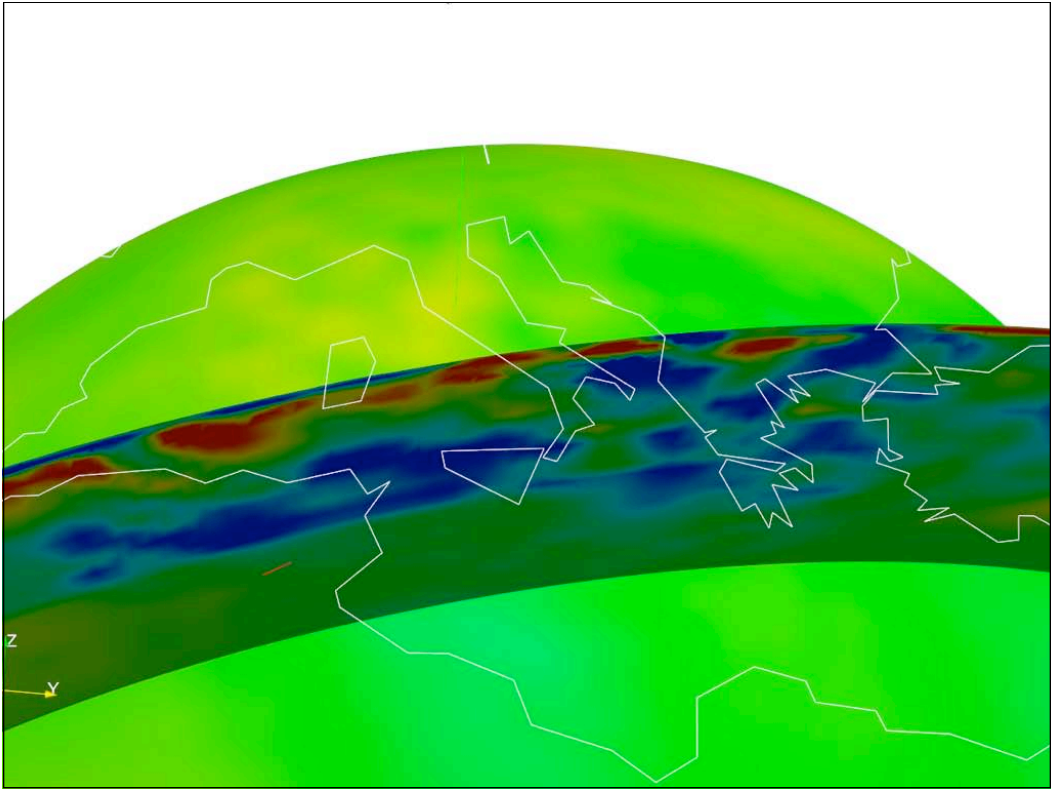

Z
Y
slab detachment
Adriatic slab start to subduct

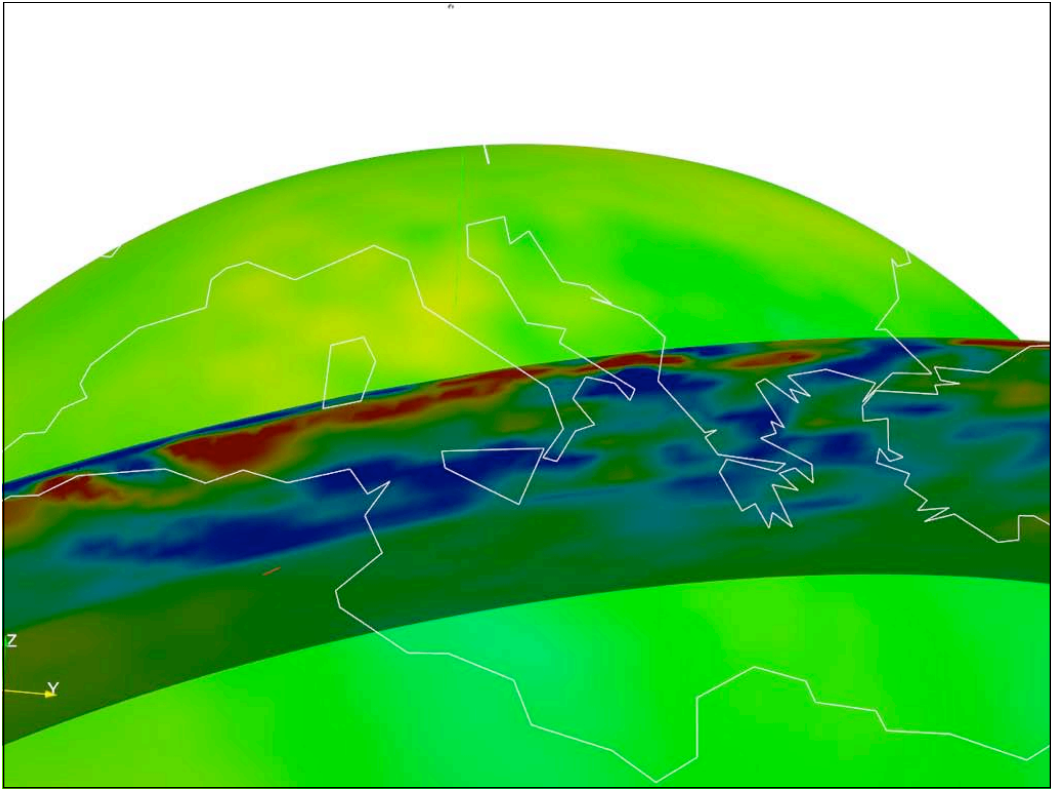

Vrancea slab
Adriatic slab
slab detachment
Hellenic slab, see slide 10
Z
Y

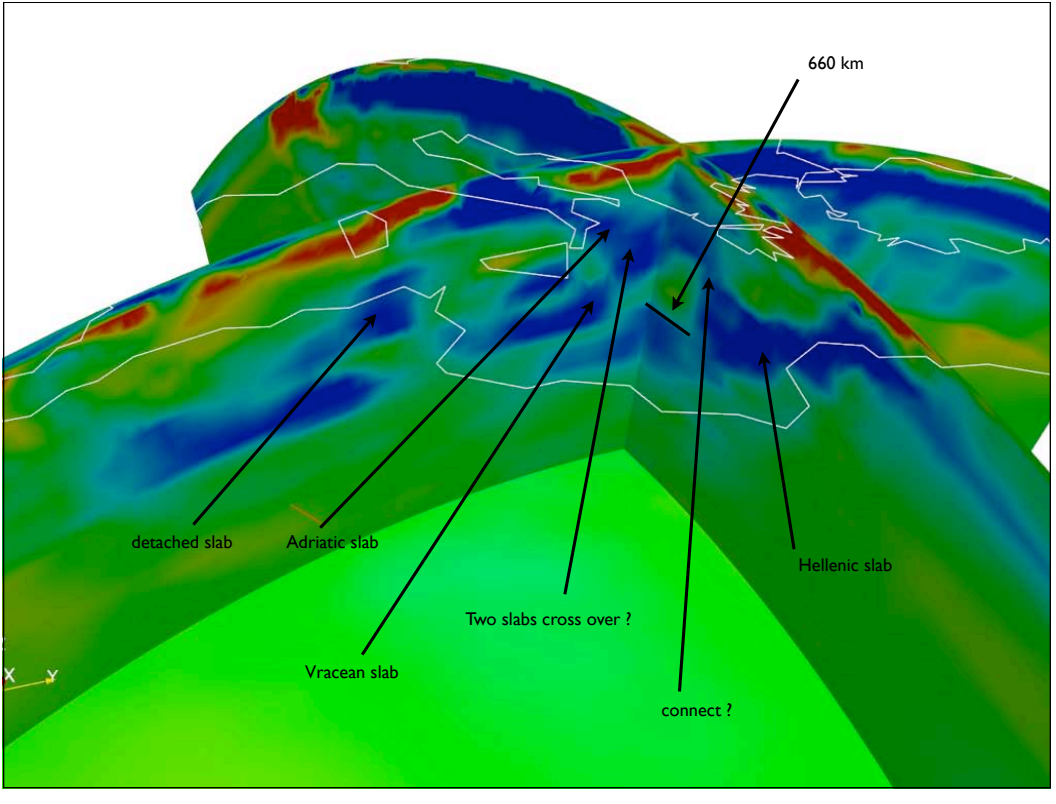

