Wave Propagation Including Small-Scale Heterogeneities and Q(f)

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Contract SAQMMA14M2208

Contracting Officer's Representative:
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Outline

- The 2009 North Korea Nuclear Test
- 3D Crustal Model of Eastern Asia (SALSA3D)
- Source Function
- Computational Resources
- Q(f)
- 0-4 Hz Regional Modeling of Wave Propagation in East Asia Constrained by Data
- Conclusions

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Review of NK nuclear explosions

Event	Size
9 October 2006	1kt, DOB ~ 310-590m
25 may 2009	2-4 kt, DOB ~ 310-590 m
12 February 2013	6-9 kt, DOB ~ 200-550 m
6 January 2016	7-9 kt

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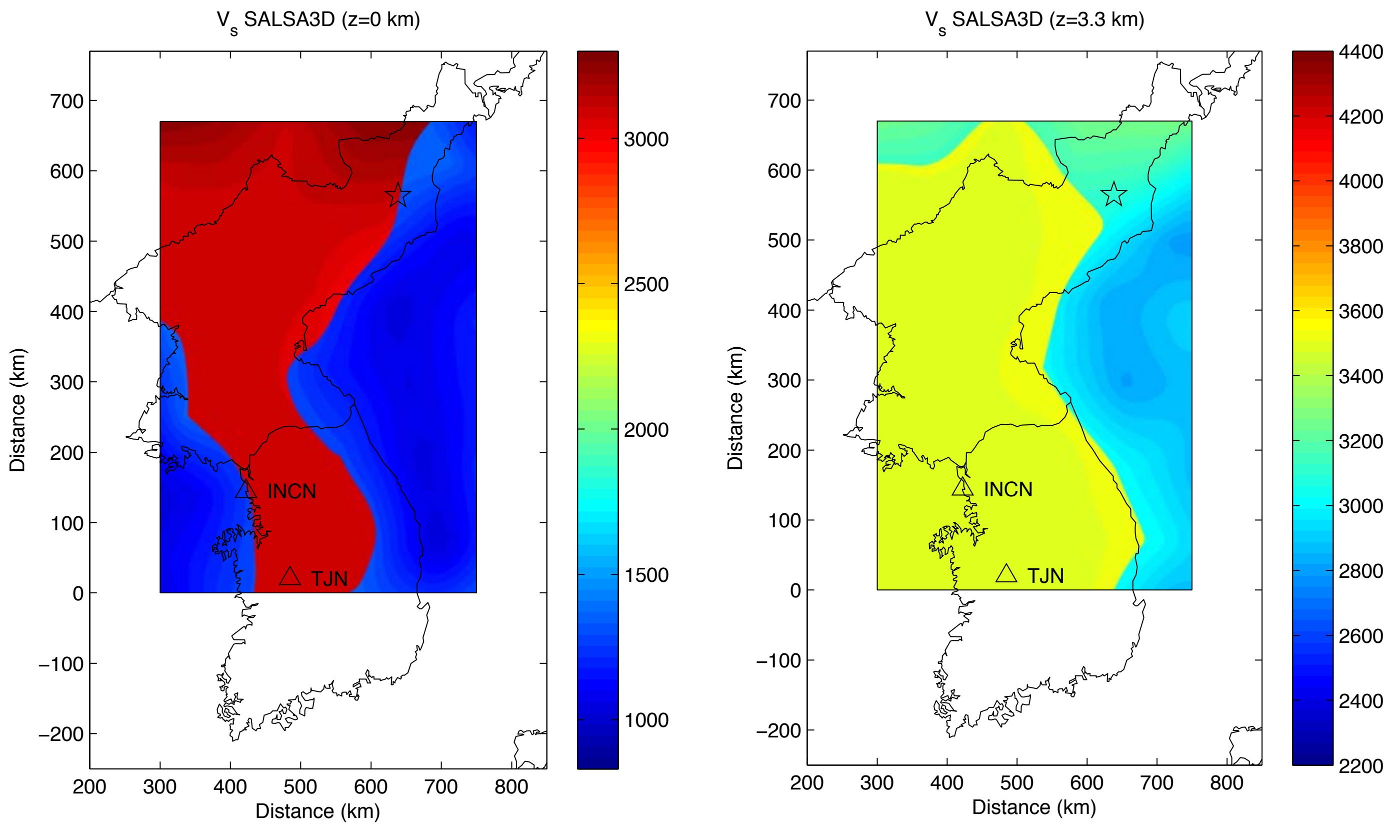
SALSA3D Crustal Model (Courtesy of LANL)



S-wave velocity at (left) the surface and (right) 3.2 km depth from the SALSA3D model used in the 3D simulations of the May 25 2009 North Korea nuclear test (star). Two stations (INCN, TJN) in South Korea have instrument-corrected records available.

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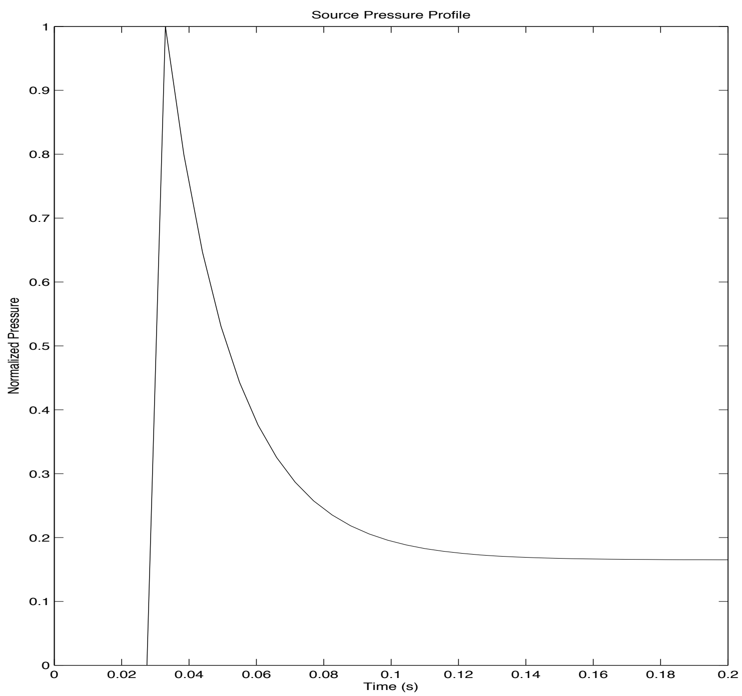
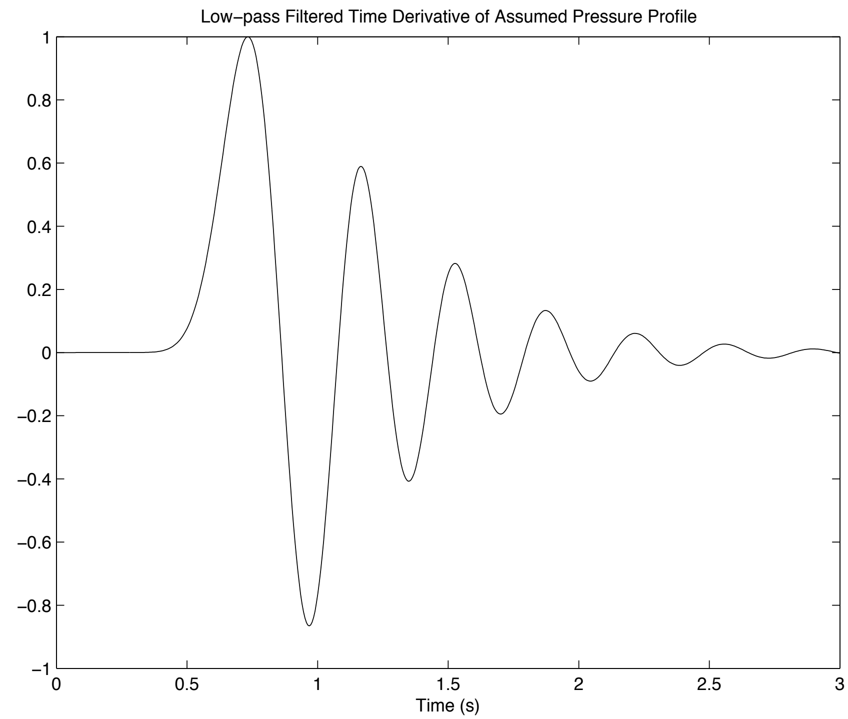
Source Description

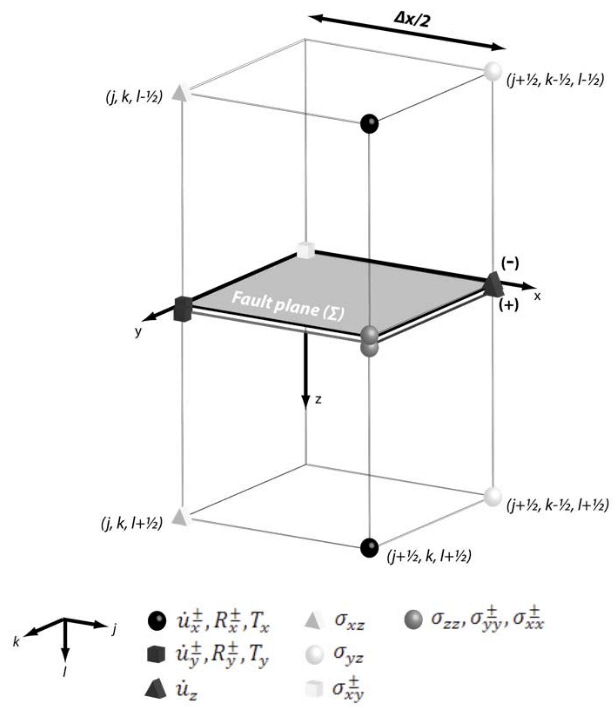




We model the 2009 North Korea nuclear test as an isotropic point source ($m_{xx}=m_{yy}=m_{zz}$ and $m_{xy}=m_{yz}=m_{xz}=0$, $P(t)=\exp(50\,t+0.15)$) located at 41.2914° N, 129.0831° E and 600 m depth with a moment magnitude of 4.05 (moment $1.4e^{15}$ Nm) (Patton and Pabian, 2014).

AWP-ODC Numerical Method

- Solves 3D velocity-stress wave equations with explicit staggered-grid FD scheme
- 4th order accuracy in space and 2nd order in time
- Staggered-grid split-node (SGSN) algorithm for dynamic fault rupture modeling
- Perfectly Matched Layer (PML) absorbing boundary conditions
- A zero-stress boundary condition applied at top of model to simulate the free surface
- Anelastic attenuation incorporated by coarse-grained approach, as standard linear solid, stress relaxation – Q(f)



Computational requirements increase as f^4 !!!

