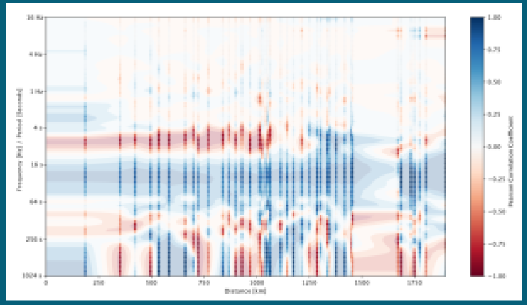
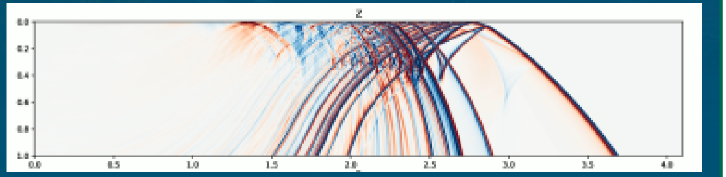
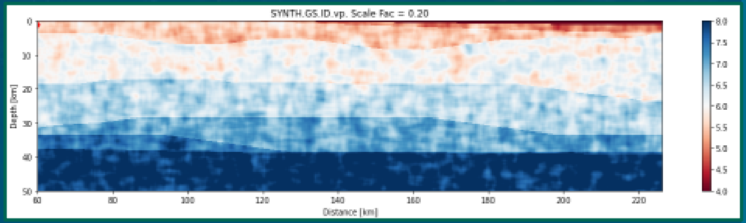
SAND2021-8043PE

Waveform Methods in GNDD Signal Propagation







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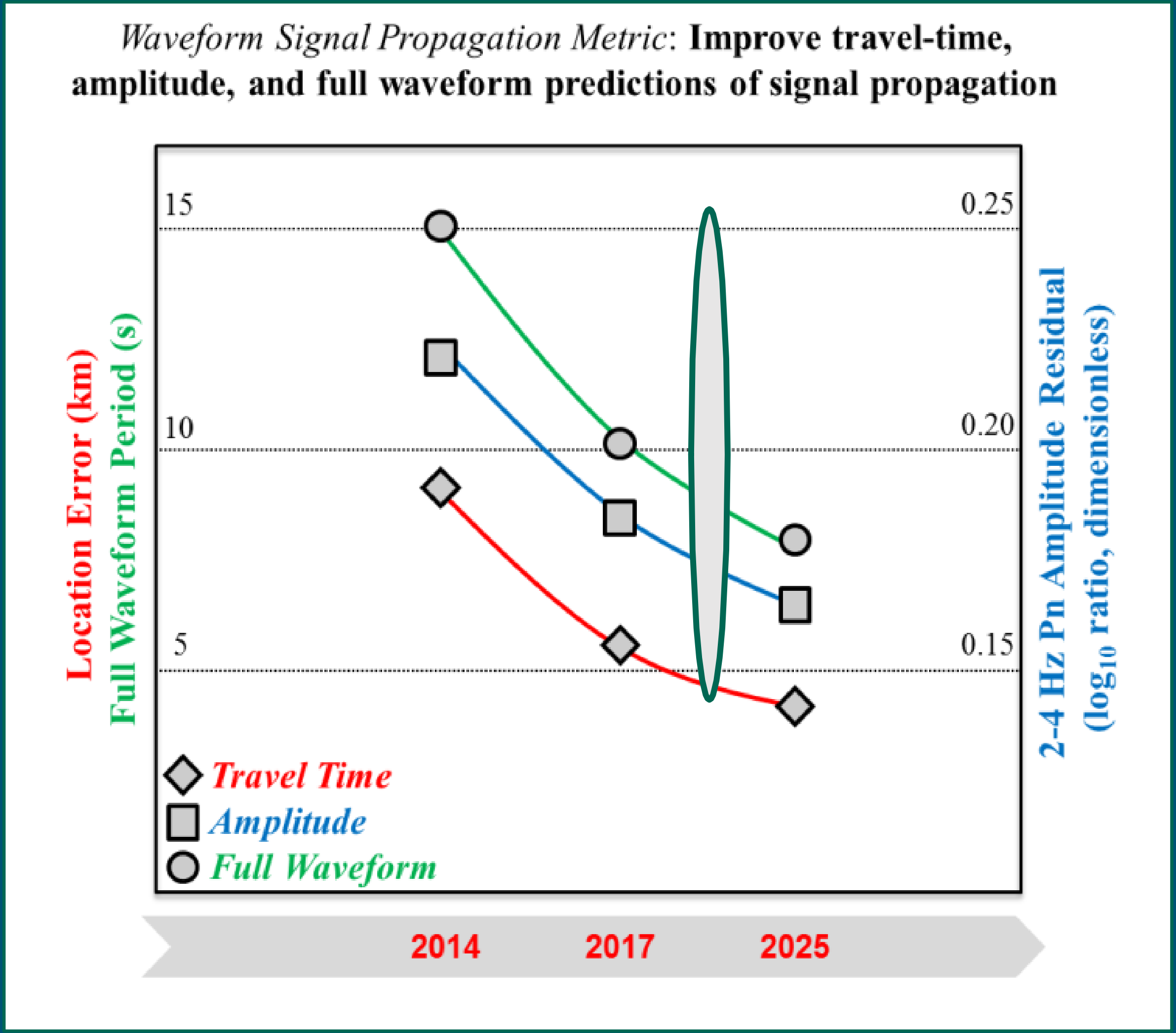
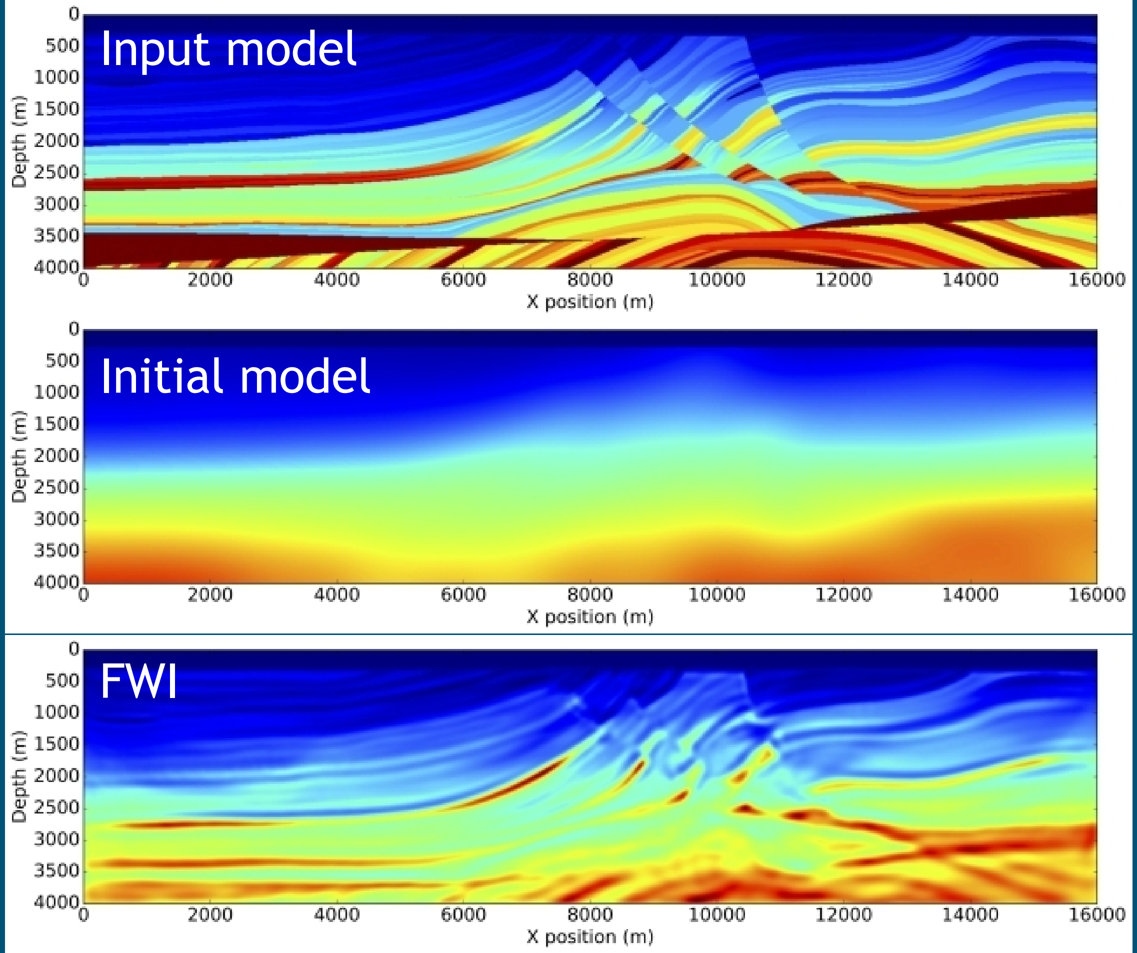
Introduction

- Waveform Methods in GNDD Signal Propagation
  - SALSA3D works with travel times, which is good for event locations.
    - The tomographic modelling inverts for the global mantle with a fixed *a priori* crustal model.
    - Next steps include inverting for the structure of the crust.
  - When we work with the full recoded wavefield, new applications can be investigated.
    - Discrimination
      - Are there ways our usual discrimination methods can be fooled by unusual sources or velocity structures?
    - Event characterization
    - Effects of attenuation, anisotropy, etc…
  - Bridging gaps between teleseismic and near-regional scales.
  - Leveraging frequency content for more detailed information.
    - Currently working with colleagues investigating Machine Learning methods for crustal scale waveform characterization.
  - Building a framework for Full Waveform Inversion (FWI).
    - More on this next slide and near the end.

