Low velocities in the oceanic upper mantle and their relations to plumes: insights from SEM-based waveform tomography

Barbara Romanowicz

UC Berkeley, Collège de France, Paris, IPGP

Scott French, Vedran Lekic

UC Berkeley
Global Seismology Group

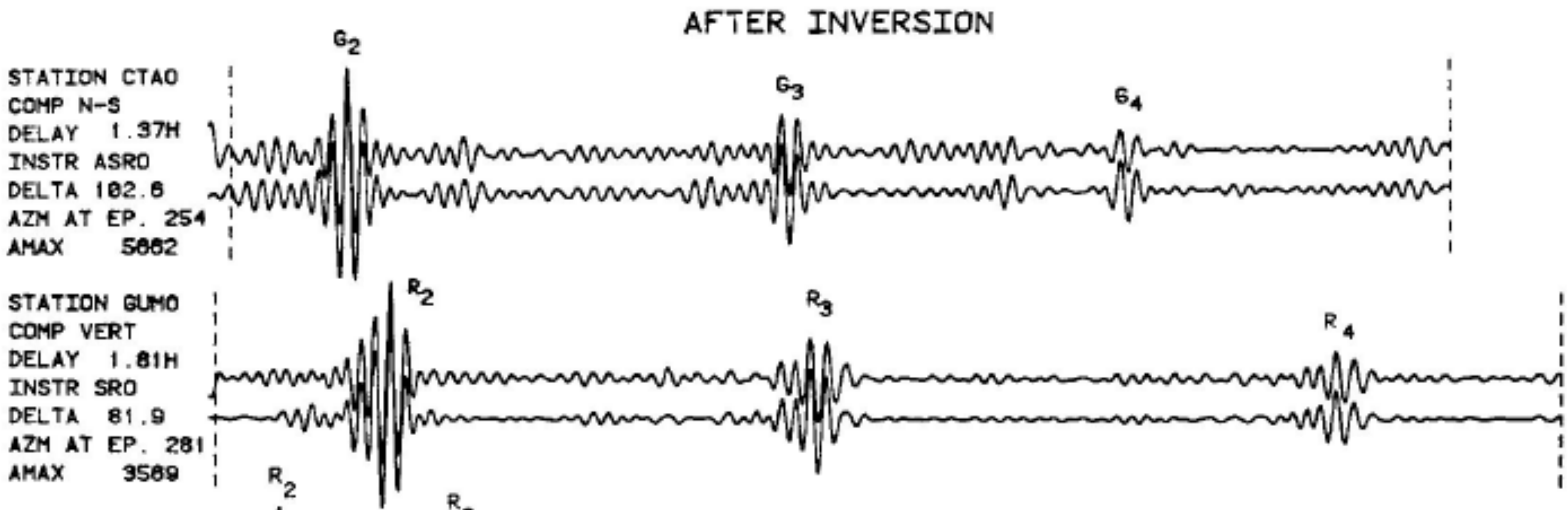
IPGP
INSTITUT DE PHYSIQUE
DU GLOBE DE PARIS

Outline

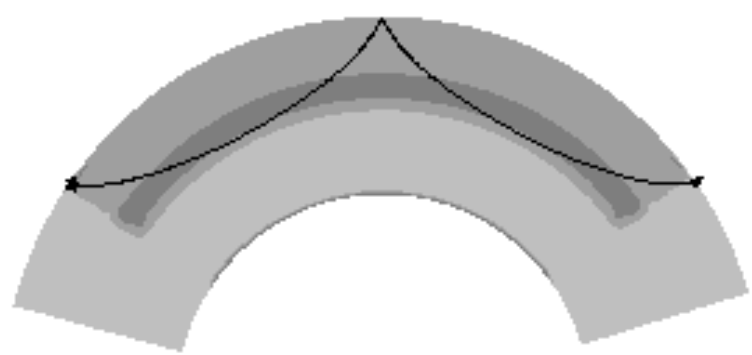
- Historical background and methods
  - > from normal modes to SEM
- Strategy and model development
- SEMum2 model salient features and the challenge of validation
- Outlook

Time domain waveform inversion in global seismology

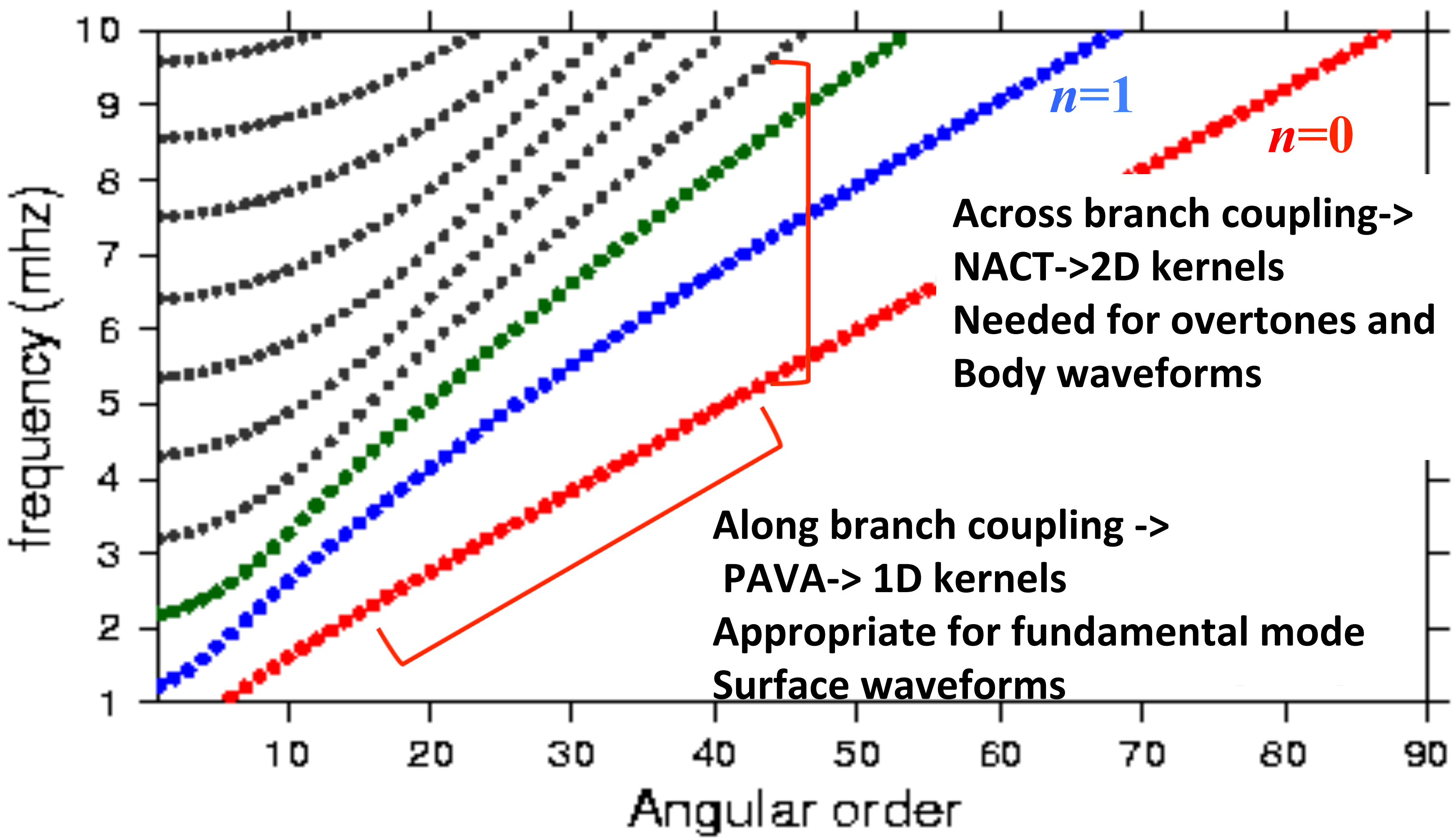
- Woodhouse and Dziewonski (1984)



- Normal mode theory
- Path AVerage Approximation (PAVA)-> 1D sensitivity kernels
- *Later, complement with body wave travel times (ray theory) to access lower mantle structure*



Toroidal modes : $_{n}\mathrm{T}_{l}$



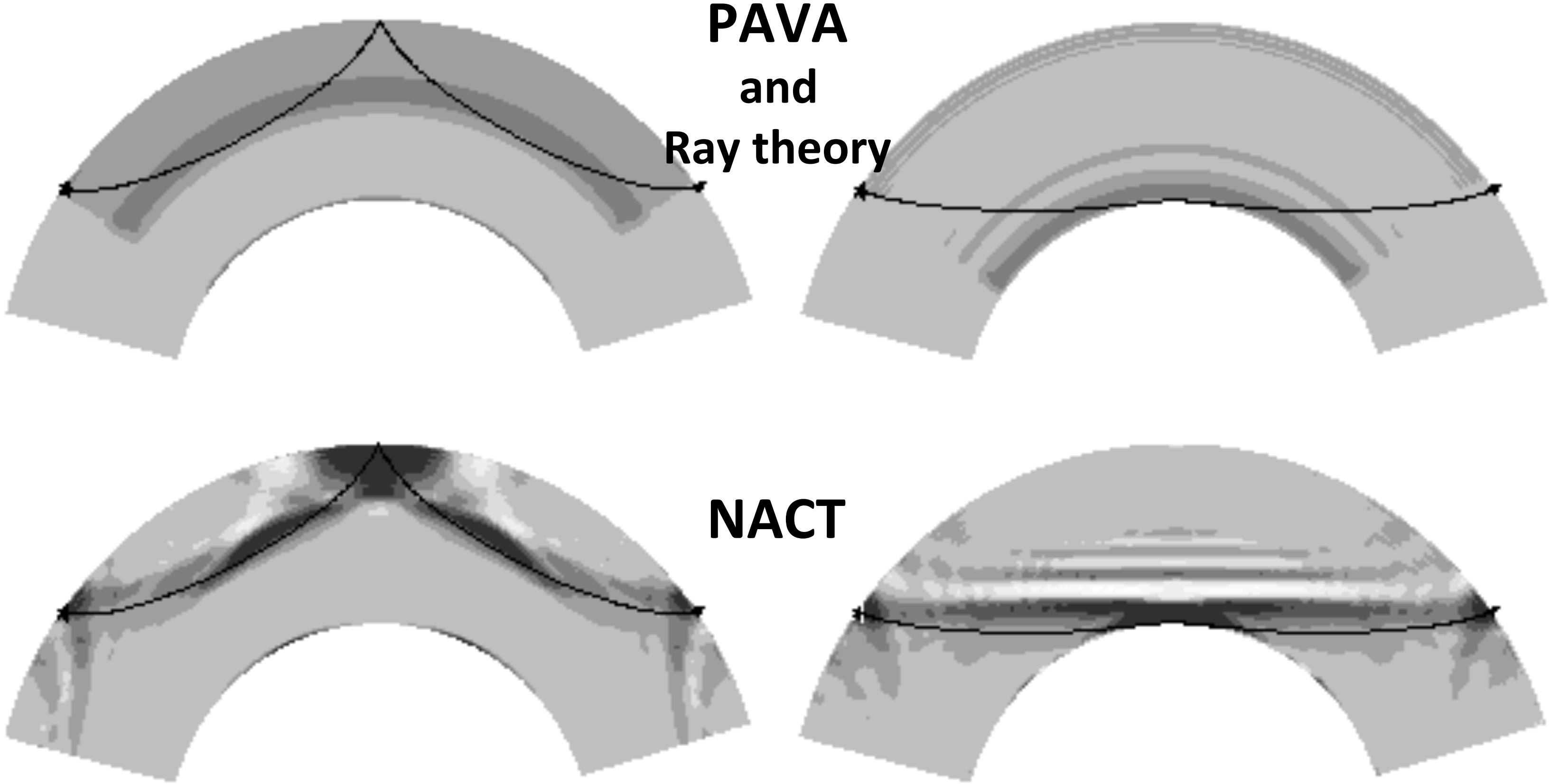
l: angular order, horizontal nodes

n: overtone number, vertical nodes

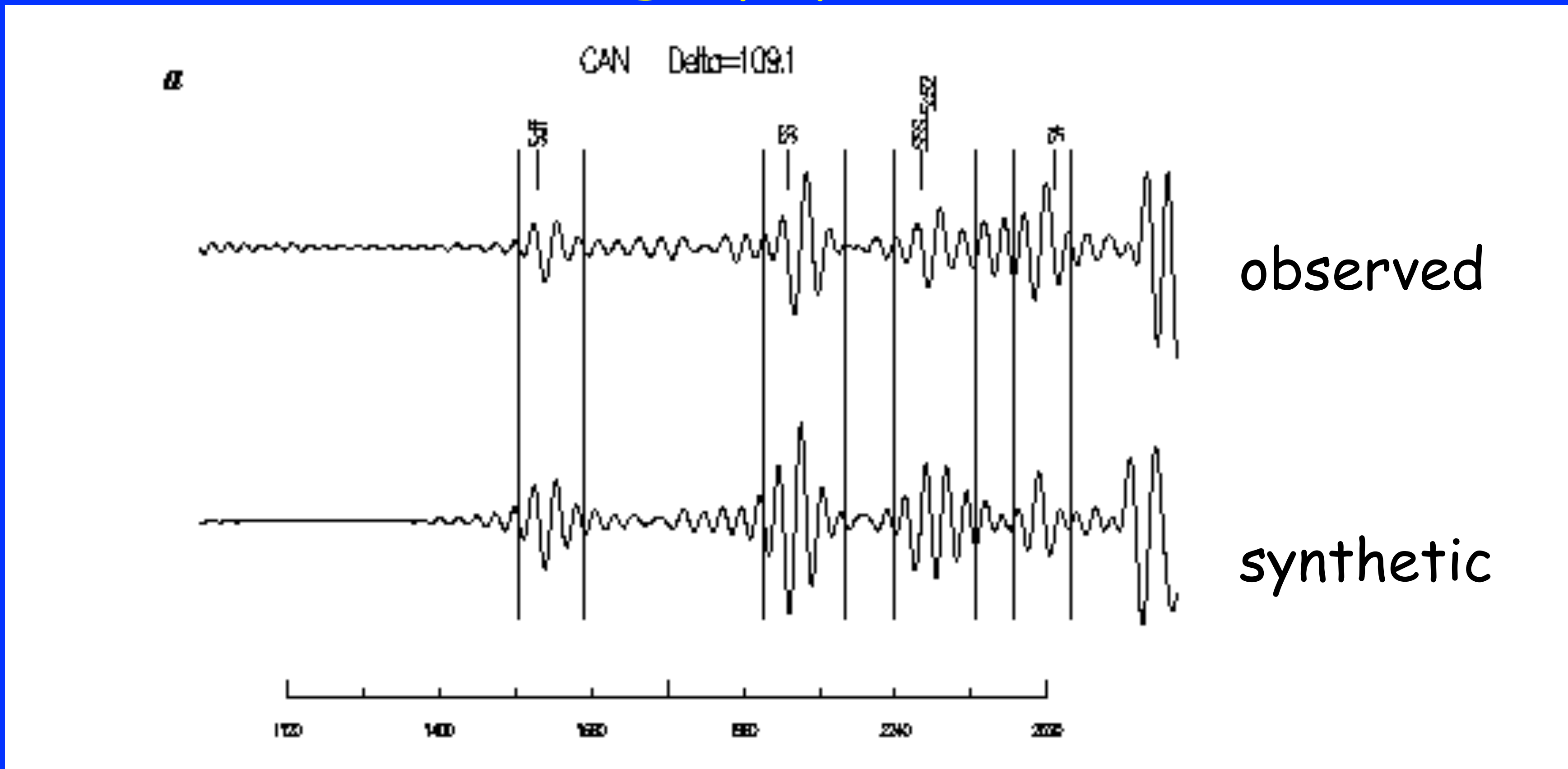
4) Non-linear asymptotic coupling theory (NACT)-> 2D kernels in the vertical plane *(Li and Romanowicz, 1995)*

$$u(\mathbf{x},t) = \mathrm{Re}\{\sum_k A_k^0(\Delta+\delta\Delta)e^{i(\omega_k+\delta\hat{\omega}_k)t} +$$

Across-branch
Coupling terms
Asymptotic Born



Full Waveform Tomography of the whole mantle



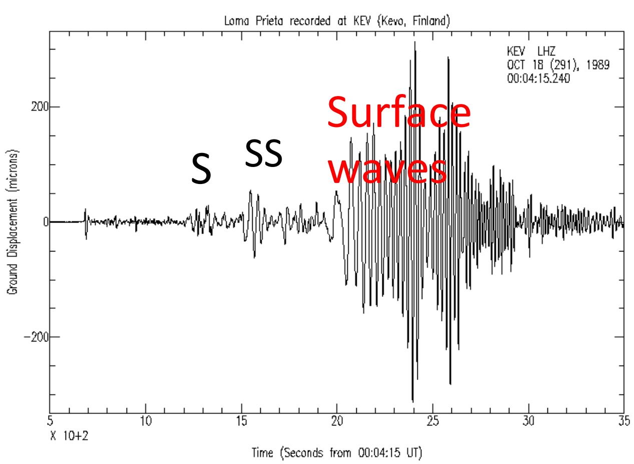
- NACT: Surface waves, overtones (T>80s), body waves (T>32 s)

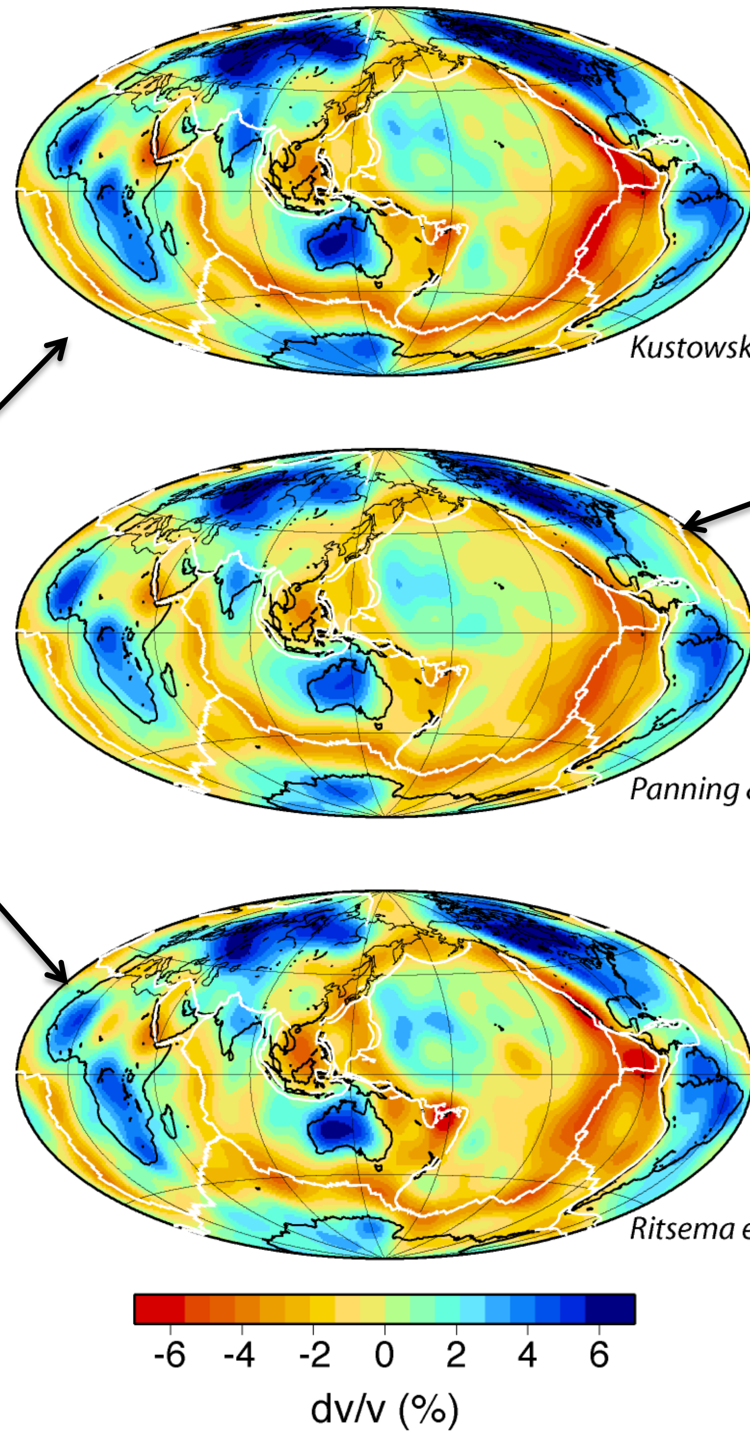
-Misfit function: waveform difference + Windowing and weighing, in order to equalize amplitudes.

-Several generations of whole mantle shear velocity models,
-Including radial anisotropy, attenuation
-→ *(Li and Romanowicz, 1996->Panning and Romanowicz, 2006*)

Isotropic Vs Depth = 100 km

- Long period S, SS, ScS, SKS…travel times
- Surface waves and overtones
- Normal Mode splitting
- High frequency Approx.