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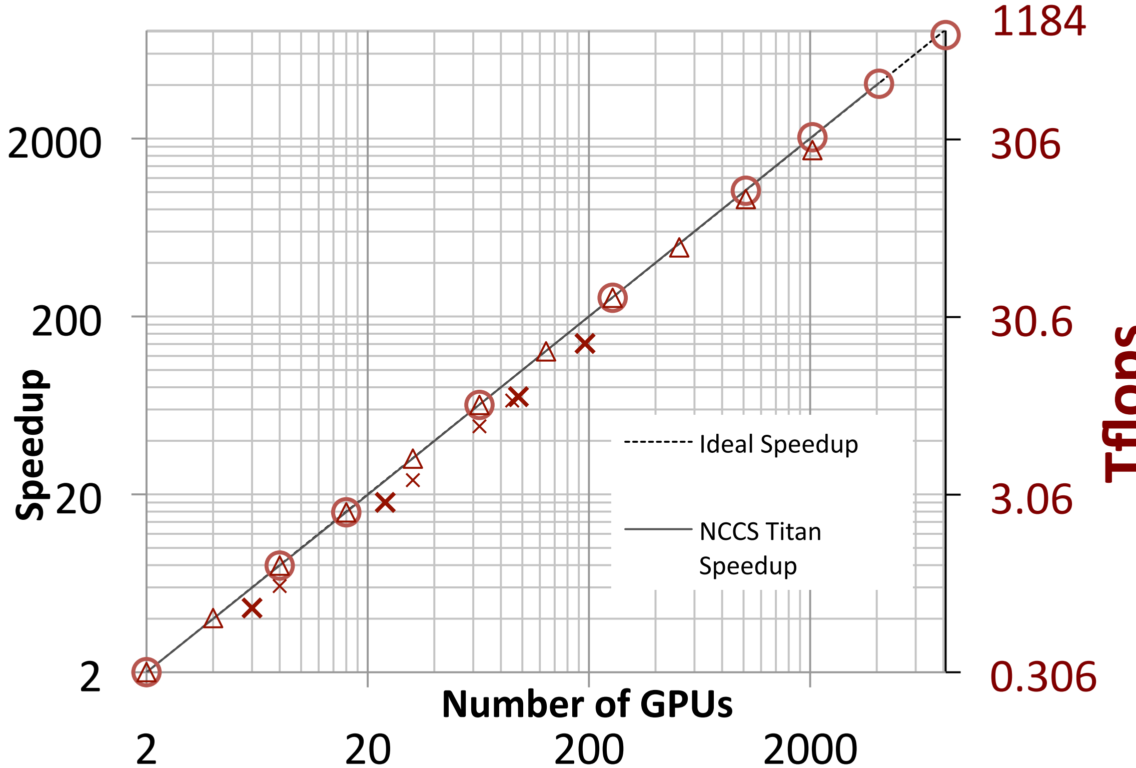
AWP-ODC Multi GPU Performance



We use the Oak Ridge National Laboratory (ORNL) Supercomputer Titan for the computations, funded by US DOE. 350 s of 0-4 Hz wave propagation in a ~500 km x 700 km x 80 km model @ dx=100m (24 billion grid points) takes ~1h 45 mins using 2,500 GPUs.

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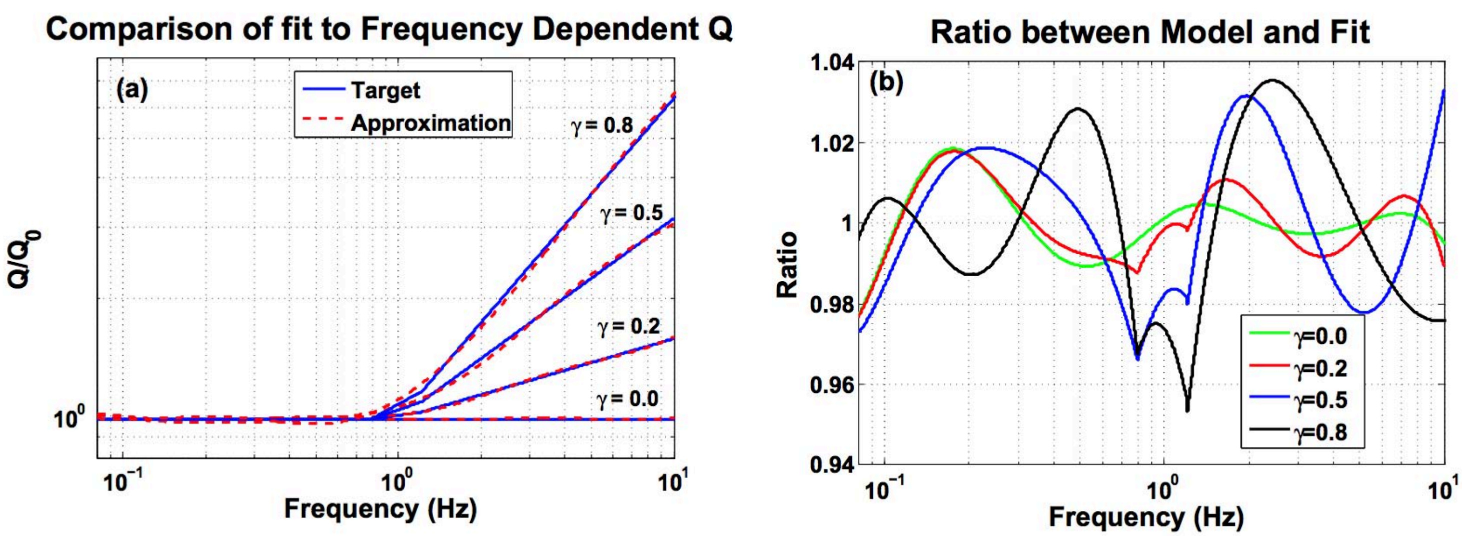
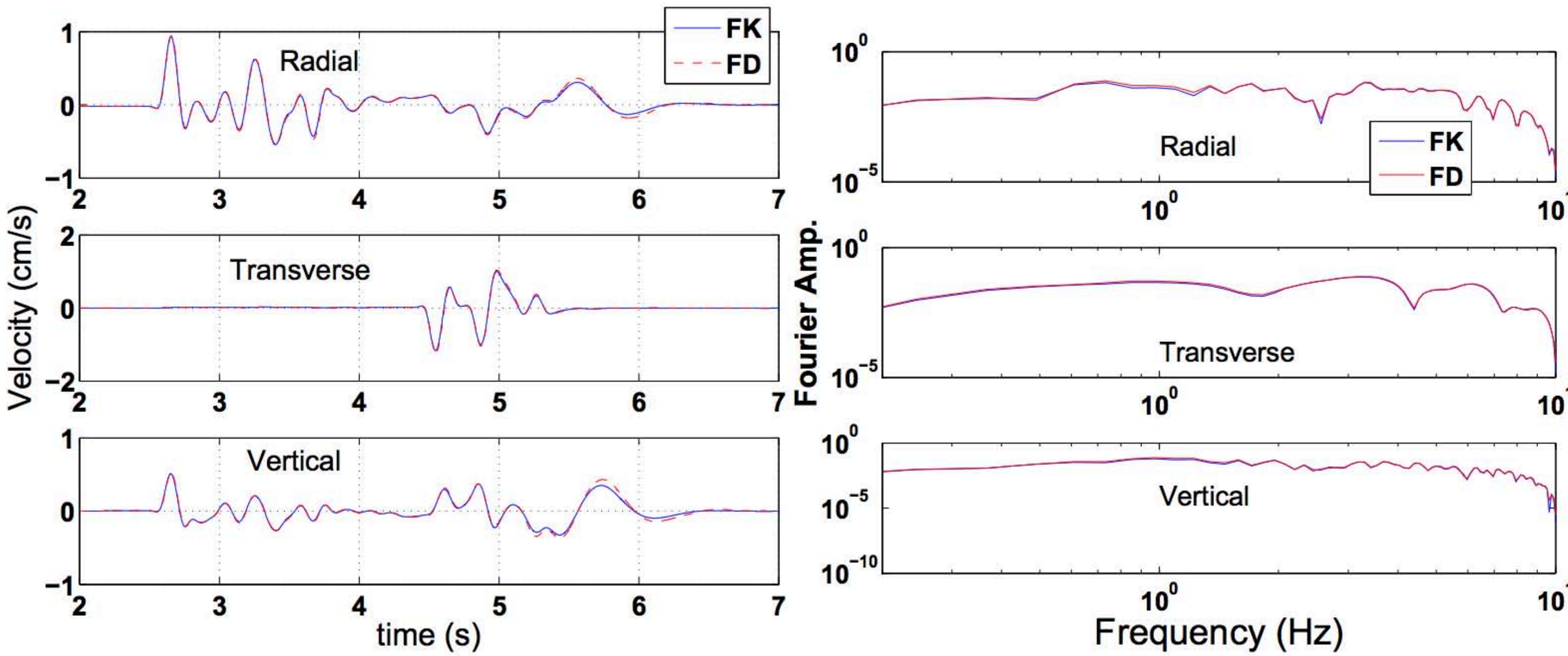
Frequency-dependent Anelastic Attenuation $Q(f) = Q_o f^{\gamma}$

Coarse-grain Q(f) memory variable implementation in fourth-order scalable FD code AWP-ODC, based on Day (1998) and Day and Bradley (2001).

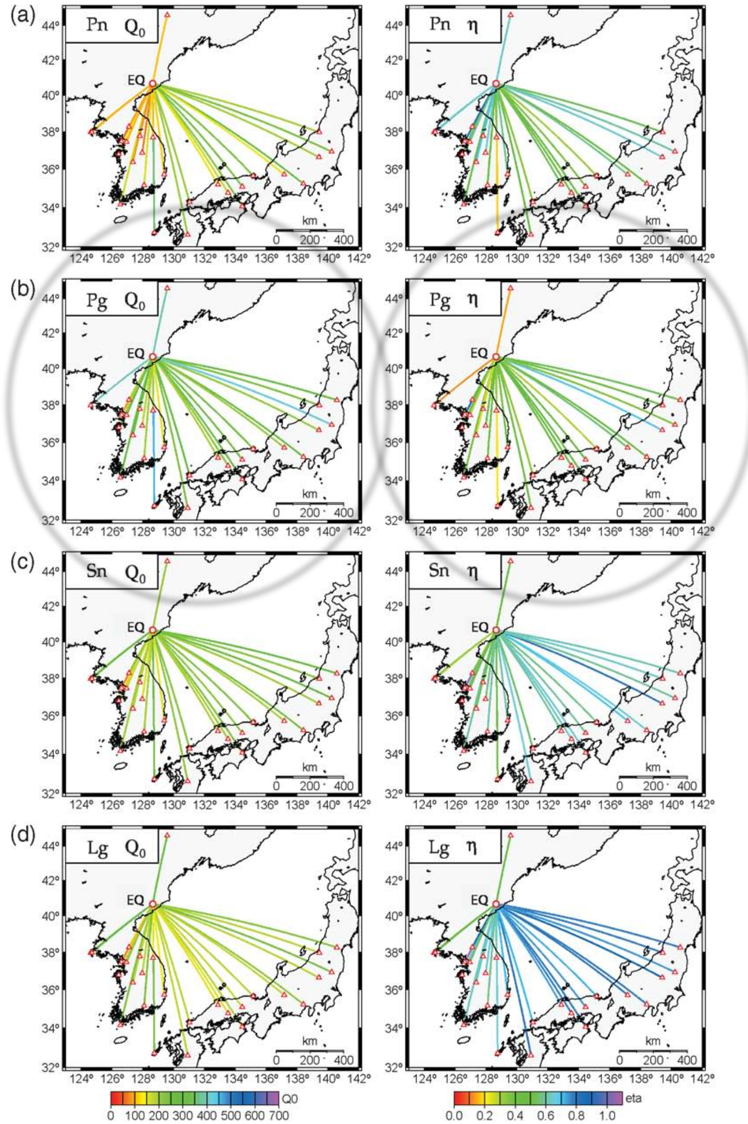
Withers, K. B., K. B. Olsen, S. M. Day (2015). Memory-efficient simulation of frequency dependent Q, *Bull. Seismol. Soc. Am.*, **v. 105**, p. 3129-3142, First published on November 3, 2015, doi:10.1785/0120150020.