Future of waveform modeling



Aspirational chart pulled from Steve Myers 2021 NEM



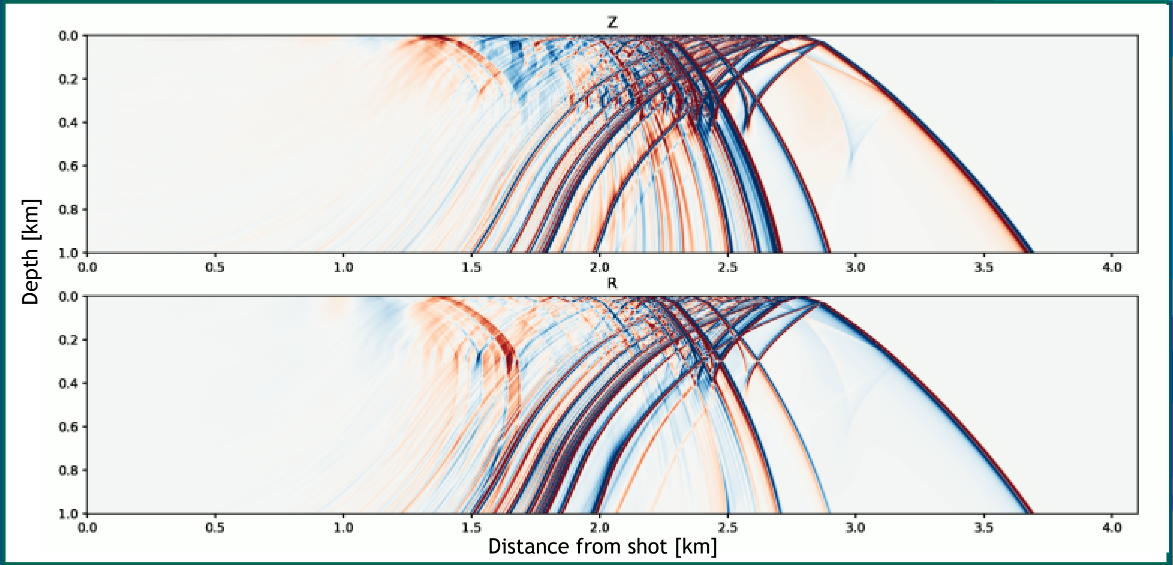
Example Full Waveform Inversion from Devito project

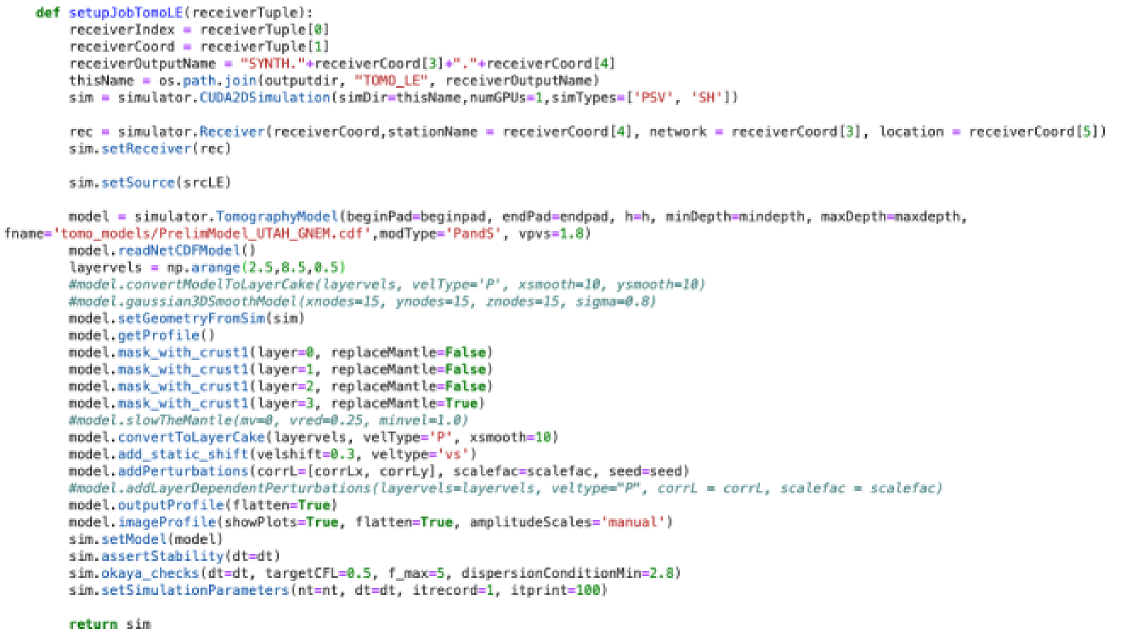
CUDA 2D Simulator

- A GPU implementation of the 2D Finite Differences code used by Caltech (Helmberger, Clayton, Vidale, et al.*)
  - Pushing the simulation to GPUs provides fast calculation and natural parallelization.
  - Simulation only considers Vp, Vs, and density (i.e. it does not account for intrinsic attenuation or lattice preferred orientation anisotropy).
  - FD is 8th-order in space, 2nd order in time
  - 2D significantly reduces the computational domain.
    - Higher spatial and temporal resolution than 3D versions.
    - P-SV and SH systems have to be run separately.
    - Out of plane scattering and attenuation is not fully accounted for.
- Simulations organized through a Python wrapper (Nathan Downey)
  - The interface script facilitates a natural method to define synthetic sources and receivers.
  - Methods are included to test 1D models or path-specific 2D cross-section models extracted from 3D models, such as CRUST1.0.
  - Functions allow the user to manipulate the 2D models with additions such as stochastic structural perturbations or overlaying parts of one model onto the existing model.
  - Built-in sanity checks prevent runs with unstable velocity models or source parameters.

*Li, Helmberger, Clayton, Sun, 2014, GJI

Shallow explosive source recorded in the near-field

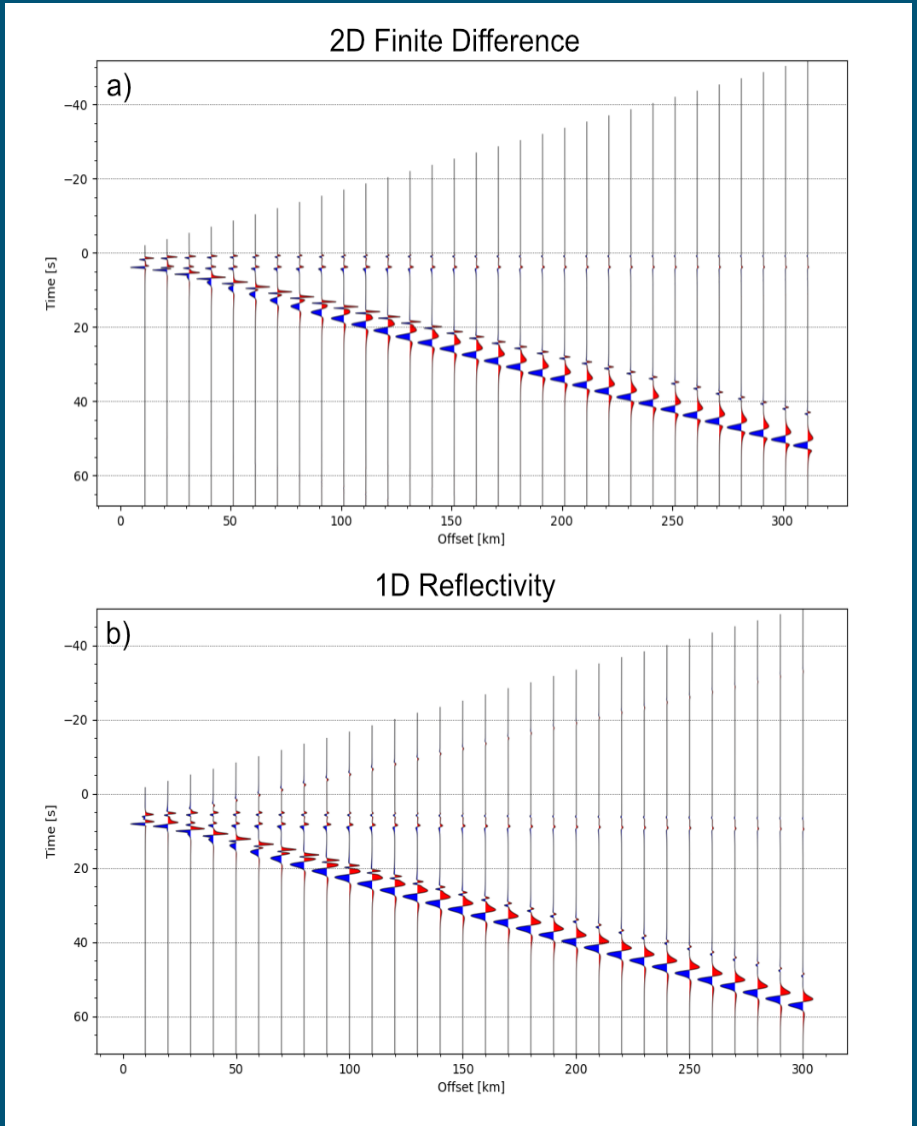




```
    def setupJobTomoLE(receiverTuple):
        receiverIndex = receiverTuple[0]
        receiverCoord = receiverTuple[1]
        receiverOutputName = "SYNTH."+receiverCoord[3]+"."+receiverCoord[4]
        thisName = os.path.join(outputdir, "TOMO_LE", receiverOutputName)
        sim = simulator.CUDA2DSimulation(simDir=thisName,numGPUs=1,simTypes=['PSV', 'SH'])

        rec = simulator.Receiver(receiverCoord,stationName = receiverCoord[4], network = receiverCoord[3], location = receiverCoord[5])
        sim.setReceiver(rec)

        sim.setSource(srcLE)

        model = simulator.TomographyModel(beginPad=beginpad, endPad=endpad, h=h, minDepth=mindepth, maxDepth=maxdepth,
fname='tomo_models/PrelimModel_UTAH_GNEM.cdf',modType='PandS', vpvs=1.8)
        model.readNetCDFModel()
        layervels = np.arange(2.5,8.5,0.5)
        #model.convertModelToLayerCake(layervels, velType='P', xsmooth=10, ysmooth=10)
        #model.gaussian3DSmoothModel(xnodes=15, ynodes=15, znodes=15, sigma=0.8)
        model.setGeometryFromSim(sim)
        model.getProfile()
        model.mask_with_crust1(layer=0, replaceMantle=False)
        model.mask_with_crust1(layer=1, replaceMantle=False)
        model.mask_with_crust1(layer=2, replaceMantle=False)
        model.mask_with_crust1(layer=3, replaceMantle=True)
        #model.slowTheMantle(mv=0, vred=0.25, minvel=1.0)
        model.convertToLayerCake(layervels, velType='P', xsmooth=10)
        model.add_static_shift(velshift=0.3, veltype='vs')
        model.addPerturbations(corrL=[corrLx, corrLy], scalefac=scalefac, seed=seed)
        #model.addLayerDependentPerturbations(layervels=layervels, veltype="P", corrL = corrL, scalefac = scalefac)
        model.outputProfile(flatten=True)
        model.imageProfile(showPlots=True, flatten=True, amplitudeScales='manual')
        sim.setModel(model)
        sim.assertStability(dt=dt)
        sim.okaya_checks(dt=dt, targetCFL=0.5, f_max=5, dispersionConditionMin=2.8)
        sim.setSimulationParameters(nt=nt, dt=dt, itrecord=1, itprint=100)

        return sim
```