Harvard

Kustowski et al. 2006

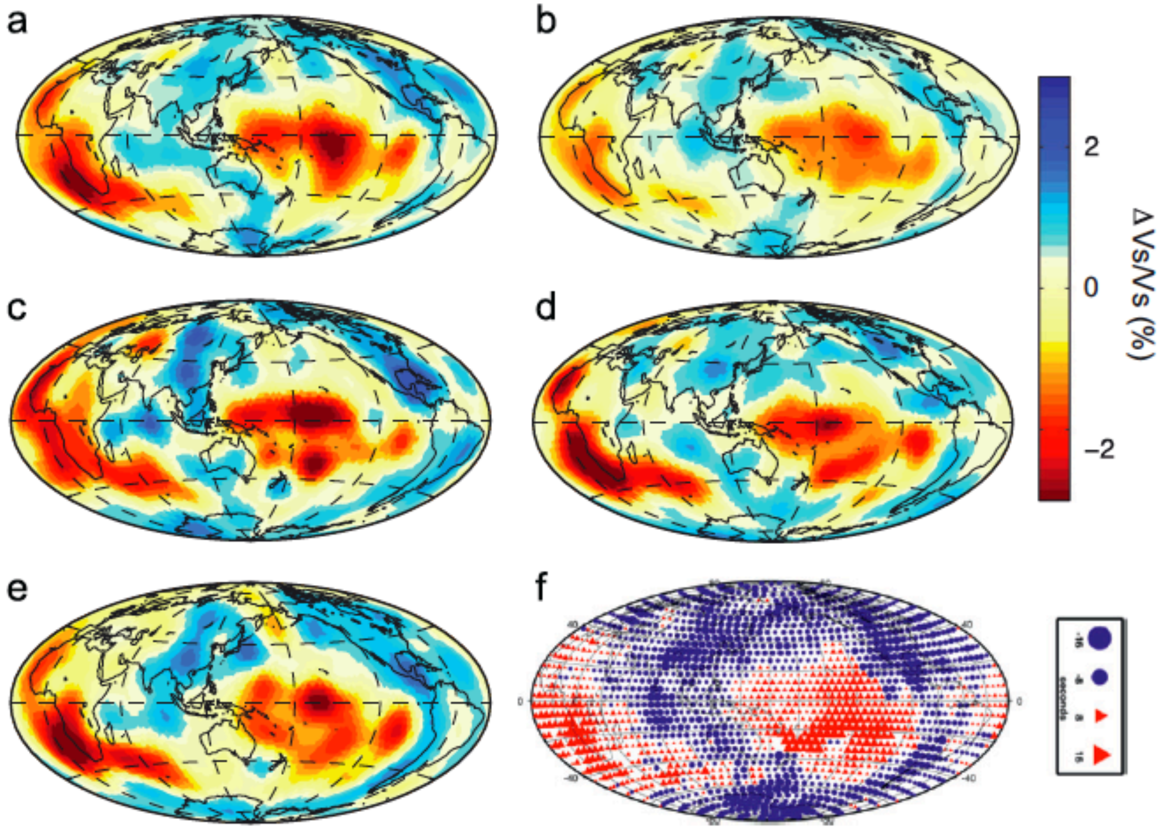
Time domain Waveforms ~20,000 +NACT

Berkeley

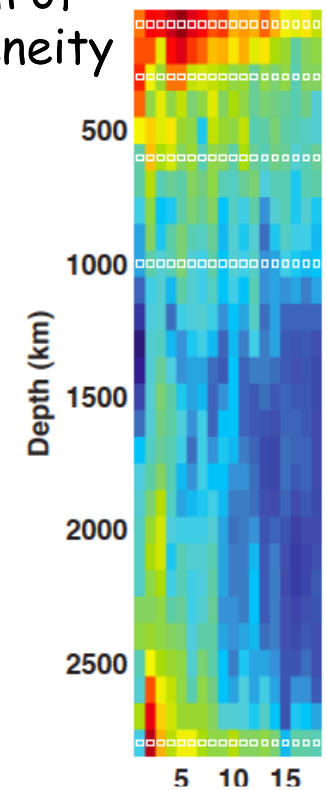
Panning & Romanowicz 2006

Caltech

Ritsema et al. 1999

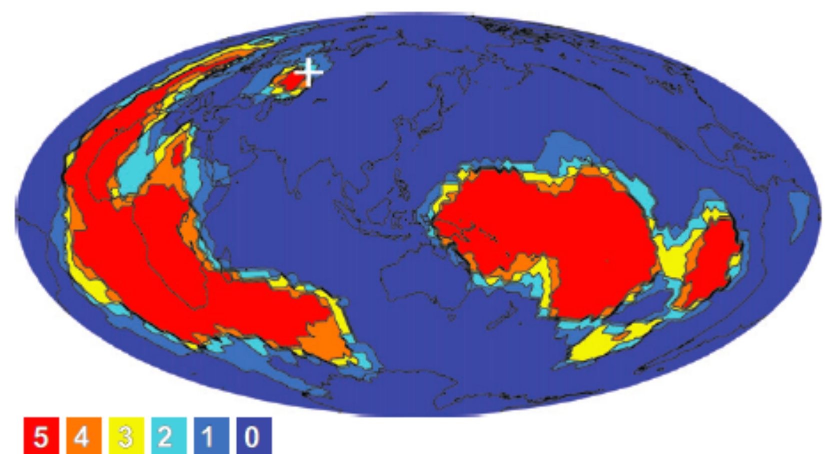


Spectrum of heterogeneity



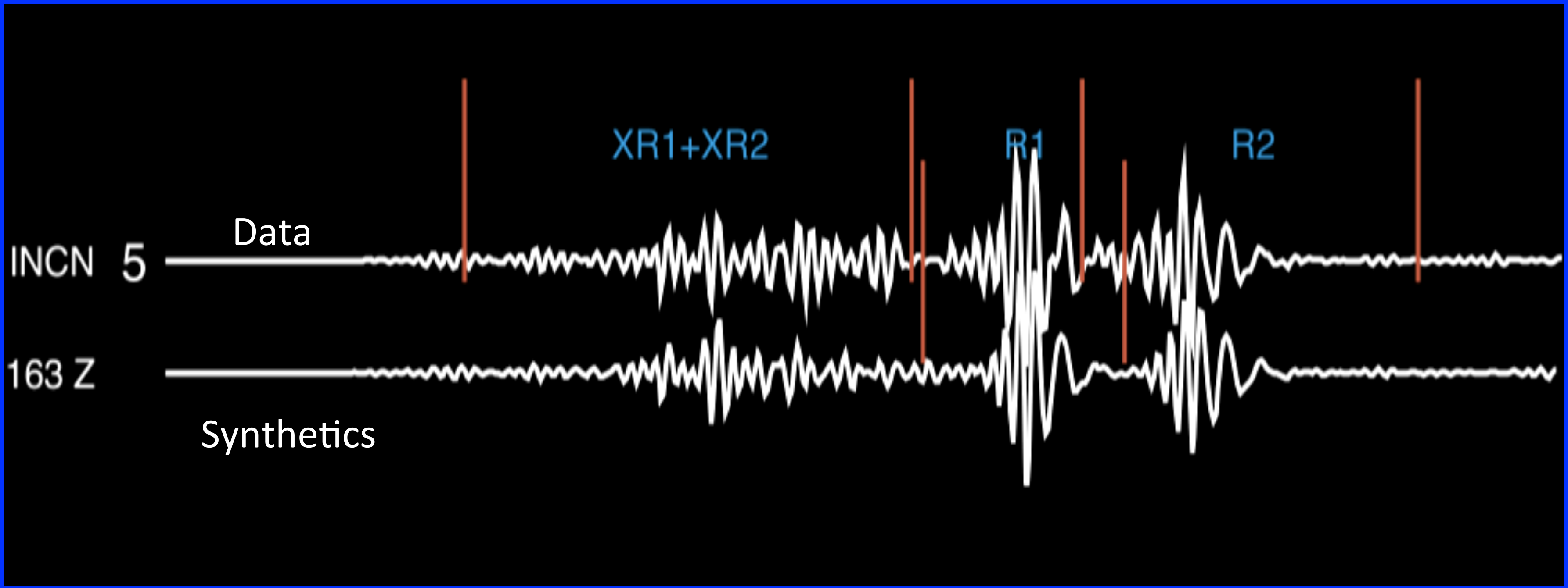
Shear velocity
Depth = 2800 km

“LLSVP”
“Superplumes”



Lekic et al, 2012, EPSL

The road forward: Full Waveform Tomography using SEM:



Replace mode synthetics by numerical synthetics computed using the Spectral Element Method (SEM)

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The 1-D Reference Earth

The View so far


Our immediate goal


The Future?

Strategy:

- Take "one step at a time" and in the process hope to learn something new about the earth:

- I – "Hybrid" inversion approach:
  - Compute forward wavefield precisely using C-SEM
    - Keep same framework for time domain inversion as in previous model developments (3 component, wavepackets)
  - Compute inverse kernels using NACT

- II -Use "homogenized", smooth crustal model appropriate for the period range considered

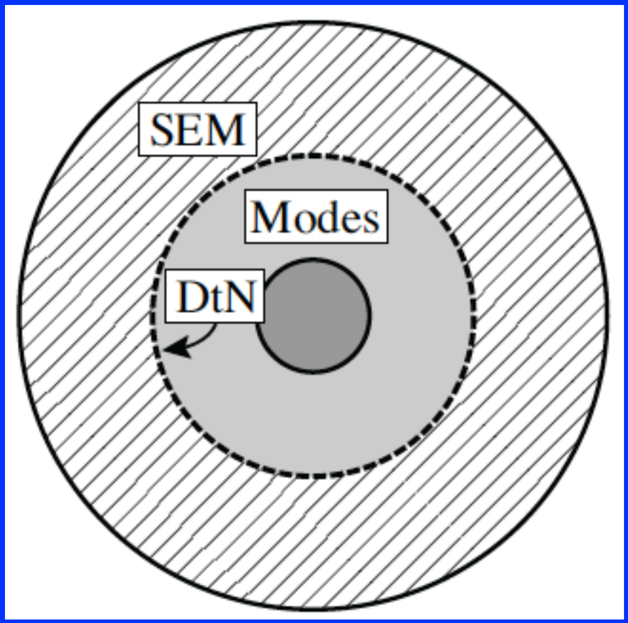
- III - Start at long periods (T>60s) and progress towards shorter periods, "assimilating" more data

I-HYBRID INVERSION APPROACH

At each iteration:

1-Forward modeling step

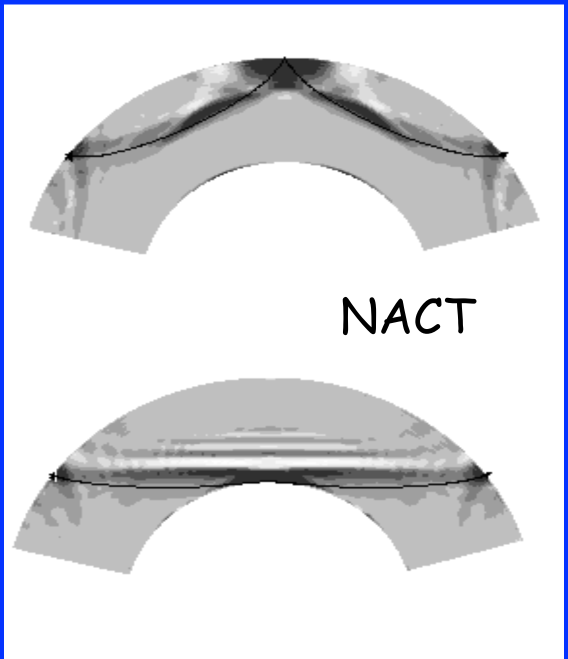
Use coupled spectral element method of Capdeville et al. (2003) to accurately forward model wave propagation through the 3D Earth



Γ1= Normal modes in 1D
Γ2 = Spectral element method

2-Inverse step

Use approximate Hessian calculated in NACT. Much faster than adjoint!



Li and Romanowicz, 1995

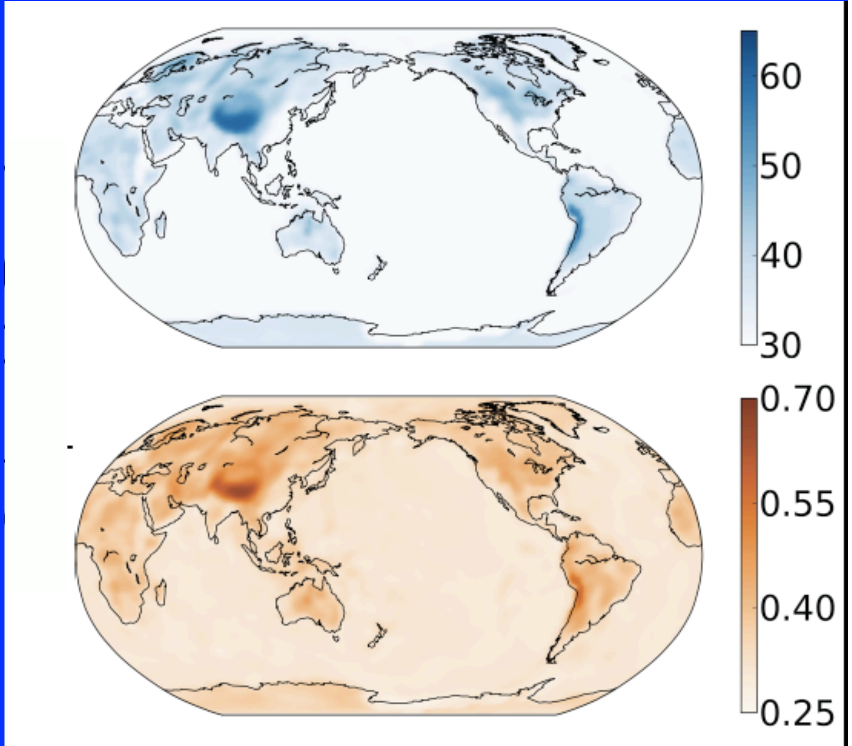
II-Smooth homogeneized crustal model

• Construct an equivalent smooth anisotropic crustal model (Backus, 1962 – effective medium theory)

- Crustal thickness saturated at 30 km

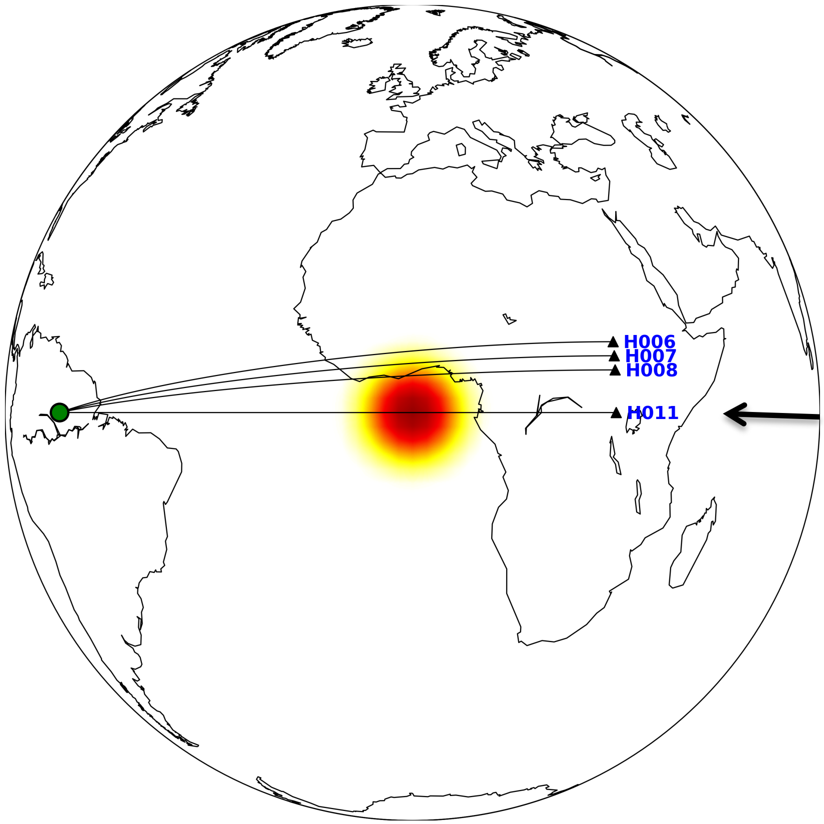
- Start with filtered Crust2.0

- Fit global dataset of dispersion maps (*Ritzwoller et al., 2002*) using Monte Carlo approach

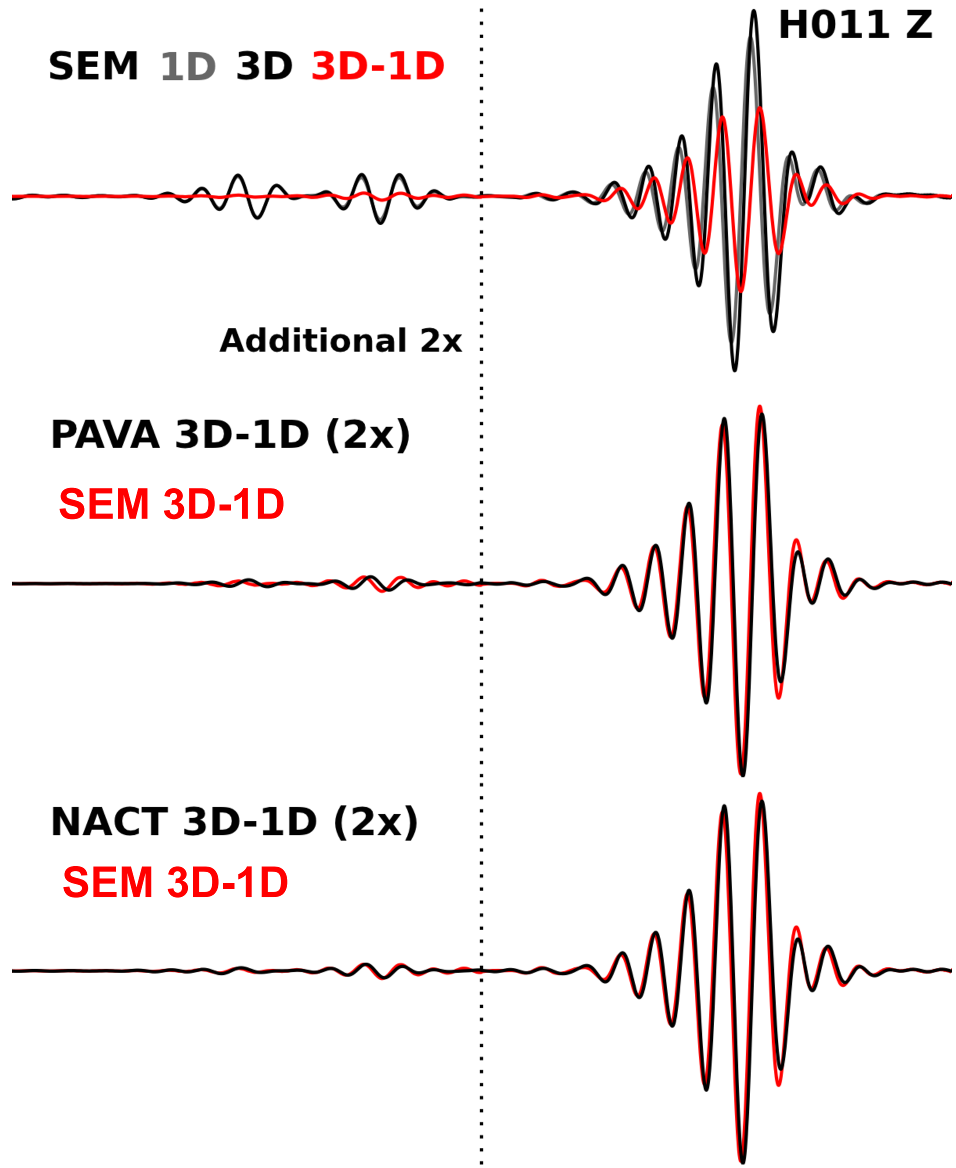


Top: Smooth Moho of SEMum2 (km); **Bottom**: SEM (C=0.4) time step (s)

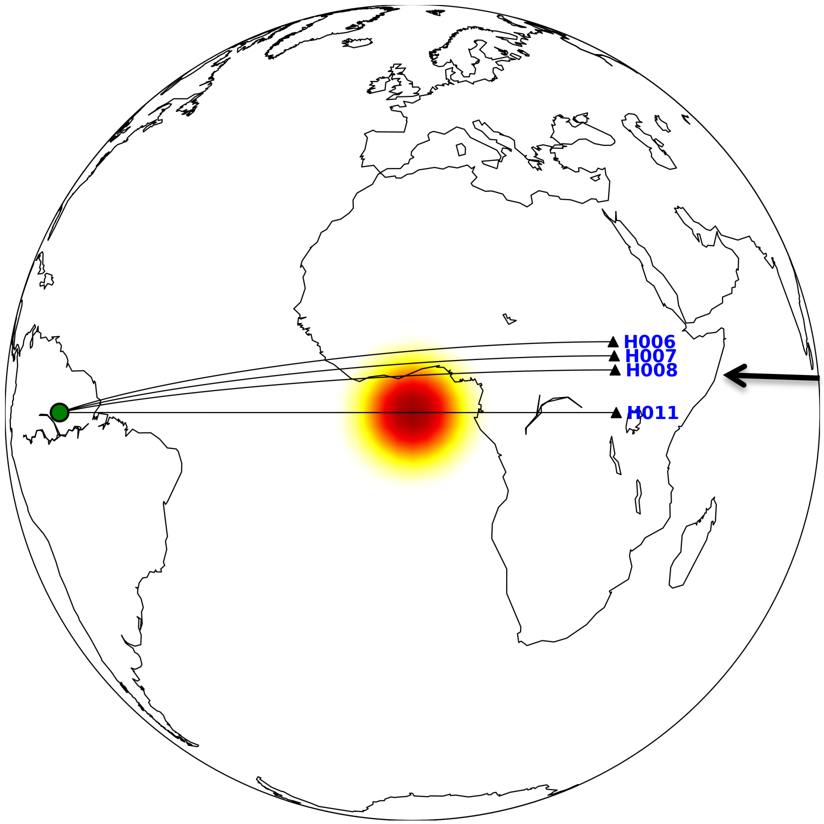
=> SEM time step prolonged ~4 times



~Degree 16 “blob” Δv/v=-5%
Radius:11.25 deg
(about 2000 km across)



