Google "AxiSEM3D Github"

UNIVERSITY OF OXFORD

Global wavefield modelling in 3-D crustal models using **AxiSEM3D**

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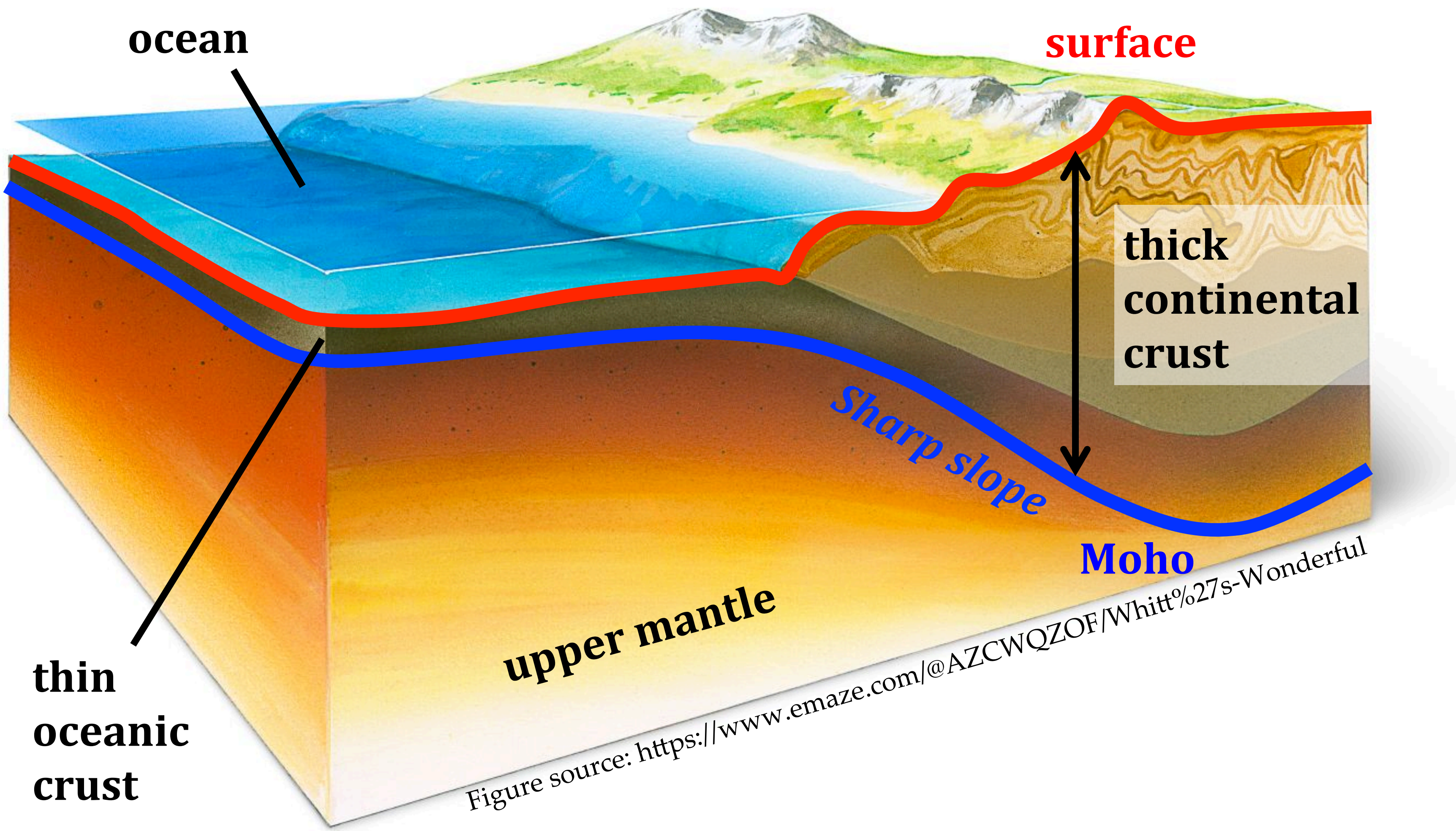
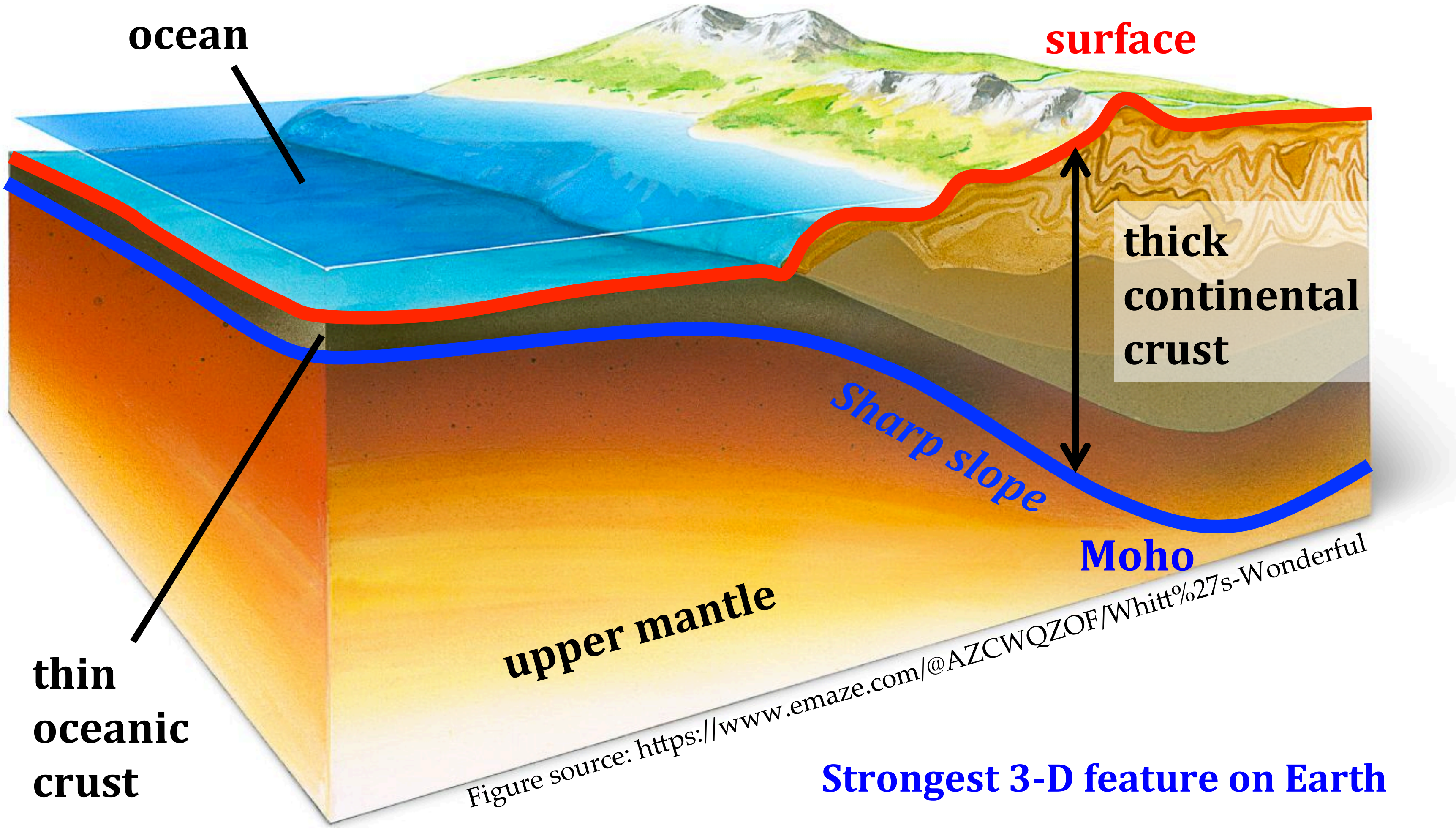
Earth's crust in nature