broken?
Hellenic slab
Z
Y

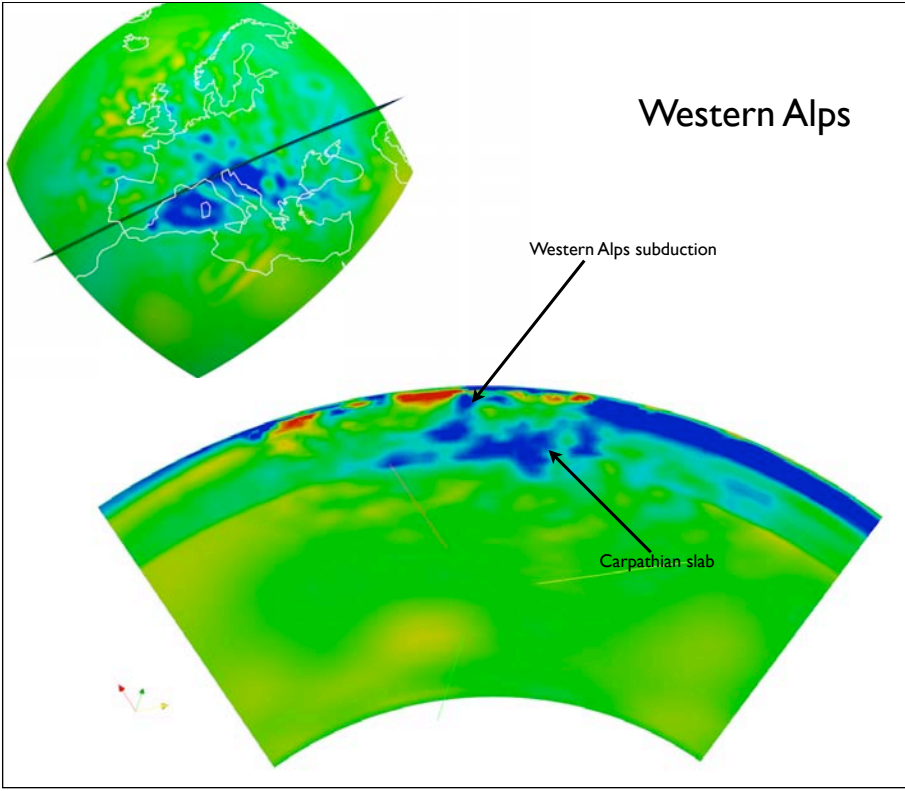

Cross over
Z
Y


Z
Y

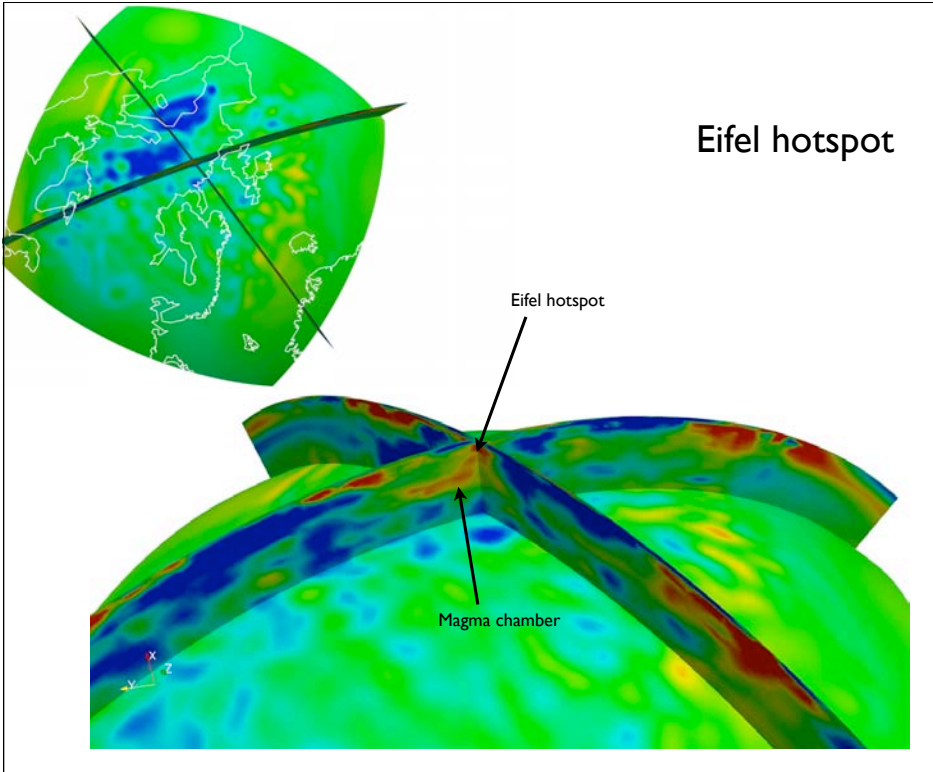

Z
Y


Z
Y


660 km
detached slab
Adriatic slab
Two slabs cross over ?
Vracean slab
connect ?