Eye test showing how easy it is to setup a simulation

Code validation: other synthetic methods

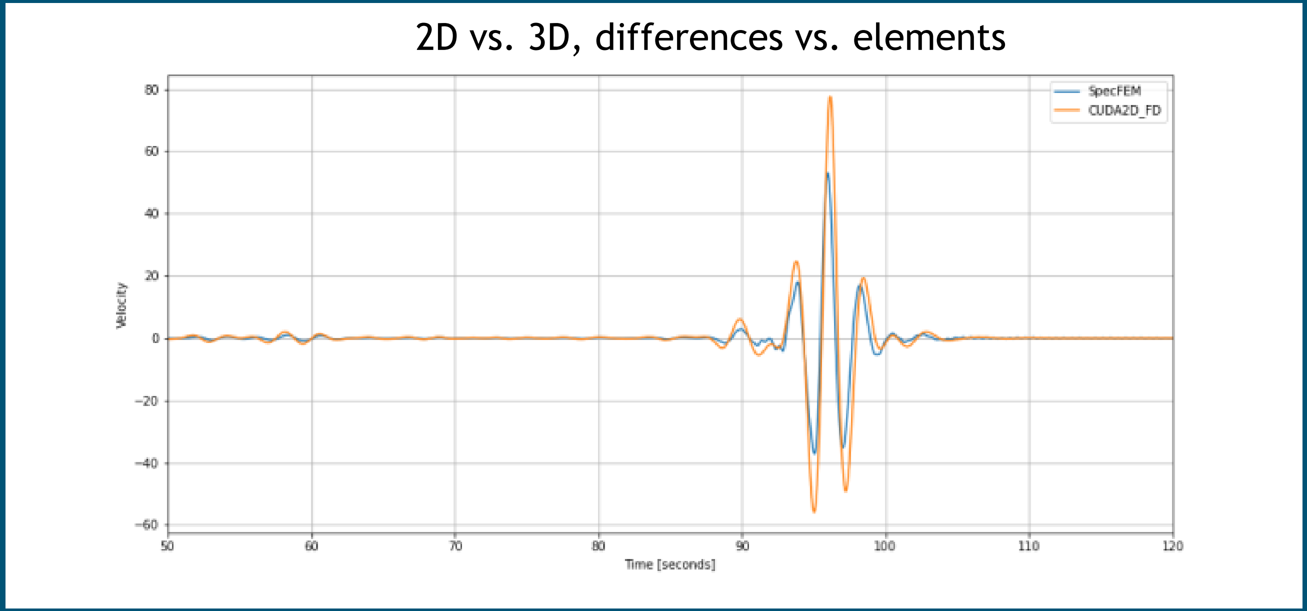


Single homogeneous half-space

The 1D Reflectivity code [Kind, Tibi] is fast, but struggles with complex media, particularly low velocity zones.

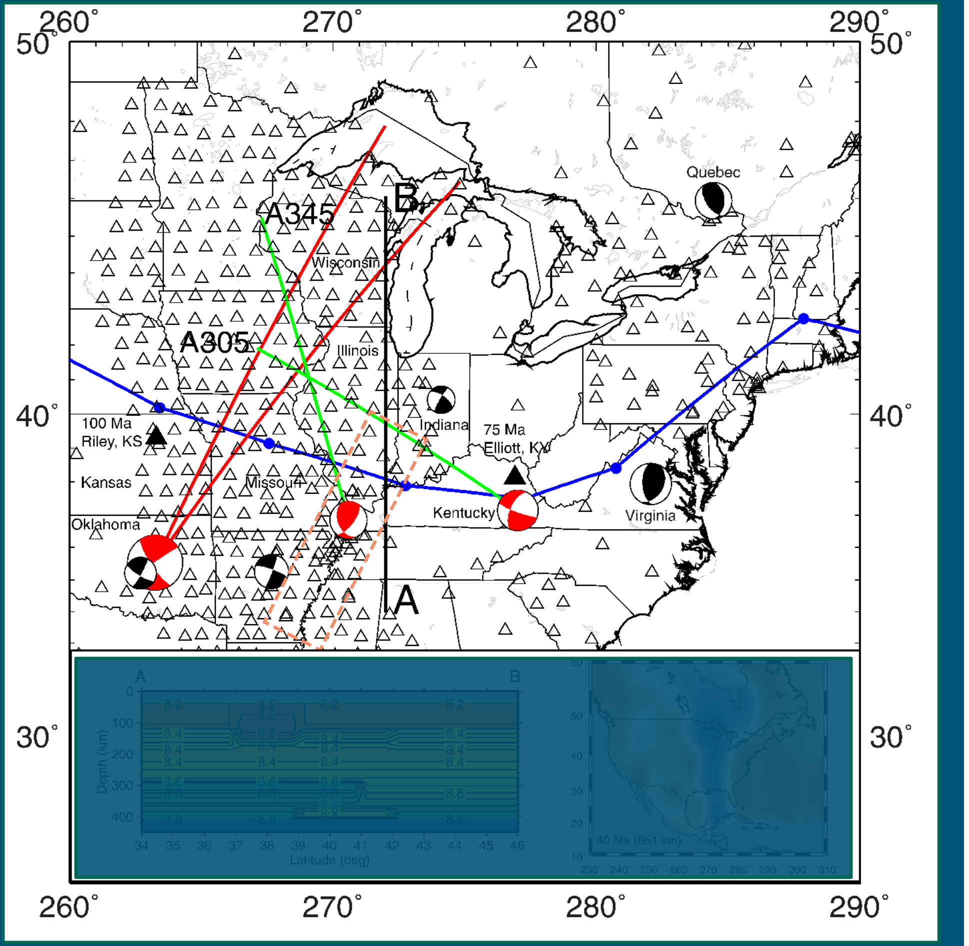
SpecFEM3D is the academic world standard for global to regional scales. However, it becomes computationally intractable for local, high frequency cases.

As with any engineering problem, it comes down to optimizing between three competing preferences. In this case, speed, accuracy, and medium complexity.