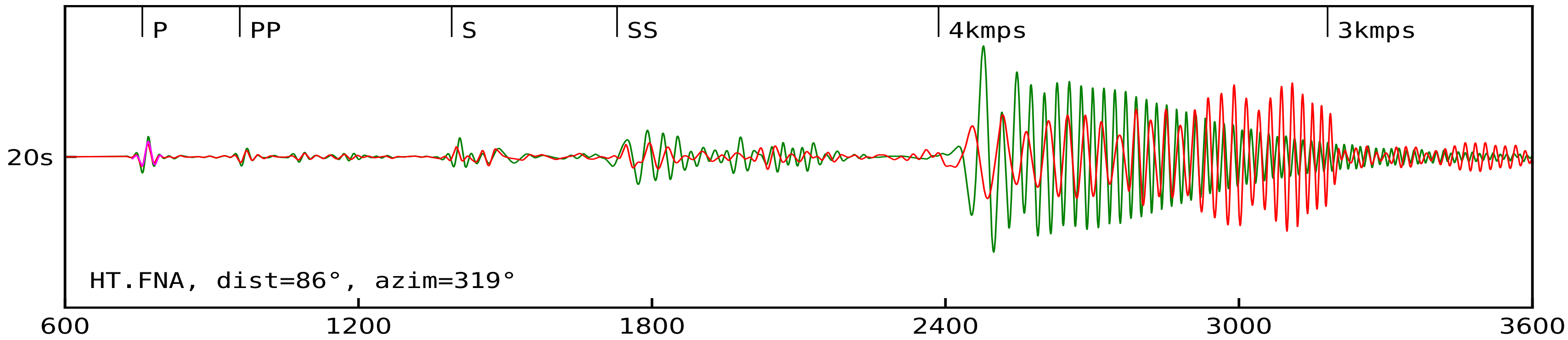
Earth's crust in nature



- Crustal thickness ranges from 5 to 80 km, with sharp transitions at ocean-continent boundaries
- Velocities varies fast both horizontally and vertically

Earth's crust in wave propagation

- 3-D crust **RESHAPES** the surface waves



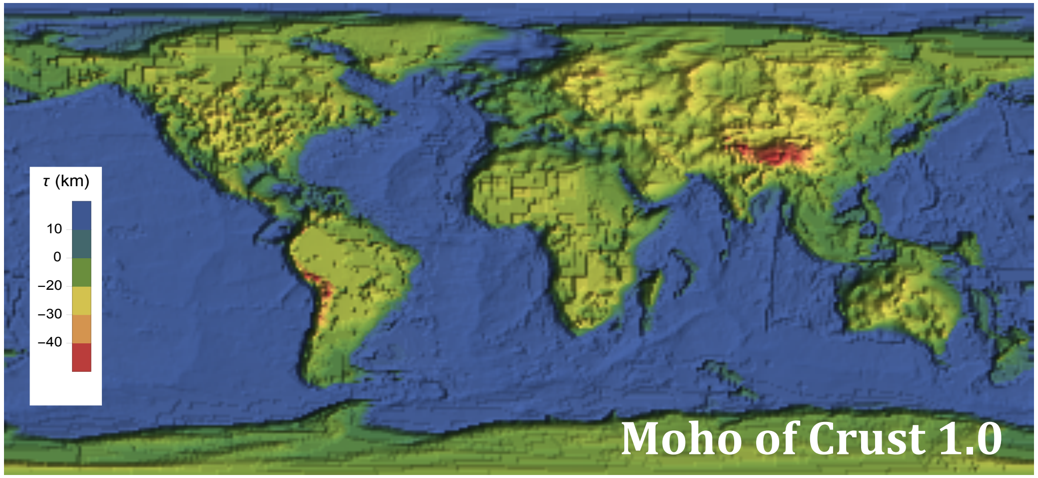
- Realistic **forward simulations** of surface waves is a fundamental issue
  - structural inferences at all scales (subduction zones, sediment basins, …)
  - earthquake sources
  - nuclear monitoring
  - site effects and hazard assessments

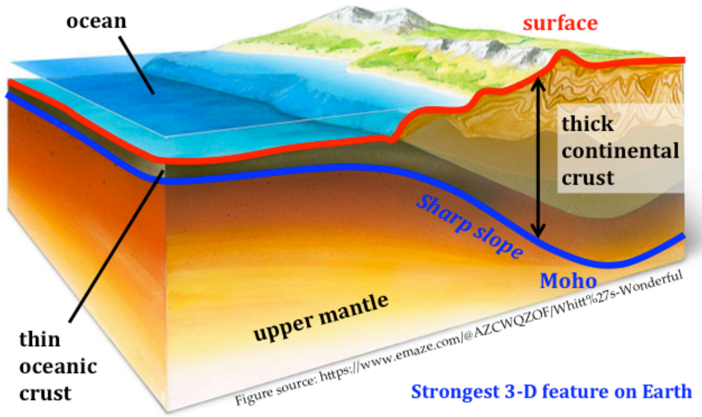
- For seismic **inverse problems**, the Born approximation based on 1-D reference models ceases to work (*Zhou et al., 2005*)
  - surface wave tomography
  - noise tomography
  - travel time and waveform corrections
  - dispersion measurements