Low Q (15) Layered Model Comparison



Published Q(f) for Korean Peninsula



$Q_{Pg}(f) \sim [200\text{-}350]\ f^{0.2\text{-}0.5}$

However, not clear how Q_{Pg}, Q_{Pn}, Q_{Sn}, and Q_{Lg} translates to Q_s and Q_p, used in FD modeling.

Hong, T.-K. and J. Rhie (2009). Regional Source Scaling of the 9 October 2006 Underground Nuclear Explosion in North Korea, *Bull. Seis. Soc. Am.* **99**, 4, 2523-2540.

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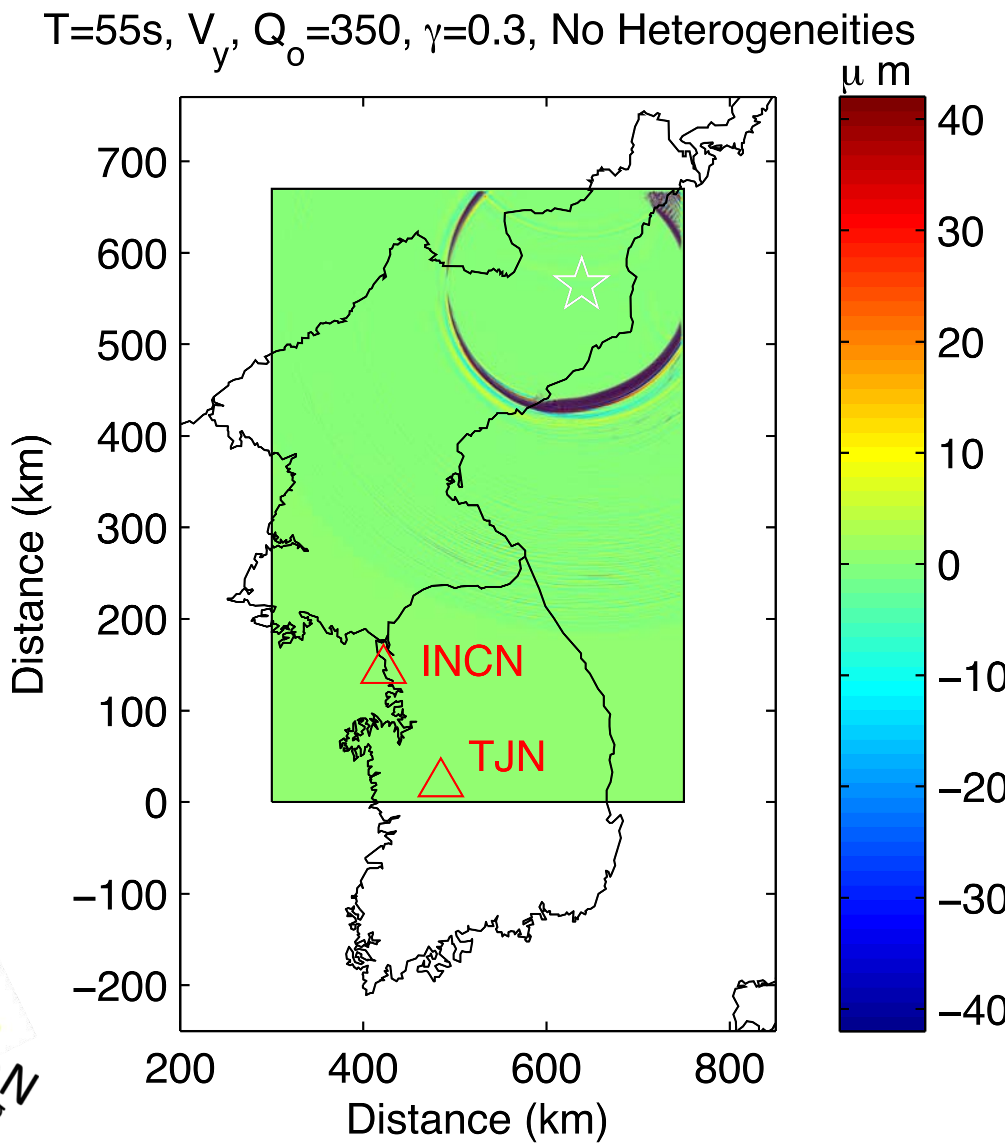
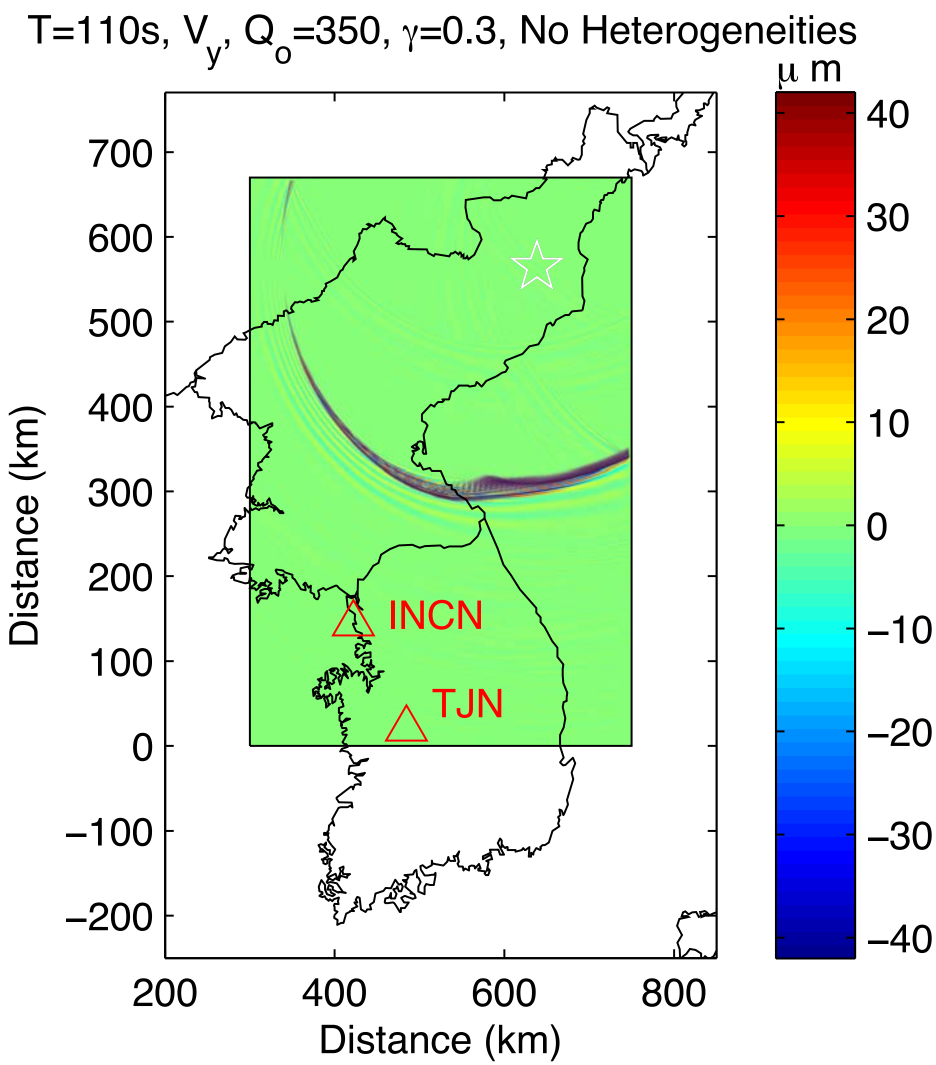
N-S Velocity Snapshot (55s)

Q(f)=350 $f^{0.3}$



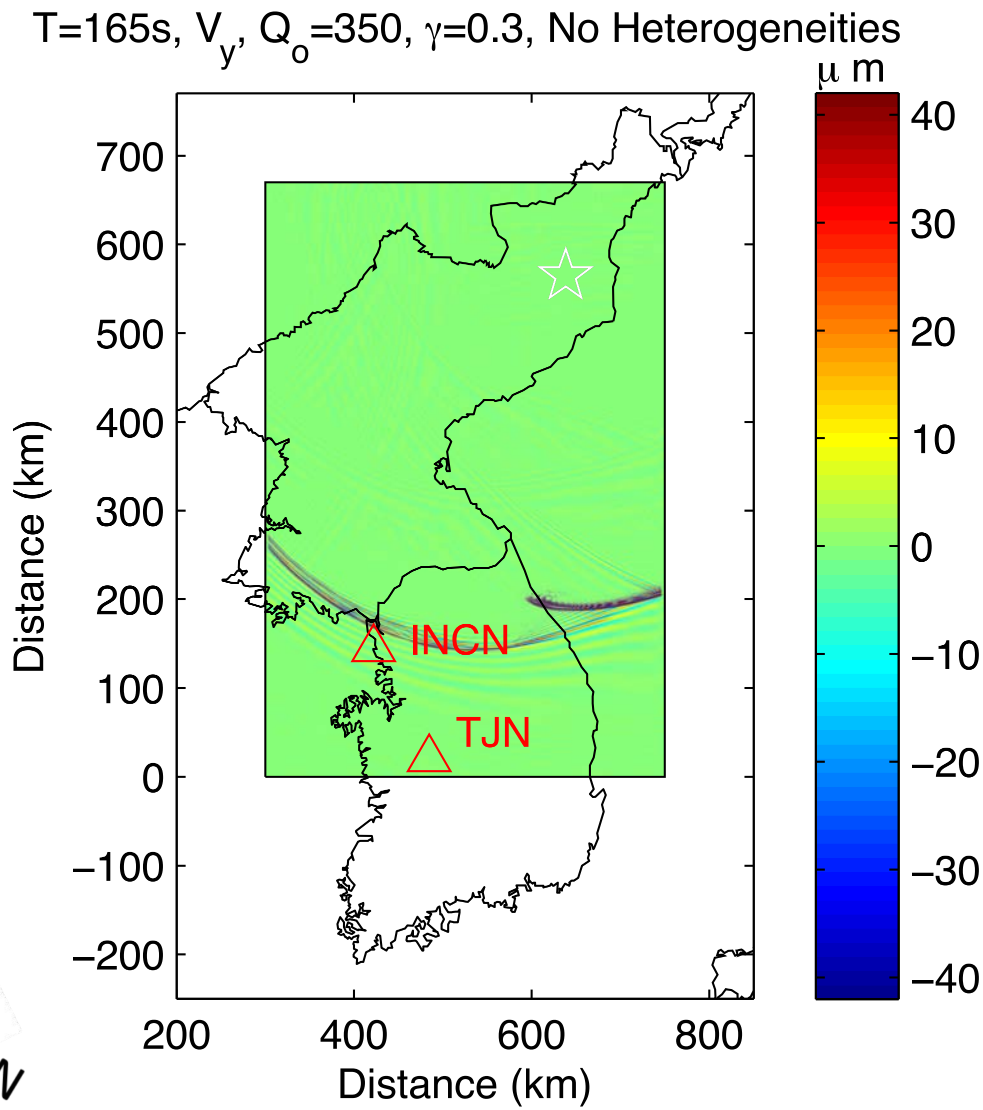
N-S Velocity Snapshot (110s)