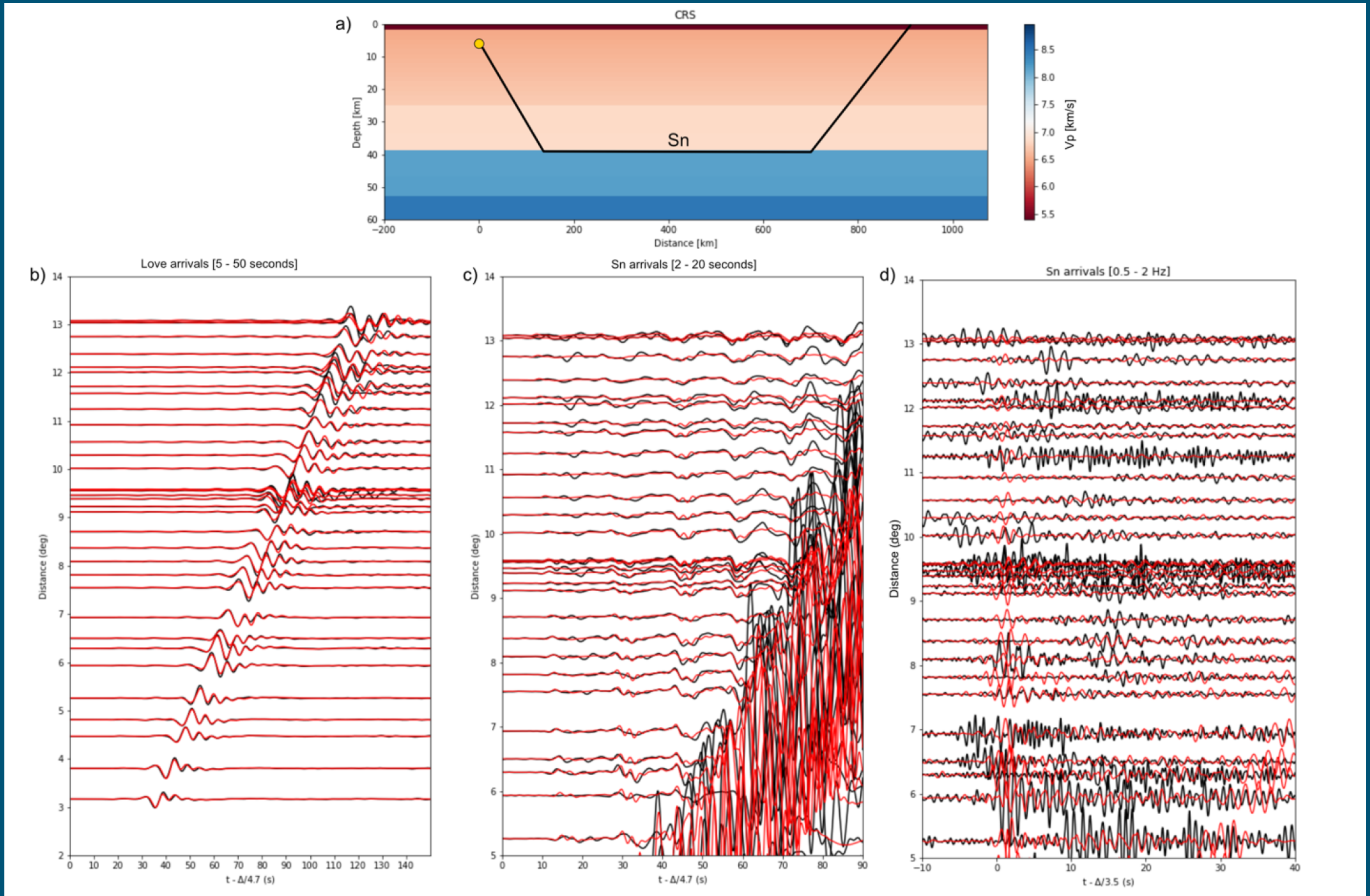

2D vs. 3D, differences vs. elements

Single homogeneous half-space, dirac comb STF

Code validation: published Oklahoma event



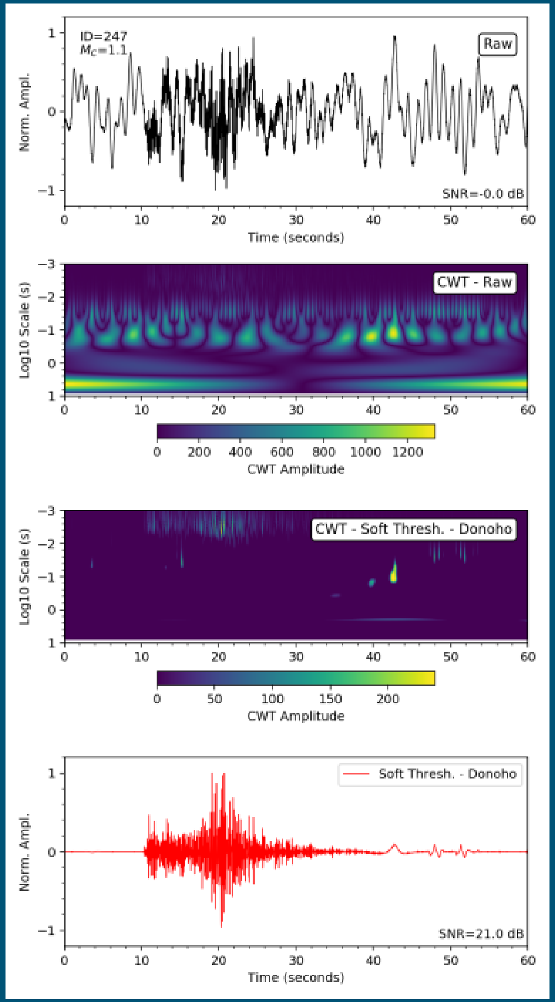
Chu and Helmberger, 2014, G^3



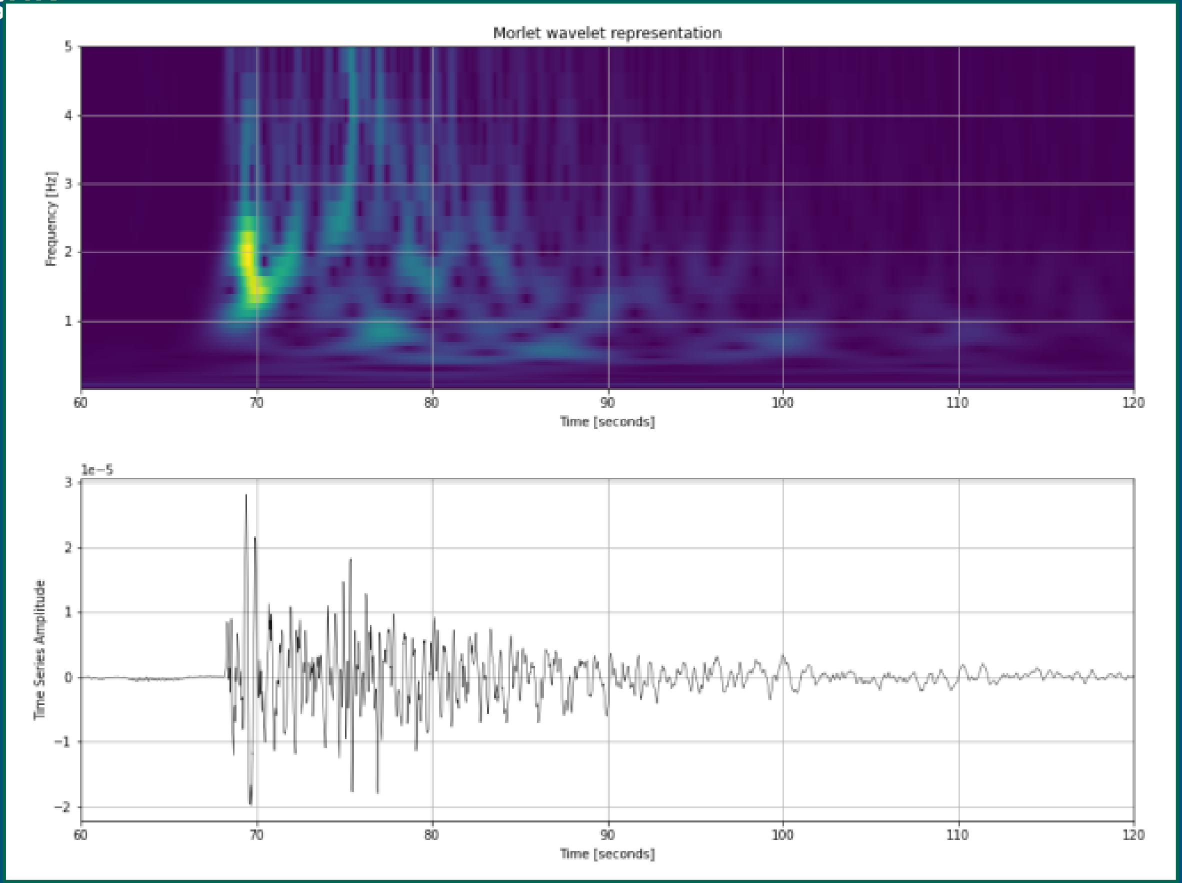
Continuous Wavelet Transform

Following Mousavi and Langston’s demonstration of the CWT for denoising, we’ve translated their Matlab software into Python for adaption into our workflows and experimentation.

Surface level advantage is that it decomposes a waveform into time-frequency space without short-time windowing needed for standard spectrograms. Deeper level advantages may stem from changing which mother wavelet(s) are used.