Hellenic slab
X
Y


Western Alps
Western Alps subduction
Carpathian slab

Eifel hotspot



Tectonic map of Europe

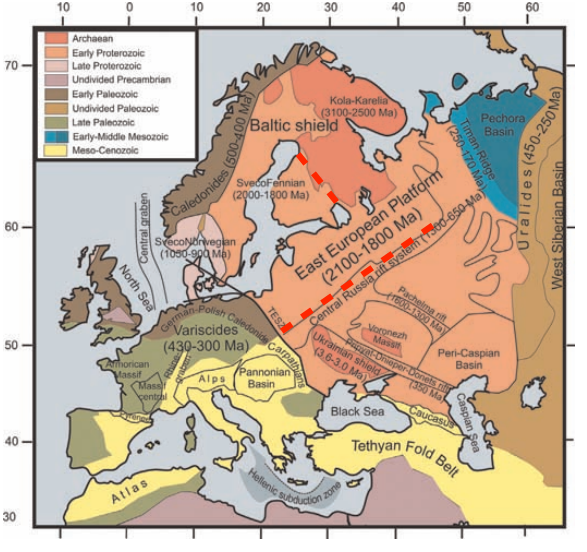
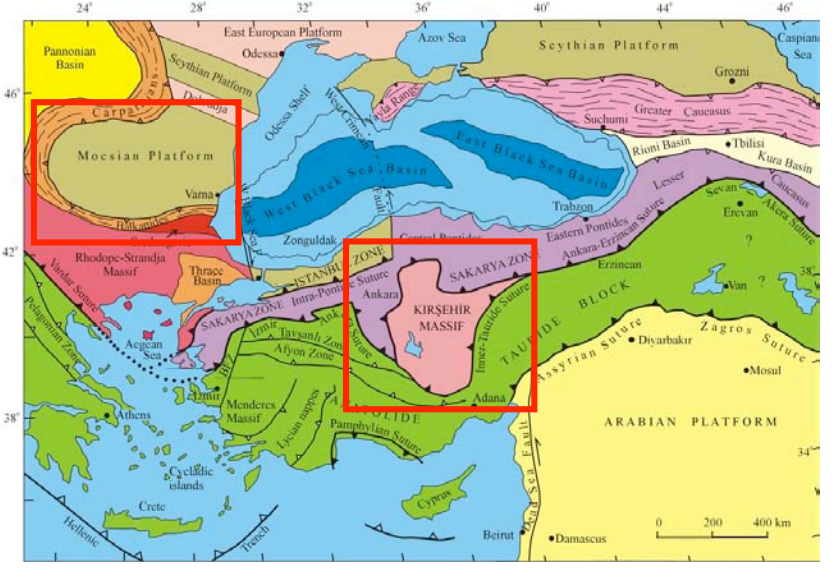
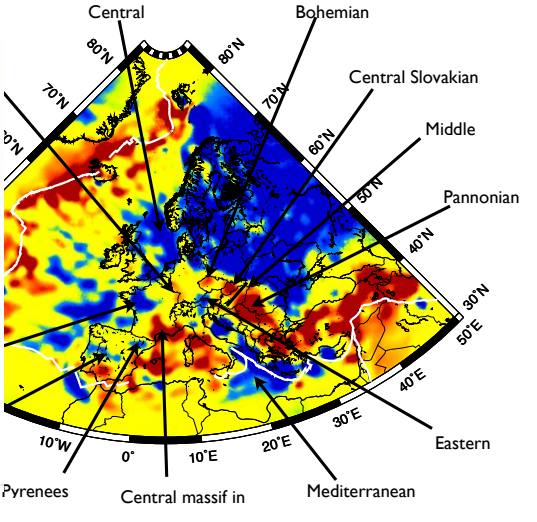