$$\mathbf{G} \cdot \delta\mathbf{m} = \delta\mathbf{d}$$

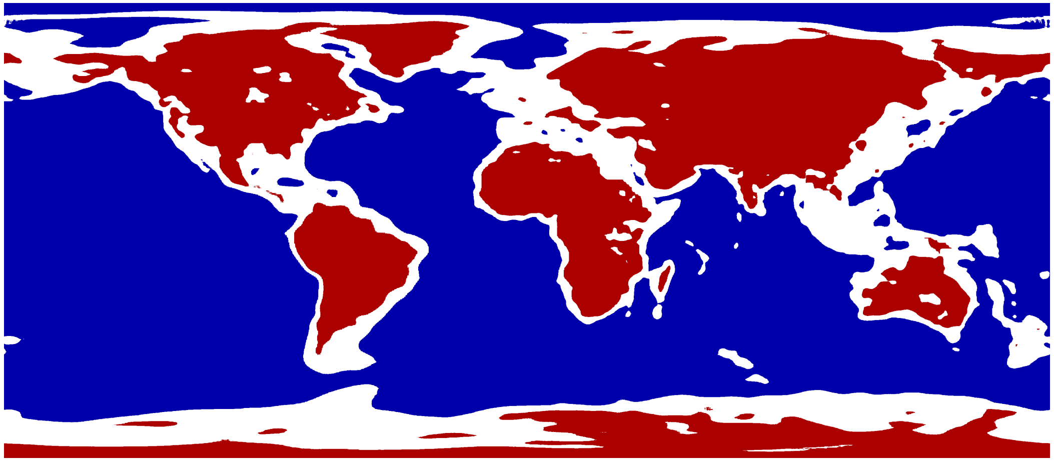
Crust implementation in 3-D methods

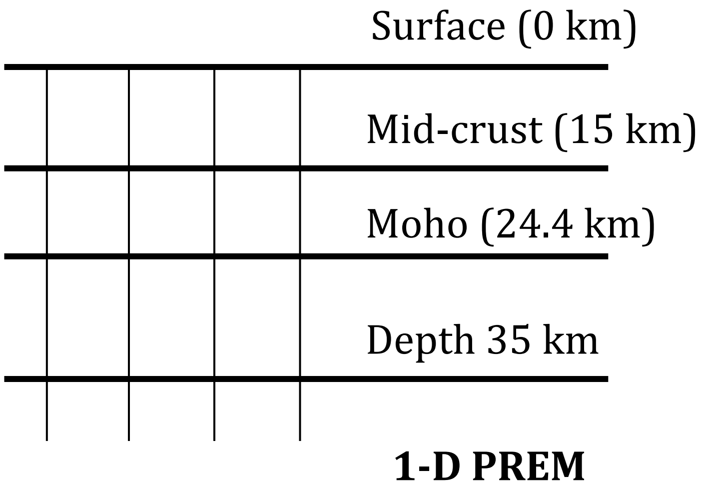
- Most challenging aspect in wavefield modelling



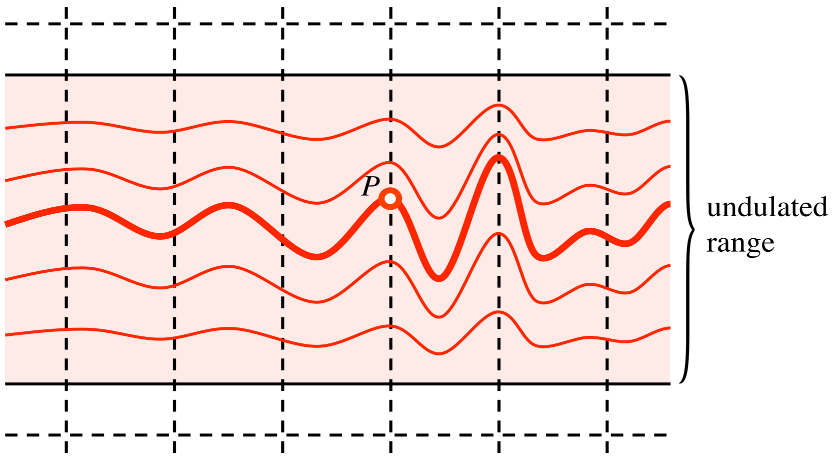


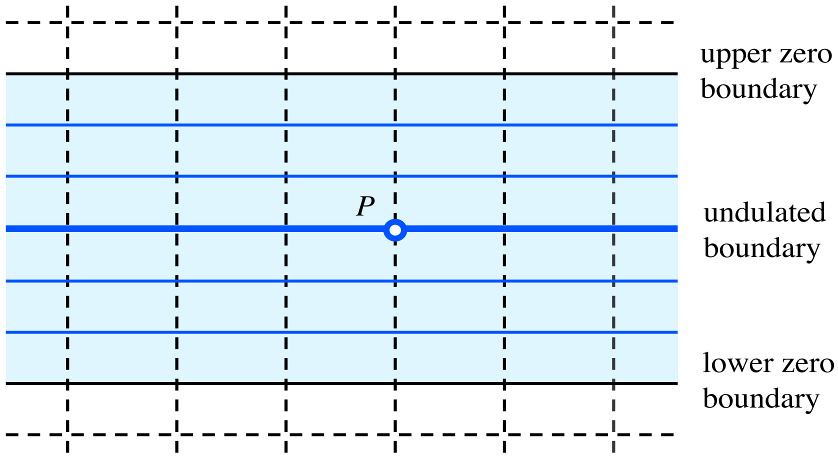
- Implementation in SPECFEM3D_GLOBE (*Komatitsch and Tromp, 2002*)





Crust implementation in AxiSEM3D





Geometric mapping: $$\tau = \tau(r,\theta,\phi) = \begin{cases} \dfrac{\tau_{\text{surf}} - \tau_{\text{moho}}}{R_{\text{surf}} - R_{\text{moho}}}\left(r - R_{\text{moho}}\right) + \tau_{\text{moho}} & r \geq R_{\text{moho}} \\ \dfrac{\tau_{\text{moho}}}{R_{\text{moho}} - R_{\text{base}}}\left(r - R_{\text{base}}\right) & r < R_{\text{moho}} \end{cases}$$

Jacobian: $$\mathbf{H} = \left[\mathbf{I} + \nabla\left(\tau\hat{\mathbf{r}}\right)\right]^{\mathrm{T}}$$

Particle relabelling transformation (*Al-Attar and Crawford, 2016*):

$$\tilde{\rho} = \rho \det \mathbf{H}, \quad \tilde{\mathbf{C}} = \mathbf{H}^{-1} \cdot \mathbf{C} \cdot \mathbf{H}^{-\mathrm{T}} \det \mathbf{H}$$

Crust implementation in AxiSEM3D

- **Particle relabelling transformation**
  - The two models are equivalent in terms of wave propagation
  - Frequency independent (compared to Homogenization, *Capdeville et al. 2013*)
  - Geometric complexity ➔ Material complexity (anisotropy)