$Q(f)=350\ f^{0.3}$



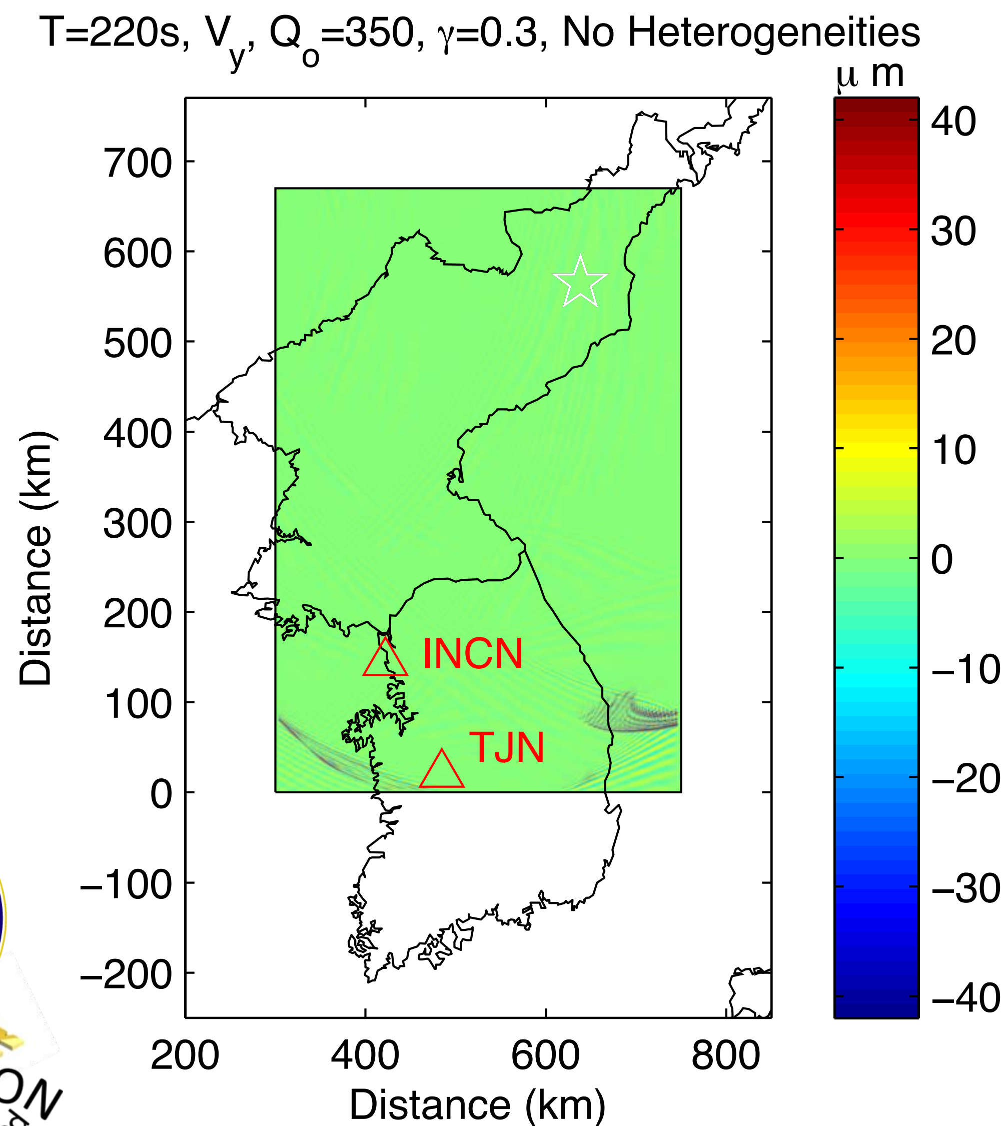
N-S Velocity Snapshot (165s)

$Q(f)=350\ f^{0.3}$

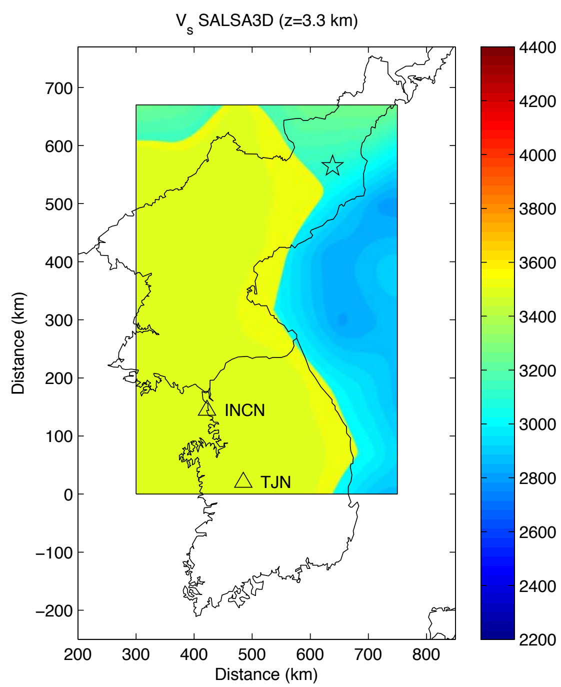


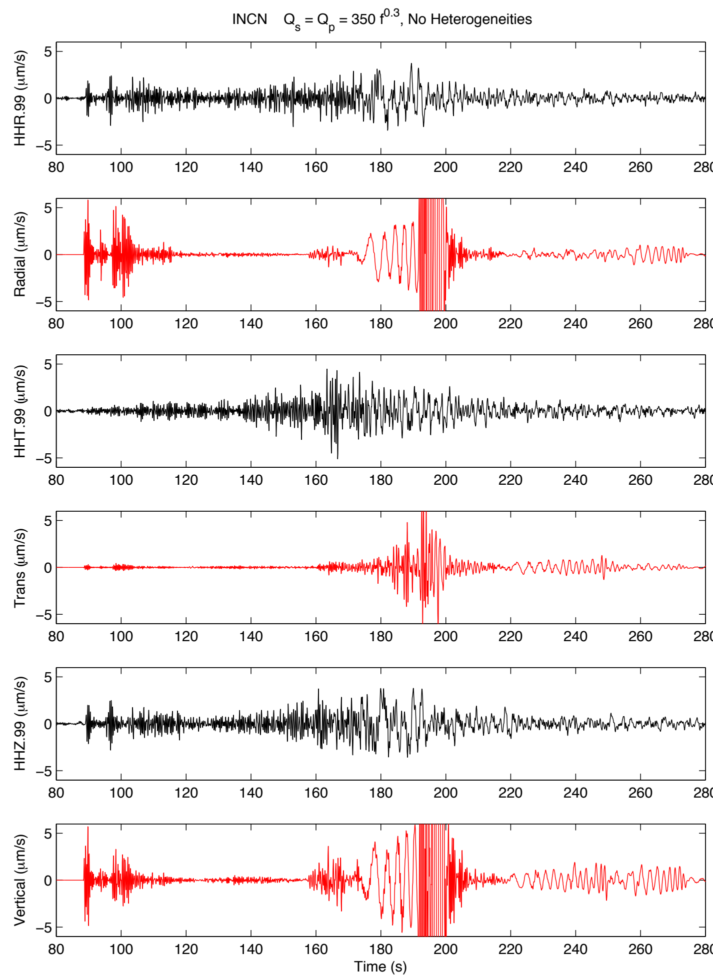
N-S Velocity Snapshot (220s)

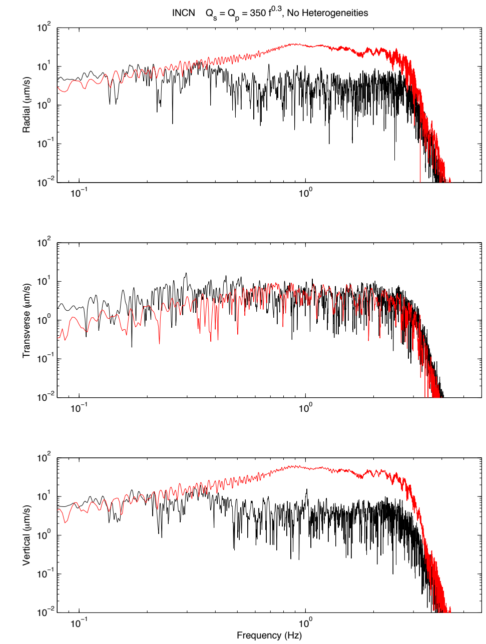
$Q(f)=350\ f^{0.3}$



INCN Waveforms Q(f)=350 $f^{0.3}$ SALSA3D

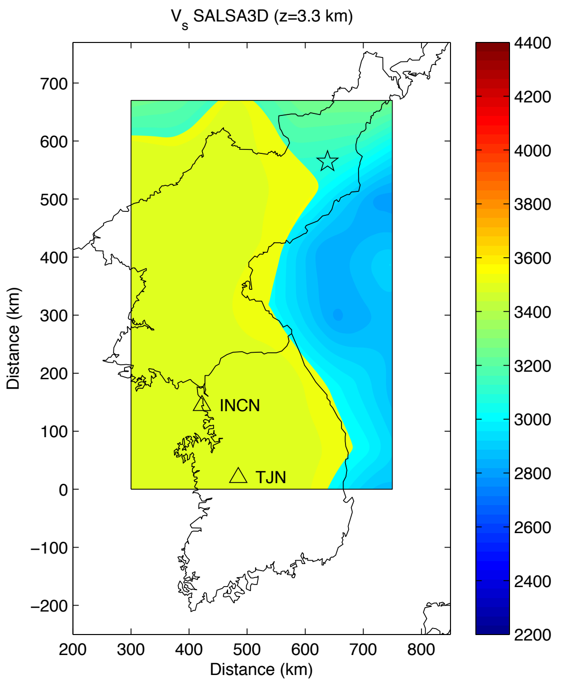


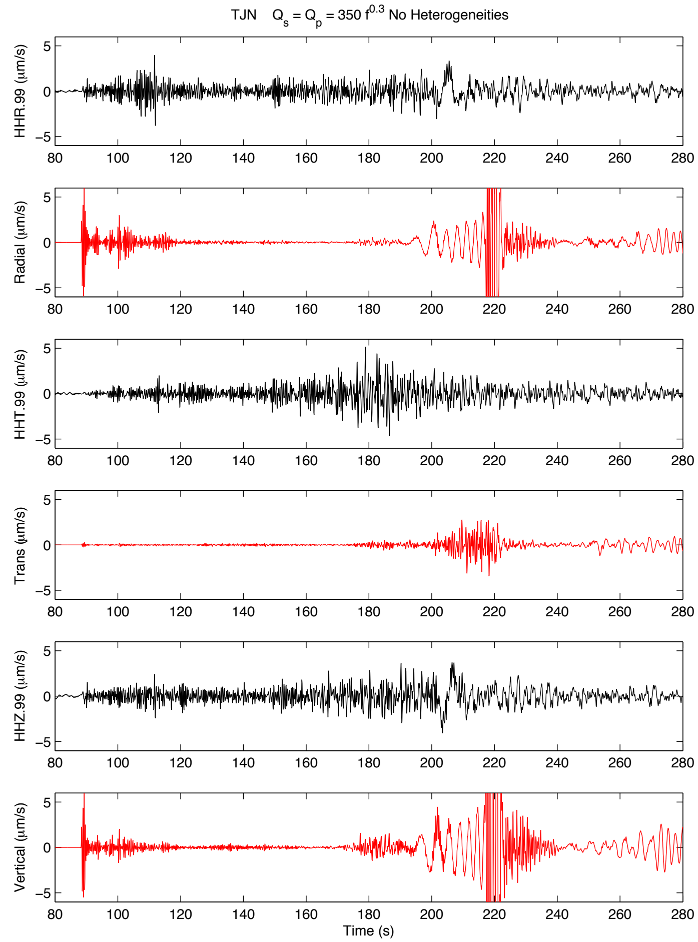


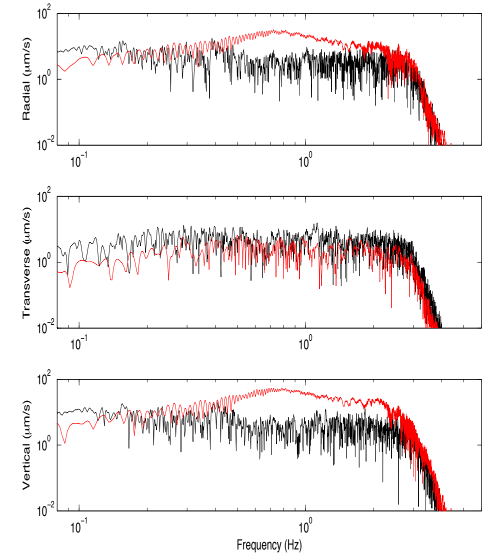


The poor fit indicates that several features of the model are off: 1) initial arrivals are too strong, 2) the Rayleigh Wave is too energetic, and 3) the amount of scattering between the P wave and surface waves is insufficient.