Fig. 1. Simplified tectonic map of Europe. TESZ, Trans-European Suture Zone.

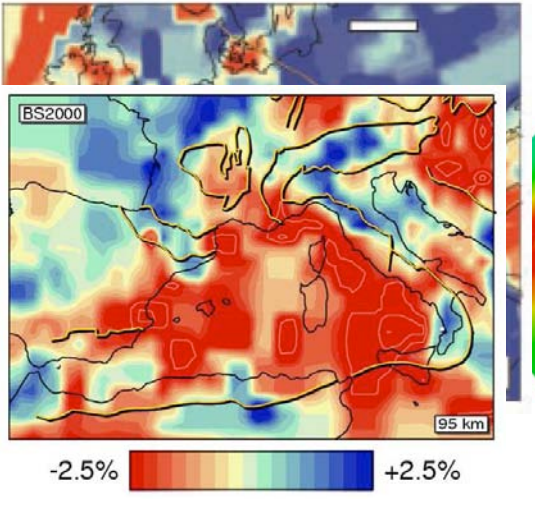
Tectonic map of Turkey



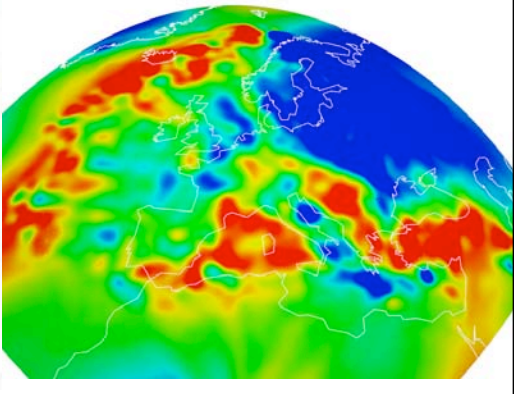
Beta_v at depth~75 km



Depth 100 km

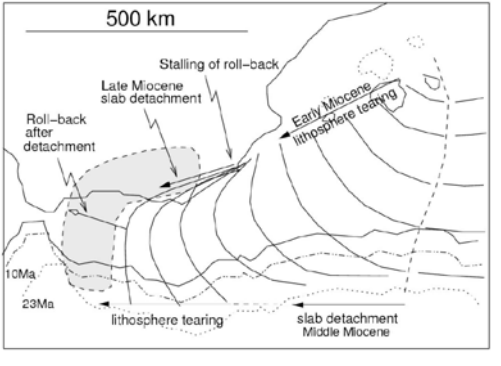


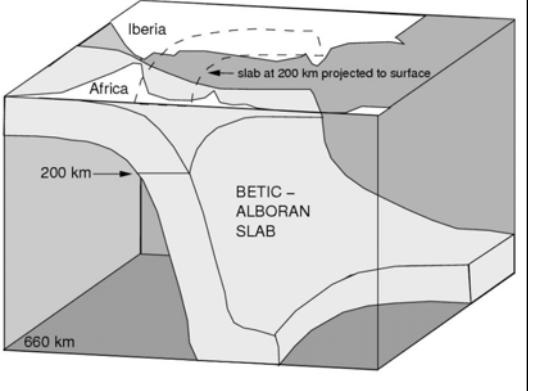
M12



- Slab rollback western Mediterranean
  1. Stage 1: Algero-Provencal basin
  2. Stage 2: Tyrrhenian basin
- Eastern Mediterranean:
  - low heat flow, old (100 My), fast
- Western Mediterranean
  - high heat flow, young (25 My), slow
- Closing of Tethys, scissor with western hinge
- Hellenic arc old, cold, retreating (rollback)
- Cyprus arc, locked (no rollback)
- Cyprus hot spot: Erathostenes sea mount?
- Betic, Calabria and Vrancea subduction arcs are similar in appearance, with similar origins
- Adria subduction not seen previously
- Upper mantle hotspots not really seen
- Downdip tension in Vrancea: slab attached, with deposition basin above
- Downdip compression in Calabria: slab detached
- Alps due to Adia collision with Europe (Eocene-Oligocene)