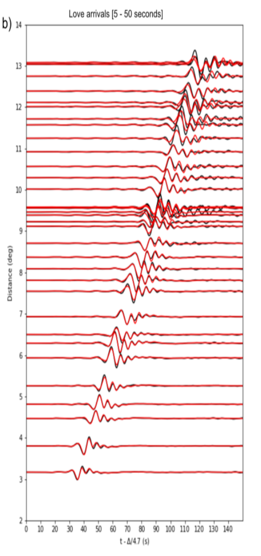


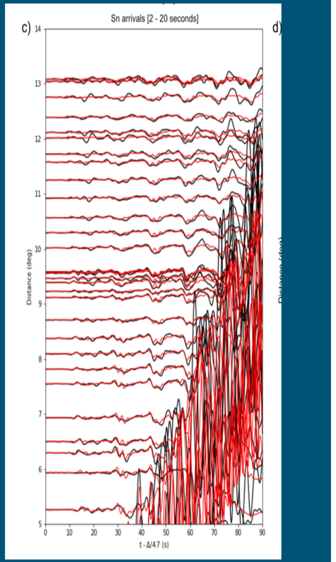
Tibi, Koch, in progress

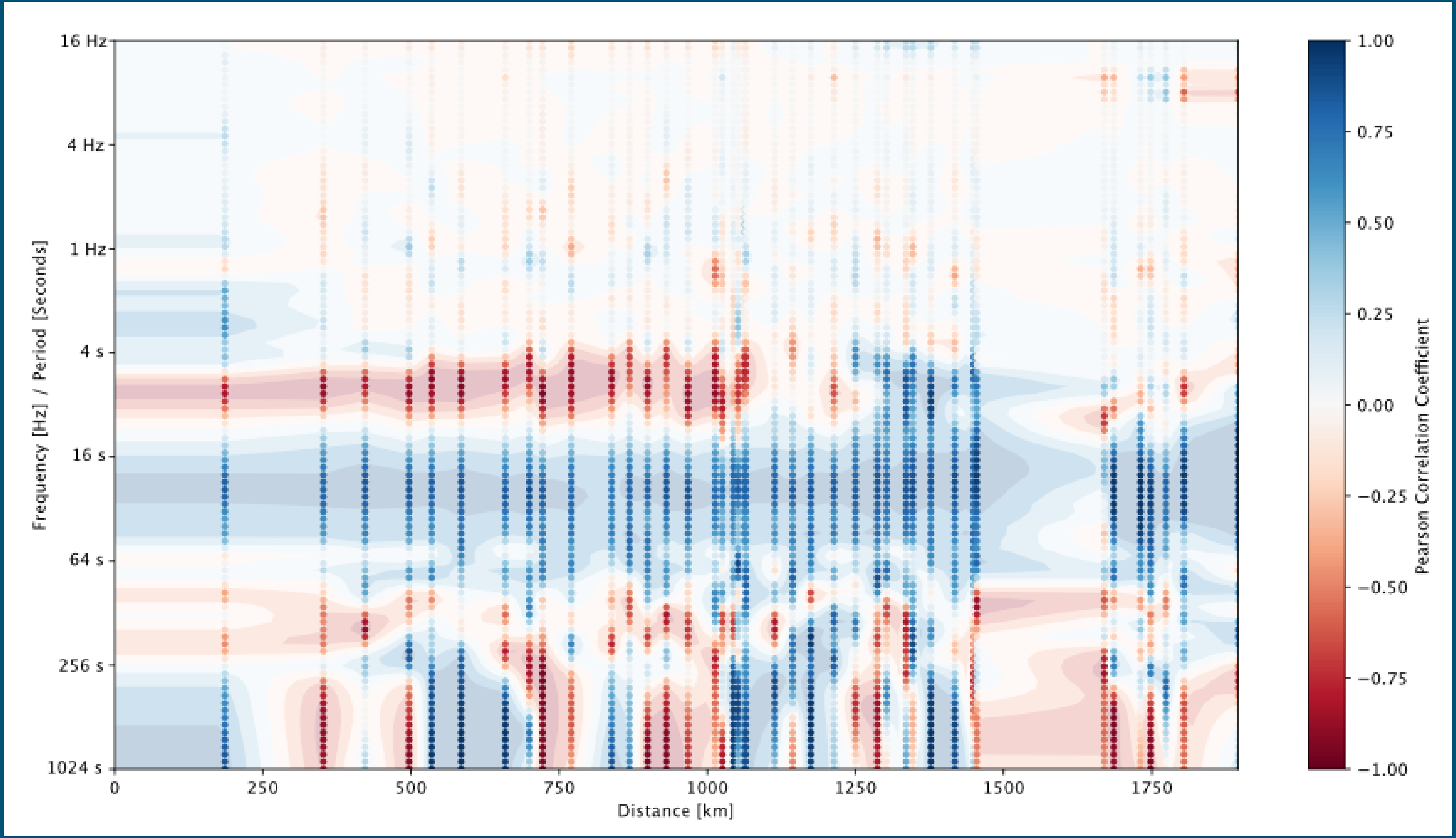


M_L 3.11
45 km away
Utah

Observed to synthetic correlation

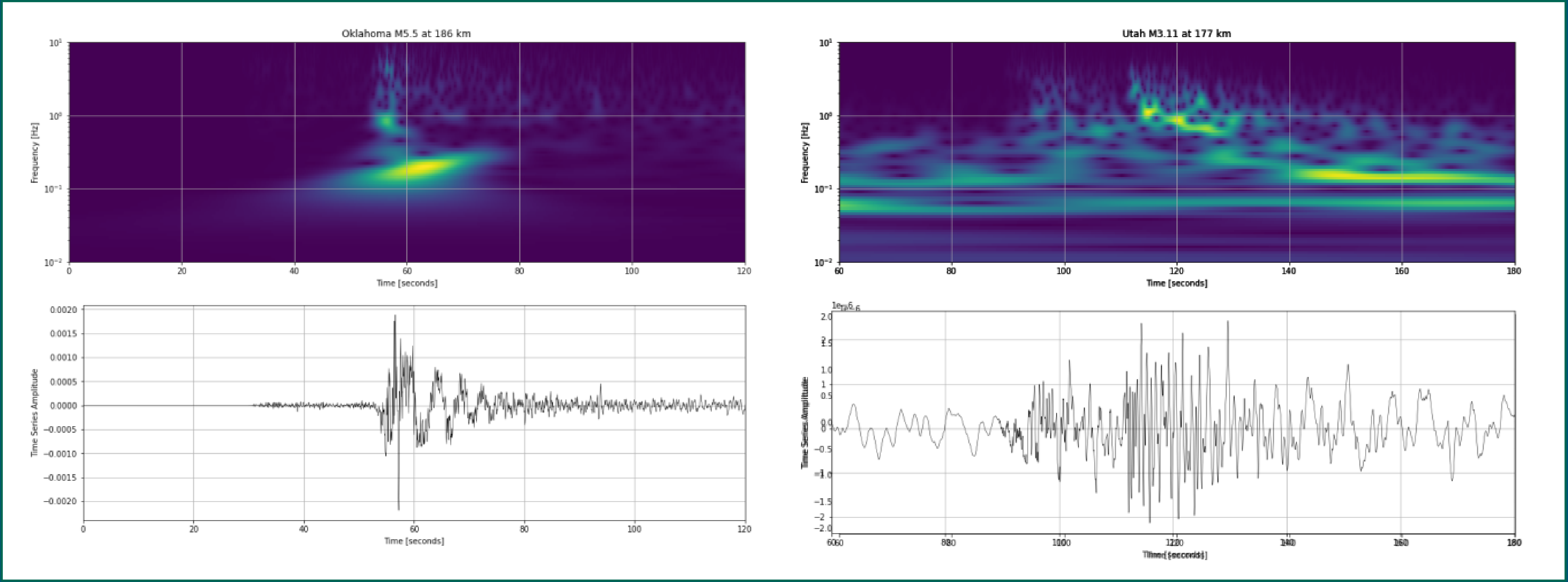






Oklahoma M5.5 as used in Chu and Helmberger, 2014

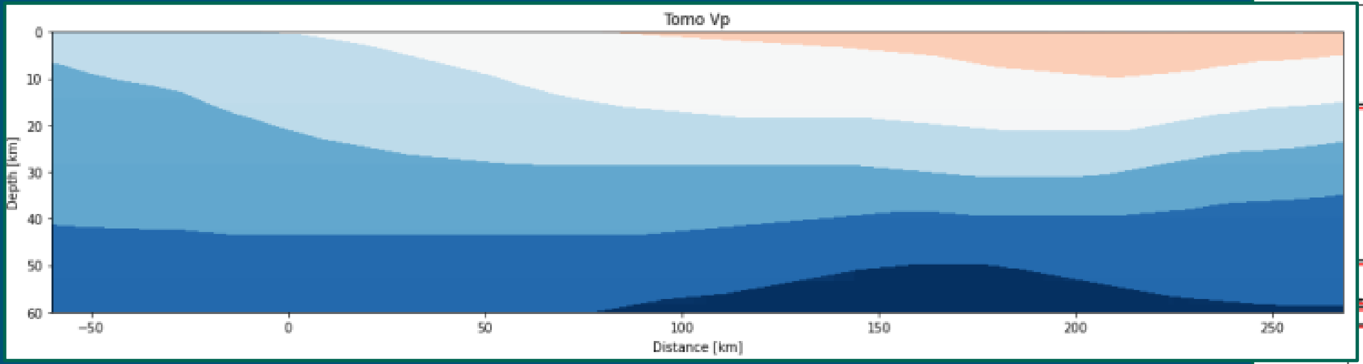
Oklahoma M5.5 vs. Utah local M3.11

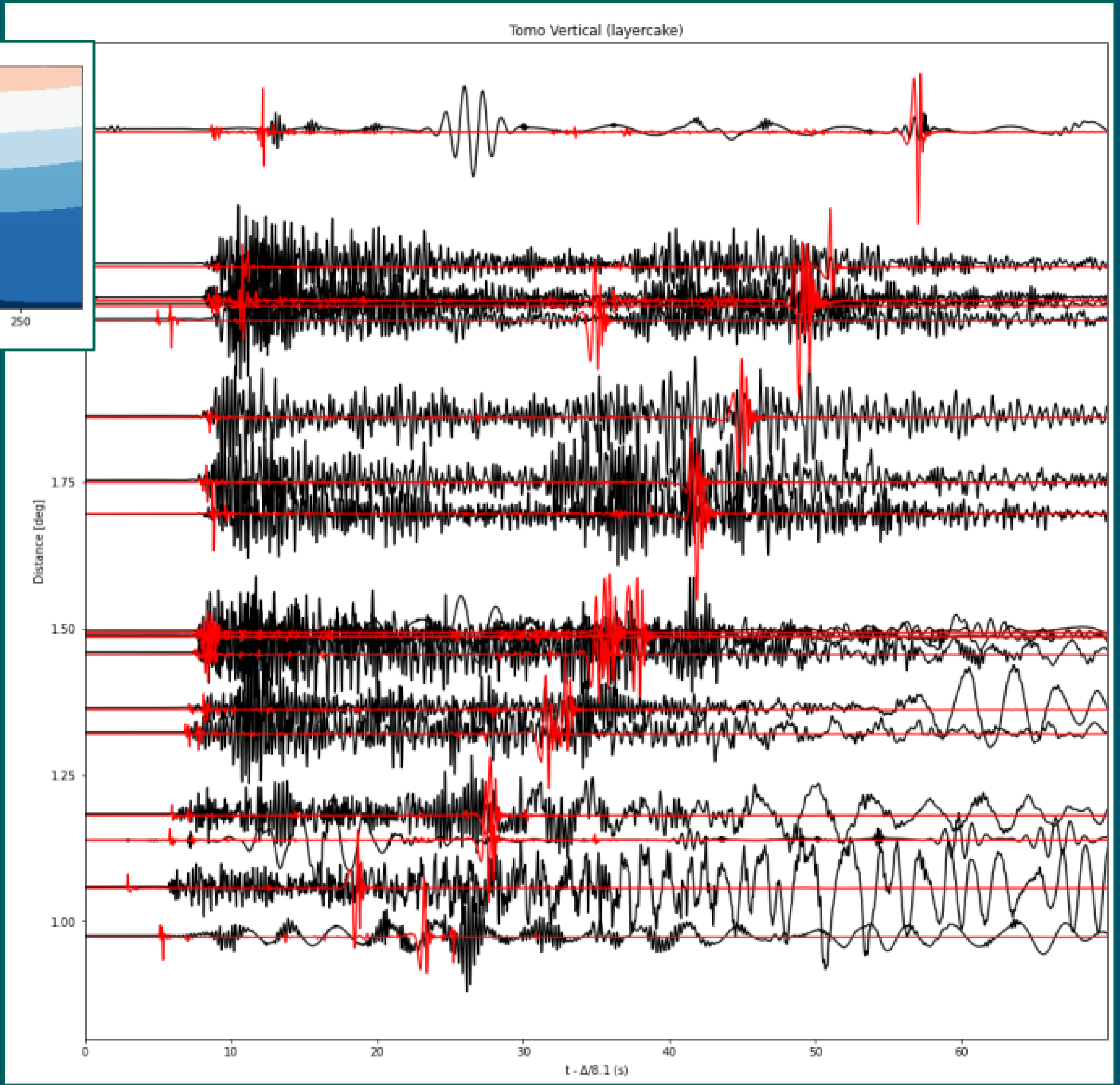


Dominated by Love wave. 5.5 km depth

Dominated by S coda. 1 km depth

Simulations with a Utah local 3D tomography model

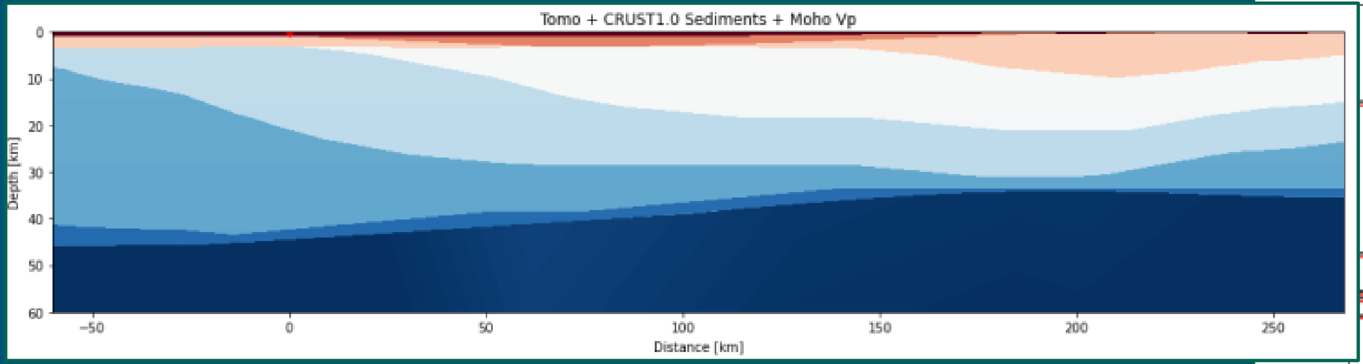




Synthetics (red) based on the above tomography model show approximately close arrival times but the coda amplitude is completely missing.

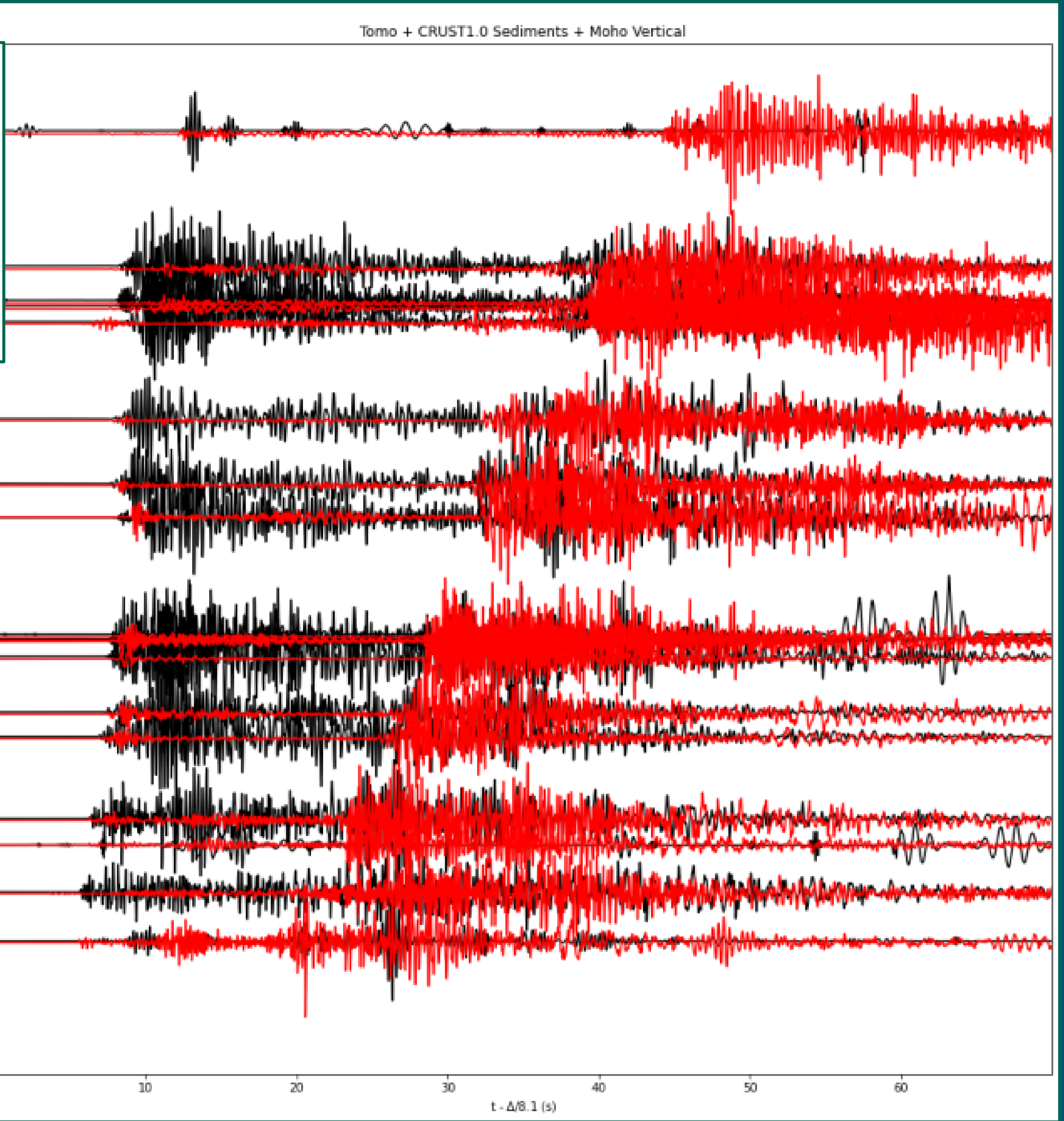
Wavelet domain denoising does cleanup the observed (black) fairly well pre-arrival, but the ‘signal-generated noise’ is still significant.