Long period synthetics filtered to 60s



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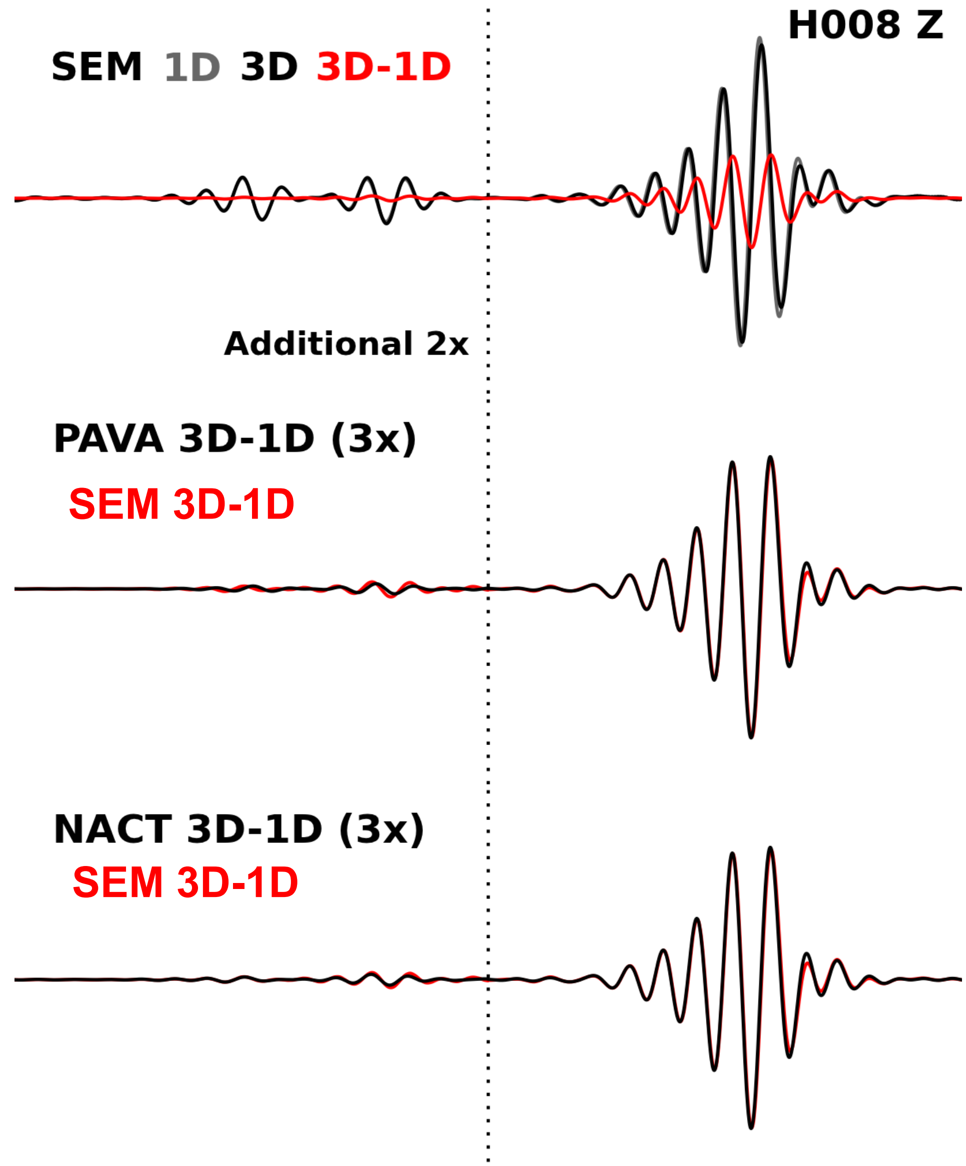
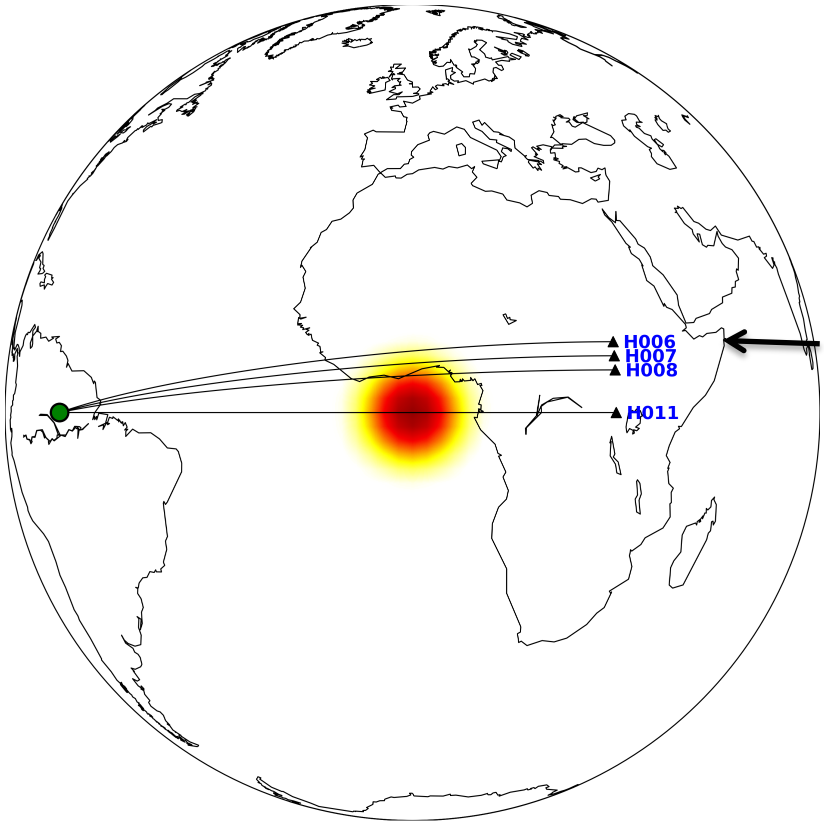


Long period synthetics filtered to 60s



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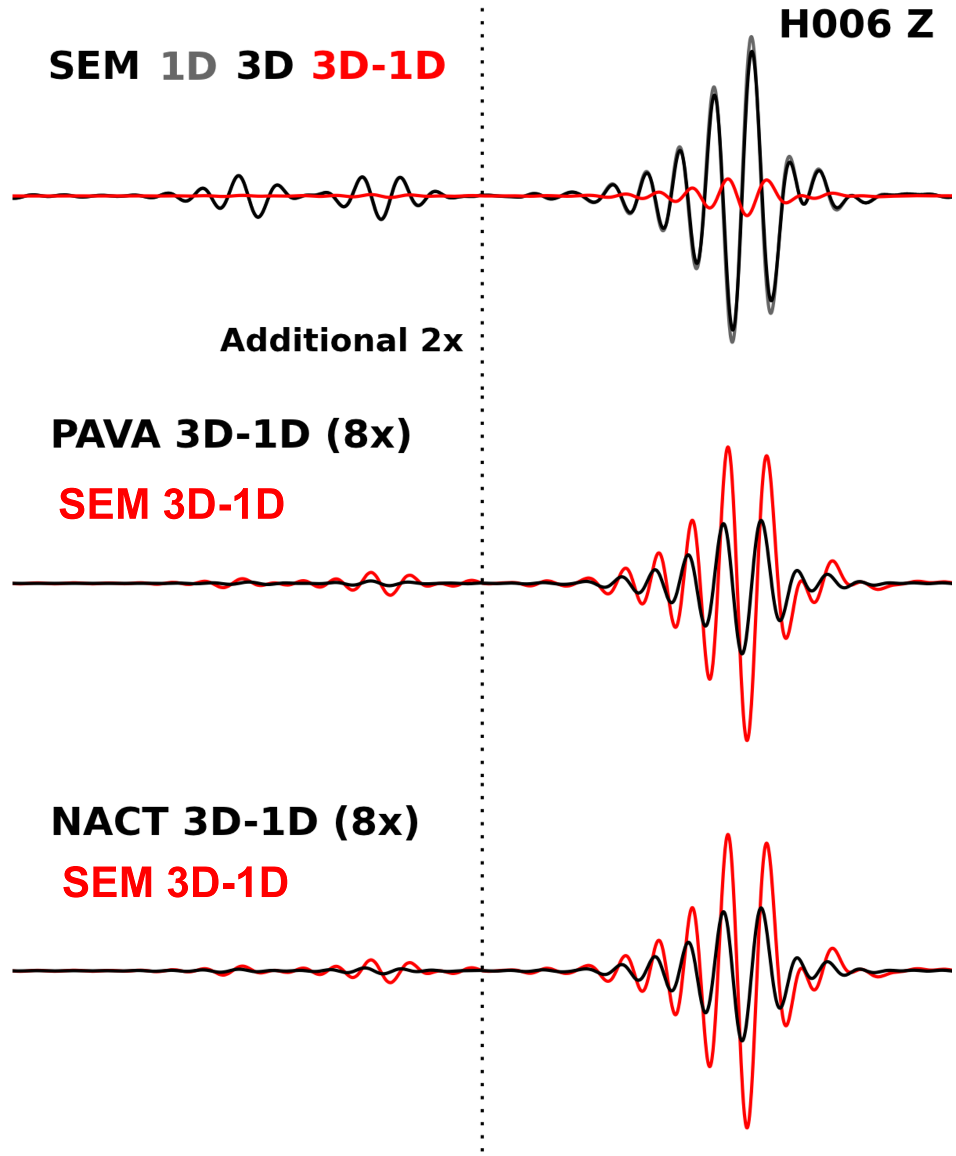


Long period synthetics filtered to 60s

SEMum and SEMum2

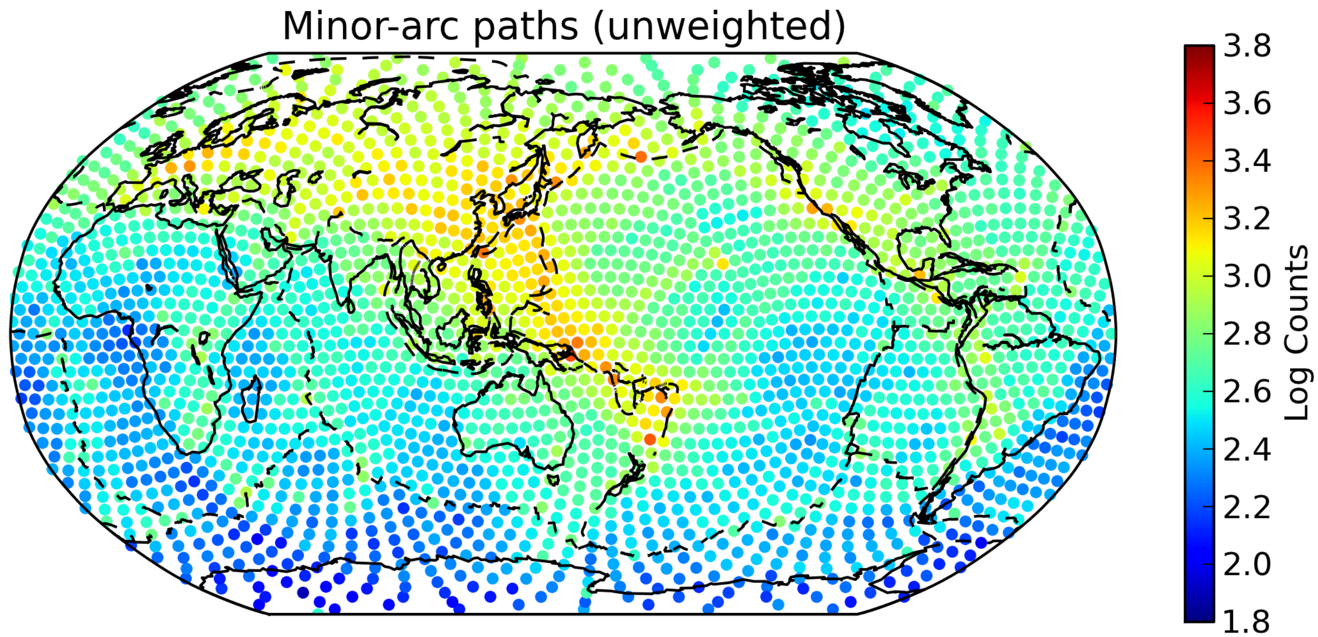
- Full waveforms, T> 60 s, 204 events
- Radially anisotropic models
  - Vs (isotropic shear velocity)
  - $\xi = (Vsh/Vsv)^2$
- Invert top 800 km of the mantle:
  - Lower mantle from existing tomographic model SAW24B16
- *1st generation model*: uniform crustal thickness of 60 km
  - Start with 1D model
  - Progressively add waveforms and refine parametrization
  - -> 10 iterations: SEMum (*Lekic and Romanowicz, 2011 GJI*)
- *2nd generation model*: SEMum2 – variable thickness crust, finer scale parametrization, 2+ iterations *(French et al., 2013)*

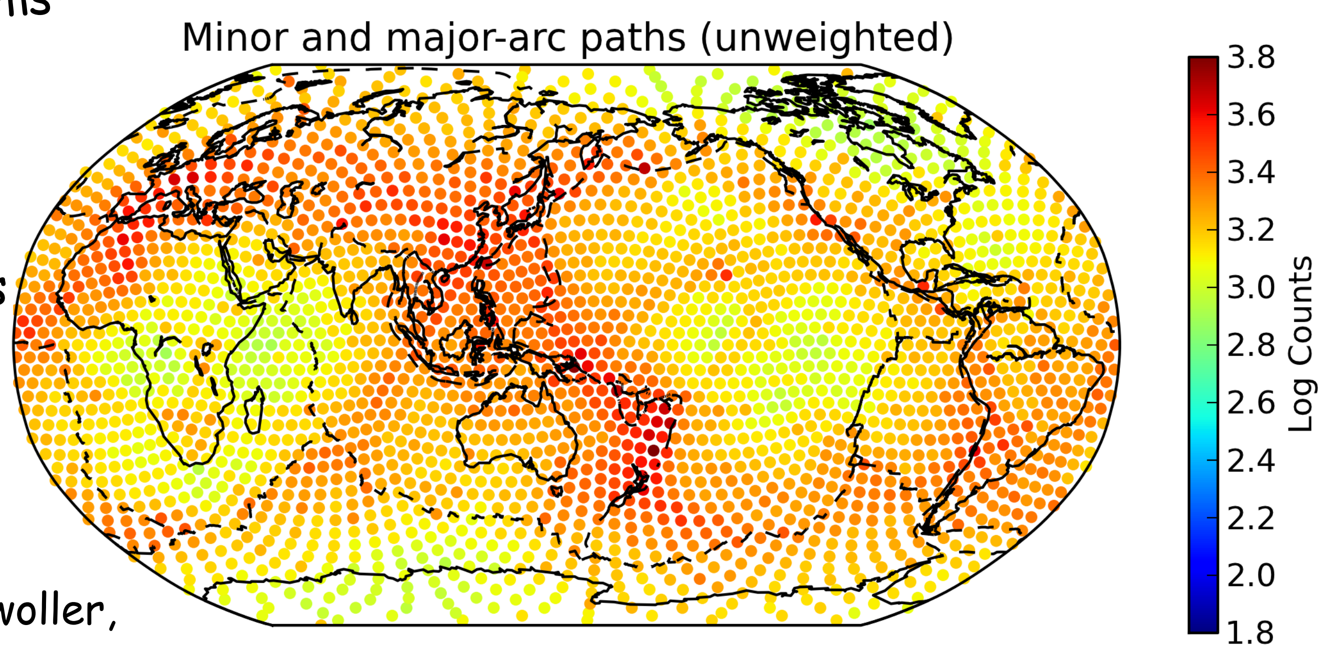
SEMum2:
204 events
~ 100,000
Wavepackets

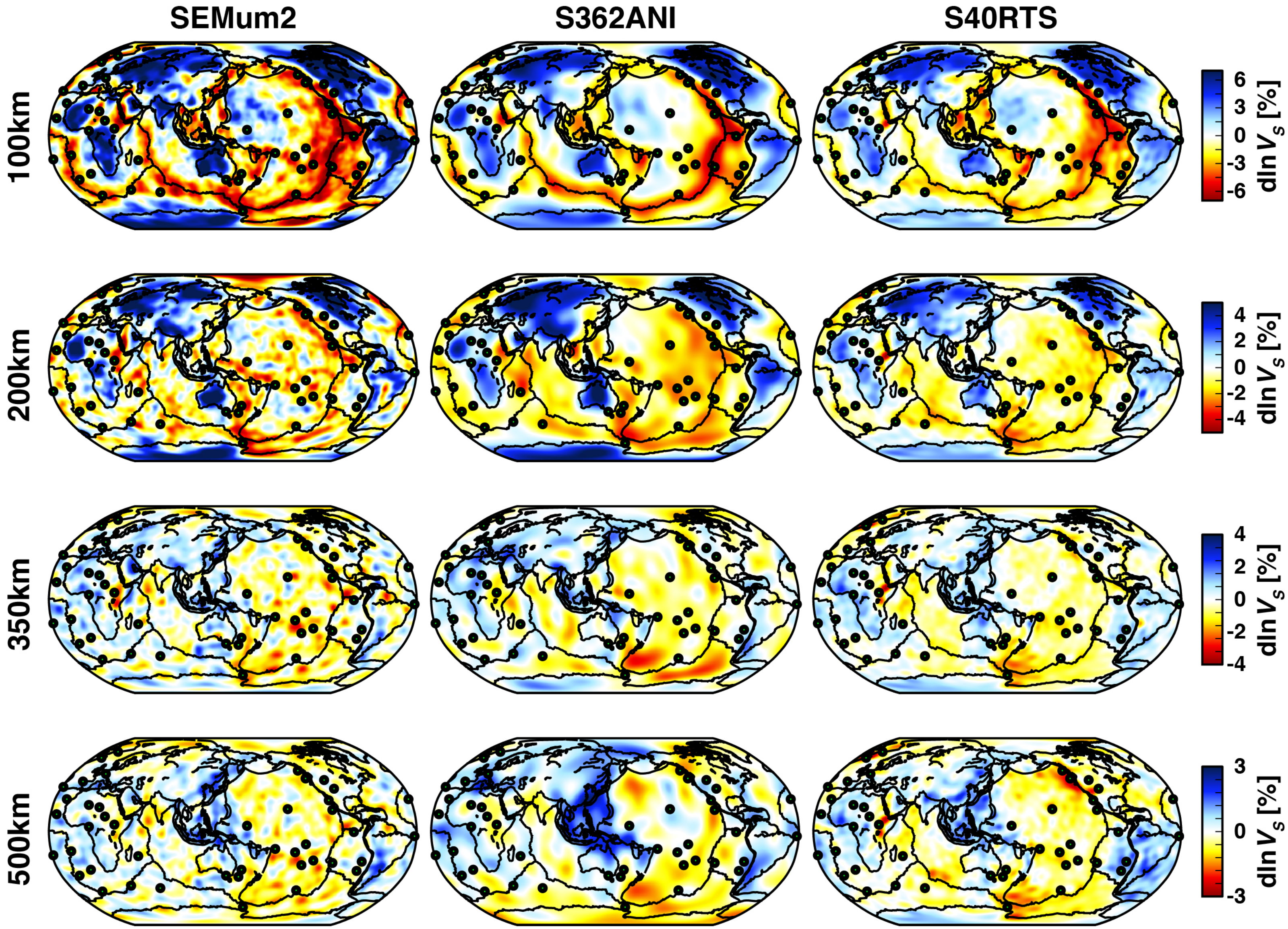
(Z,R,T) waveforms
- Surface waves
- Body waves