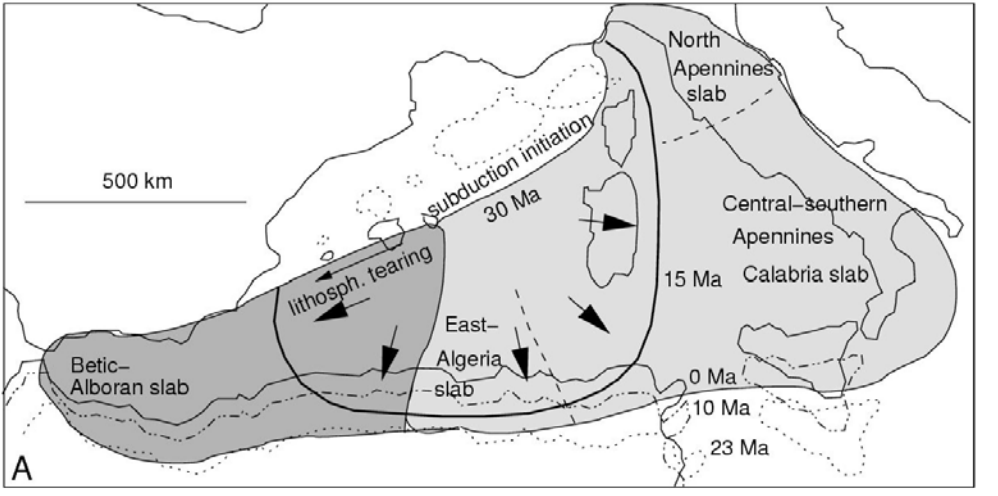
Betic-Alborian





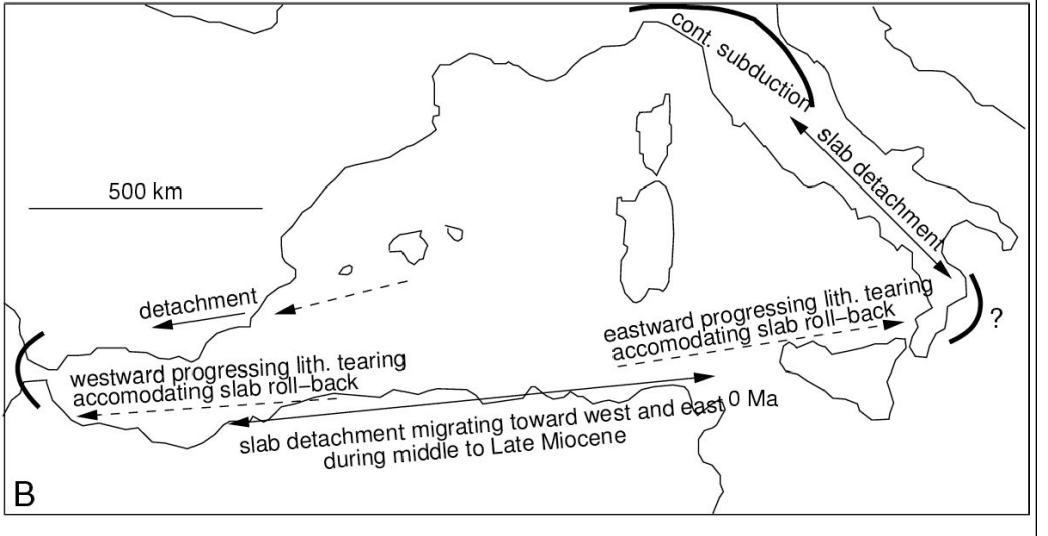
Spakman & Wortel (2004)

Western Mediterranean



Spakman & Wortel (2004)

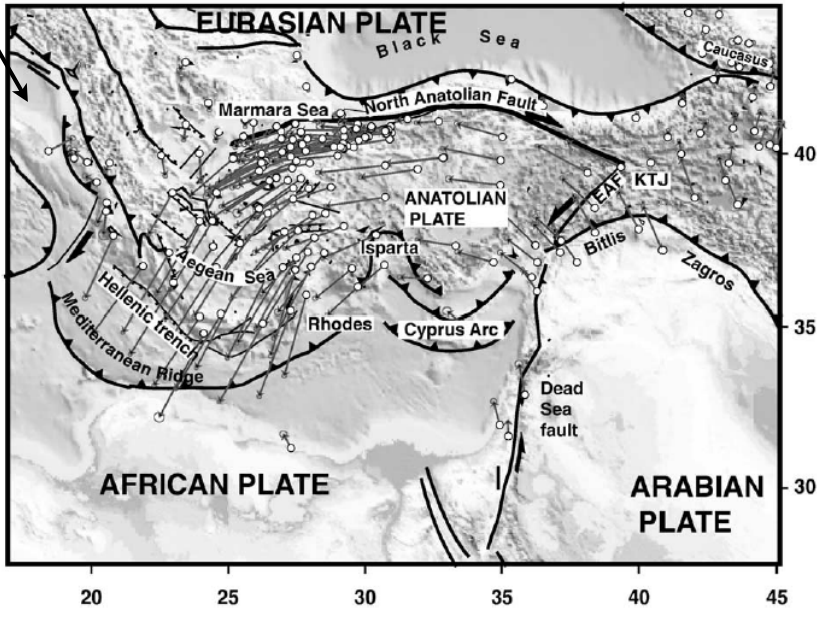
Western Mediterranean



Spakman & Wortel (2004)