TJN Waveforms Q(f)=350 $f^{0.3}$ SALSA3D

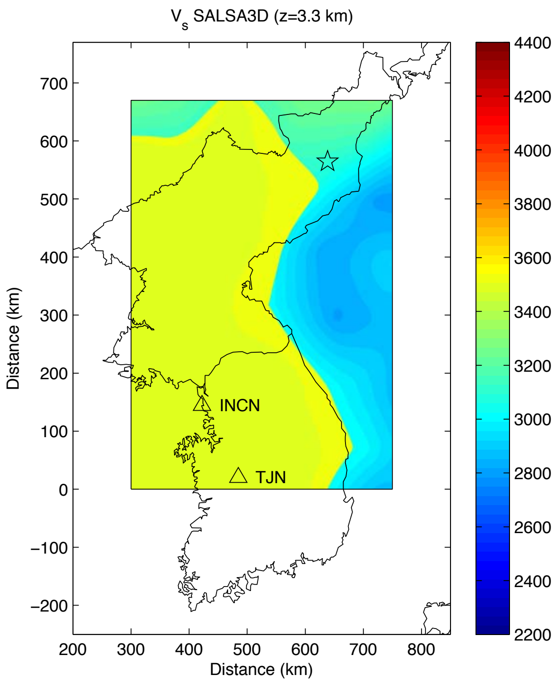


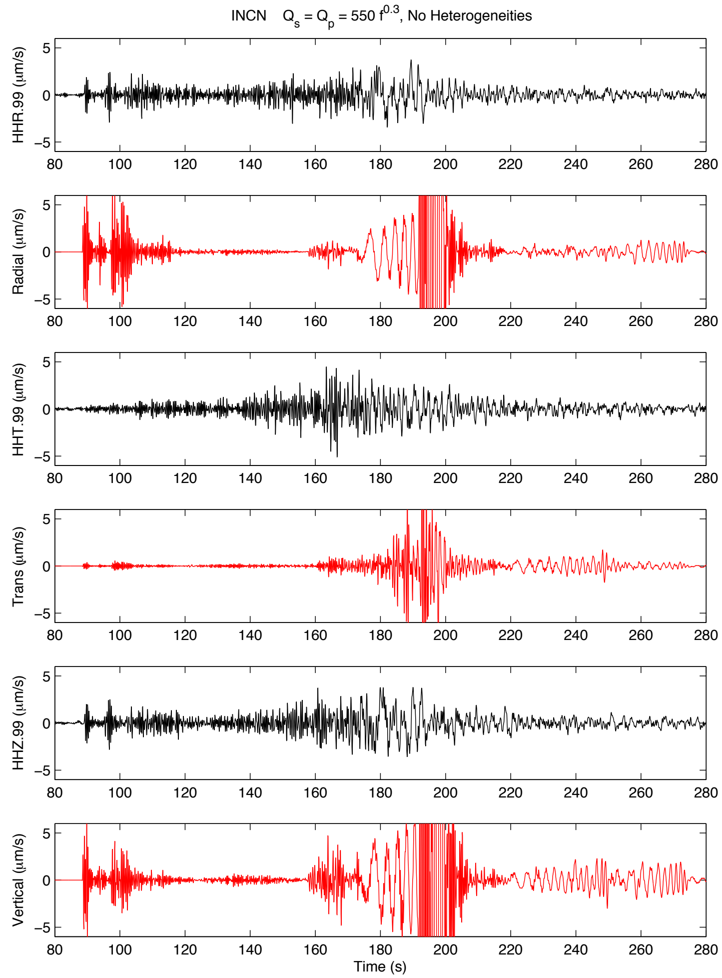


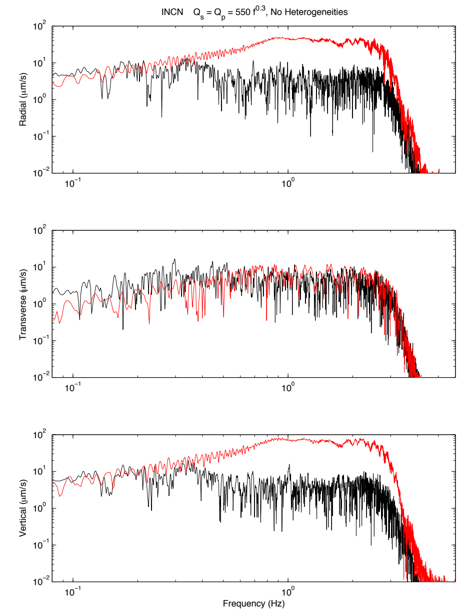


Same story for TJN

TJN Waveforms Q(f)=550 $f^{0.3}$ SALSA3D

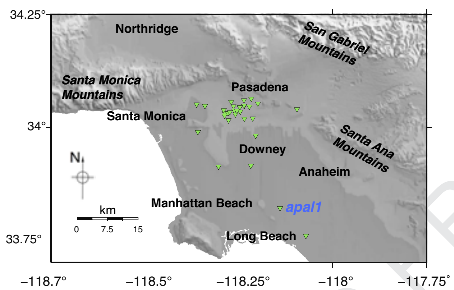




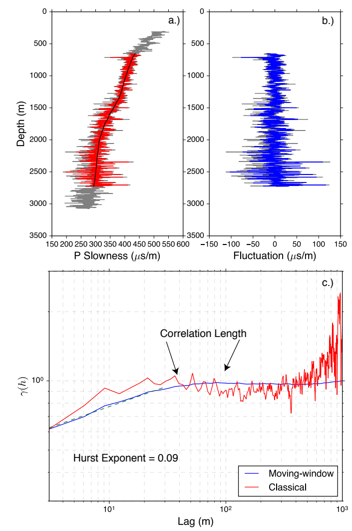


Increasing $Q_s = Q_p$ to 550 worsens the fit.

Introducing Small-scale Heterogeneities



Deep boreholes from the Los Angeles basin suggests Hurst Numbers H~0.1, correlation length a~150 m, (Savran and Olsen, GJI 2016)

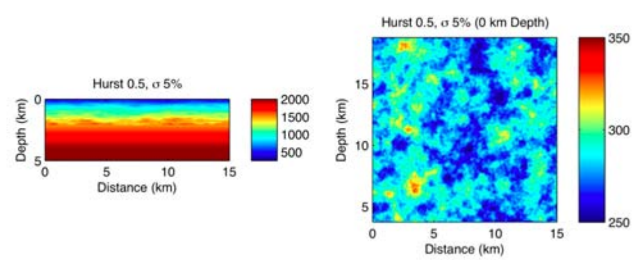


Other studies report a along vertical up to 5-10 km, with a horizontal-vertical anisotropy of ~5

In 3D, a fractal distribution has a high wave-number decay of the power spectrum P(k) as:

$$P(k) = \frac{\sigma^2 (2\sqrt{\pi}a)^E \Gamma(\nu + E/2)}{\Gamma(\nu)(1 + k^2 a^2)^{\nu + E/2}}$$

where ν is the Hurst number, E is the Euclidian dimension, and σ is the standard deviation w/r to the mean



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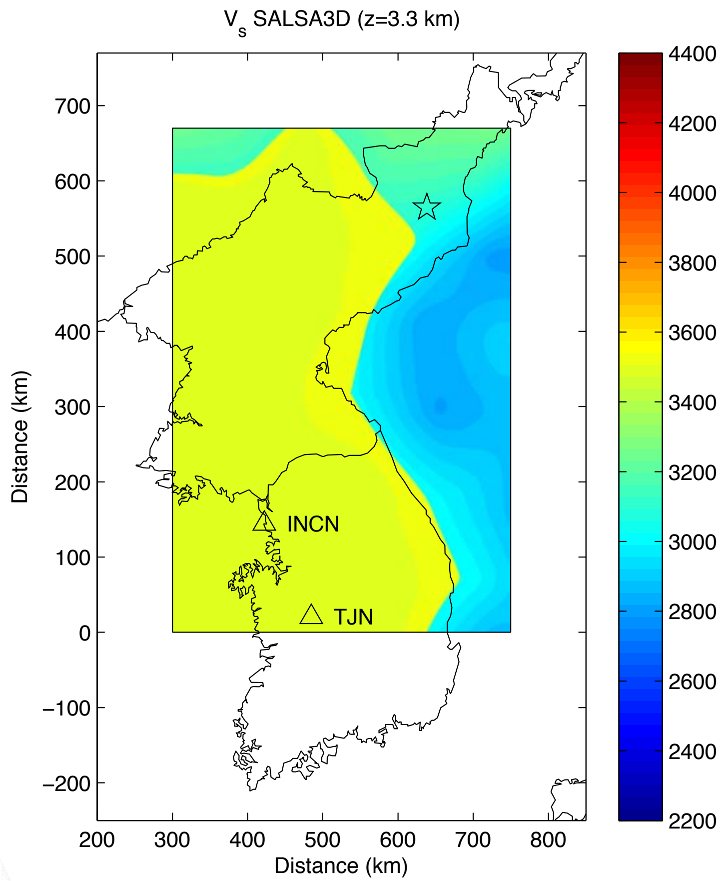
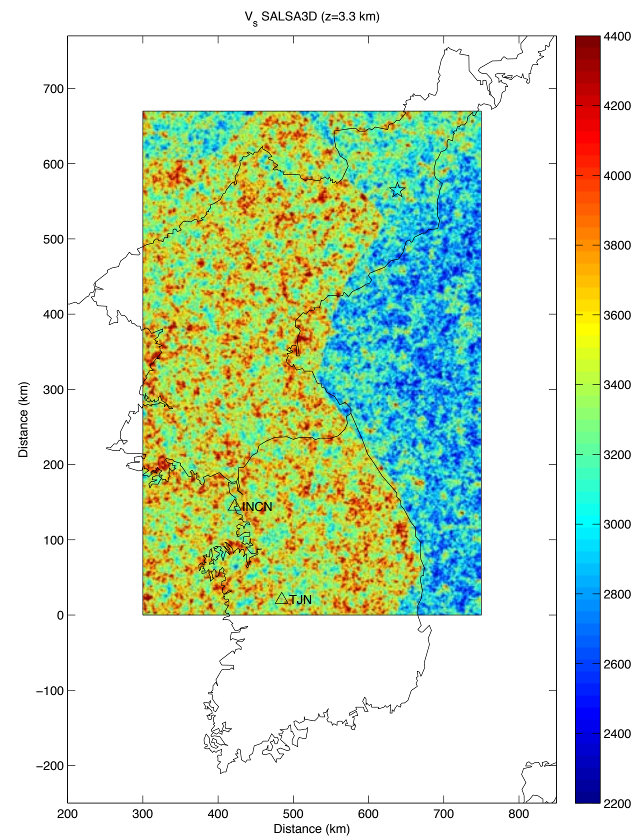
Introducing Small-scale Heterogeneities