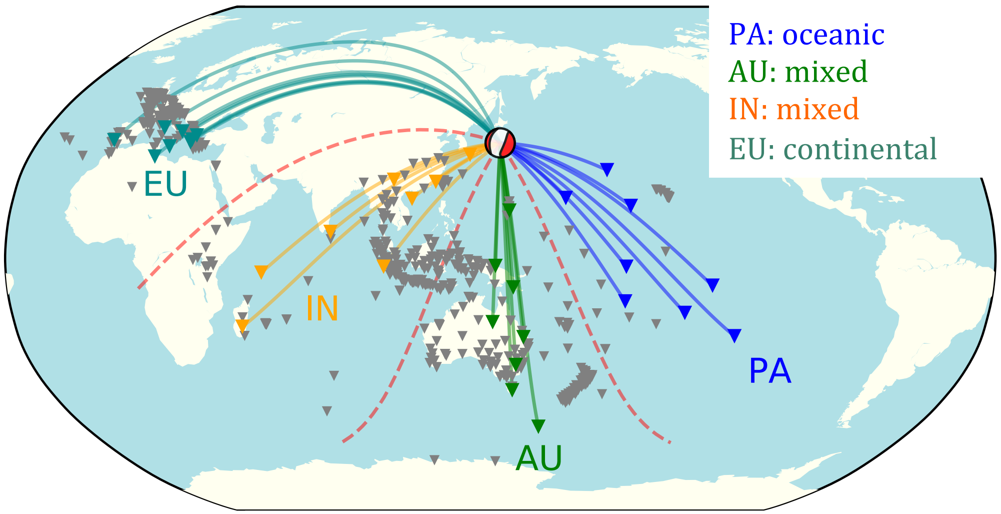
- **Pros and Cons**

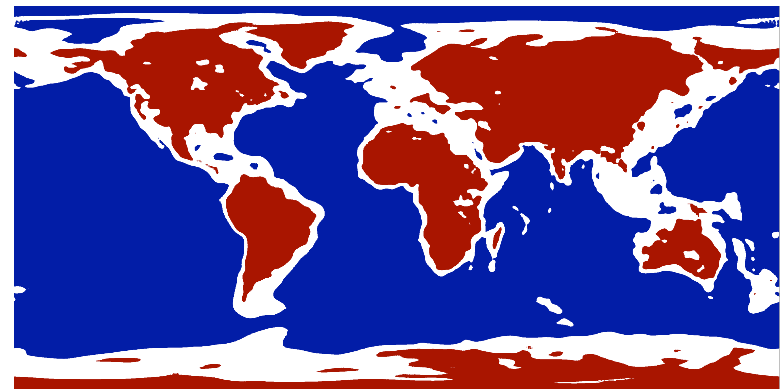
	SPECFEM	AxiSEM3D
Moho discontinuity	**patched**	**integrated**
Robustness	**weak**	**Strong**
Extensibility (CMB, transition zone, Mars)	**difficult (hardcoded for Earth's crust)**	**easy**
time step	**similar to PREM crust**	**half of PREM crust**

  - Even with a smaller time step, AxiSEM3D is still 1-2 orders of magnitude faster than 3-D methods such as SPECFEM

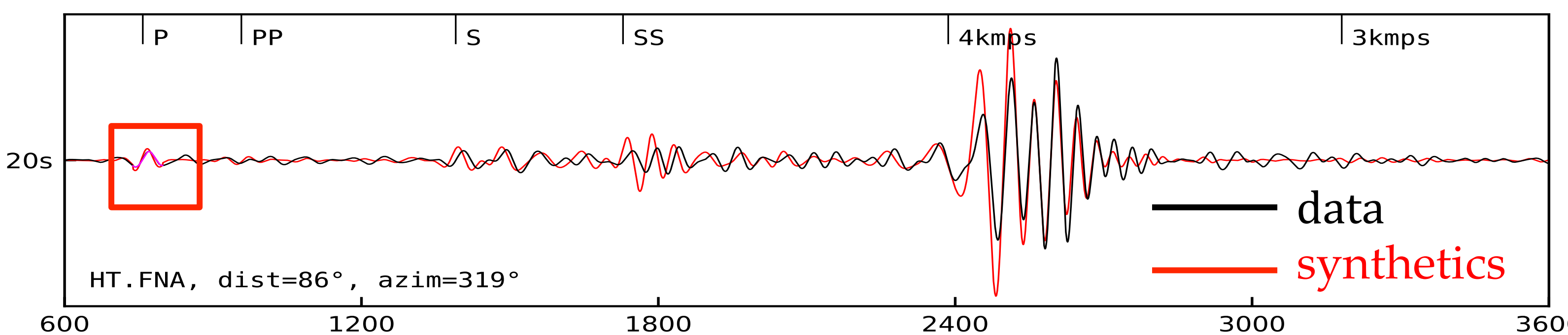
Comparison to data

- **No reference solution** for global wave propagation with crustal models
- Model: **Crust 1.0** for the crust, **S40RTS** for the mantle, Period = 10s
- Source (Japan, 20 km) and stations (620 in total)



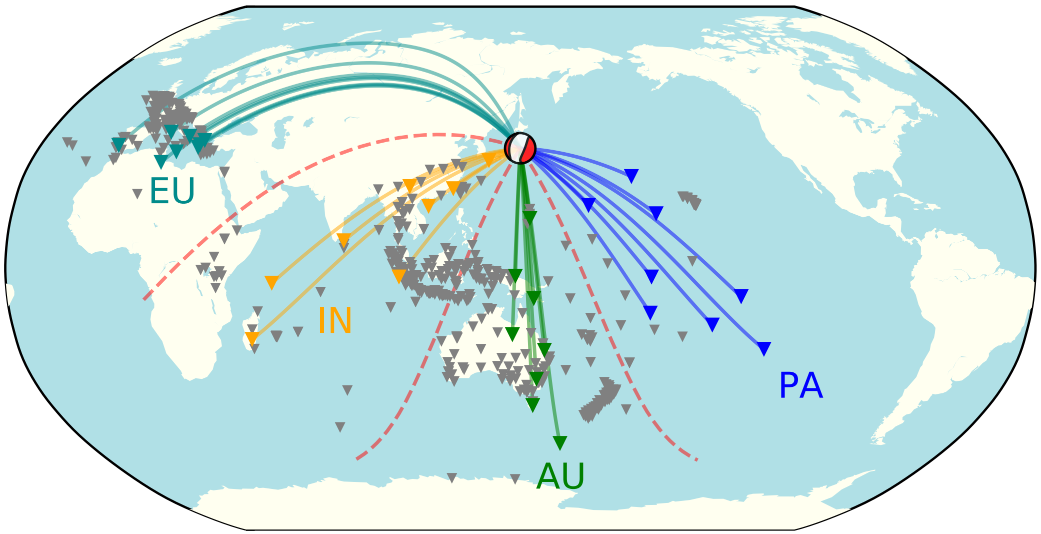


- Processing (filtered at 40 s and 20 s before comparison)