Greece & Turkey

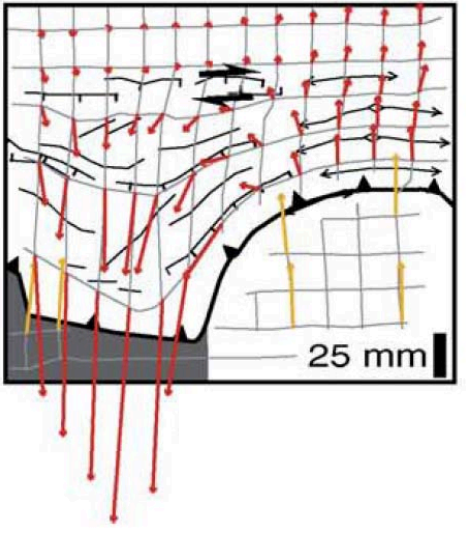
Adria Plate?



Faccena et al. (2006)

Greece & Turkey

Lab Experiment

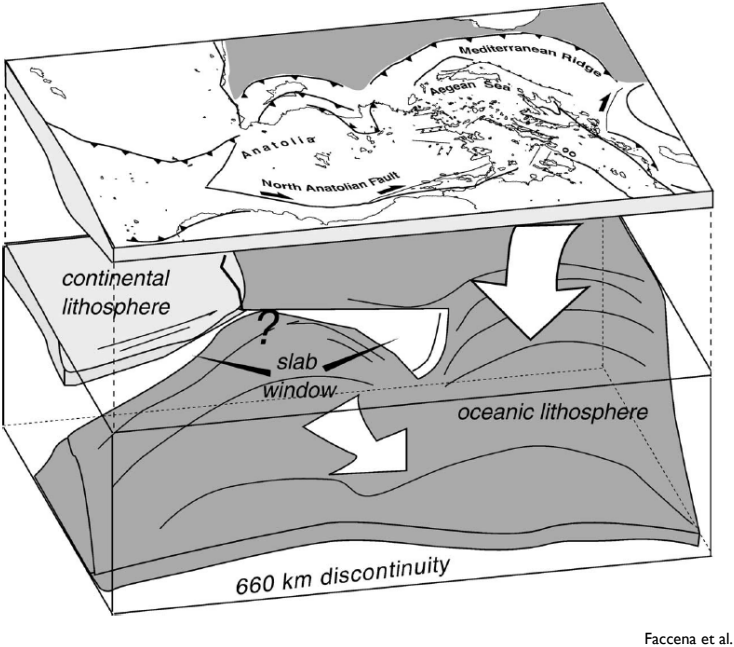


Faccena et al. (2006)

Plate motions relative to Eurasia

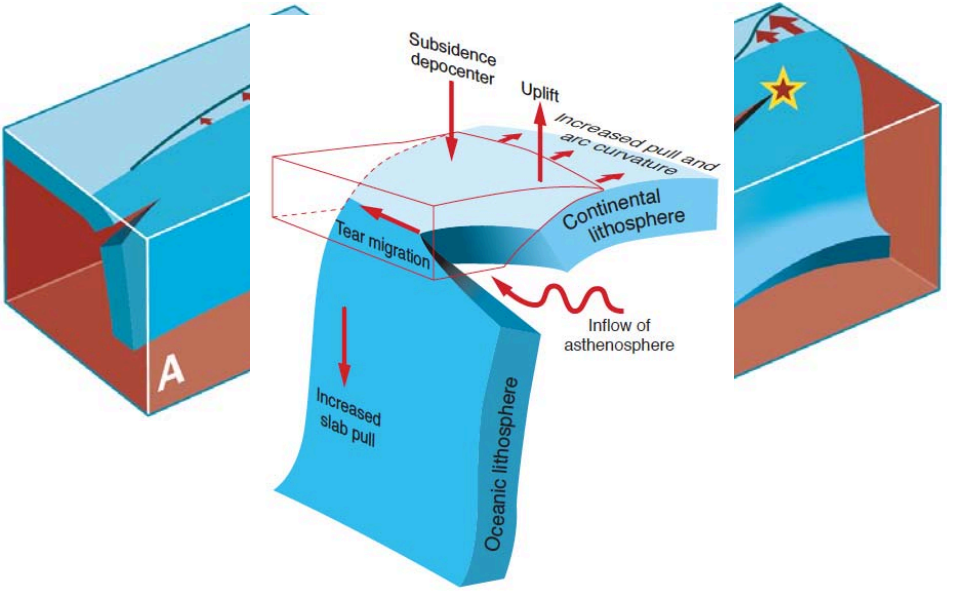
Wortel & Spakman (2000)