Simulations with a Utah local 3D tomography model and CRUST1.0

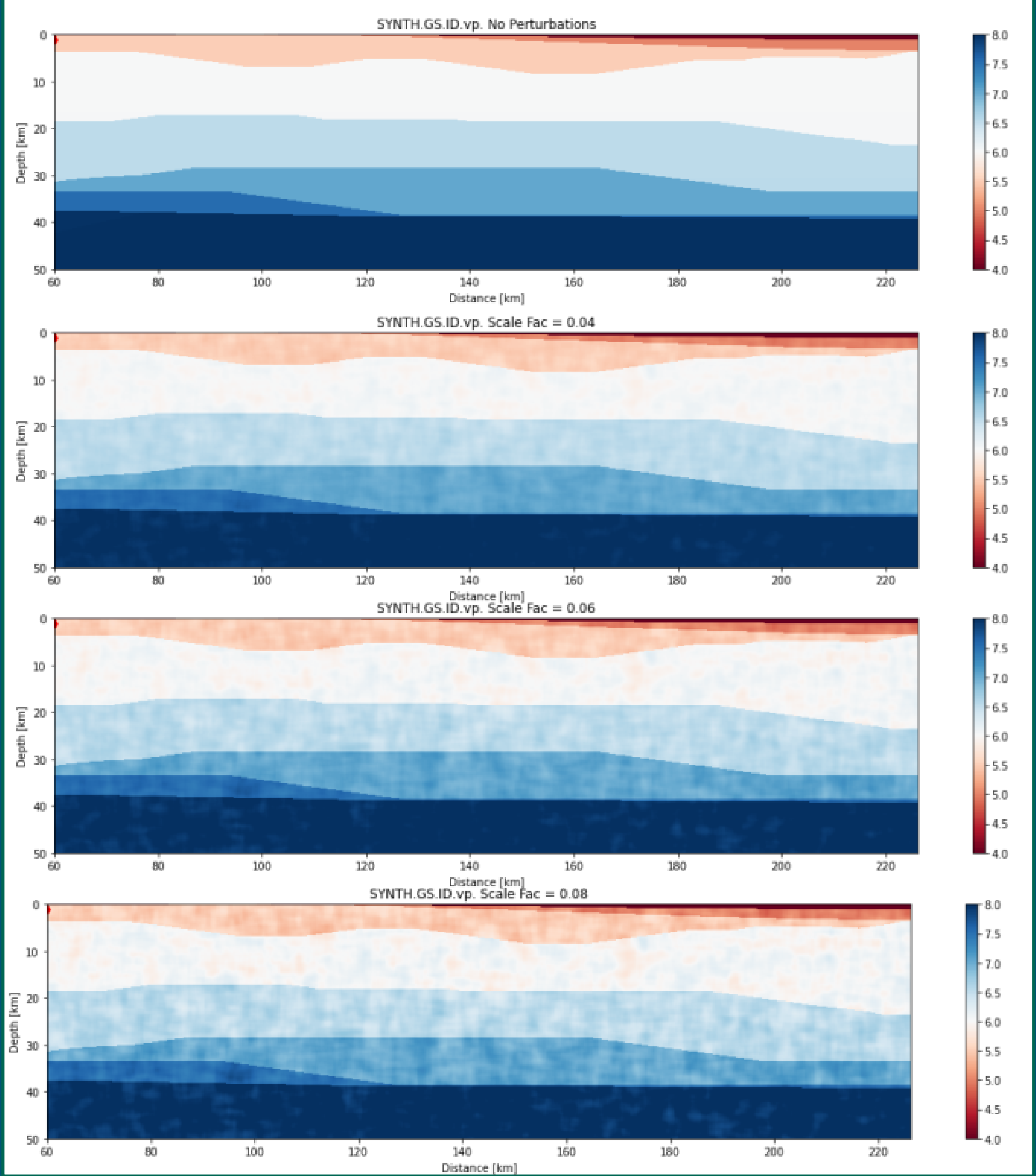


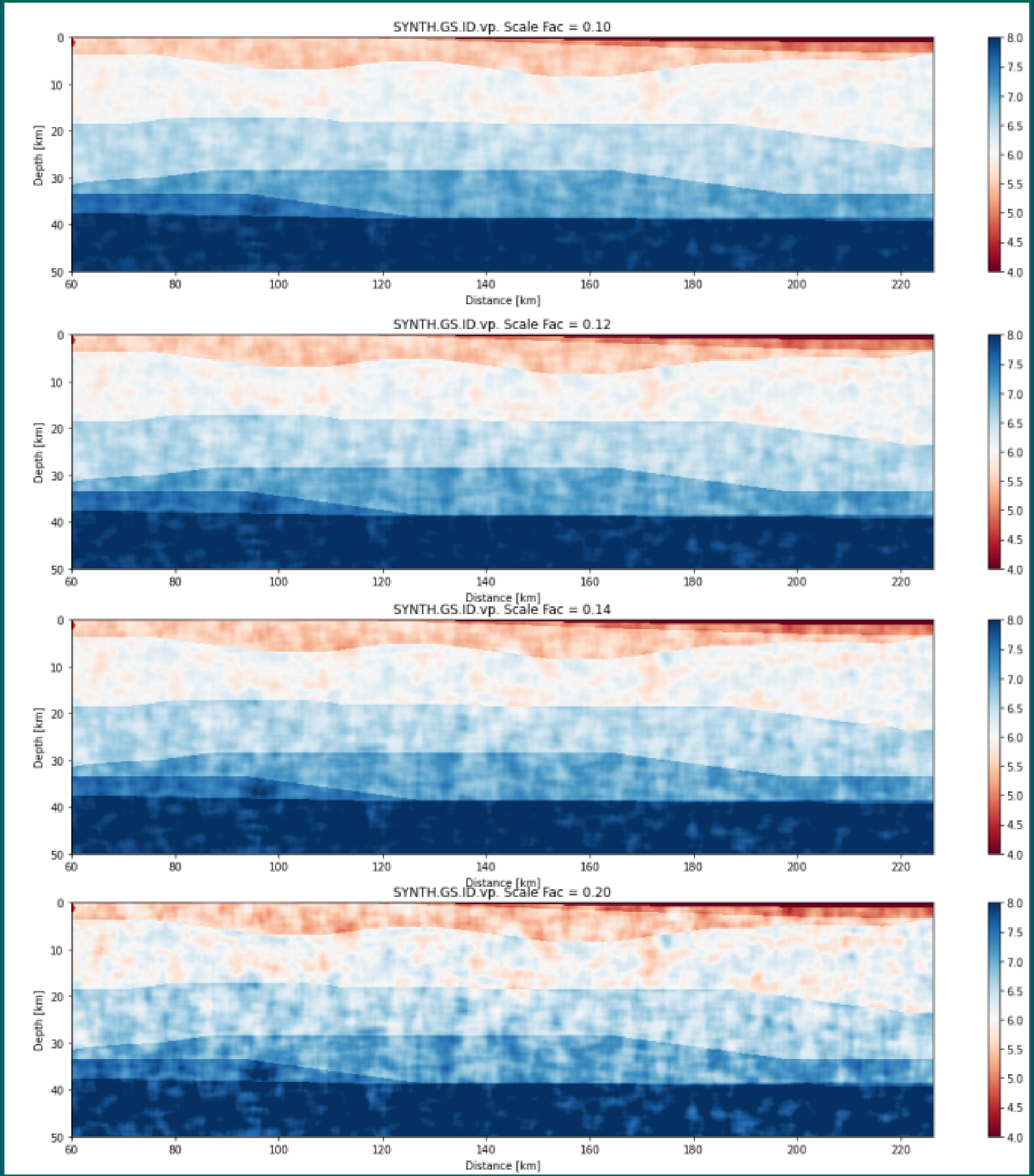
Adding the sedimentary layers from CRUST1.0 creates a significantly more realistic surface wave train as well as the P wave coda.

While the current example also includes the Moho from CRUST1.0, it has a negligible effect compared with the sedimentary layer.