Comparison to data – Summary

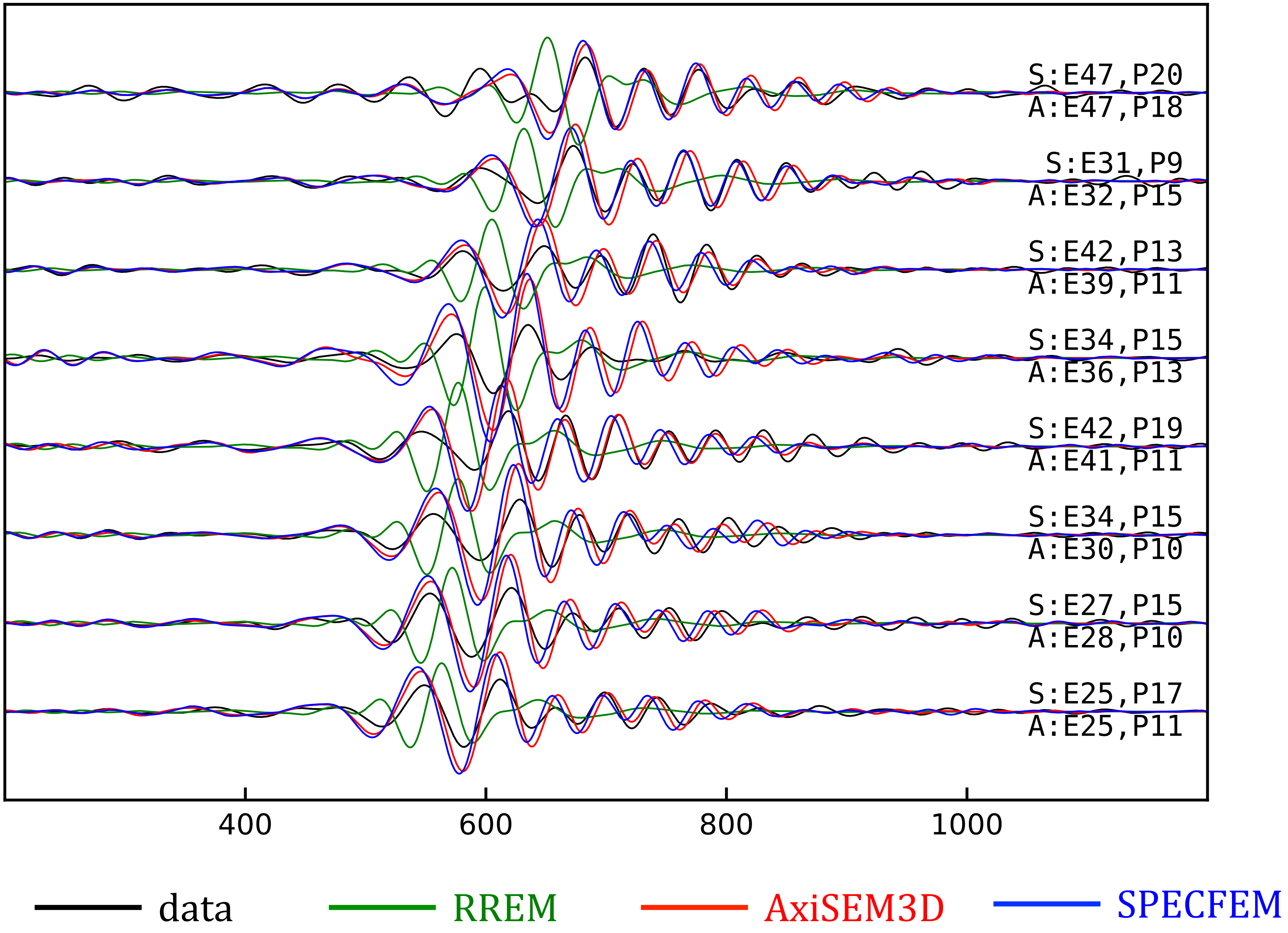
- The 3-D model fits the data much better than PREM does.
- AxiSEM3D is more accurate for PA, AU and IN.
- SPECFEM and AxiSEM3D have very similar accuracy for EU.



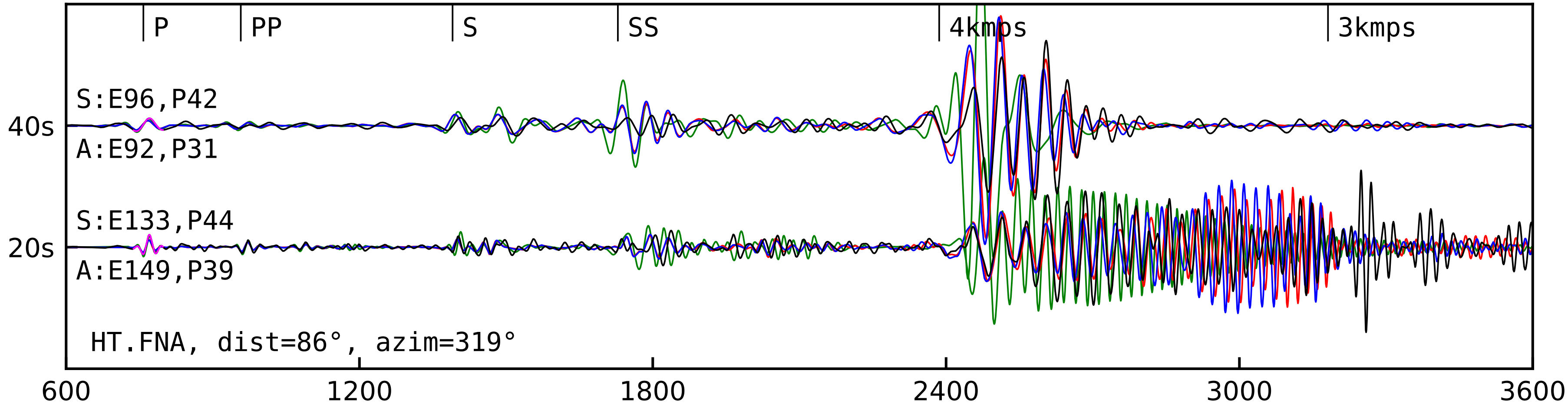
PA: oceanic
AU: mixed
IN: mixed
EU: continental