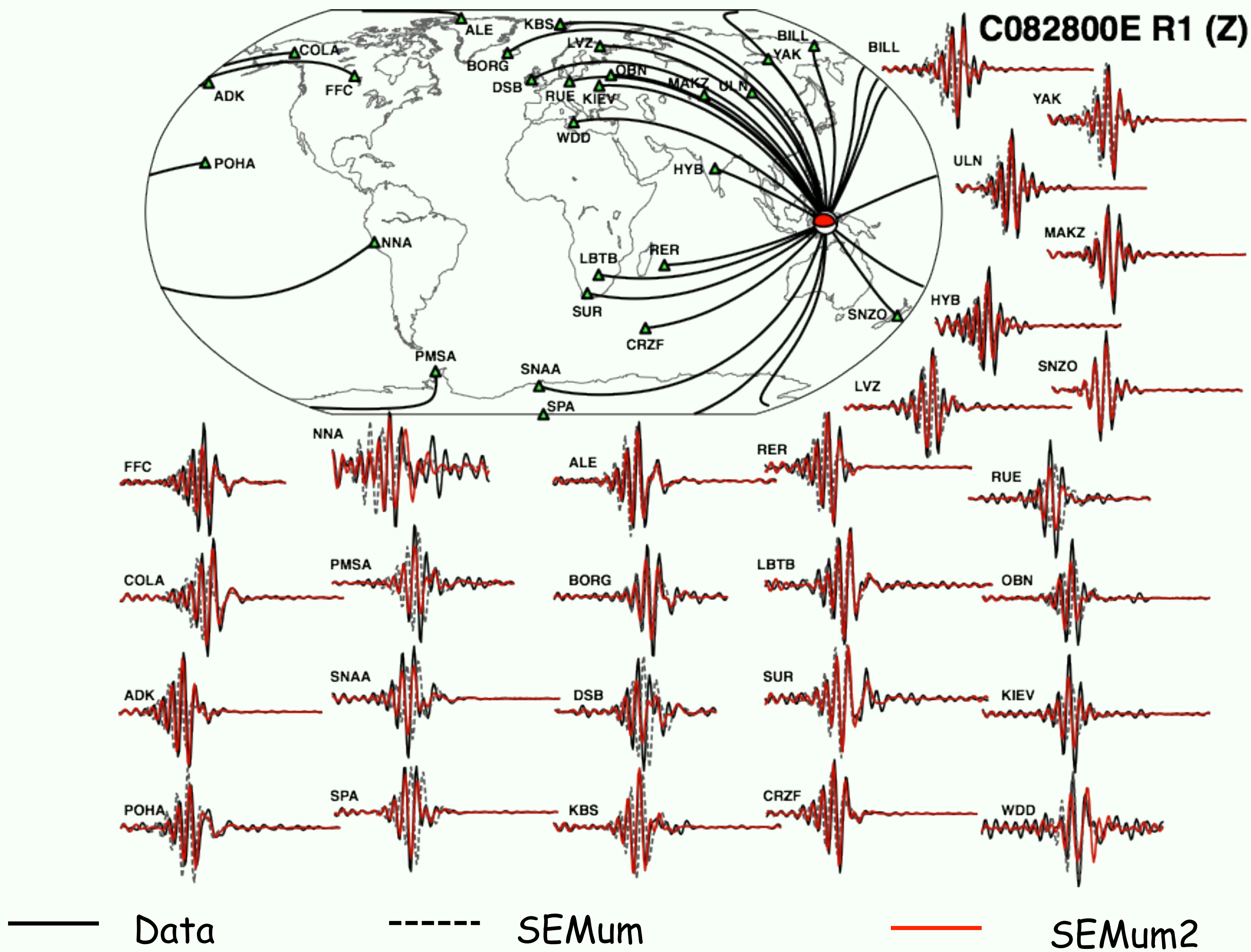
~5M indep.
data constraints

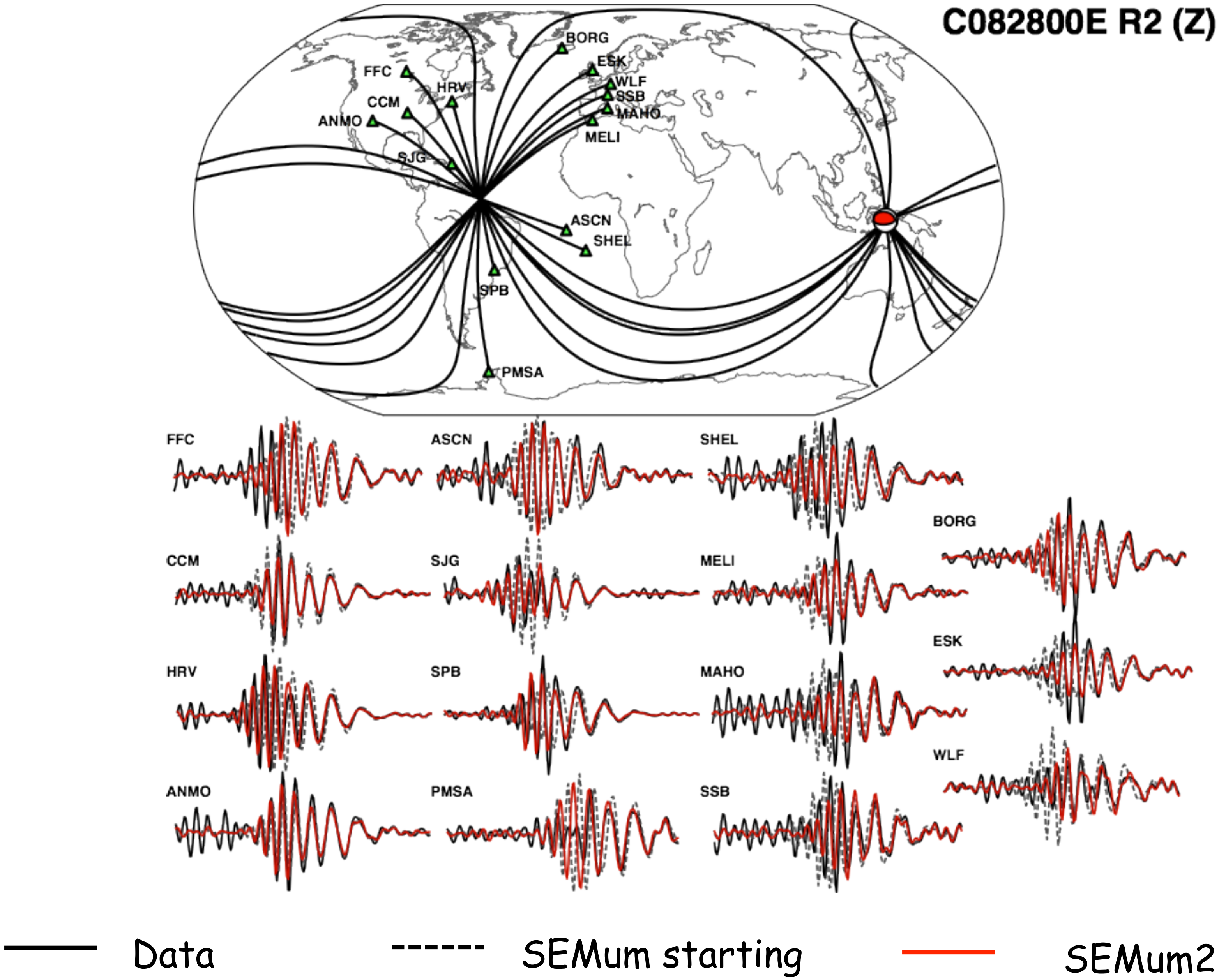
+Surface wave
dispersion
25-60s to
constrain crust
(Shapiro and Ritzwoller,
2002)

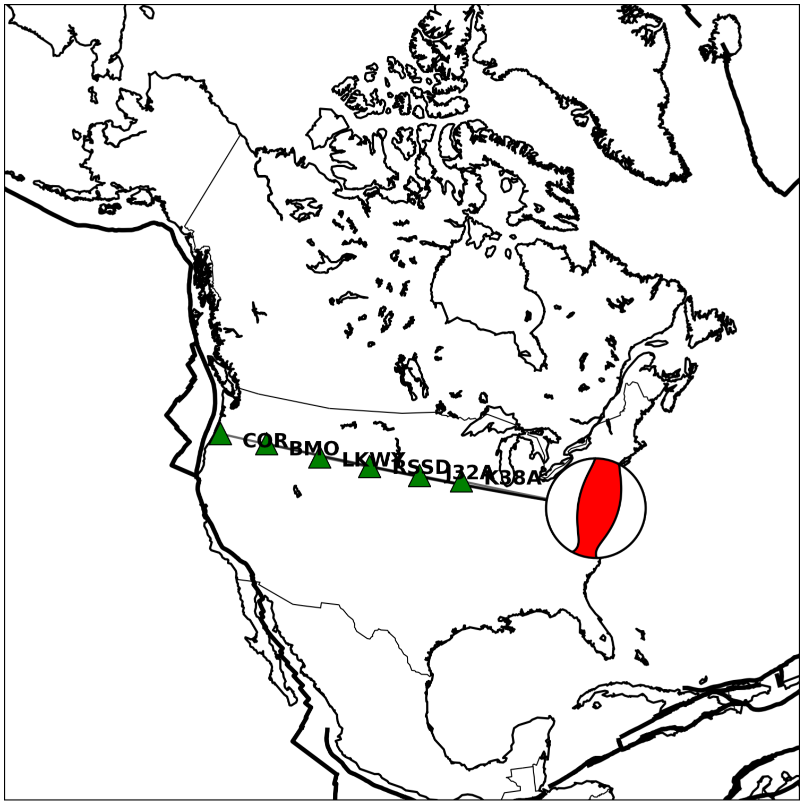




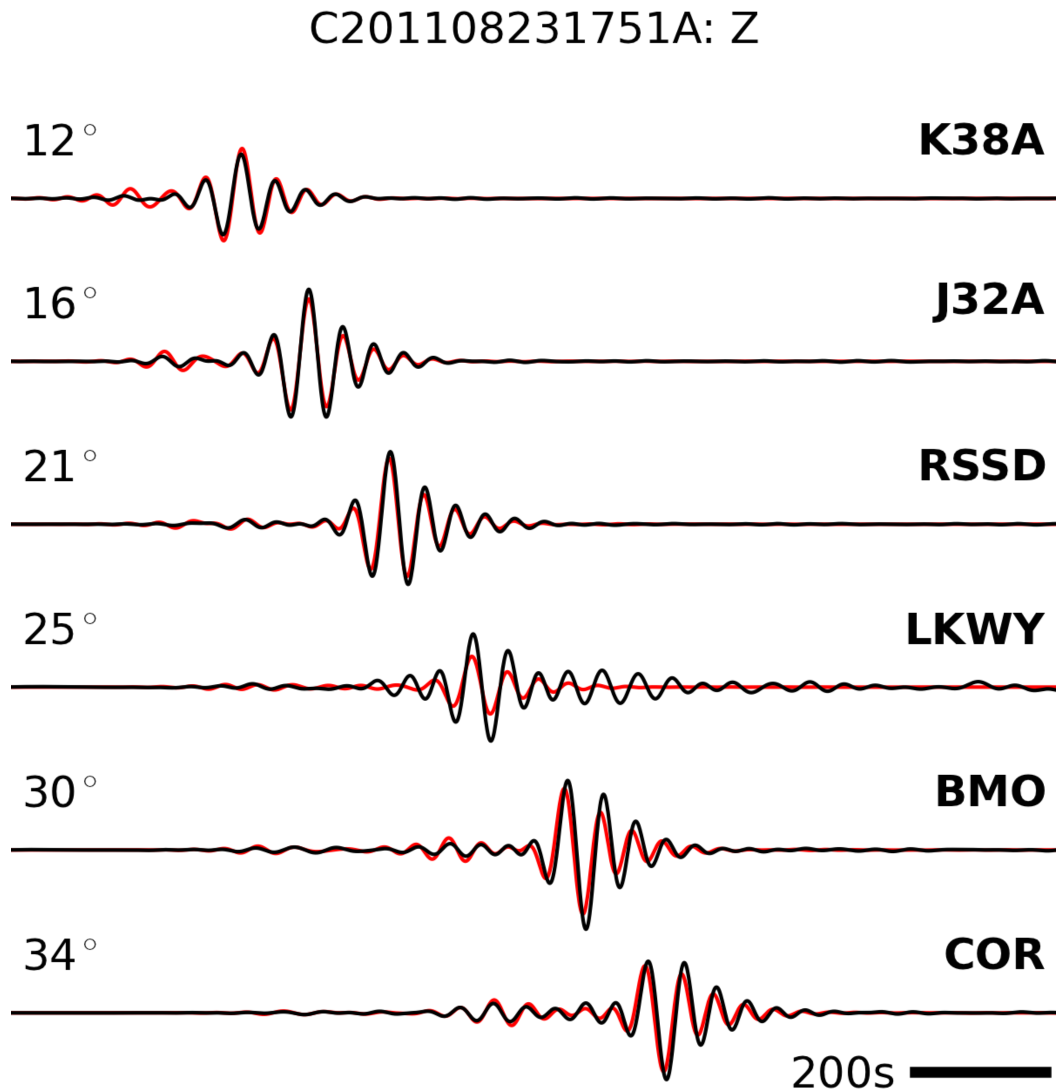

SEMum2
S362ANI
S40RTS
100km
200km
350km
500km
6
3
0
-3
-6
4
2
0
-2
-4
4
2
0
-2
-4
3
0
-3
dln V_S [%]


C082800E R1 (Z)
BILL
YAK
ULN
MAKZ
HYB
SNZO
LVZ
RUE
OBN
KIEV
WDD
FFC
NNA
ALE
RER
COLA
PMSA
BORG
LBTB
ADK
SNAA
DSB
SUR
POHA
SPA
KBS
CRZF
Data
SEMum
SEMum2


C082800E R2 (Z)
BORG
ESK
WLF
SSB
MAHO
MELI
FFC
HRV
CCM
ANMO
SJG
ASCN
SHEL
SPB
PMSA
FFC
ASCN
SHEL
BORG
CCM
SJG
MELI
ESK
HRV
SPB
MAHO
WLF
ANMO
PMSA
SSB
Data
SEMum starting
SEMum2



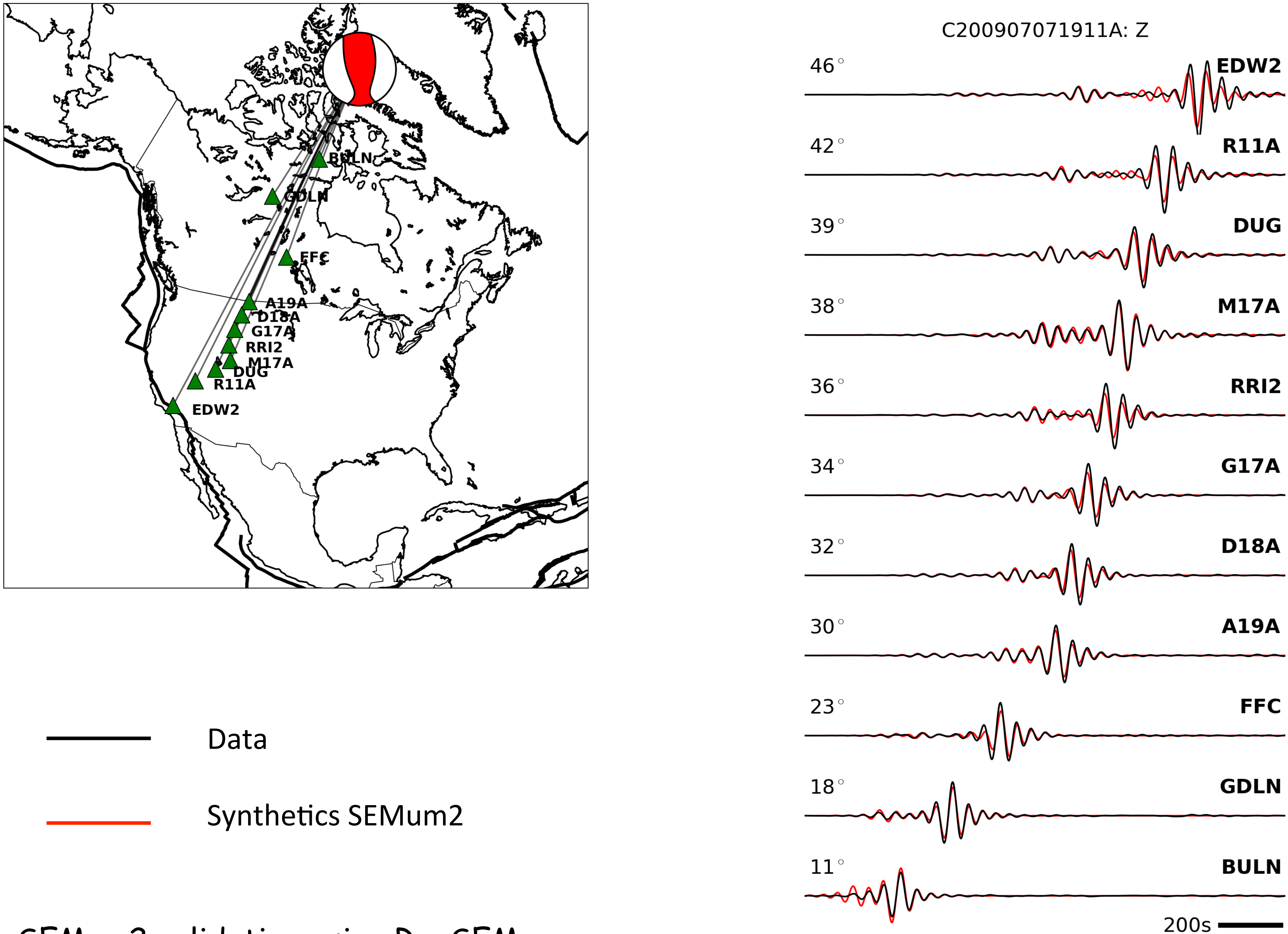
08/23/2011 Virginia eq.Mw 57



Data

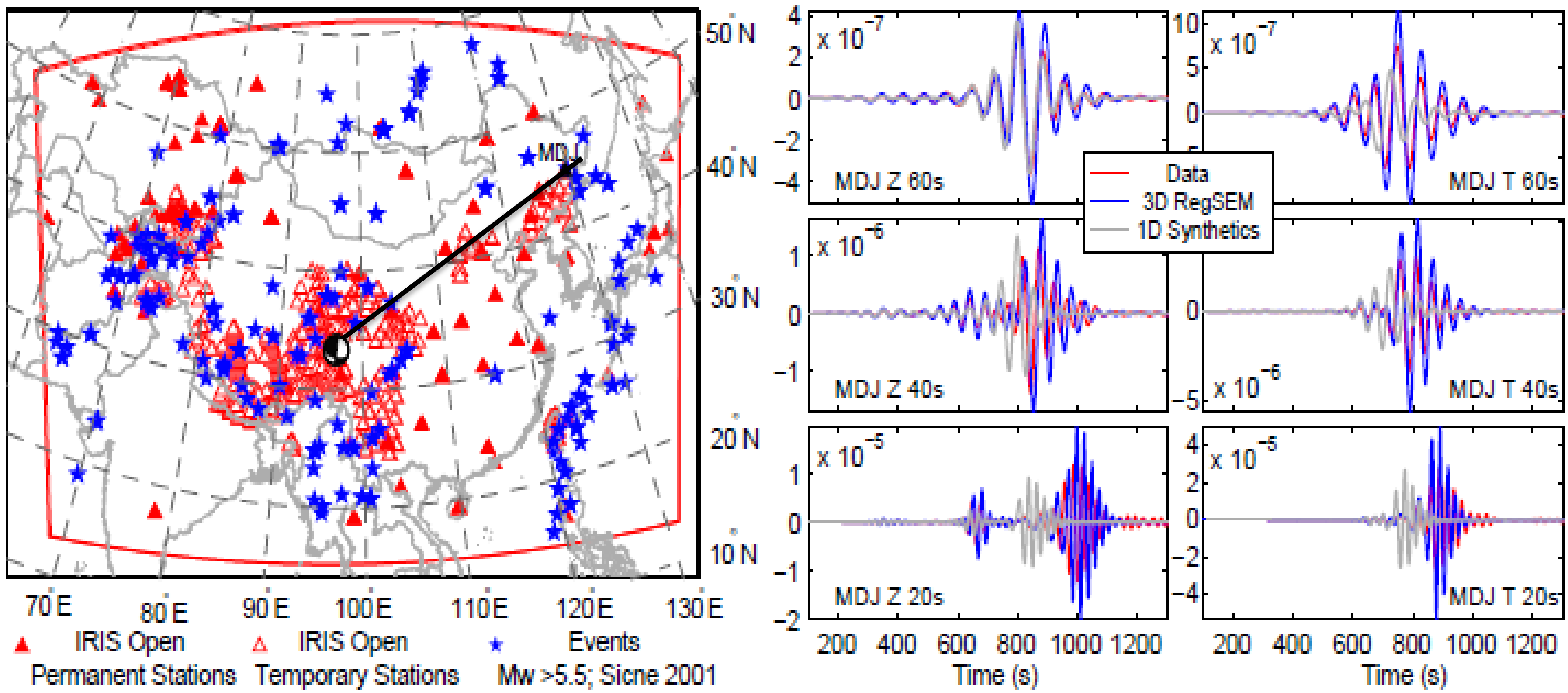
Synthetics SEMum2

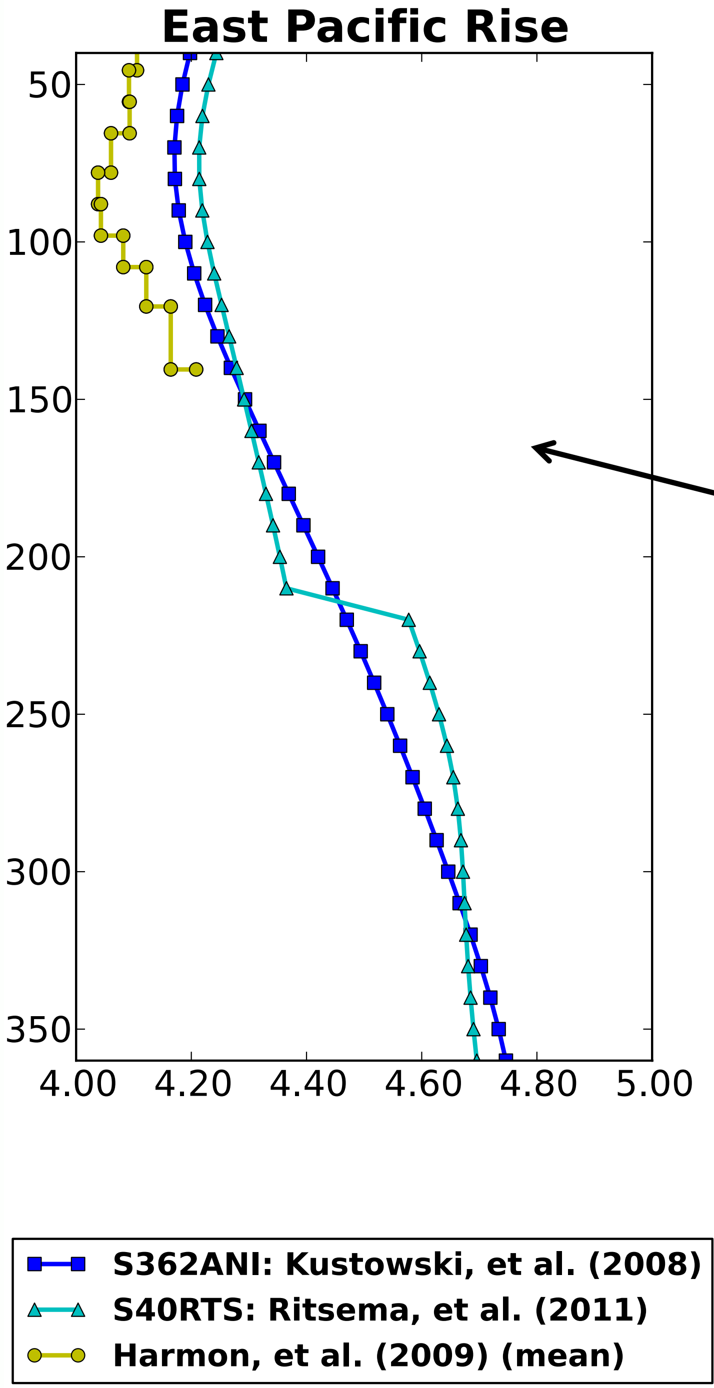
SEMum2 constructed with data at Δ>15°,T>60 s;
Here: comparison is shown down to 40 s and regional distances
Event not used in the inversion