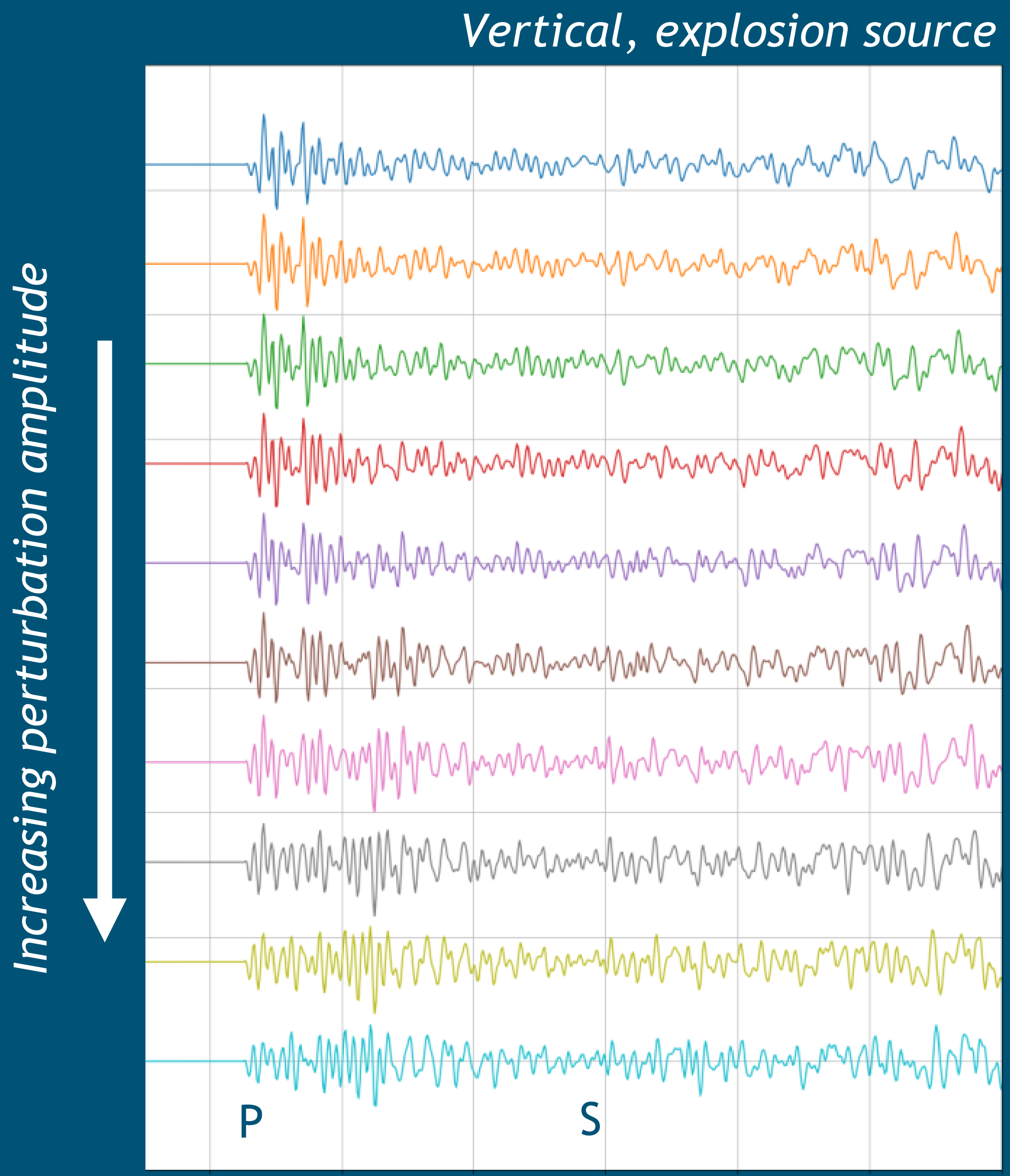


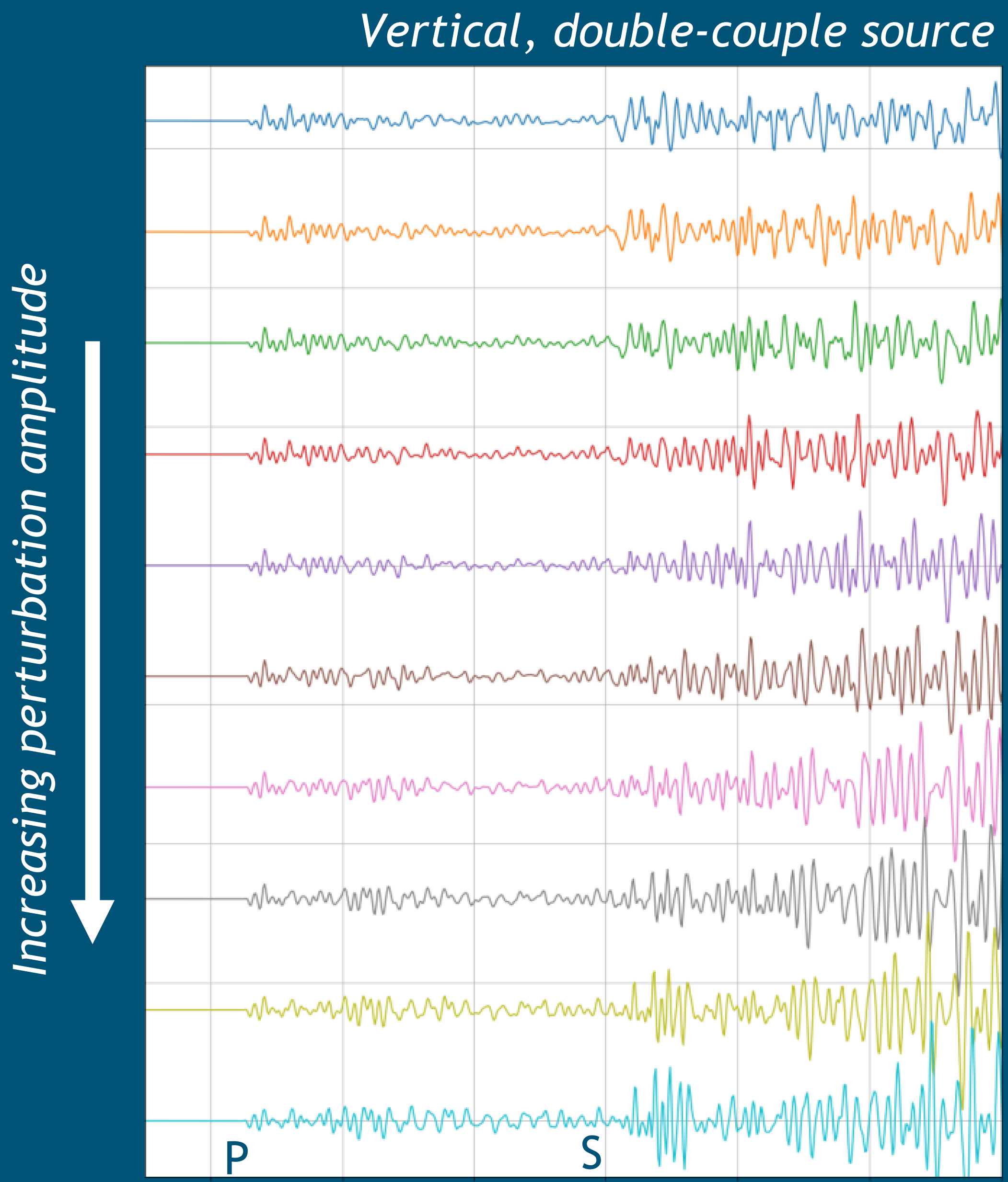
Effect of stochastic perturbations





Resulting waveforms





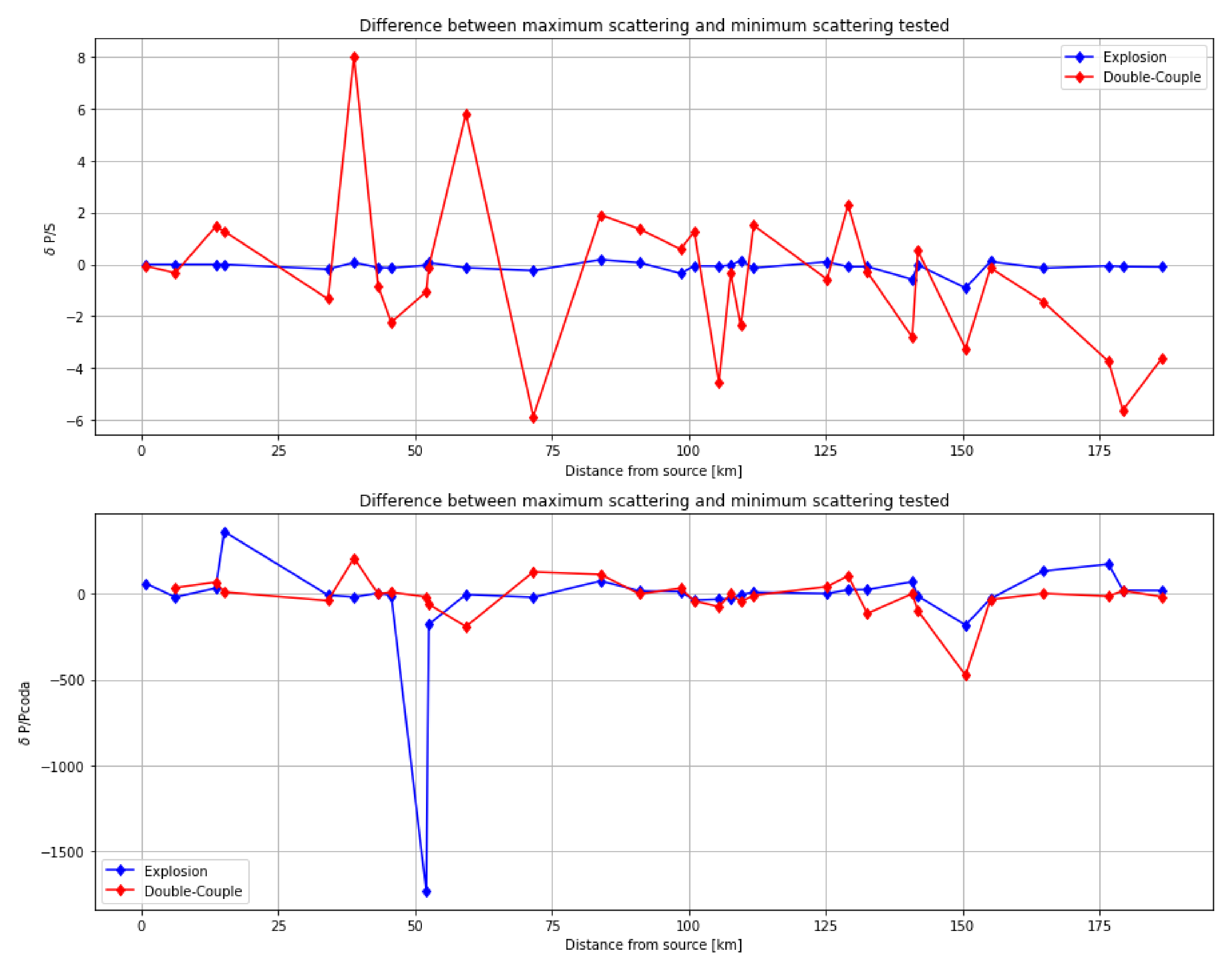
Quantifying P/S and P/Pcoda

These plots show the difference between the maximum perturbation value tested and the minimum perturbation value tested.

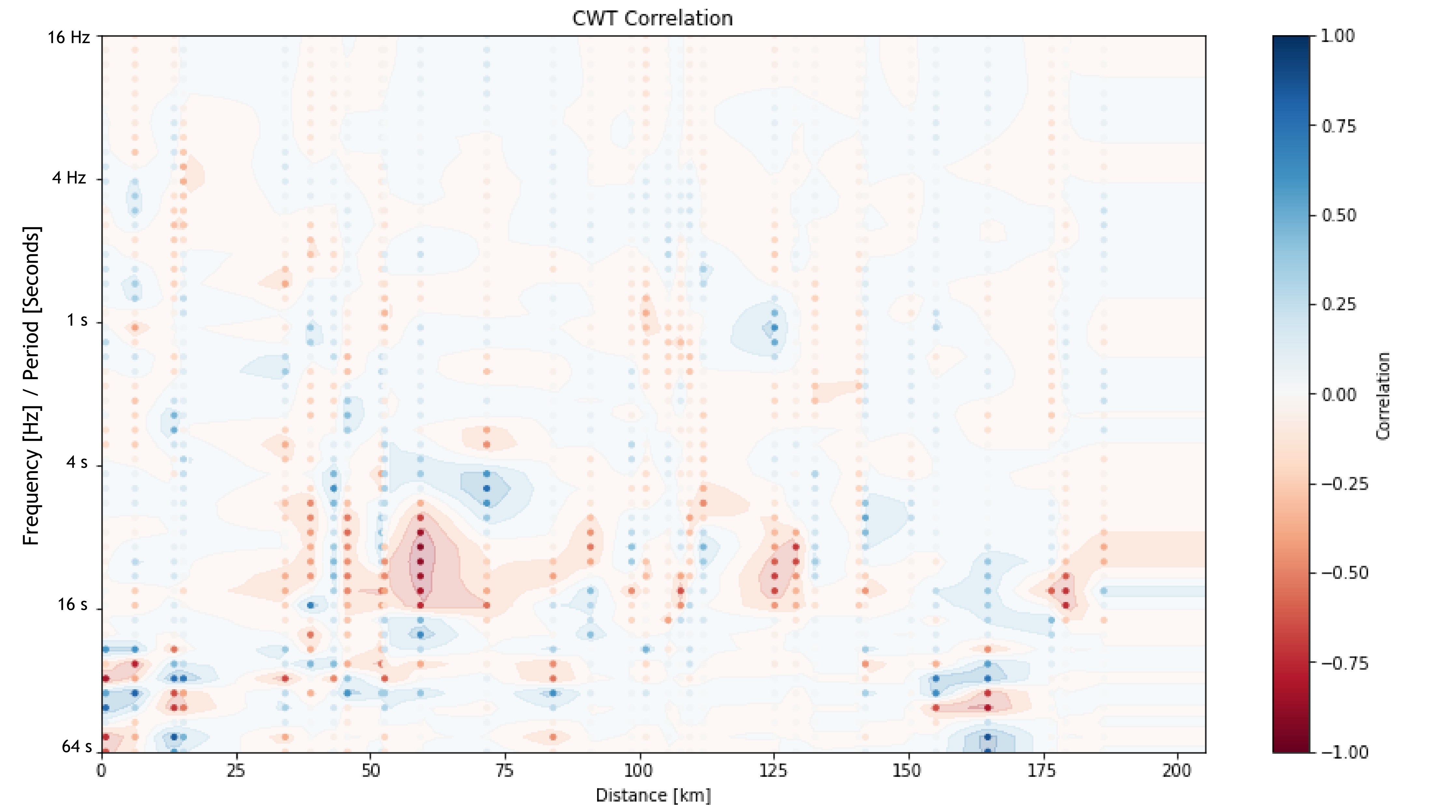
Variability is dominant, but may reflect variable background structures as this is not a true record section along one structural swath.