	ALL, 40 s	PA, 40 s	AU, 40 s	IN, 40 s	EU, 40 s	ALL, 20 s	PA, 20 s	AU, 20 s	IN, 20 s	EU, 20 s
total number of stations	616	53	210	171	182	616	53	210	171	182
AxiSEM3D fits better	65%	96%	67%	64%	53%	61%	82%	71%	52%	49%
Ave. m_e SPEC / Axi3D	0.117	0.094	0.149	0.100	0.102	0.317	0.122	0.284	0.298	0.435
Ave. m_e SPEC / data	0.609	0.293	0.701	0.701	0.510	0.868	0.496	1.047	0.948	0.707
Ave. m_e Axi3D / data	0.601	0.247	0.694	0.679	0.511	0.851	0.461	1.038	0.954	0.666
Ave. m_e PREM / data	0.723	0.705	0.785	0.783	0.602	1.060	1.076	1.011	1.035	1.134
Ave. m_p SPEC / Axi3D	0.108	0.119	0.143	0.064	0.105	0.437	0.282	0.517	0.384	0.447
Ave. m_p SPEC / data	0.398	0.507	0.493	0.426	0.231	0.514	0.560	0.588	0.498	0.432
Ave. m_p Axi3D / data	0.371	0.406	0.454	0.413	0.230	0.485	0.402	0.519	0.489	0.447
Ave. m_p PREM / data	0.590	0.600	0.493	0.532	0.754	0.587	0.594	0.570	0.569	0.621

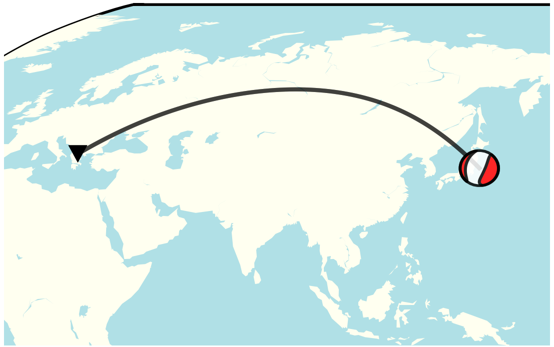
Comparison to data – record section EU (40 s)