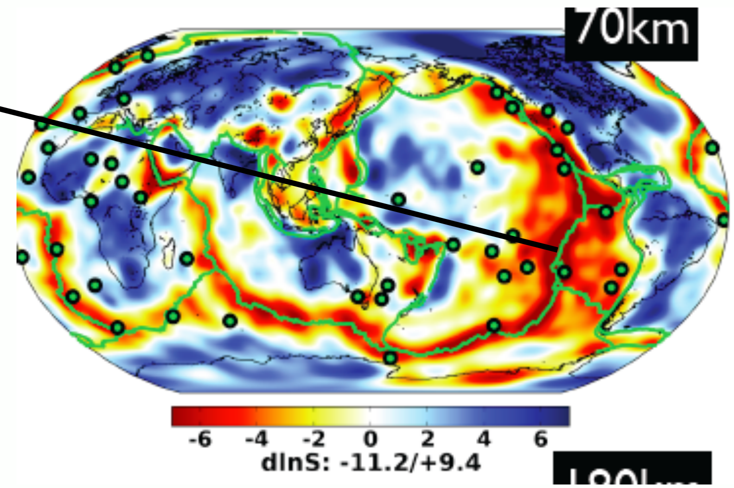
SEMum2 validation using RegSEM

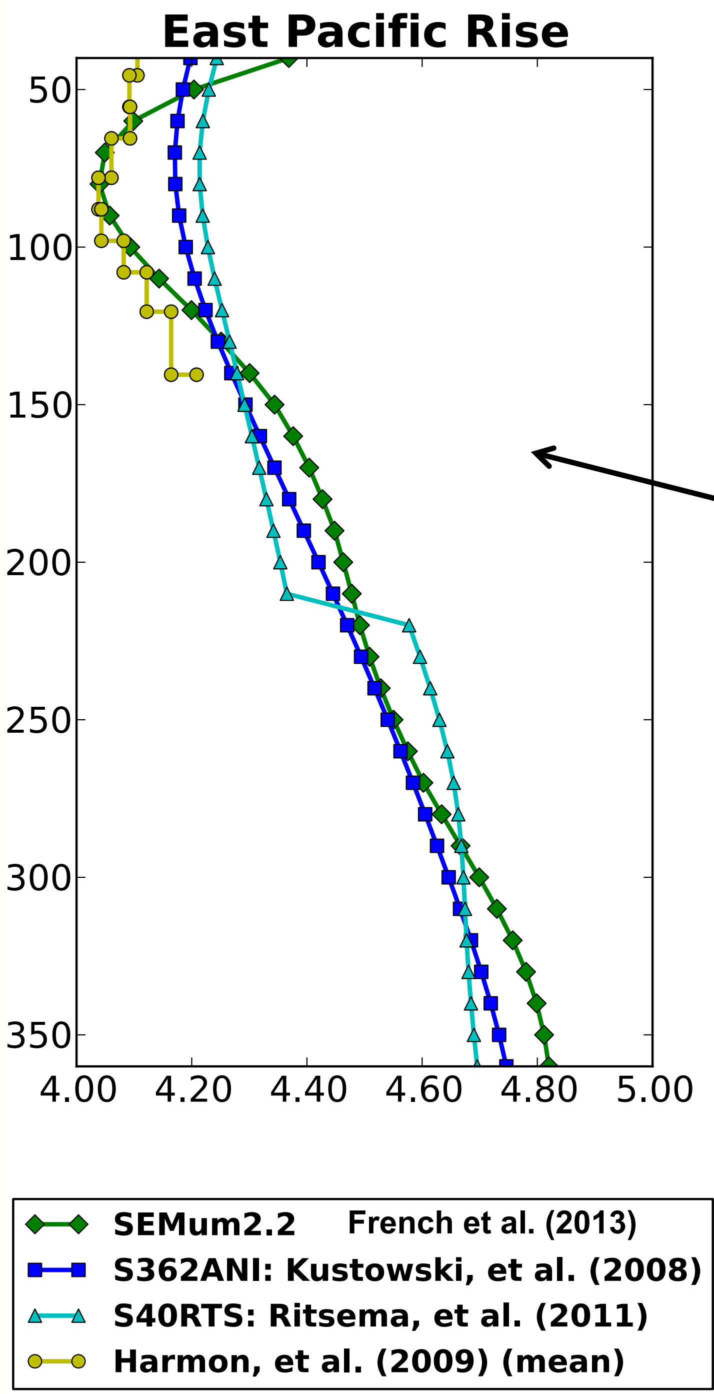
SEMum2 validation using RegSEM



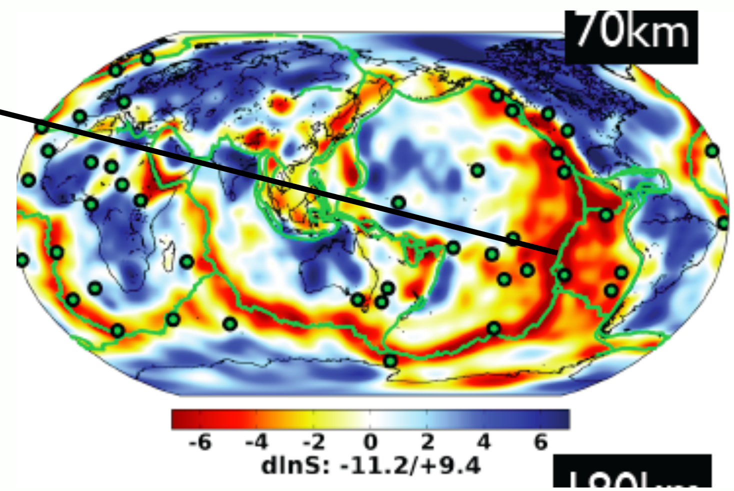


Validation by comparison with regional results

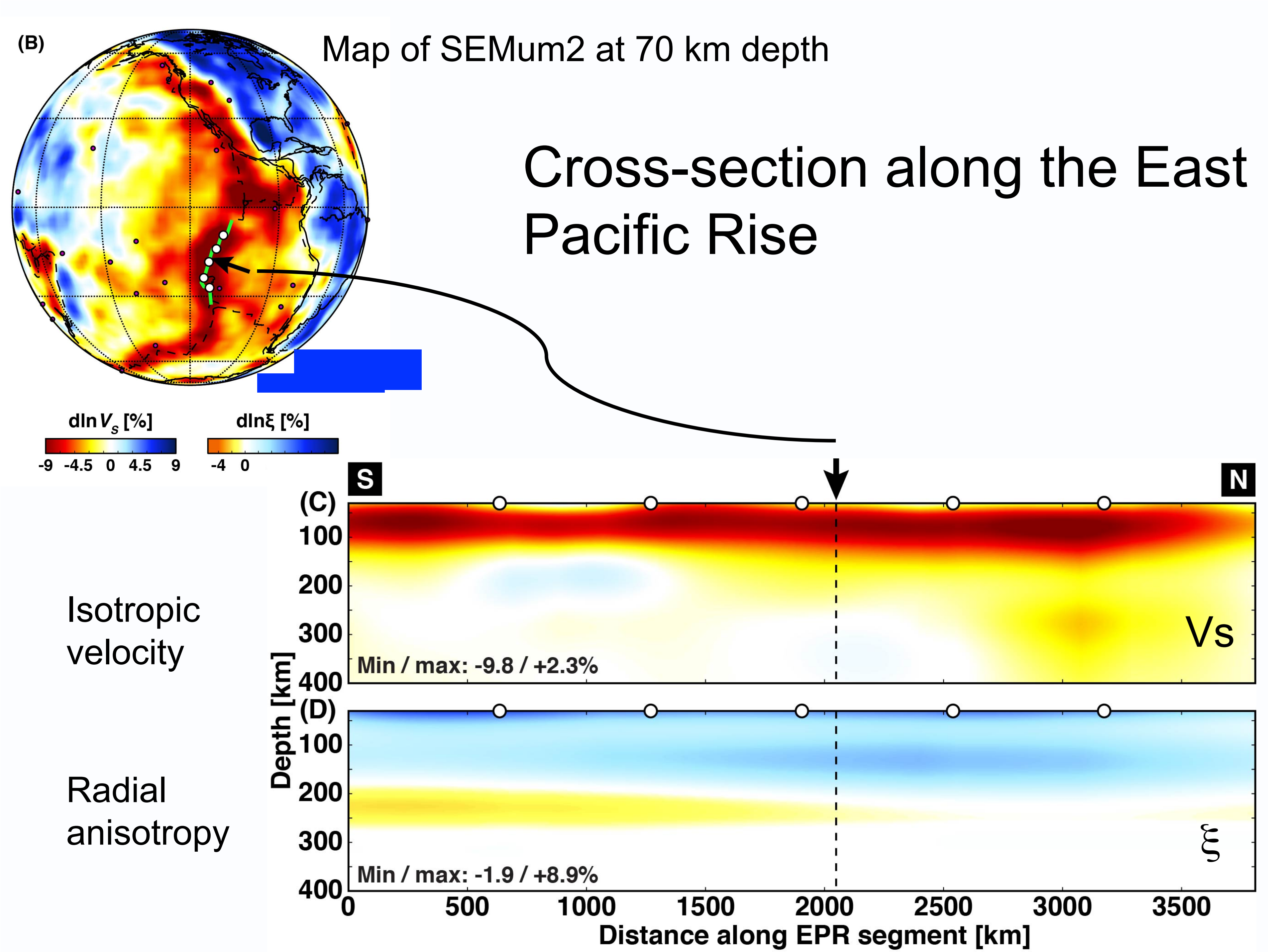




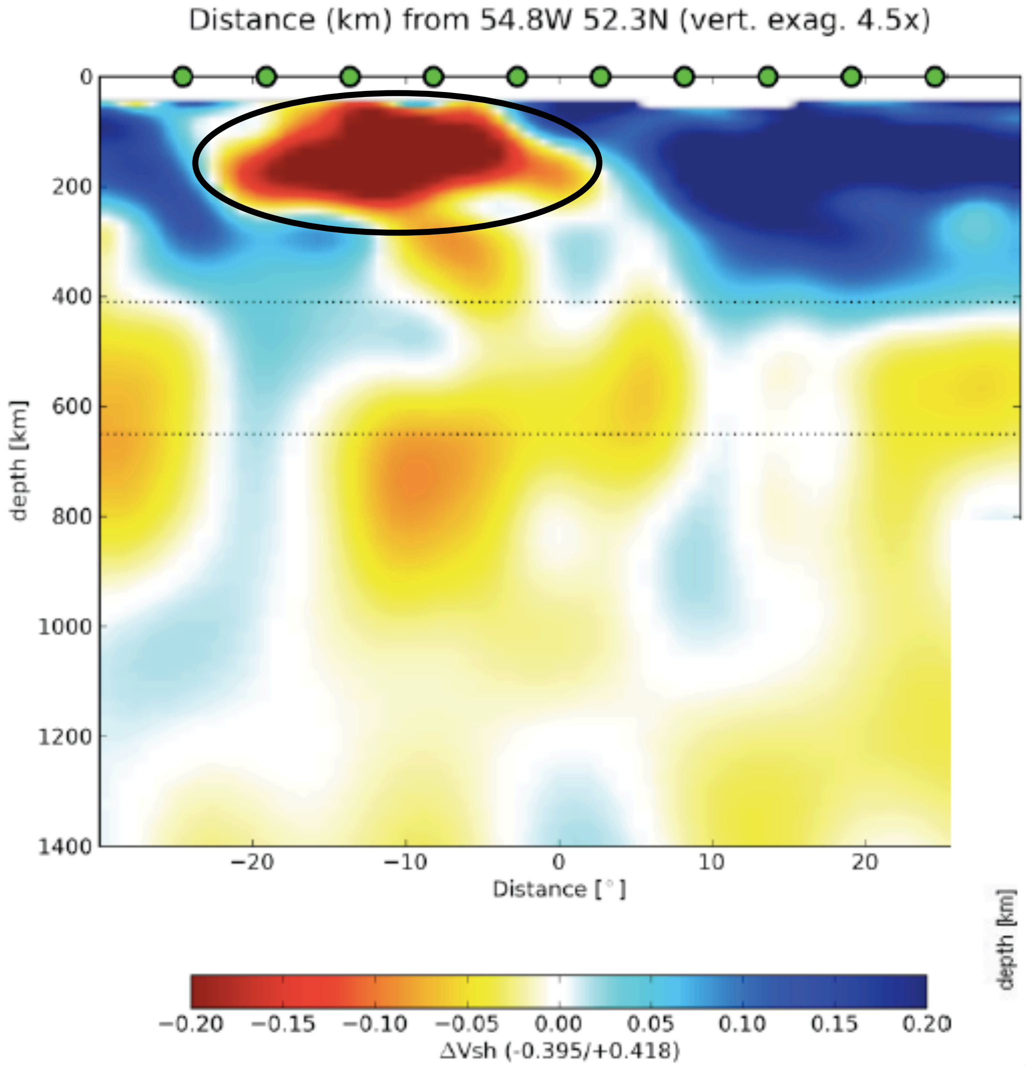
Validation by comparison with regional results

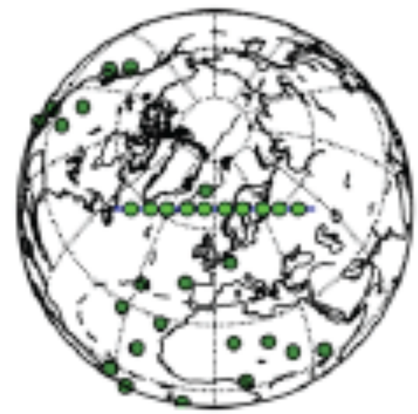


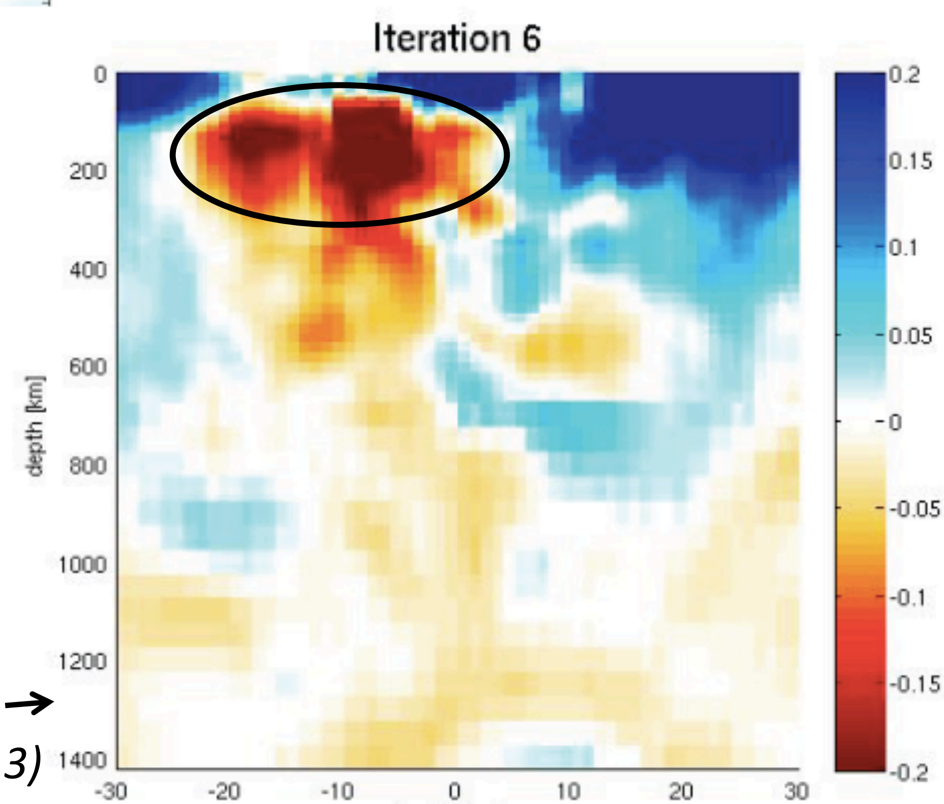
Cross-section along the East Pacific Rise