Correlation length for SALSA3D appears to 10s-100s of kilometers

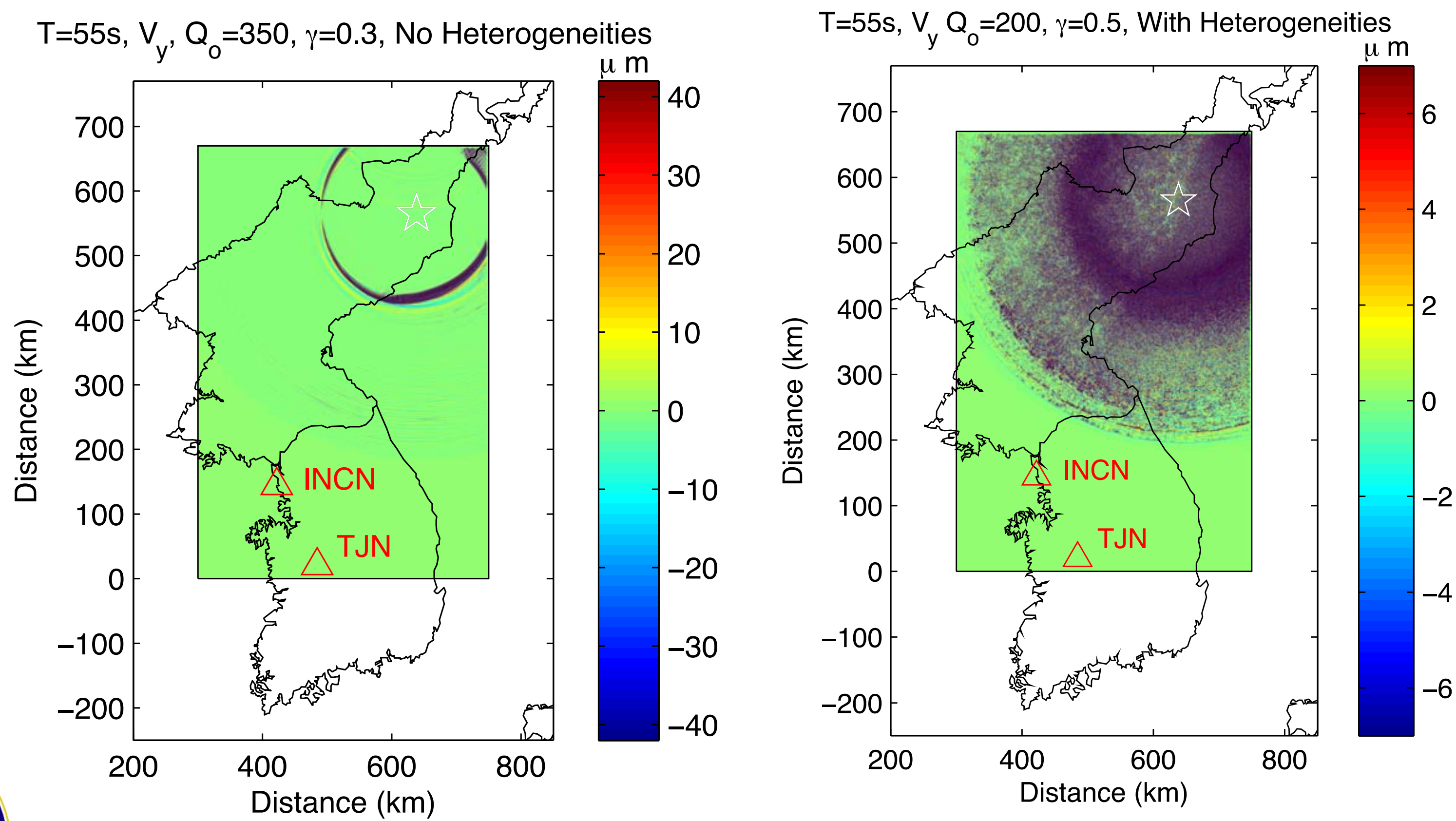
SALSA3D



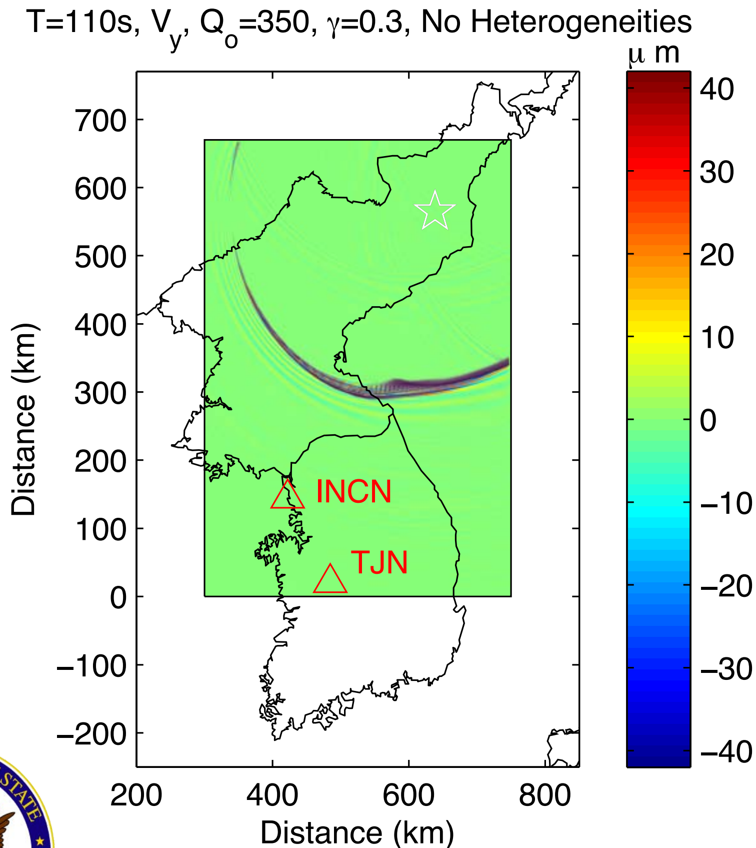
SALSA3D + [H=0.1, a=1000m, σ=10%]

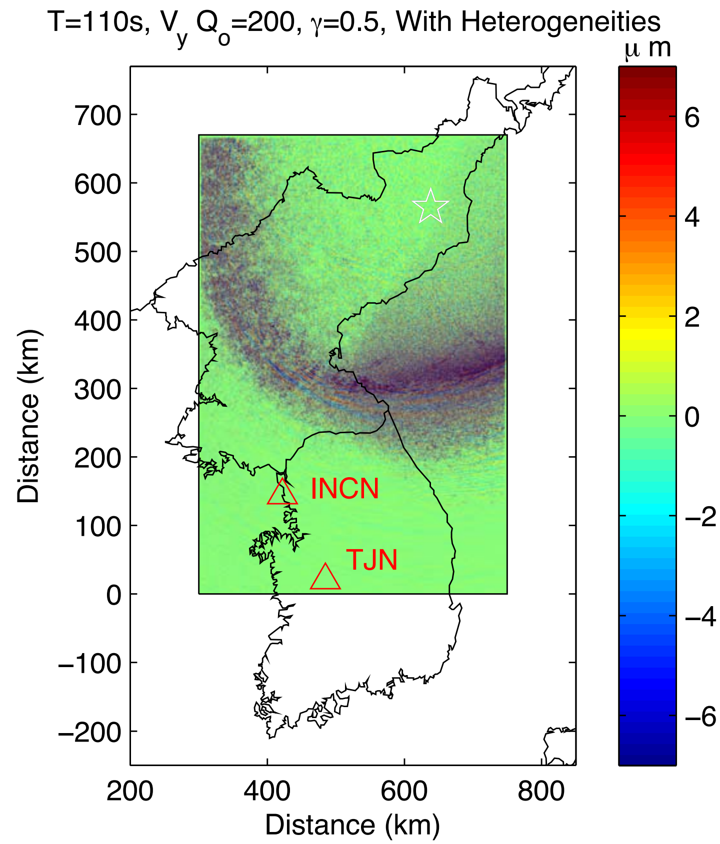


N-S Velocity Snapshots (55 s)

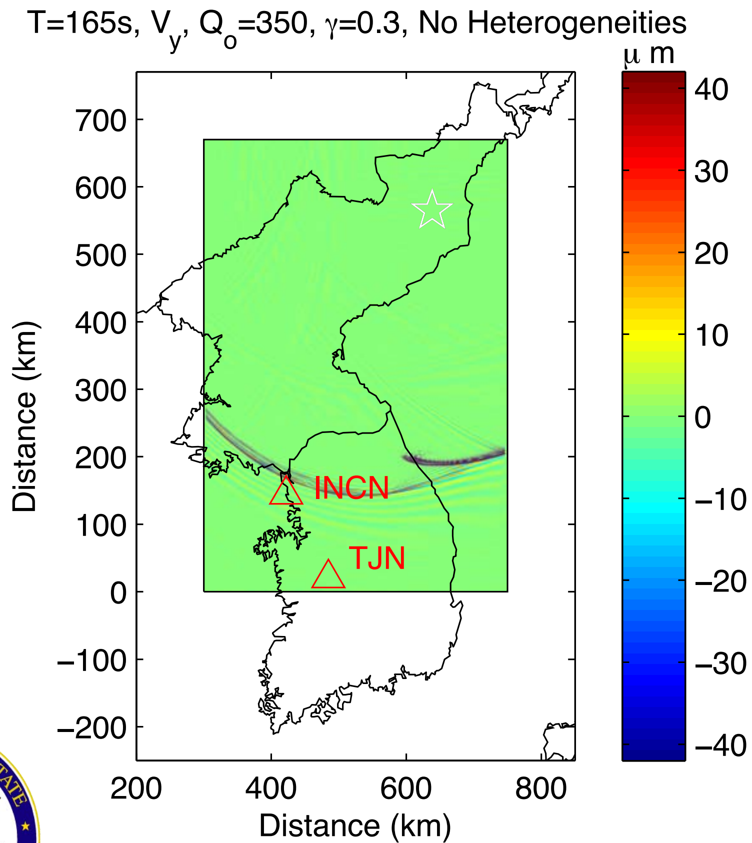


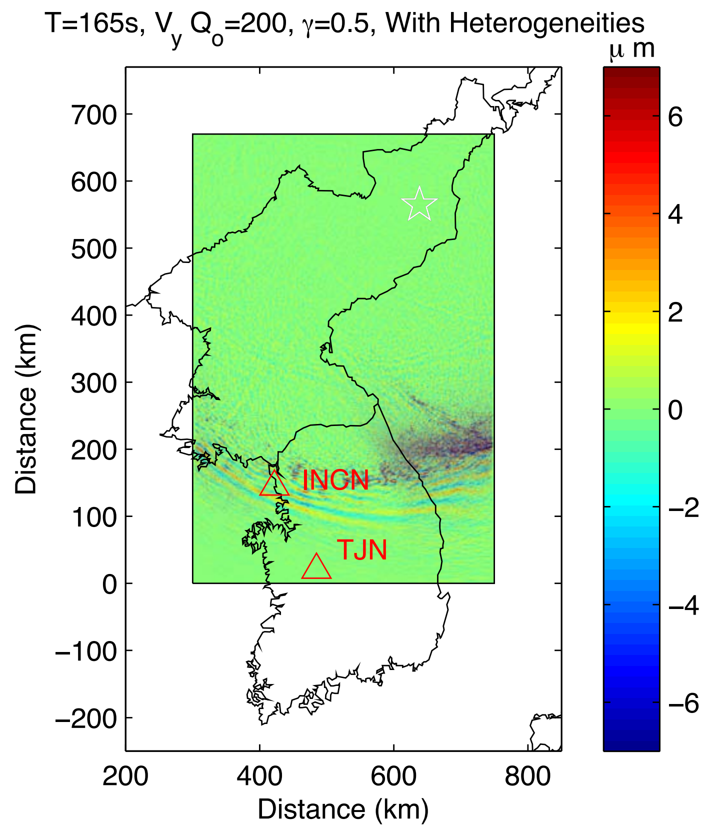
N-S Velocity Snapshots (110 s)