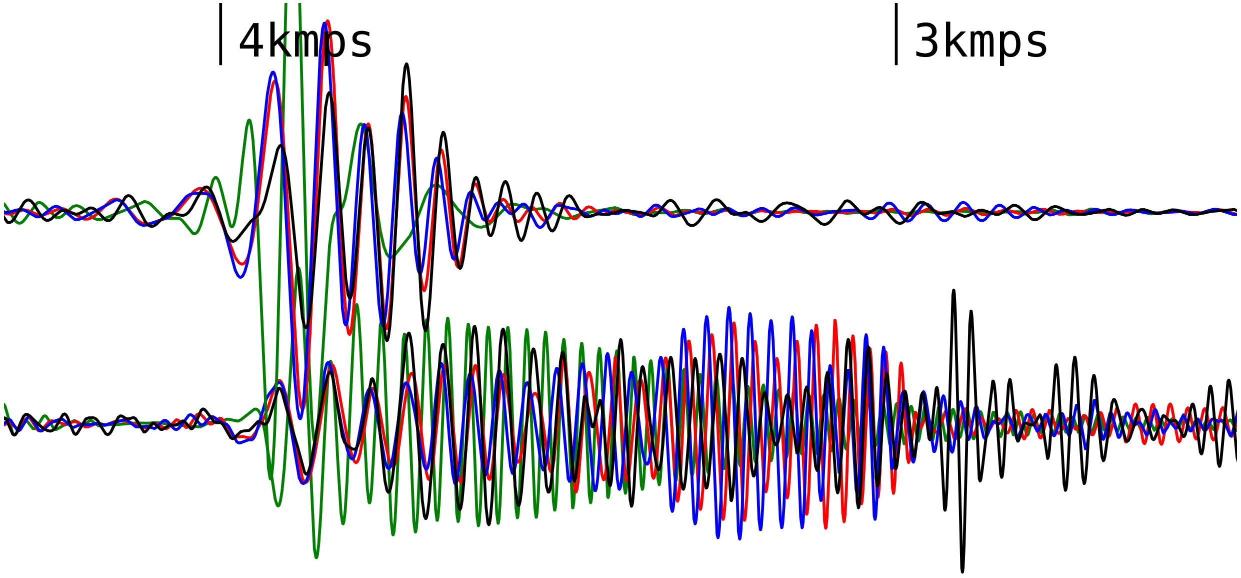


Comparison to data – single stations



Florina, Greece





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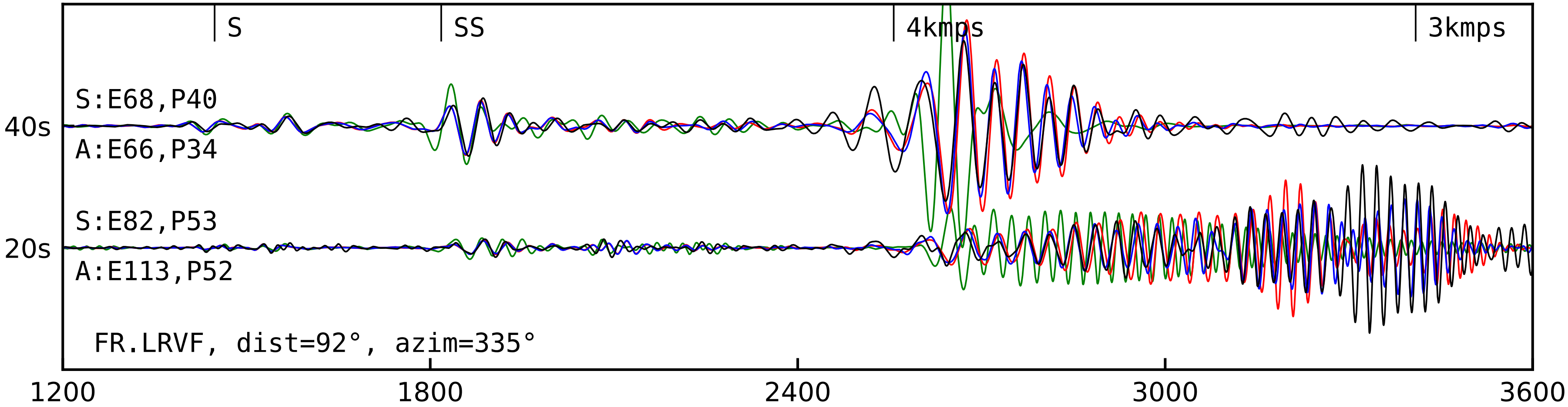
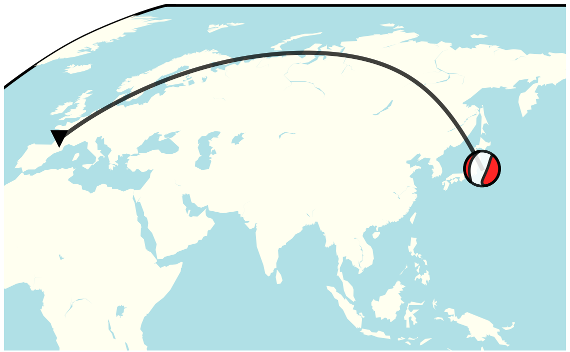
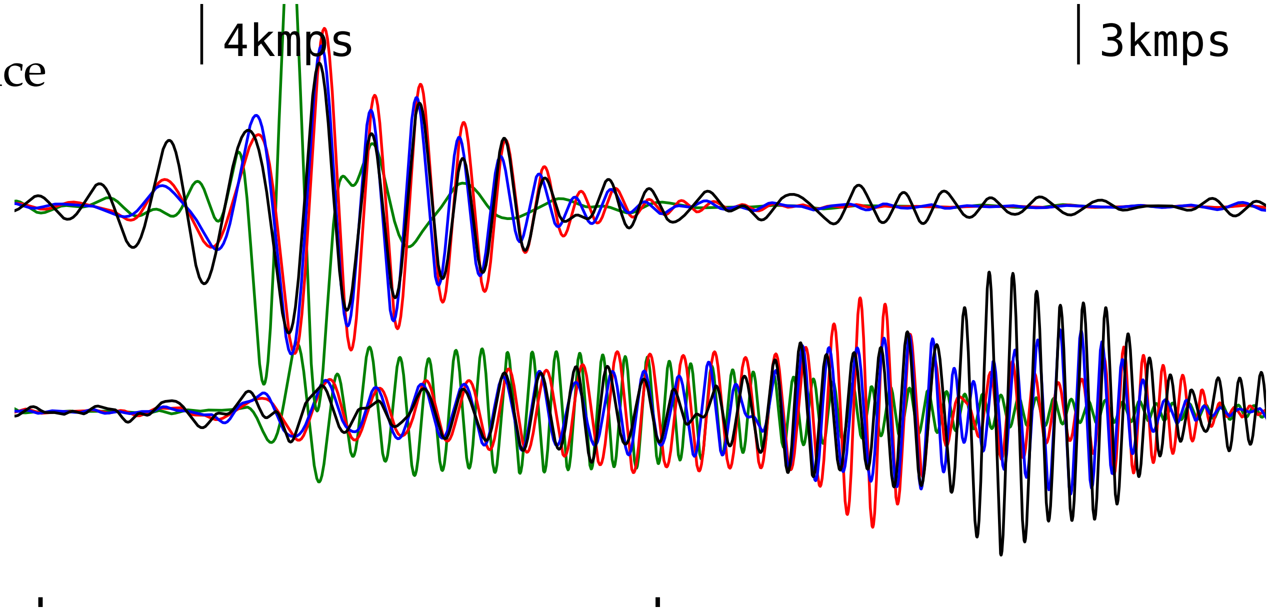


Nouvelle-Aquitaine, France





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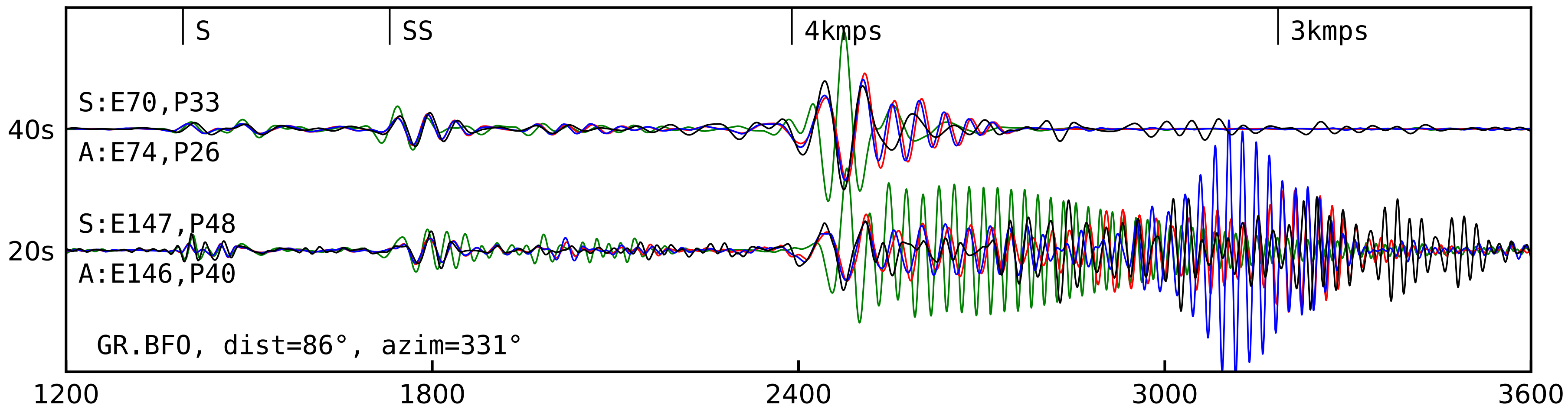
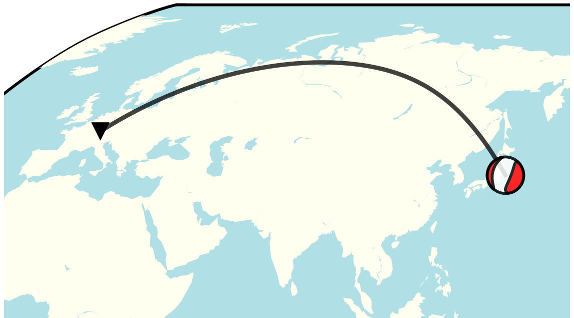
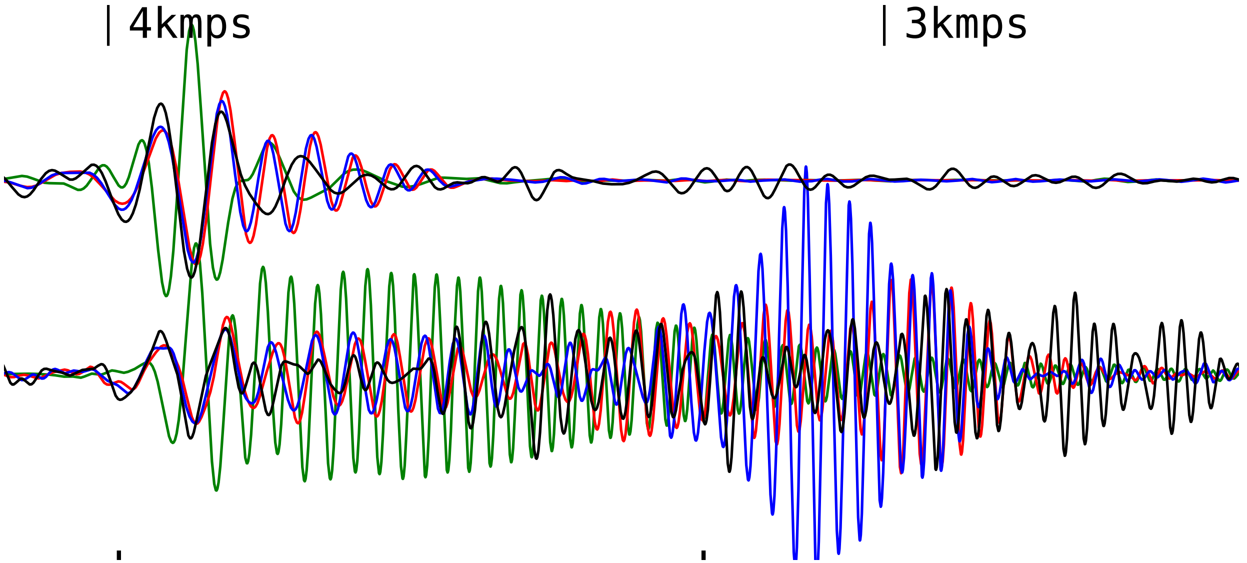