Nonetheless, we do see for the earthquake case, large P/S ratio for large scattering near the source and the reverse is the case for more distant stations.

Despite our visual inference previously, there is no quantifiable difference in P/P coda ratio.

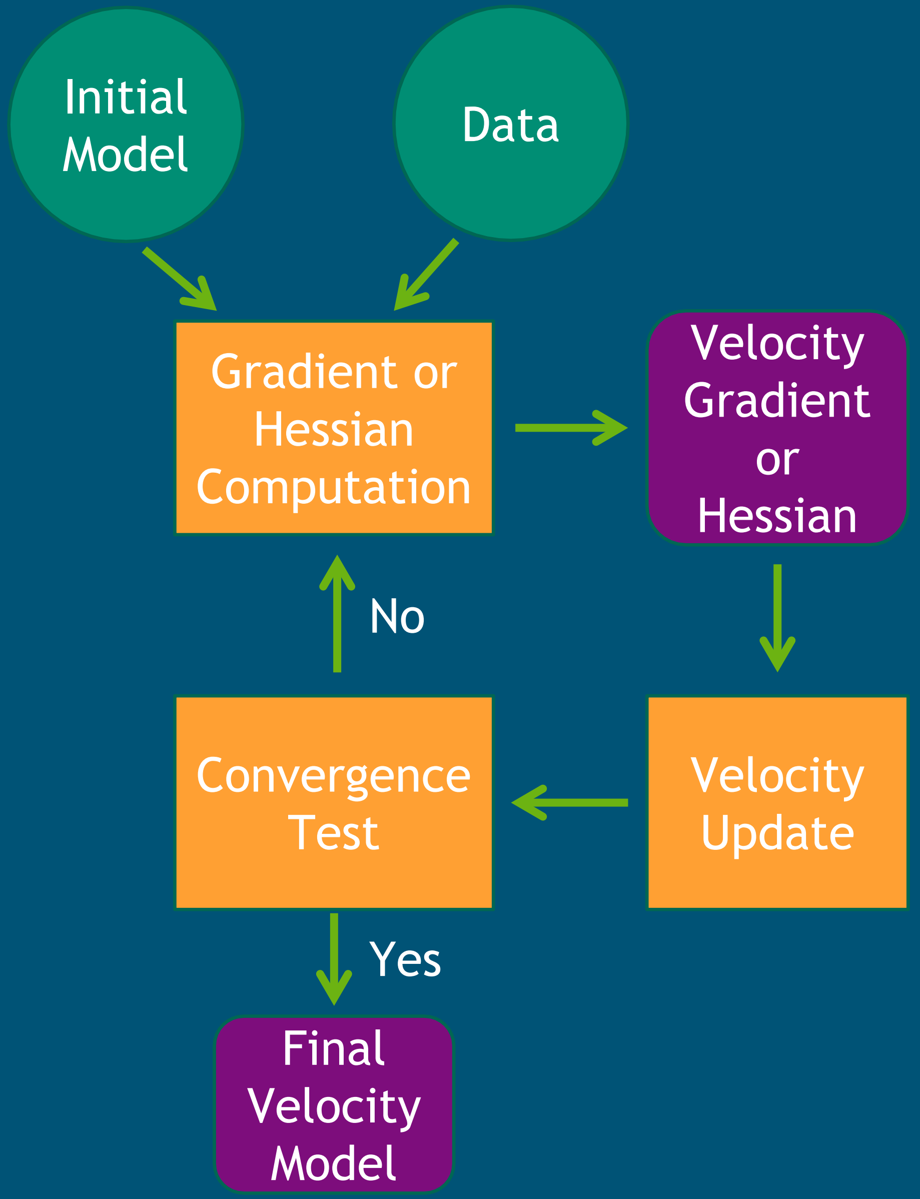


CWT Correlation for M3.11 in Utah



Introduction to FWI

● Input 🟧 Computation 🟪 Output



Initial Model

Data

Gradient or Hessian Computation

Velocity Gradient or Hessian

Velocity Update

Convergence Test

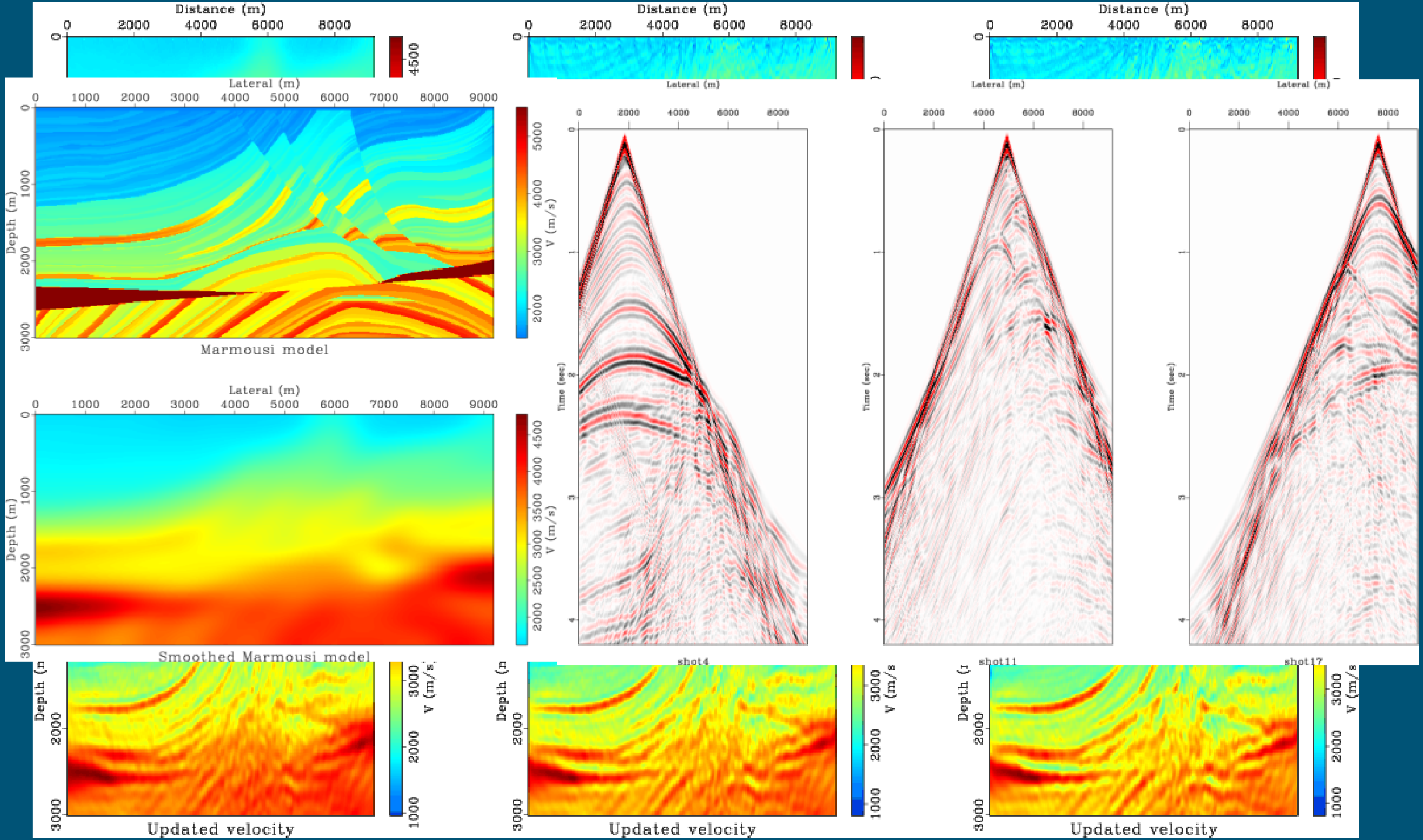
No

Yes

Final Velocity Model

- FWI is an iterative method to update a velocity model using a data residual (Ref: Tarantola, 1984)
- The required tools are
  1. Waveform simulator
  2. An optimization algorithm
- Algorithm dates to early 80’s but became part of industry standard methods in early 2010’s
- Many specialized tricks are required to get proper convergence

Introduction to FWI



Images from our preliminary SNL FWI

Obstacles to FWI

1. Computation
   - Single simulation is expensive, need one per source, gradient computation costs 3x a single simulation, line search is 3-4x a single simulation
   - Selection of windows to fit is non-trivial
   - Noise, particularly for small events, can mask true structure
2. Data Coverage
   - Good coverage means crossing raypaths
   - Successful industrial applications use GIANT datasets (6000 channels per source, ~ million sources)
3. Need an appropriate initial model
   - Close enough to the true model to avoid a local minima
   - Usually FWI requires a previous tomographic inversion to converge to “true” solution

Next Steps

- Develop and test more metrics for parameter similarity.
- Continue to explore signals in the wavelet domain.
- Look to fit large events at short periods to push towards higher frequencies and smaller events.
- Quantify trade-offs with 3D codes.
- Explore Full Waveform Inversion for global and regional scales.

Summary

- We’re working with an efficient 2D finite differences simulator which has been validated against alternative 1D and 3D methods and real-world earthquakes.
- Decomposing the waveforms into the wavelet domain provides a method of quantifying data fit as a function of frequency.
- Shallow, low velocity structure and stochastic structural perturbations have significant effects on the surface wave and coda amplitudes at high frequencies.
- Validating synthetic waveforms at frequencies above ~1 Hz and for small events may require a focus on matching waveform based measurements, rather than wiggle for wiggle replication.
- We’re exploring FWI, but find that having a good handle on waveforms expected from synthetic tests first will provide useful sanity checks during the FWI process.