Greece & Turkey



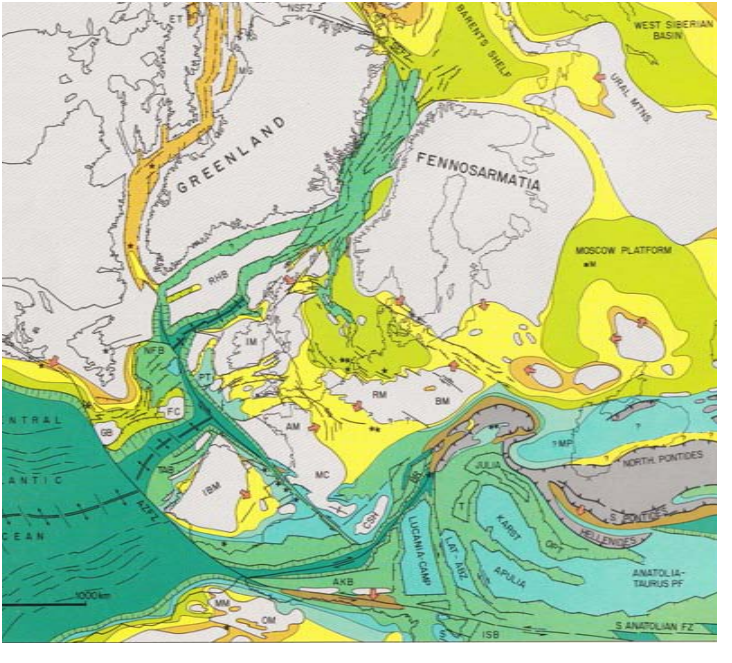
Faccena et al. (2006)

Migration of Slab Detachment

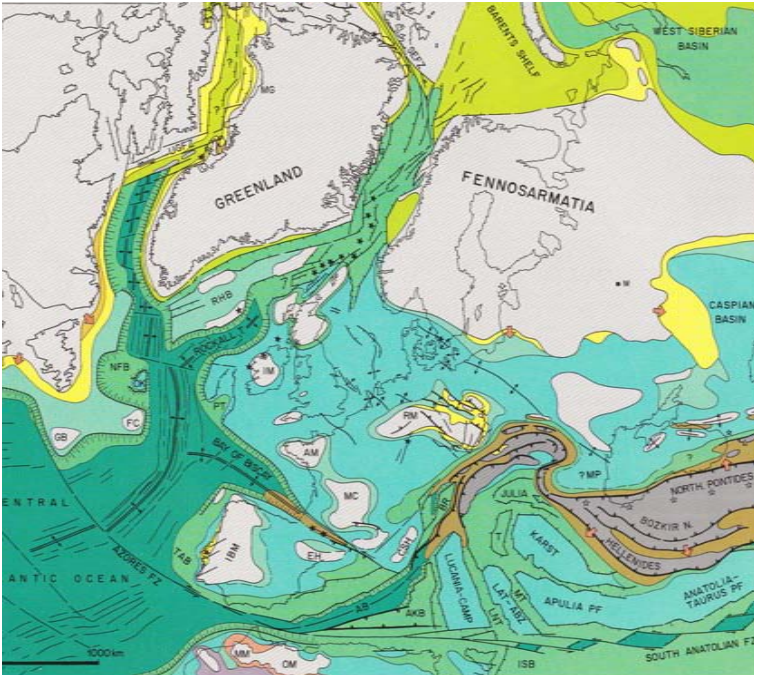


Wortel & Spakman (2000)

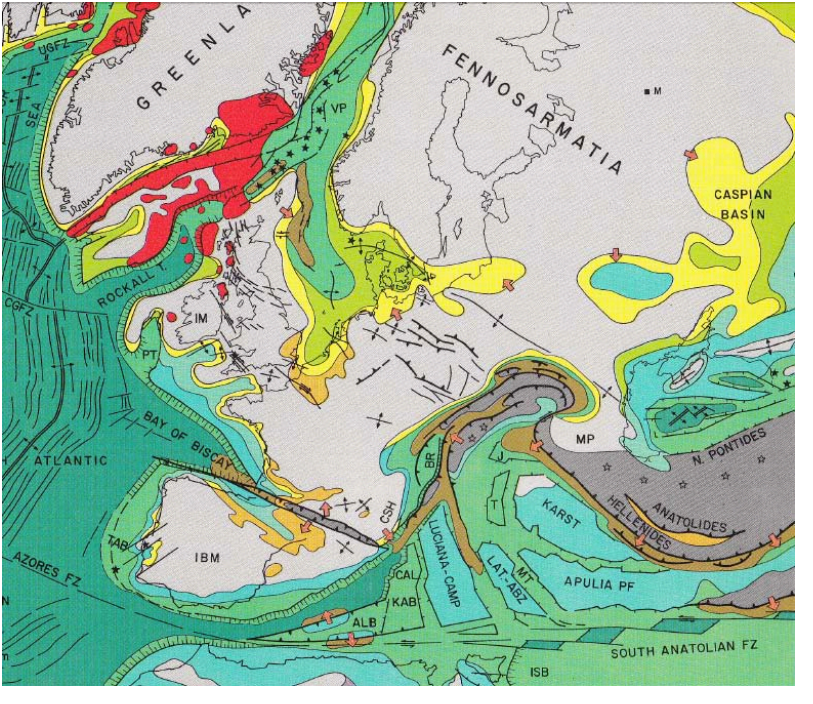
Early Cretaceous (~110 MYA)