Black Forest, Germany





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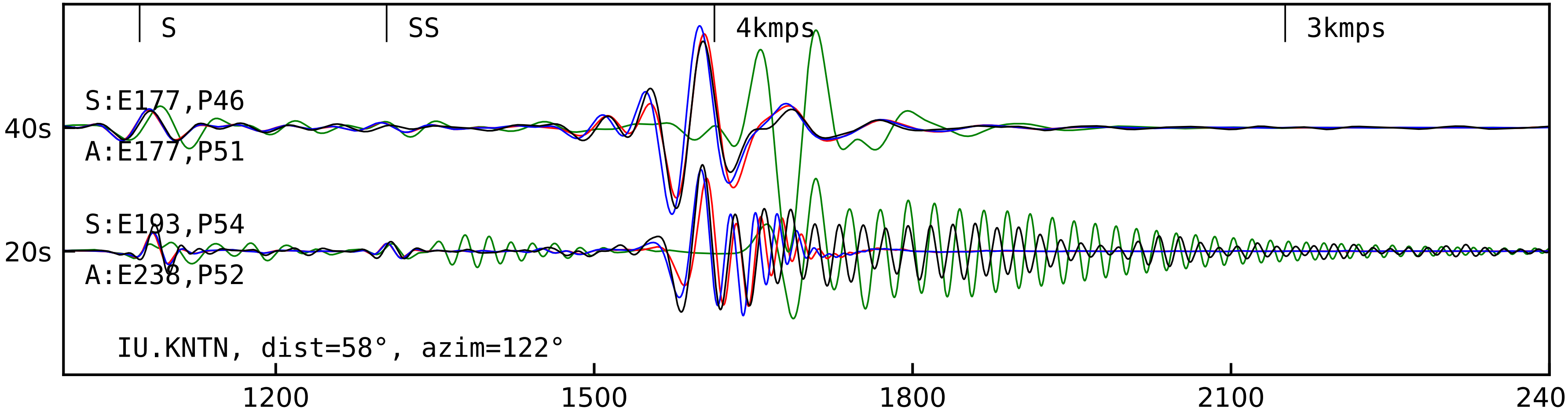
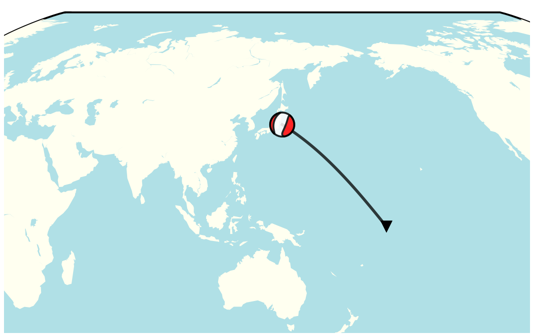
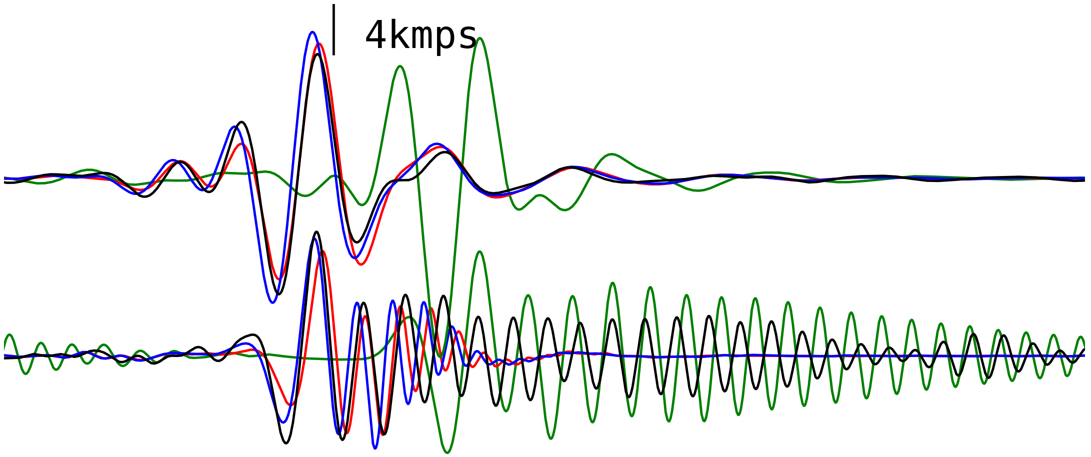


Kanton Island, Kiritibati





The load approximation of oceans?
The station is on an island but we place at ocean bottom in the simulation?


P-WAVE
S-WAVE
EARTH

Conclusions

- AxiSEM3D has an equivalent (or better) accuracy as full 3-D SEM such as SPECFEM to simulate surface waves in the state-of-the-art global crustal models, such as Crust 1.0
- AxiSEM3D is 1-2 orders of magnitude faster than 3-D SEM
- Particle relabelling transformation is powerful in handling boundary undulations in terms of material perturbations

Outlook

- Realistic ocean (subject to theoretical limitations of PRT)
- Local to regional scale extensions
- 3-D sensitivity kernels for surface wave tomography

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Thank you for your attention!