SEMum2.3S6: Iceland section

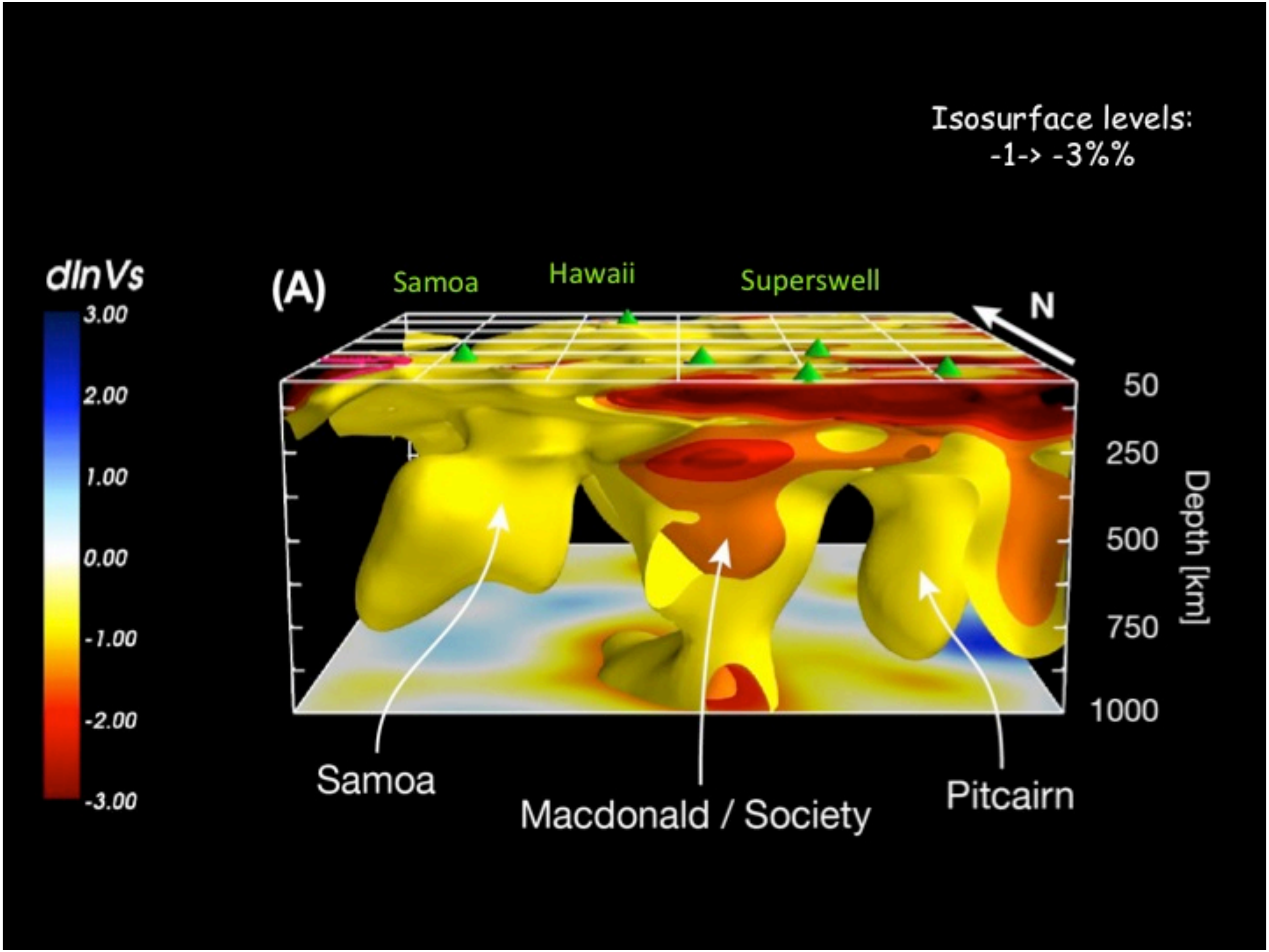


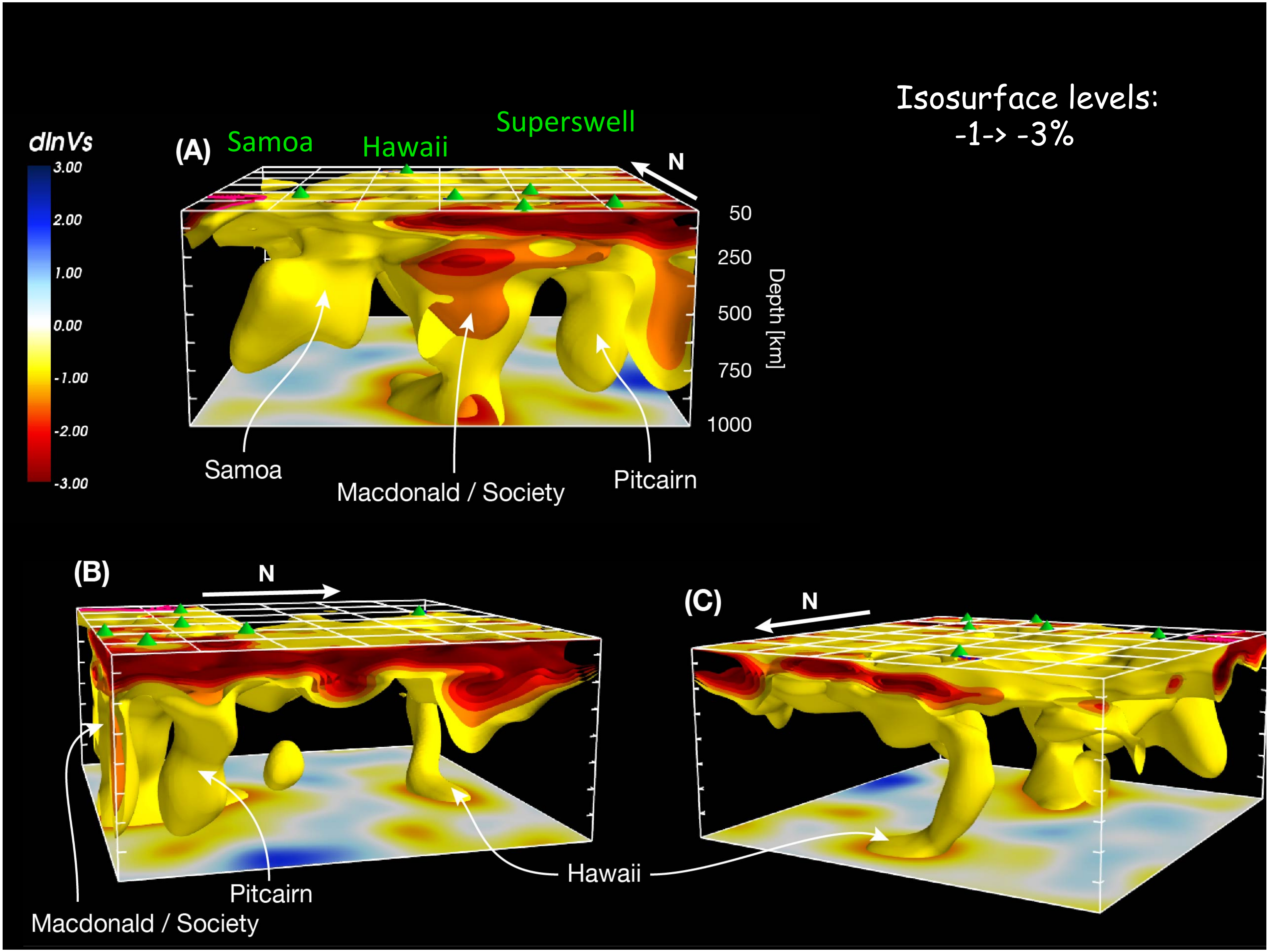


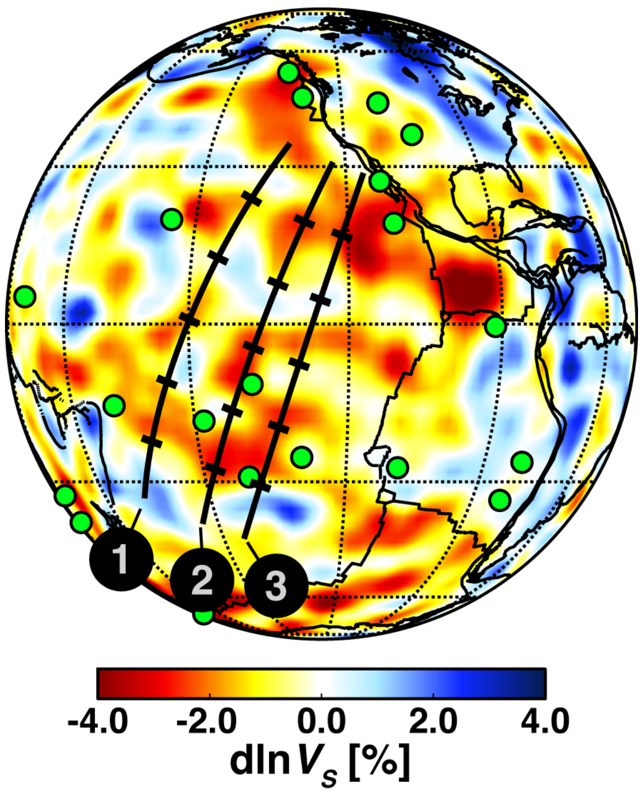


Courtesy of F. Rickers →

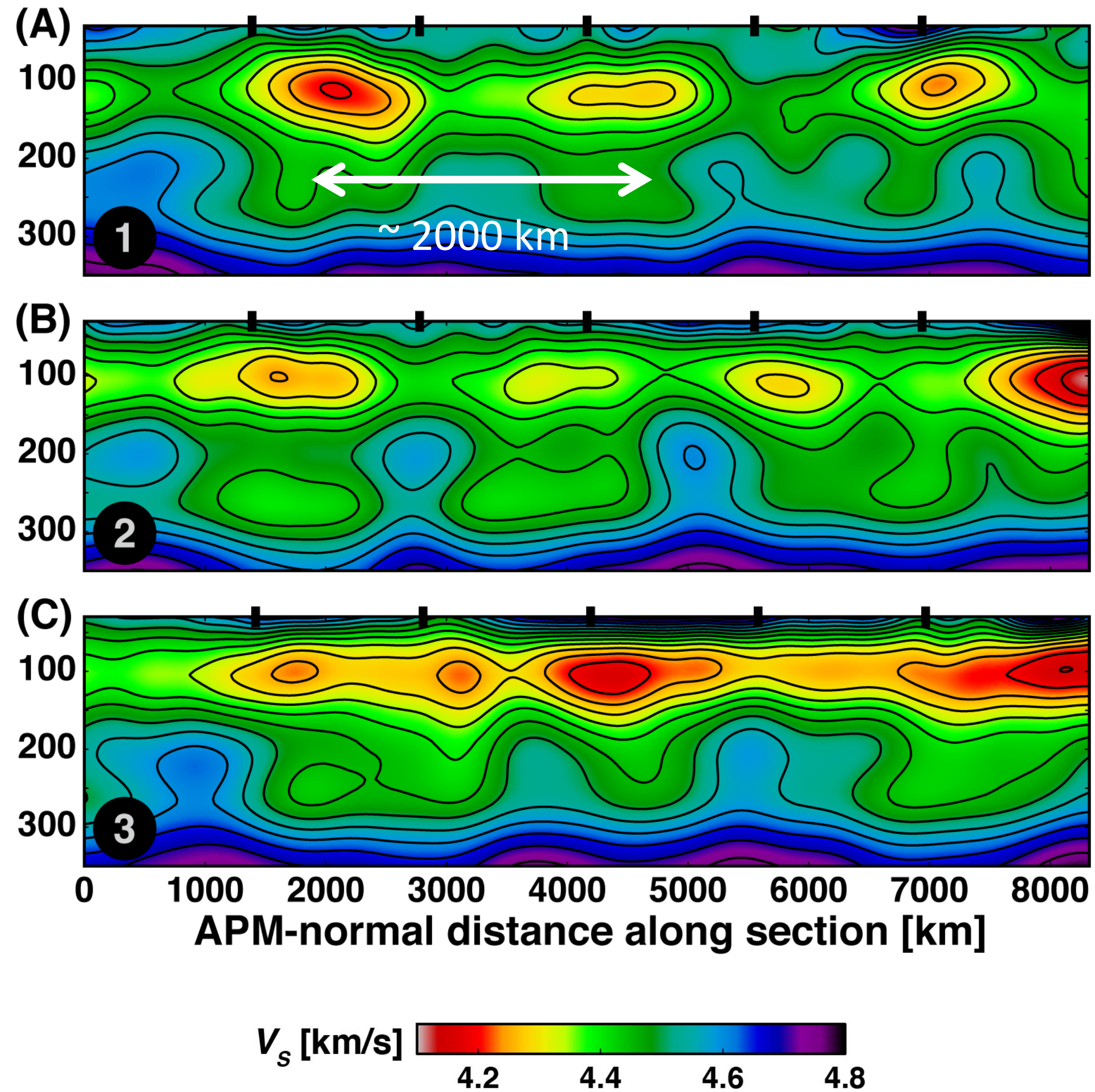
(Rickers et al., 2013)


Isosurface levels:
-1-> -3%%
dlnVs
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
(A)
Samoa
Hawaii
Superswell
N
50
250
500
750
1000
Depth [km]
Samoa
Macdonald / Society
Pitcairn


Isosurface levels:
-1-> -3%
dlnVs
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
(A)
Samoa
Hawaii
Superswell
N
50
250
500
750
1000
Depth [km]
Samoa
Macdonald / Society
Pitcairn
(B)
N
(C)
N
Hawaii
Pitcairn
Macdonald / Society

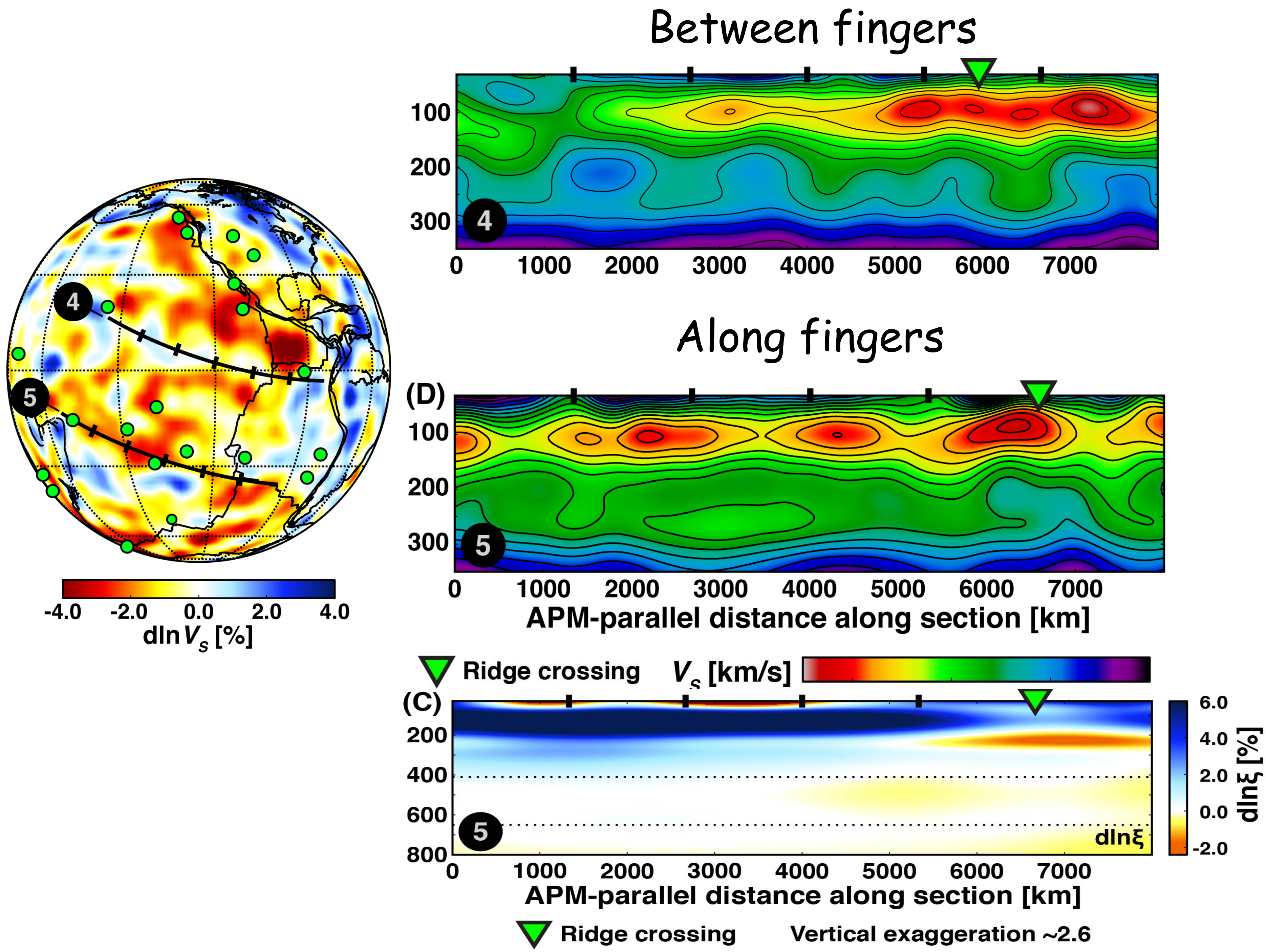


Velocity perturbation from the mean



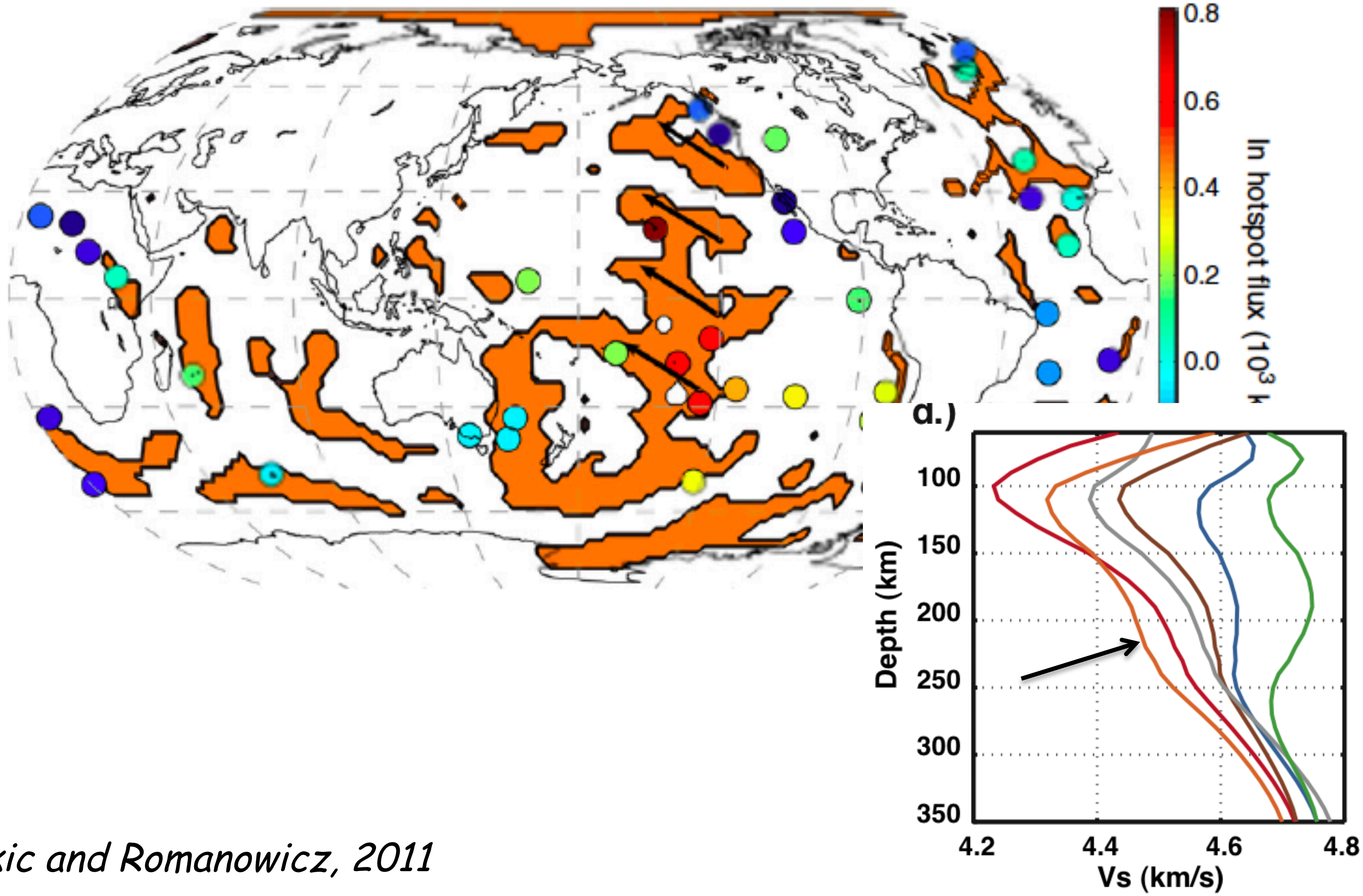
Absolute velocity

French et al., 2012



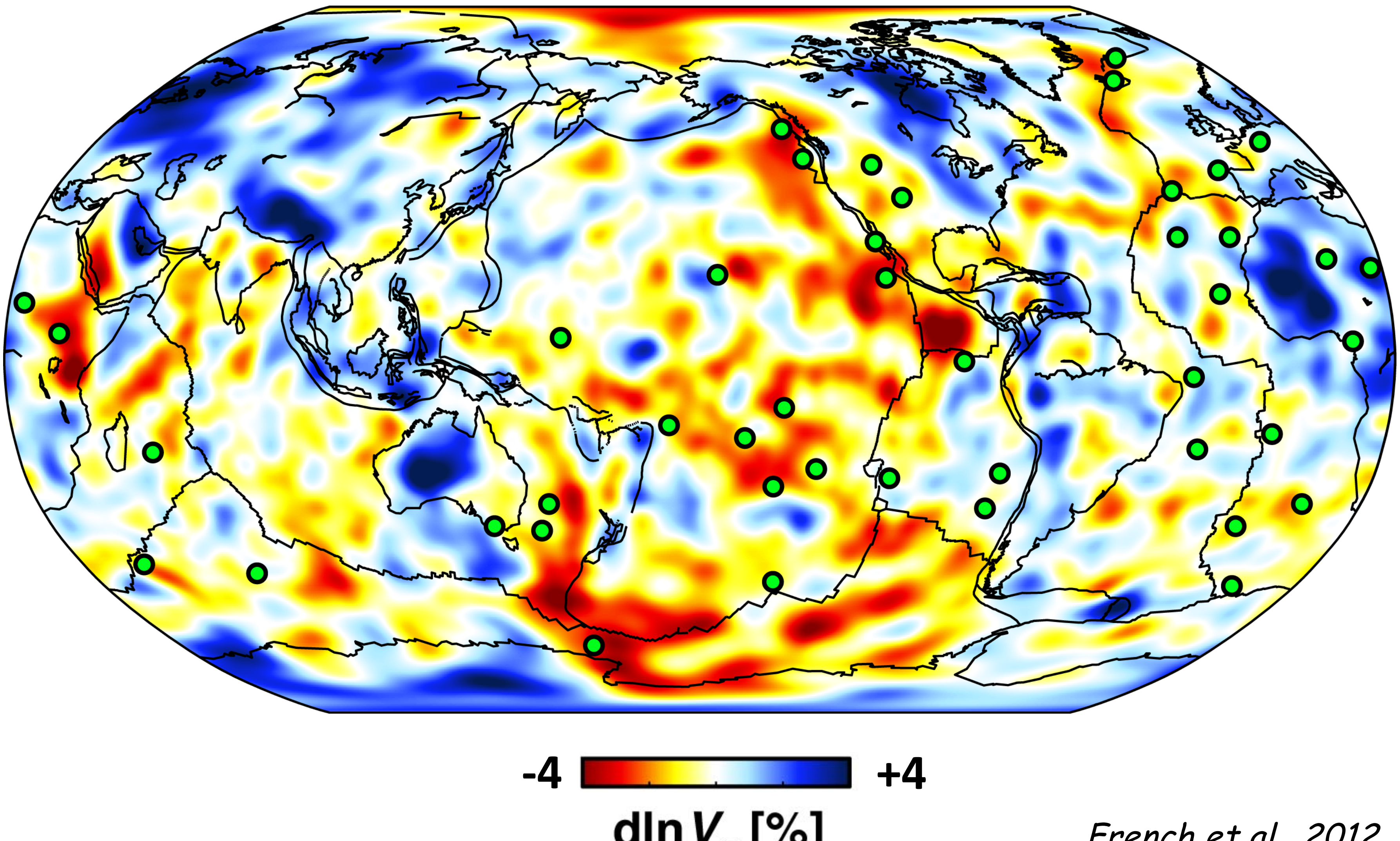
Between fingers
Along fingers
(D)
(C)
4
5
100
200
300
400
600
800
0
1000
2000
3000
4000
5000
6000
7000
-4.0
-2.0
0.0
2.0
4.0
dlnV_s [%]
APM-parallel distance along section [km]
Ridge crossing
V_s [km/s]
6.0
-2.0
dlnξ [%]
dlnξ
Vertical exaggeration ~2.6

Geographic extent of oceanic region OR2 in clustering analysis of SEMum with N=6, and the location of major hotspots