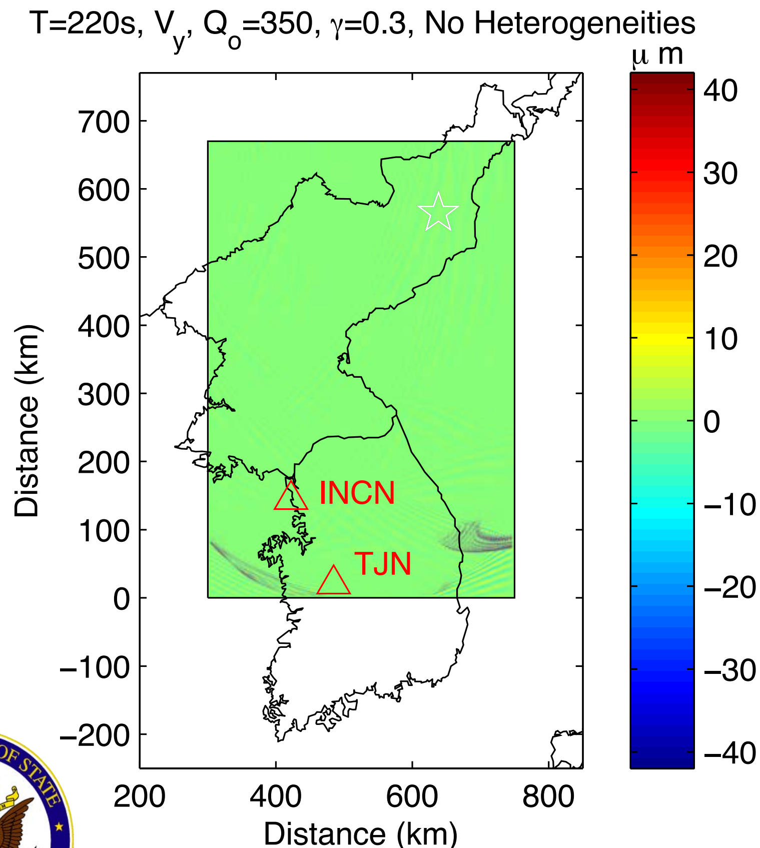


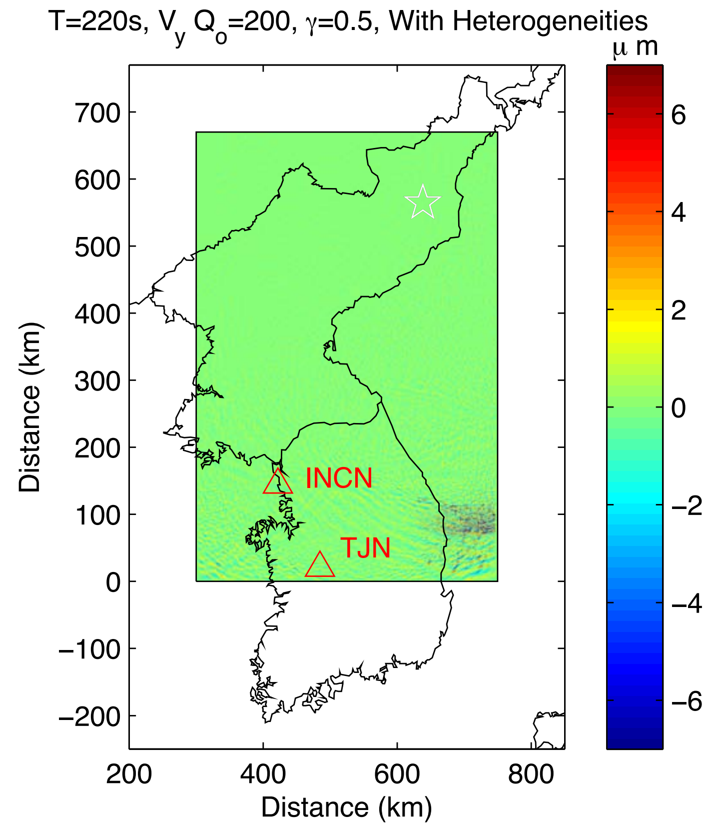
N-S Velocity Snapshots (165 s)





N-S Velocity Snapshots (220 s)





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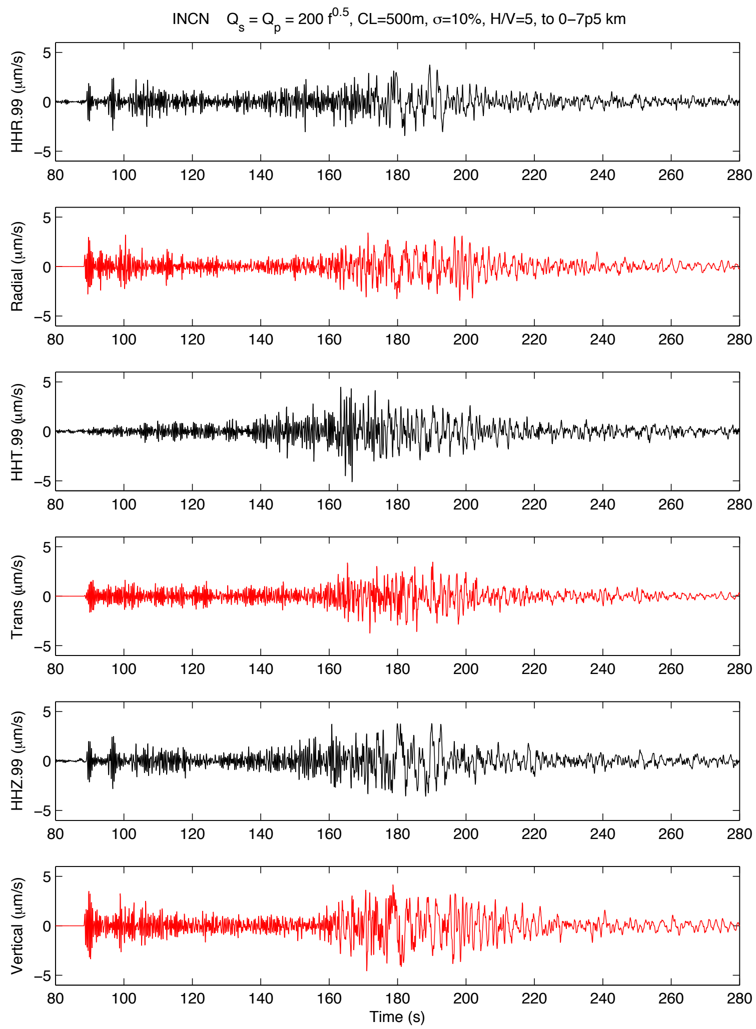
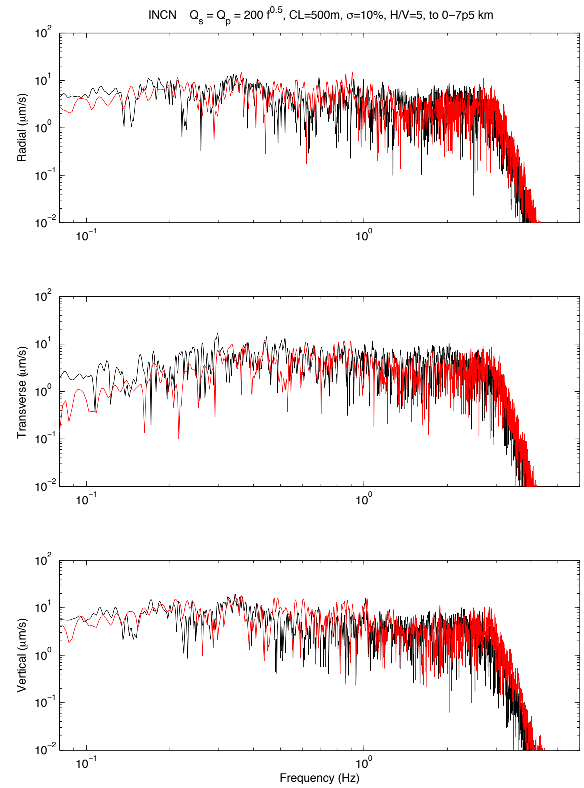
Results at INCN

Optimal parameters after ~25 trial-and-error simulations:

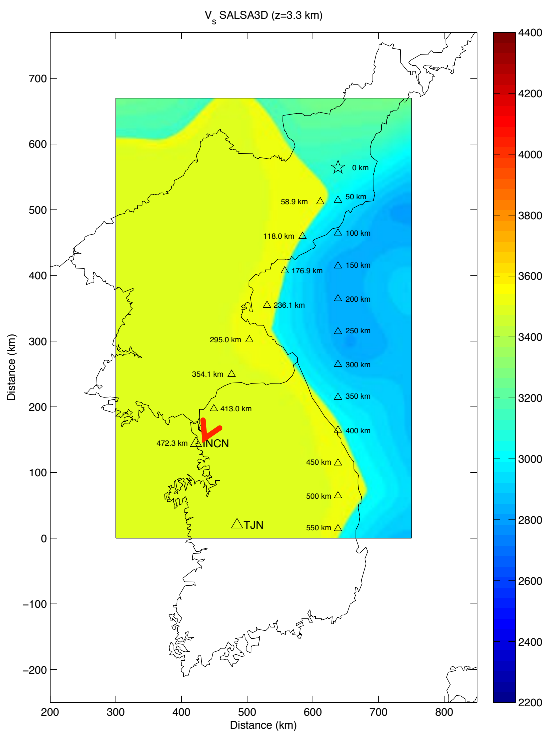
H~0.1
CL_H~5,000m
CL_V~1,000m
σ=10% (top 7.5-10km)
$Q(f)=Q_o f^{\gamma}$
Q_o~200-300
γ~0.3-0.5