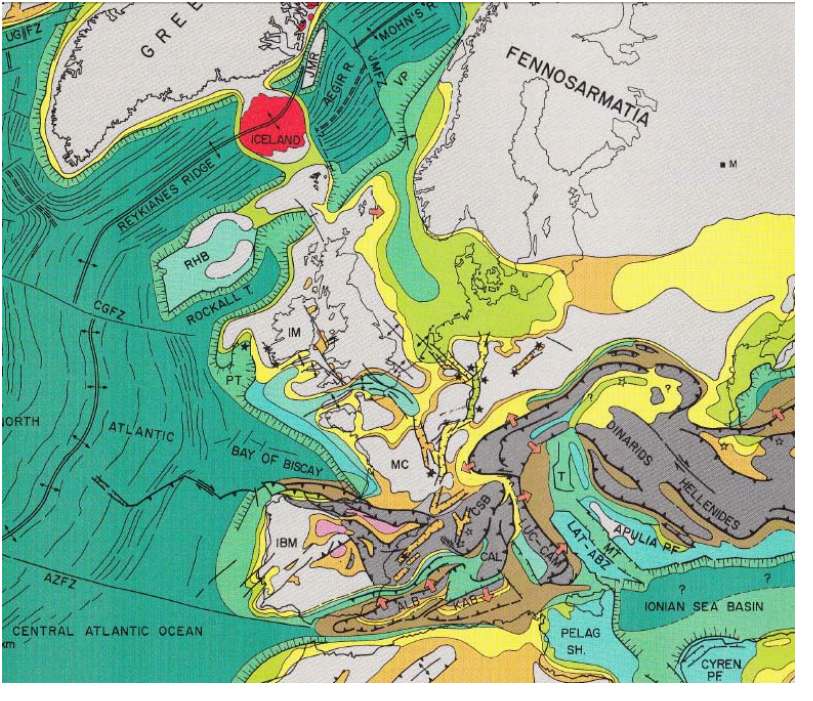
Late Cretaceous (~85 MYA)



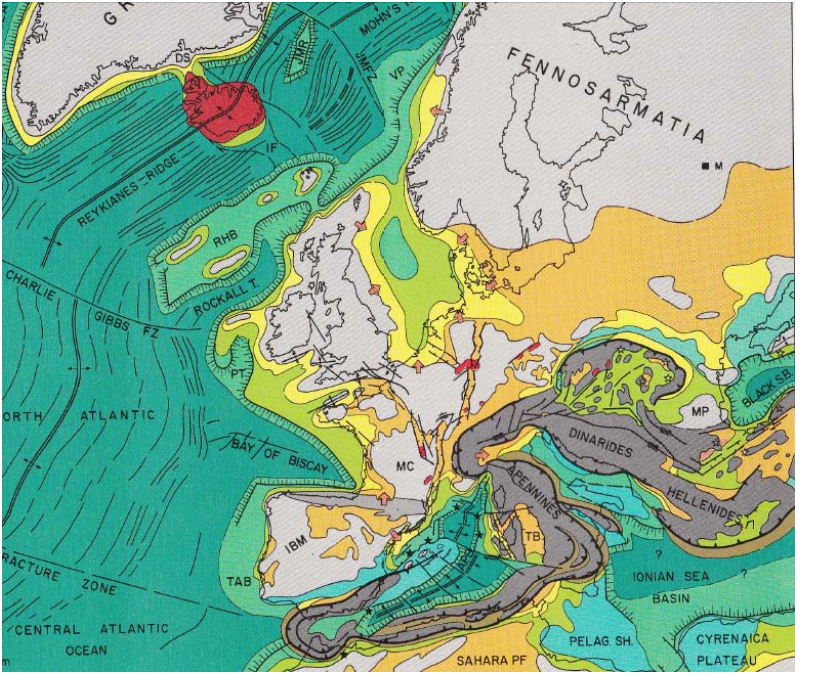
Paleocene (~60 MYA)



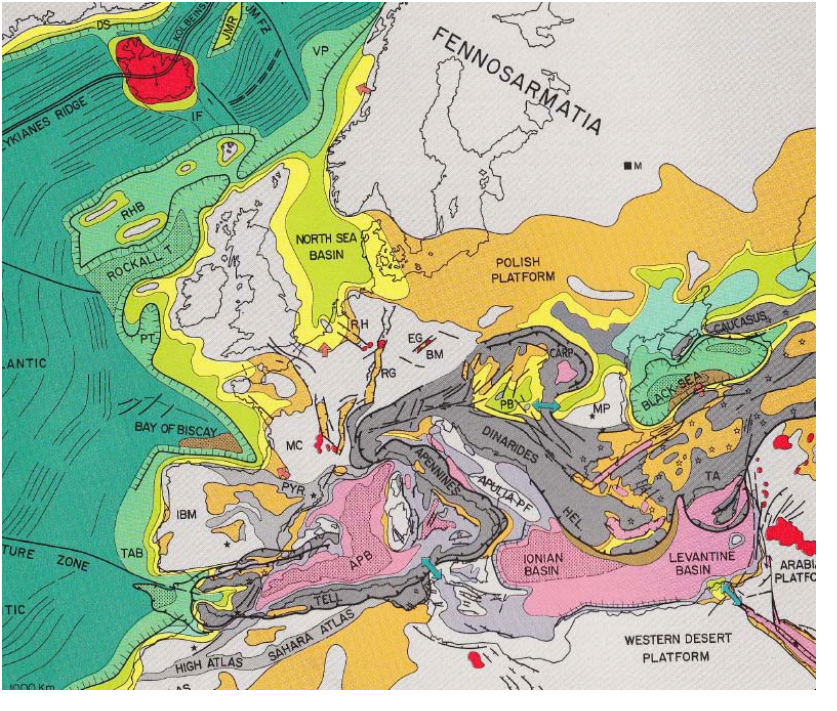
Late Oligocene (~25 MYA)



Middle Miocene (14 MYA)



Messinian (~6 MYA)



Pliocene (~2 MYA)