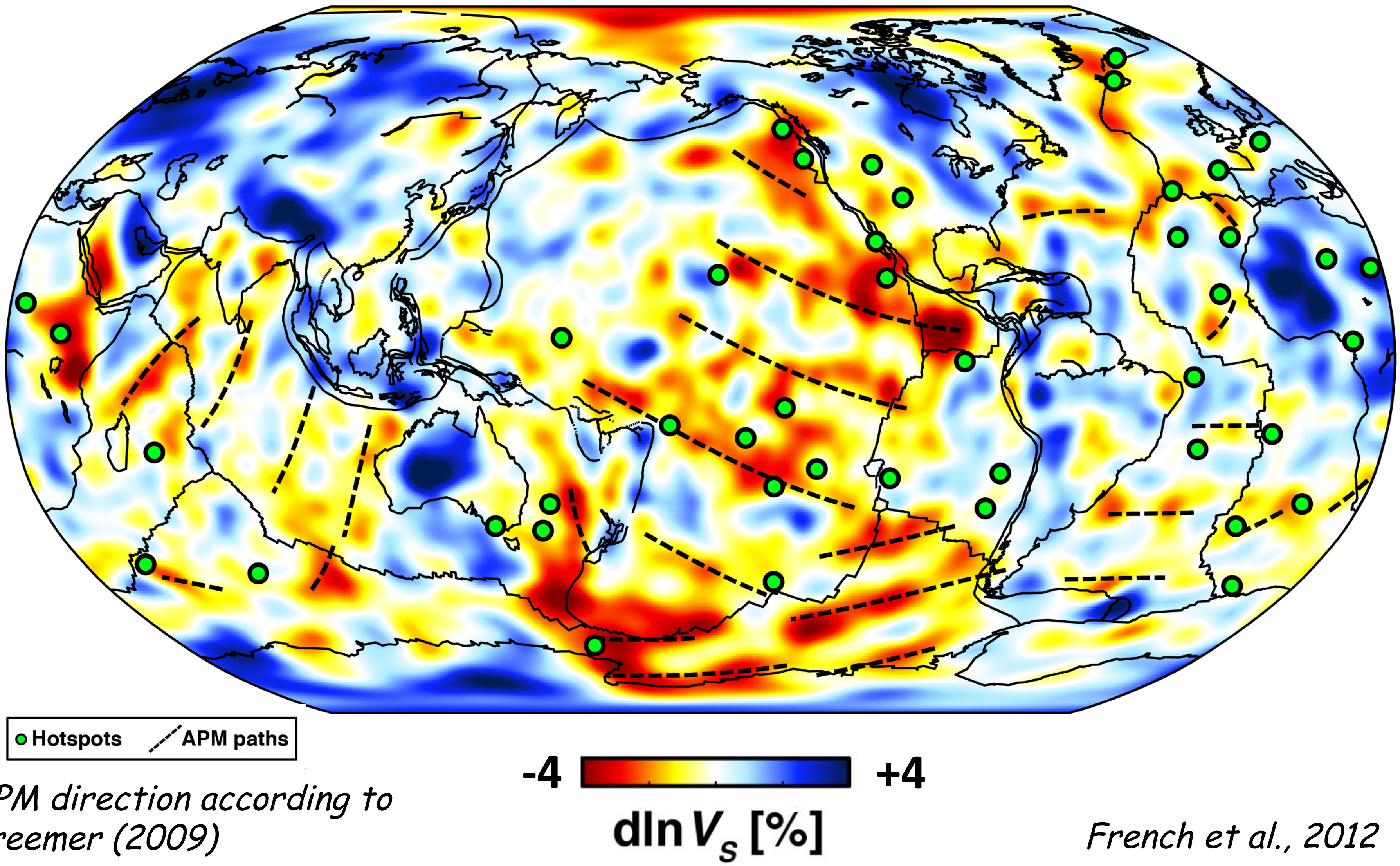
Lekic and Romanowicz, 2011

SEMum2 at 250 km depth



French et al., 2012

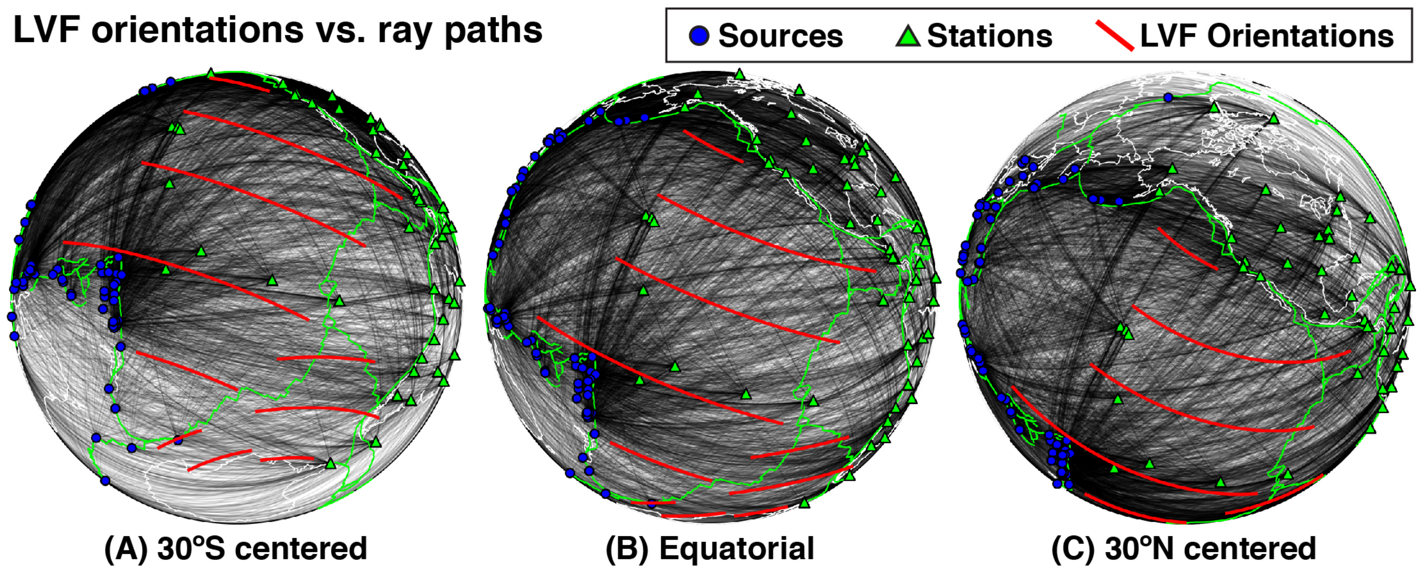
SEMum2 at 250 km depth

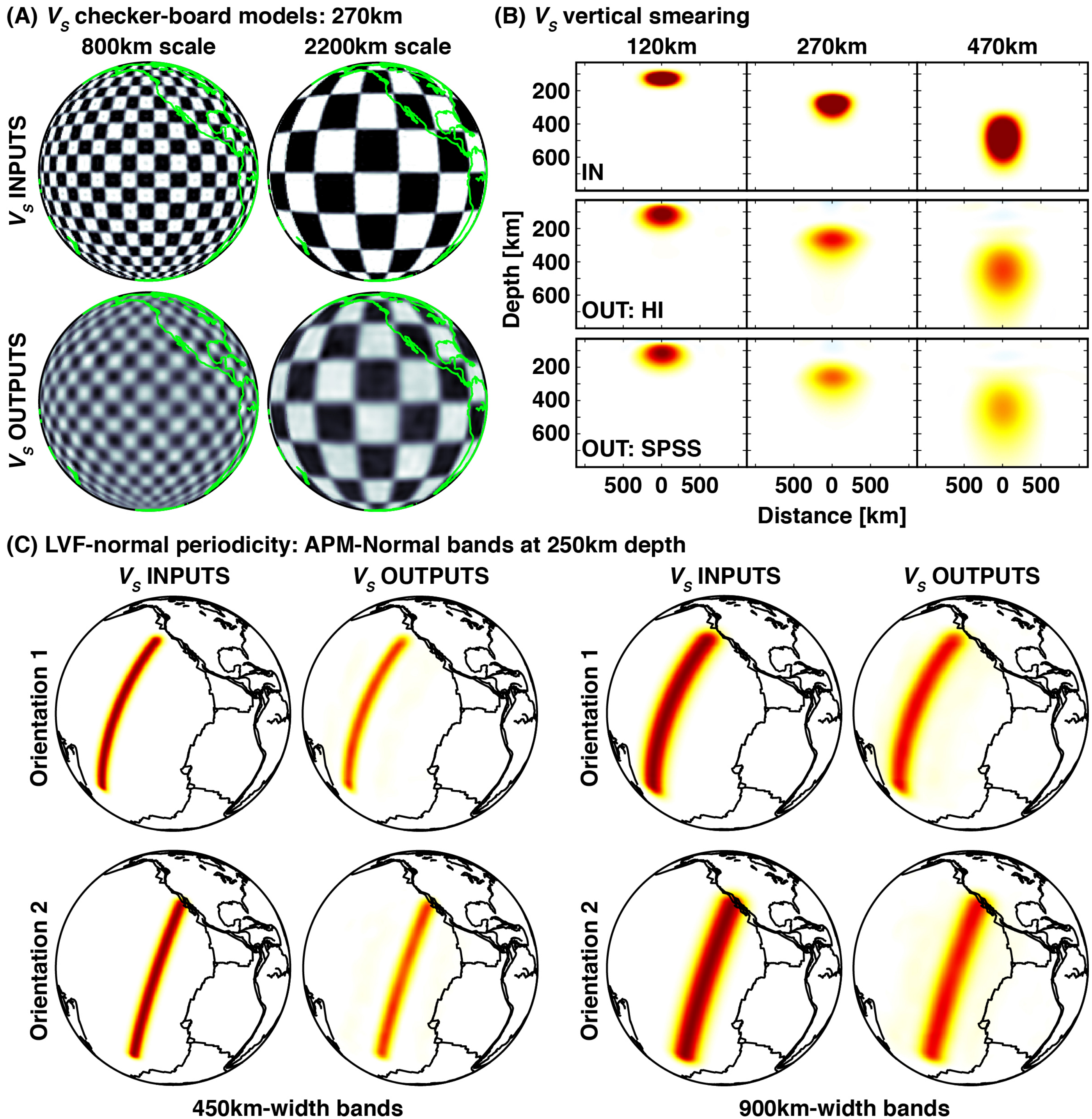


APM direction according to Kreemer (2009)

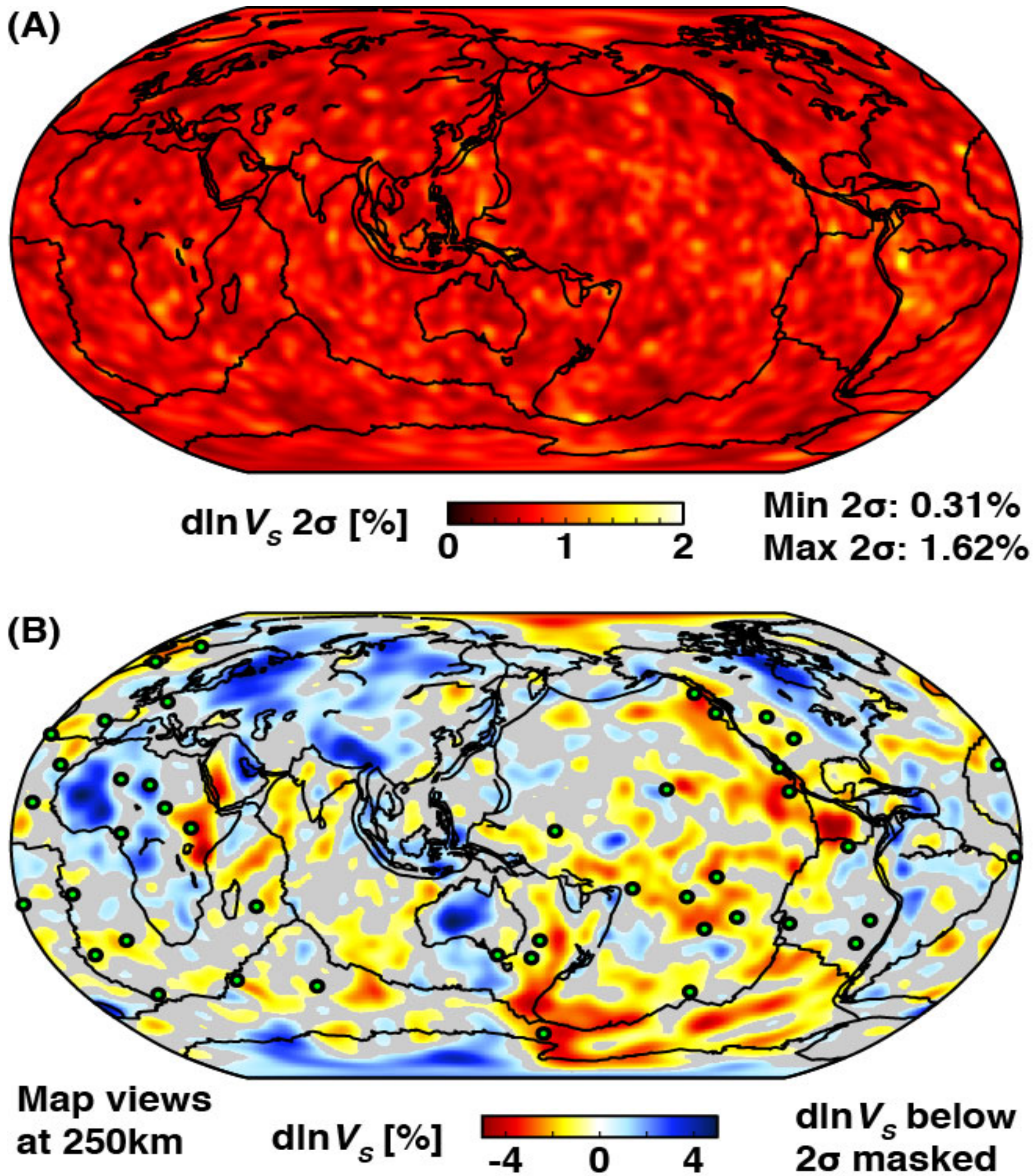
French et al., 2012

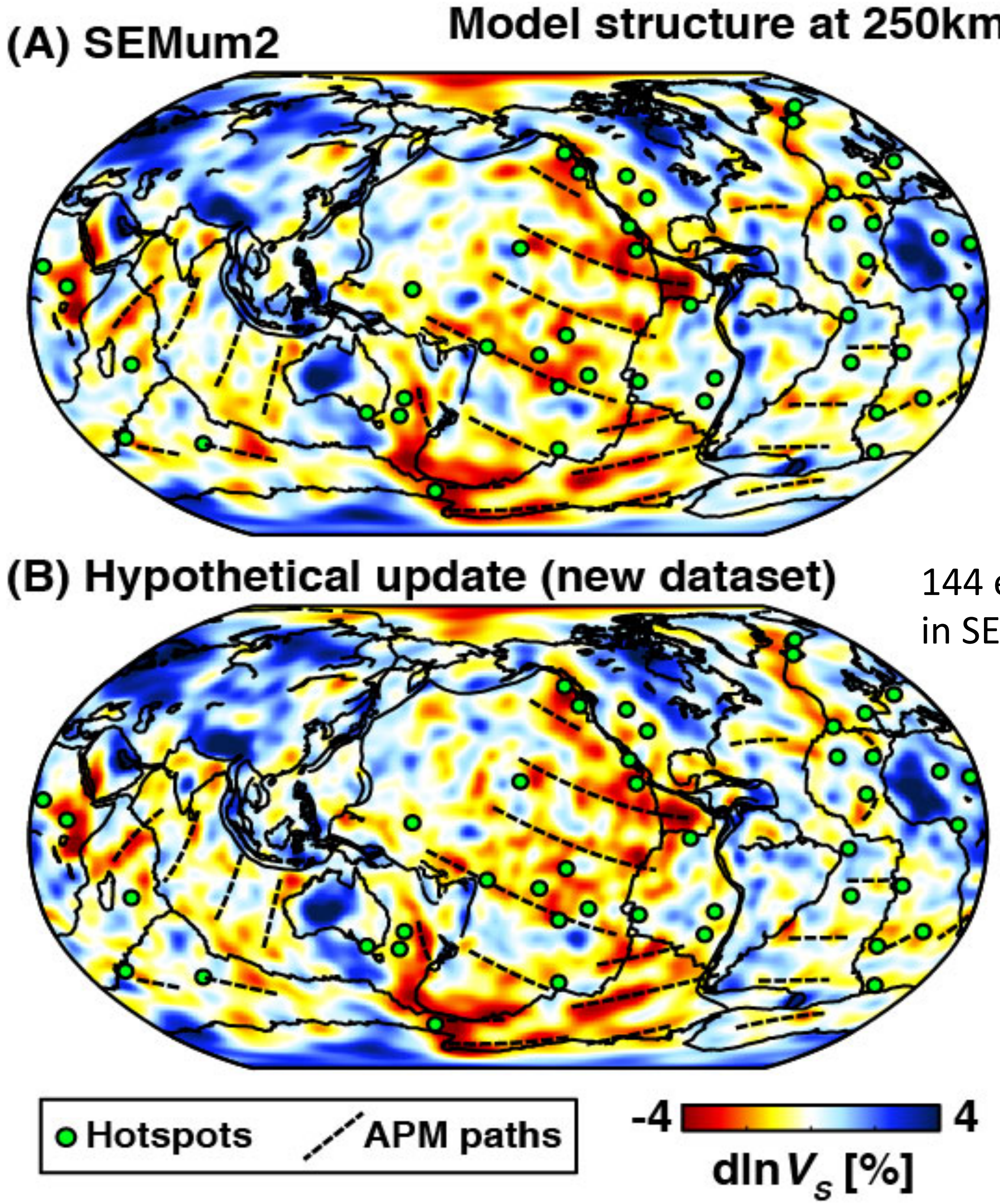
LVF orientations vs. ray paths




(A) V_S checker-board models: 270km
800km scale
2200km scale
V_S INPUTS
V_S OUTPUTS
(B) V_S vertical smearing
120km
270km
470km
200
400
600
IN
OUT: HI
OUT: SPSS
Depth [km]
500 0 500
Distance [km]
(C) LVF-normal periodicity: APM-Normal bands at 250km depth
V_S INPUTS
V_S OUTPUTS
Orientation 1
Orientation 2
450km-width bands
900km-width bands

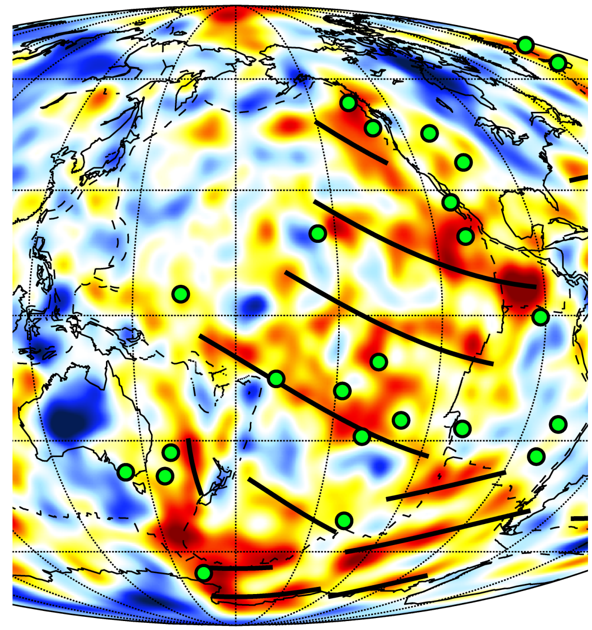
Bootstrapping Test:20 resampled data realizations



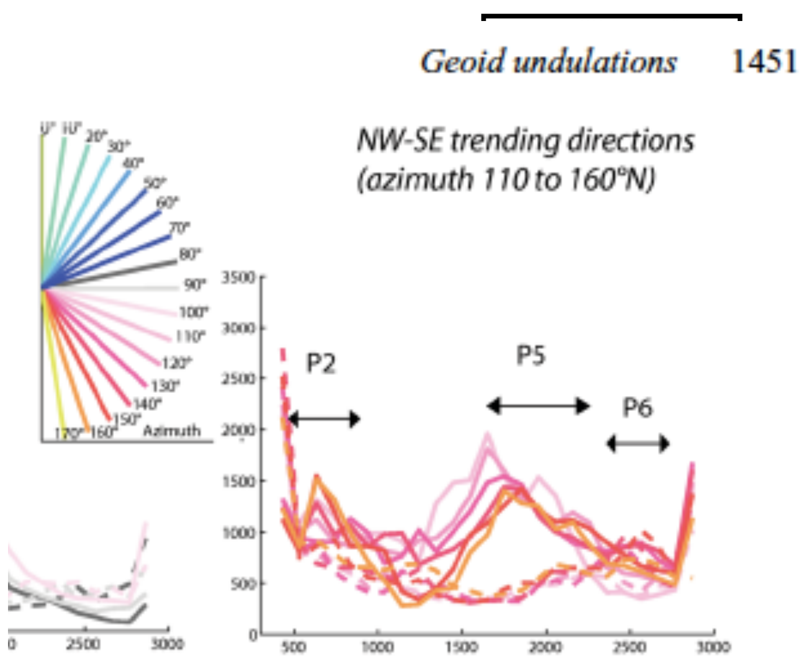


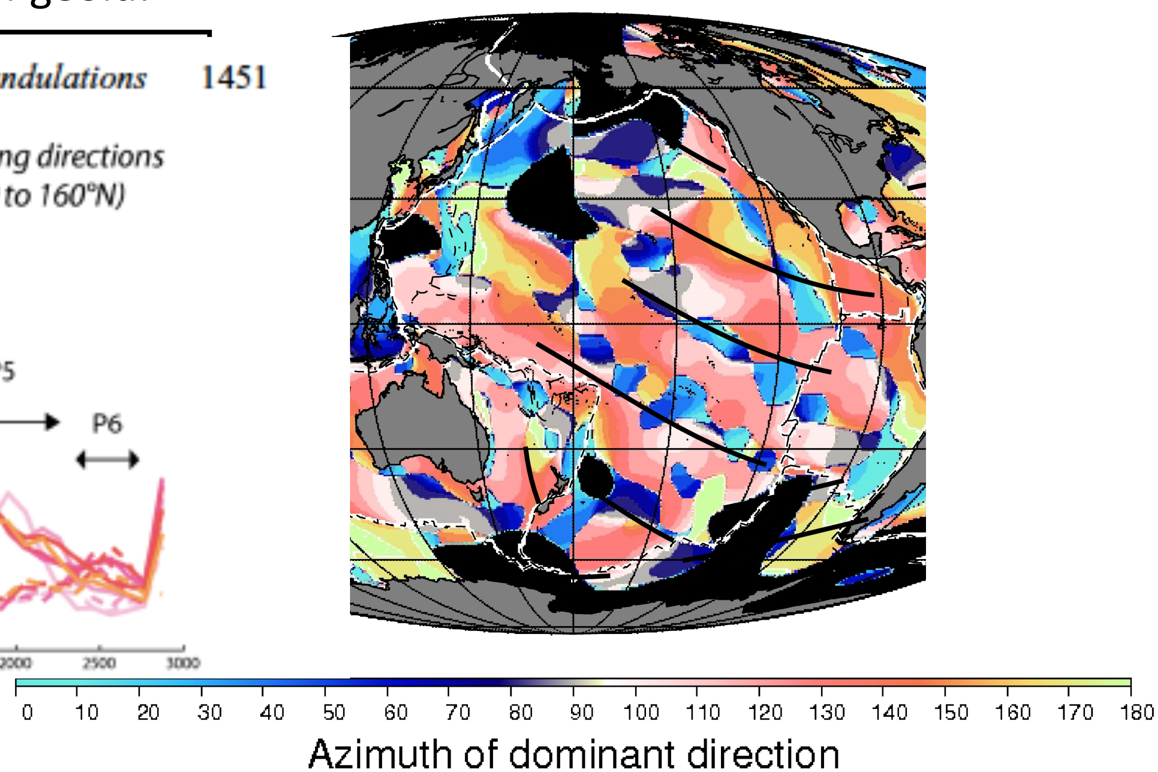
144 events not used
in SEMum2 construction

SEMum2 at 250km depth:



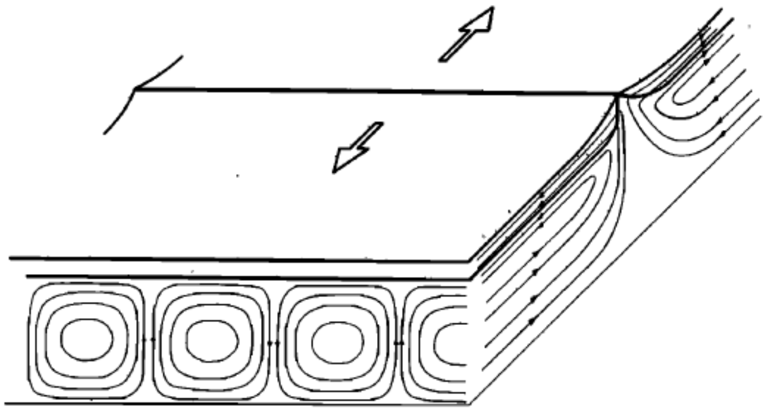
Directional wavelet analysis of geoid:





Hayn et al., 2012

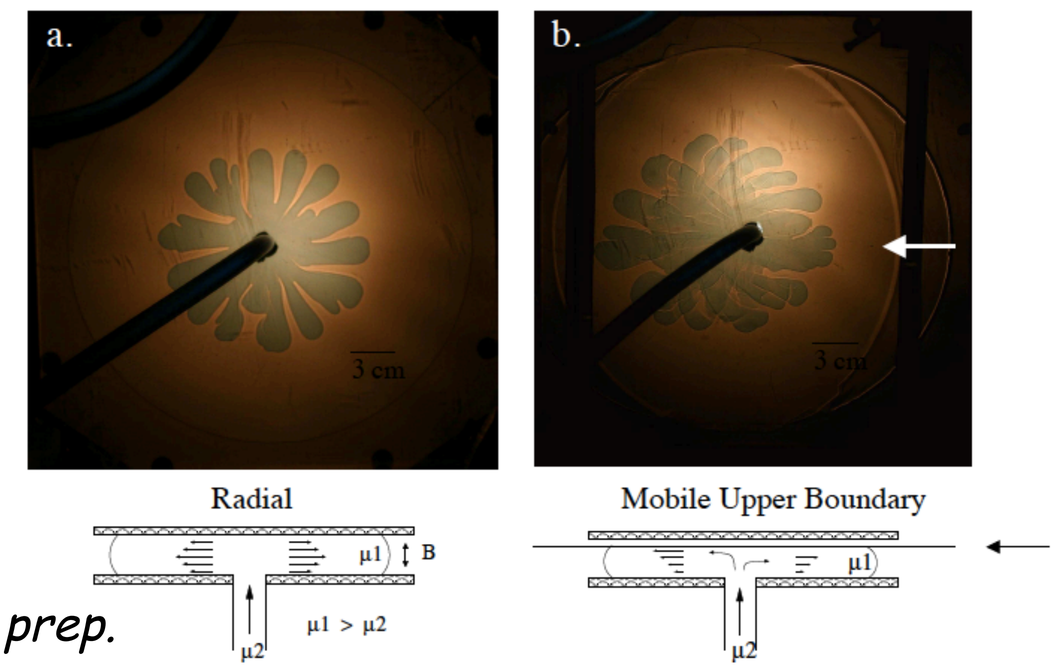
"Richter Rolls"



Richter and Parsons, 1975

Versus…

Viscous fingering fed by plume-like conduits

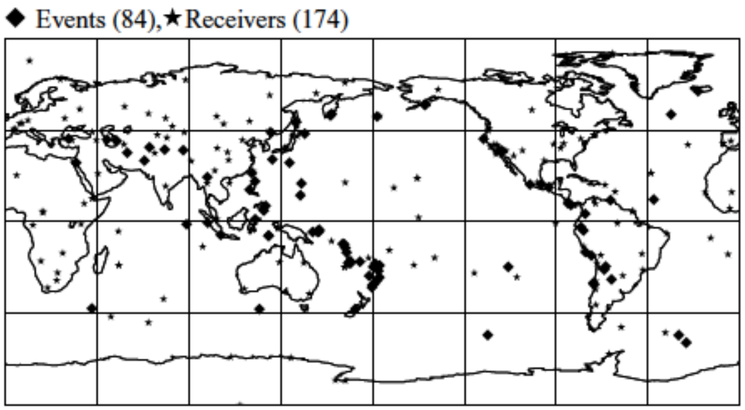


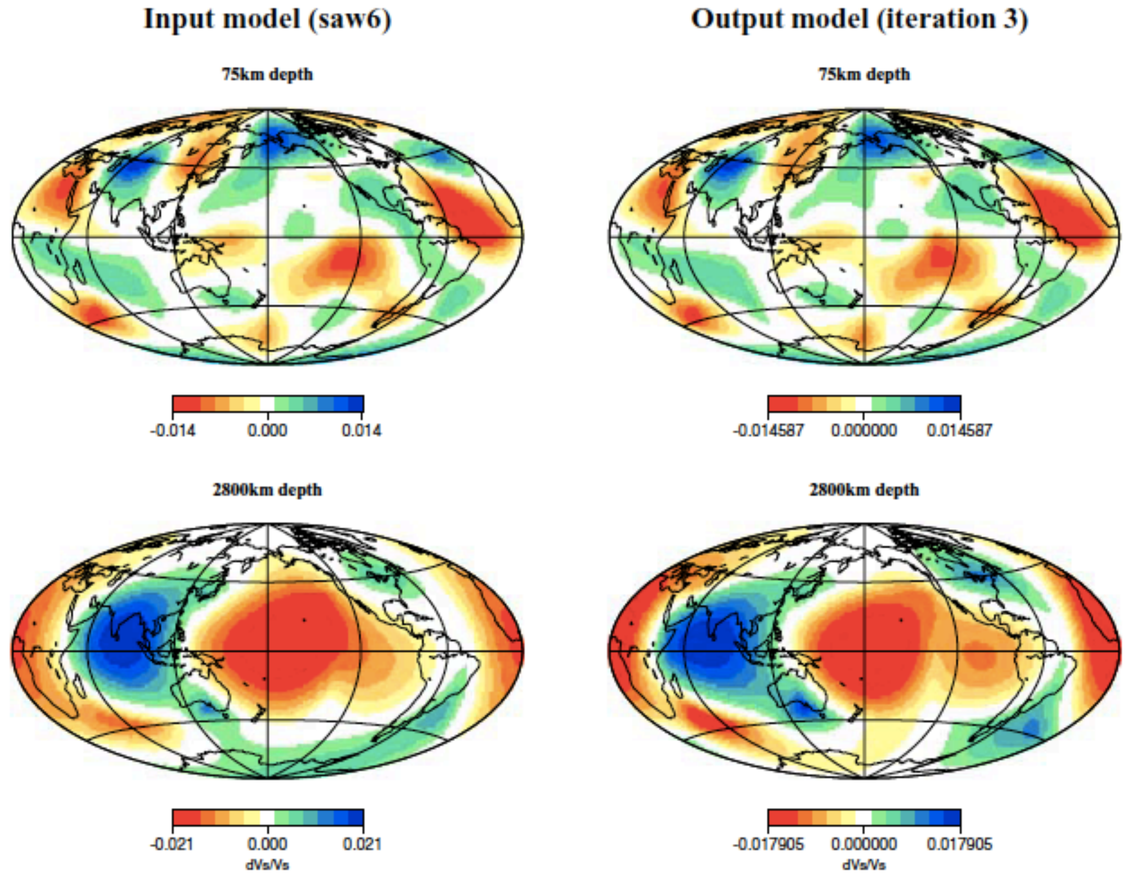
Weeraratne and Parmentier, in prep.

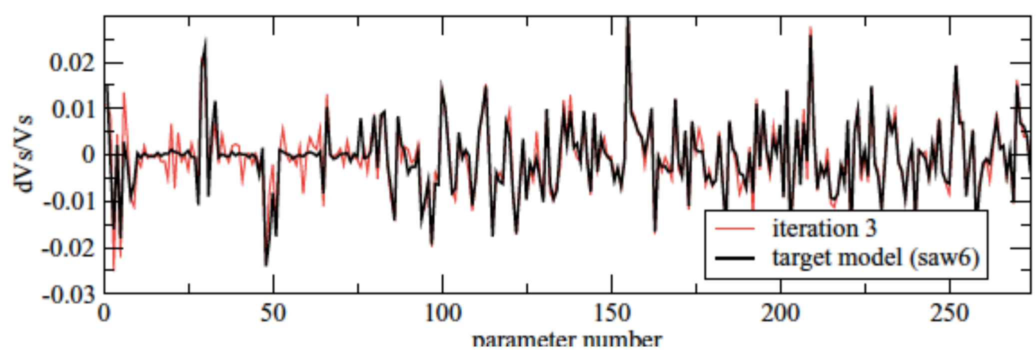
Outlook

- Complete geodynamic interpretation of the low-velocity finger structures
- Extend to shorter periods (30-40s) and include body wavepackets
- Attenuation and azimuthal anisotropy
- Combine gradient computation (adjoint) with approx. Hessian
- Implement summed event (encoded source) approach

Source stacking

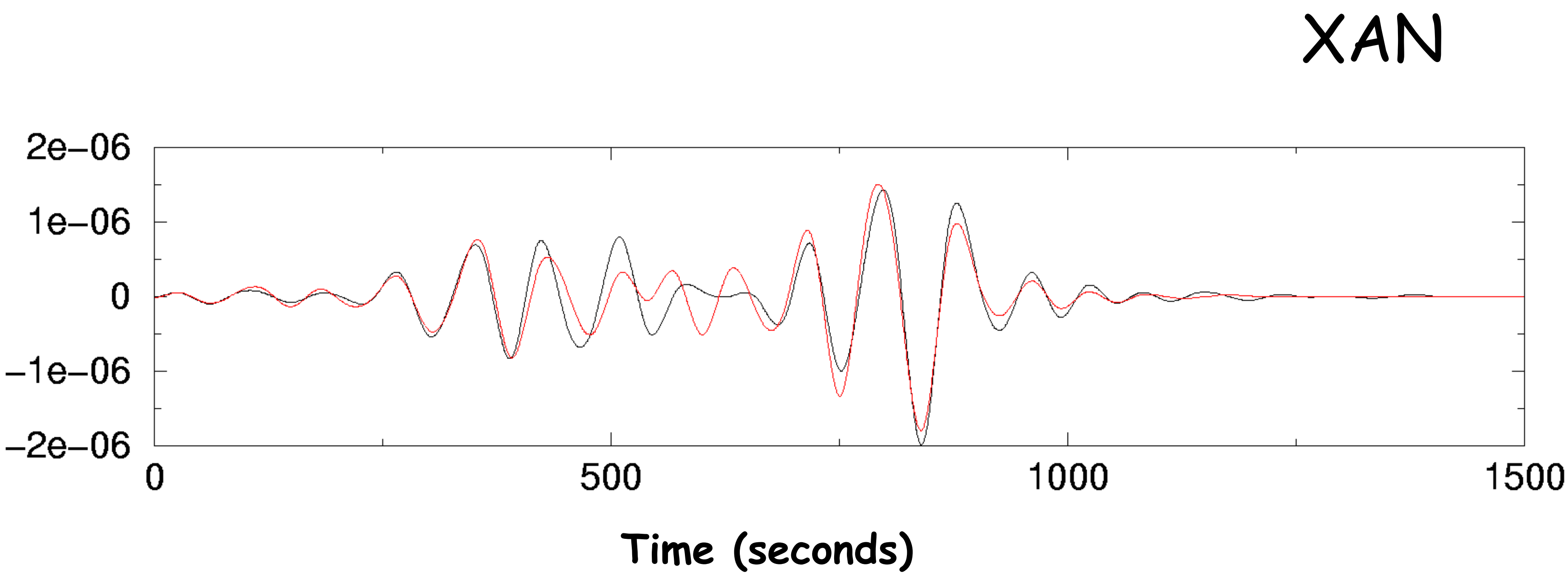






Capdeville, Gung, Romanowicz, GJI, 2005

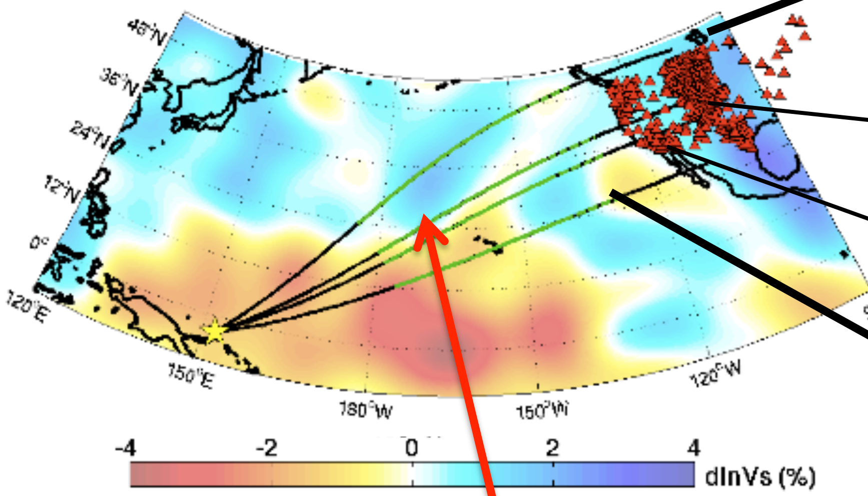
Summed seismograms at station XAN



Black: observed trace (filtered between 60 and 250 s)
Red: RegSEM synthetic in the 3D N-Born starting model

Detection of an "ultra low velocity zone" at the base of the mantle

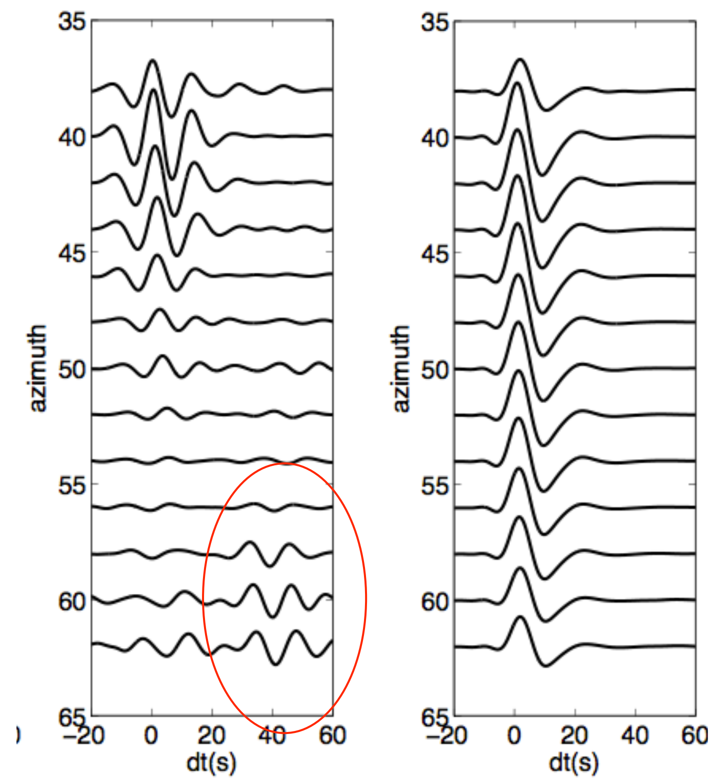
SH_{diff}, 100-110 degrees



azimuth (dg)

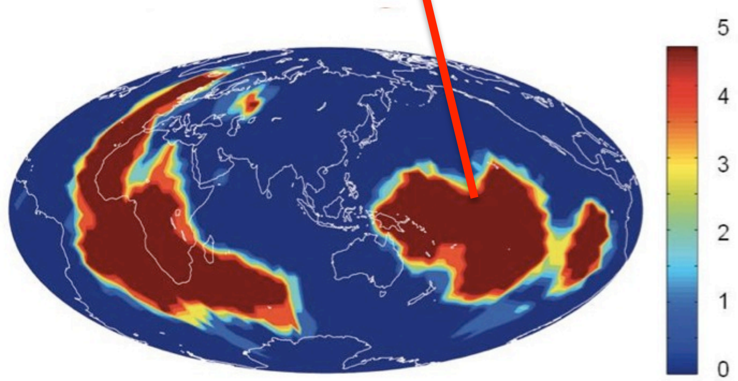
Filter: 10-30 s

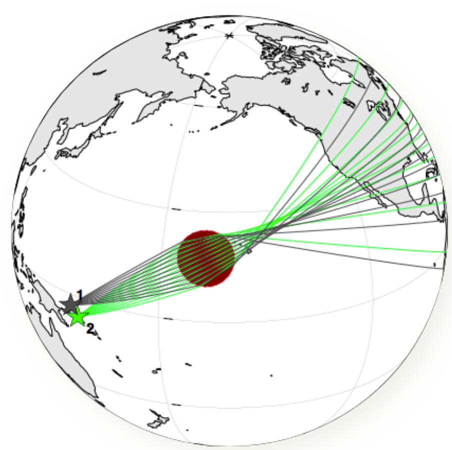
Observation *Prediction*



time around S_{diff} (s)

Cottaar and Romanowicz, 2012, EPSL





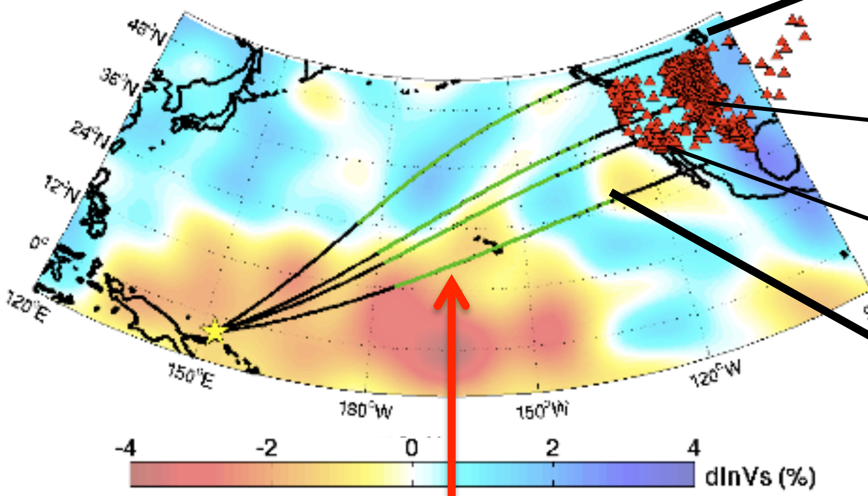
Height:
Diameter:
Velocity reduction:

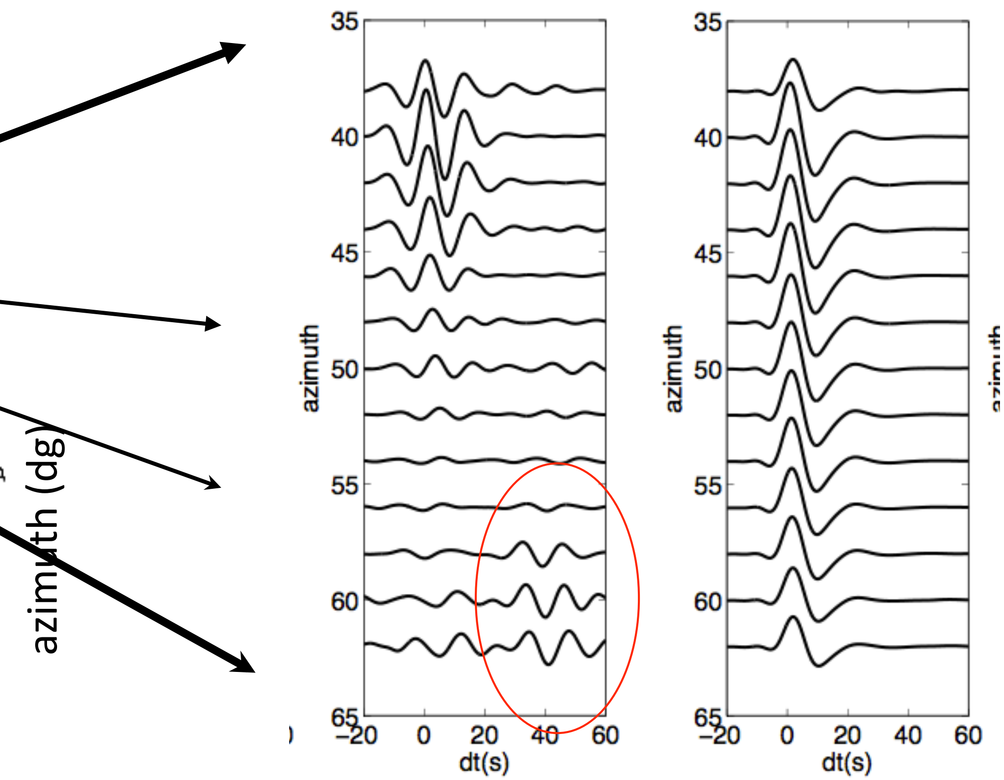
Detection of an "ultra low velocity zone" at the base of the mantle

Filter: 10-30 s

Observation *Prediction*

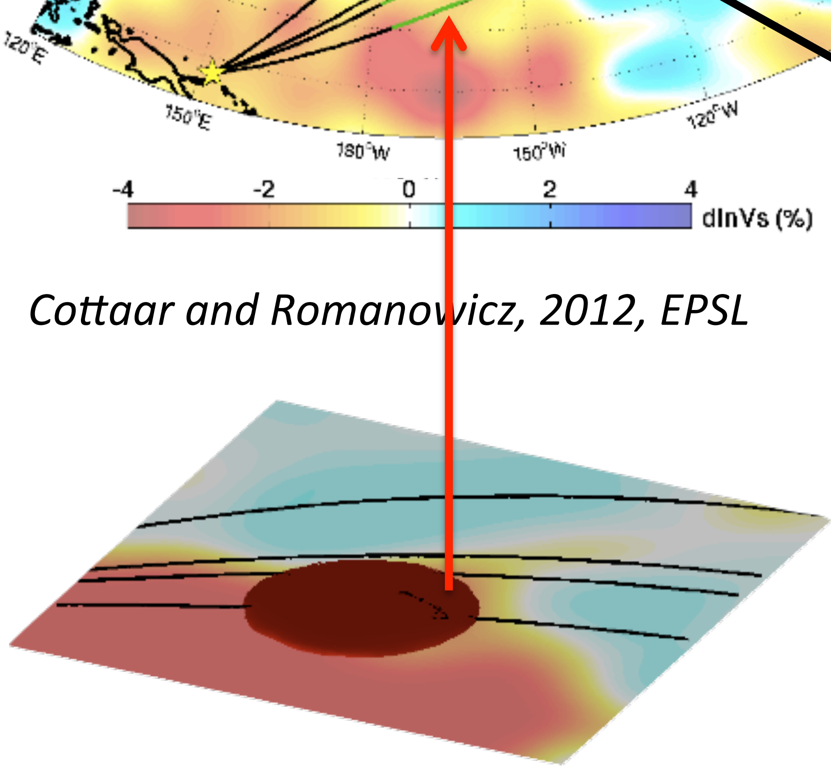
SH_{diff}, 100-110 degrees

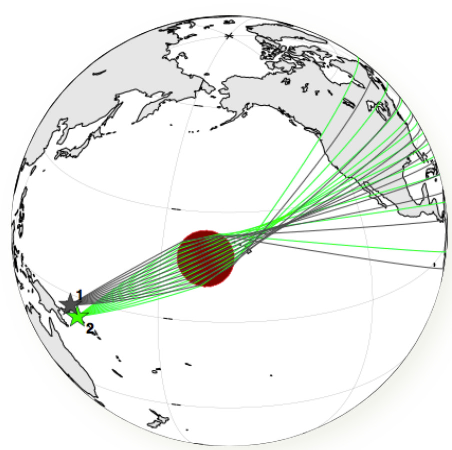




time around S_{diff} (s)

Cottaar and Romanowicz, 2012, EPSL





Height: ~25km
Diameter:~800 km
Velocity reduction:~20%