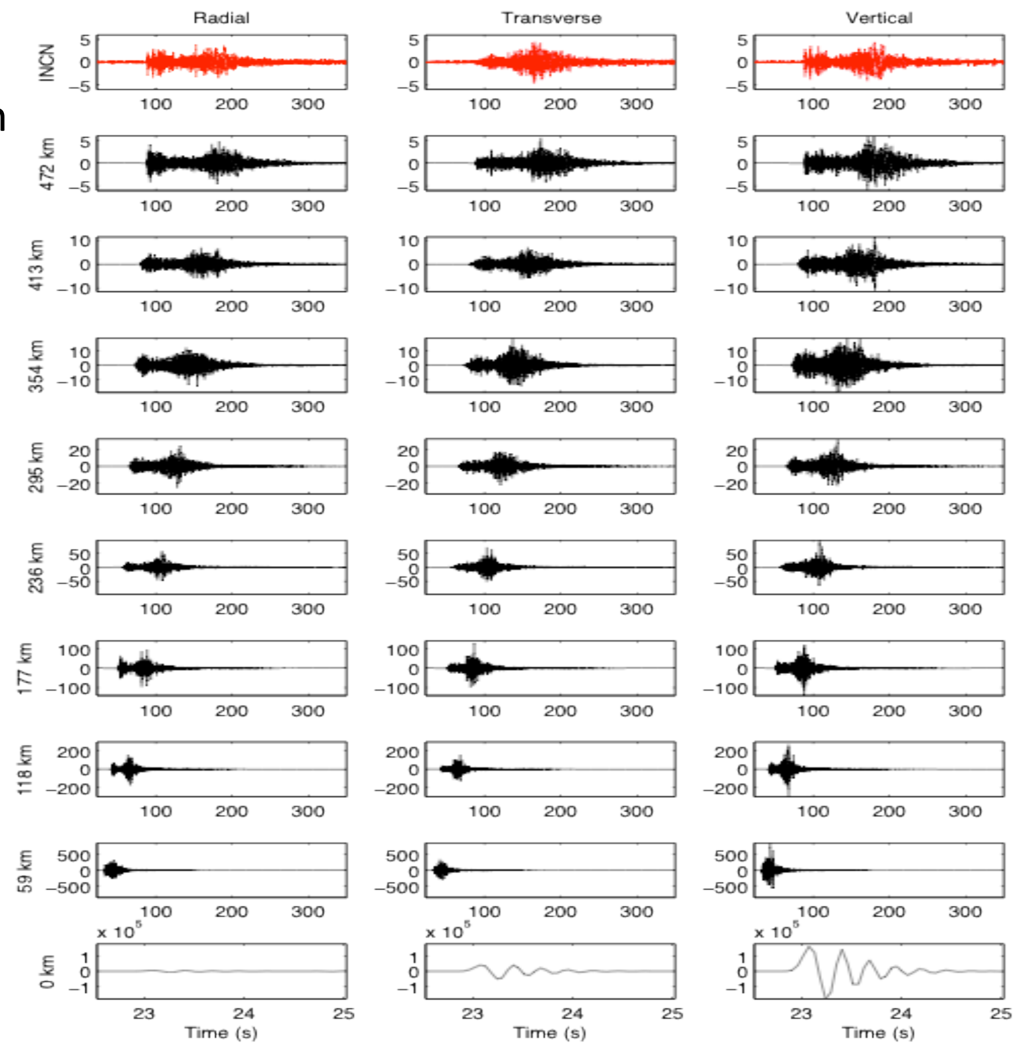




Profiles of Synthetics, From Source to INCN

SALSA3D + CL1000m, H0.1, σ10%, heterogeneities only in upper 10km

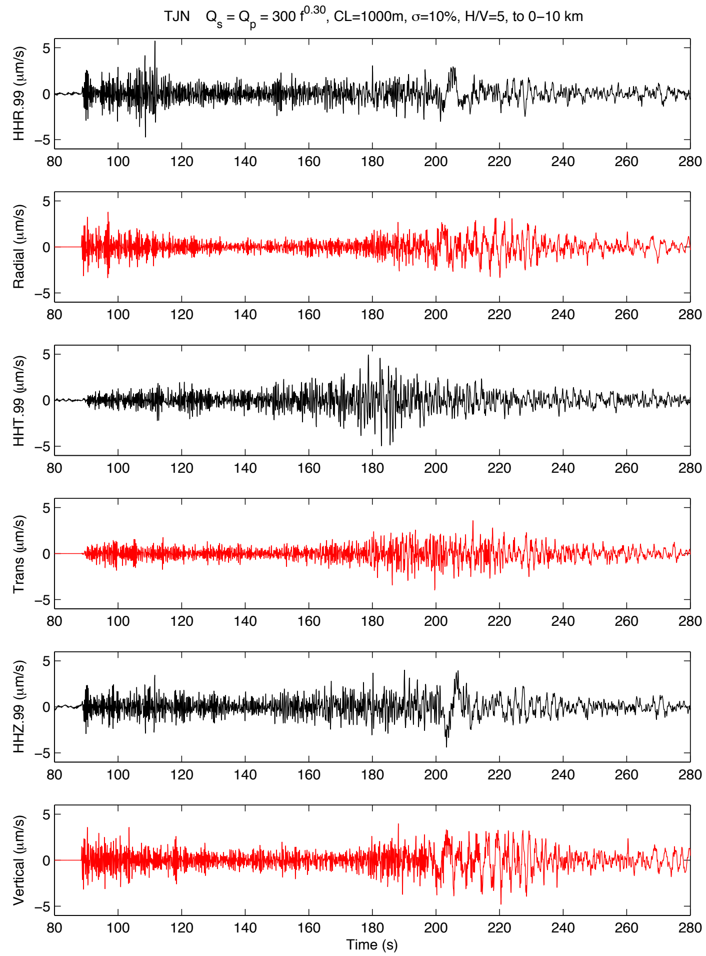


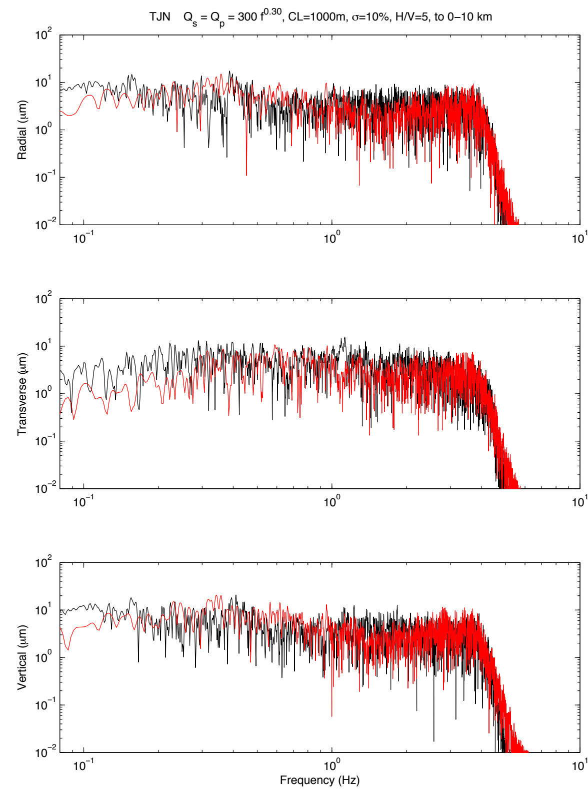


Optimal Result at TJN

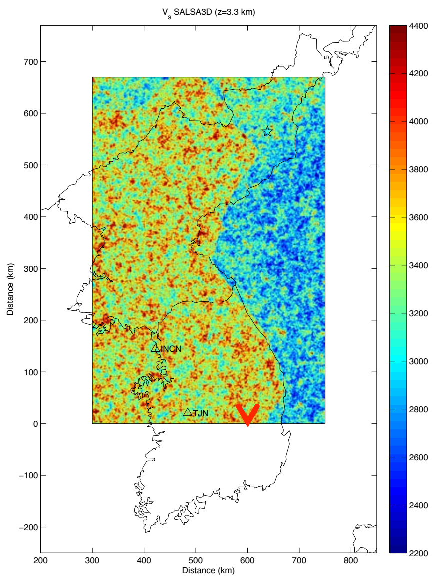
Optimal parameters after ~25 trial-and-error simulations:

H~0.1
CL_H~5,000m
CL_V~1,000m
σ=10% (top 7.5-10km)
$Q(f)=Q_o f^\gamma$
Q_o~200-300
γ~0.3-0.5

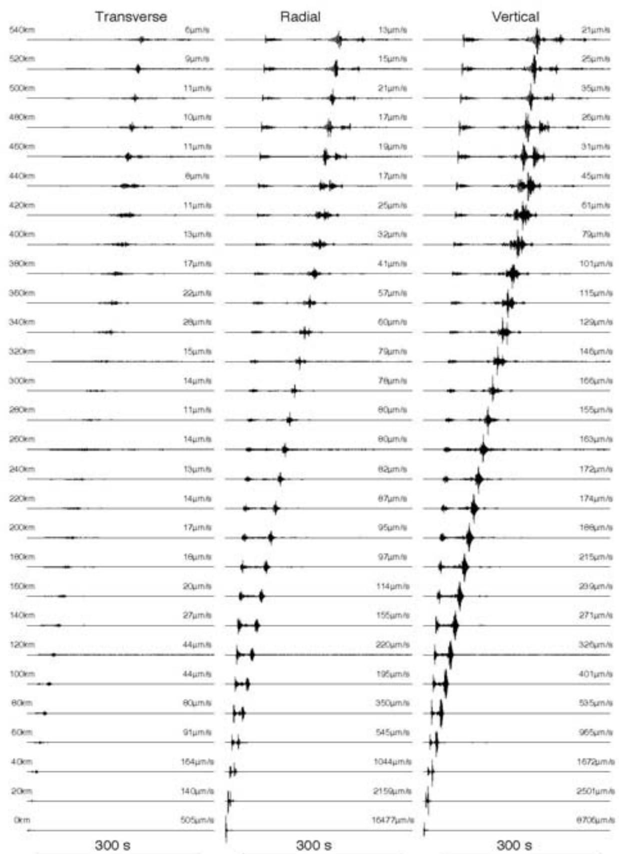




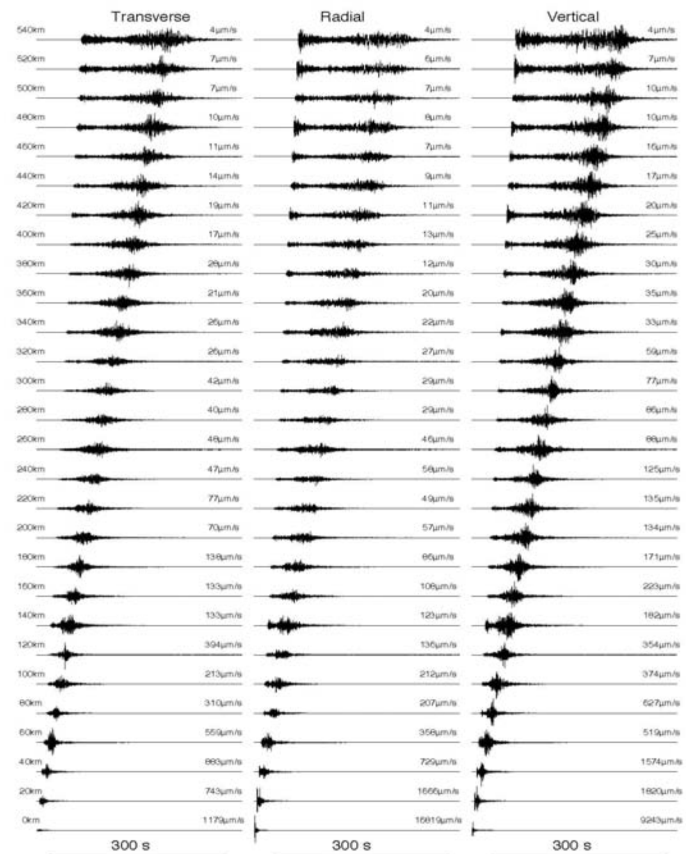
Profiles of Synthetics



SALSA3D



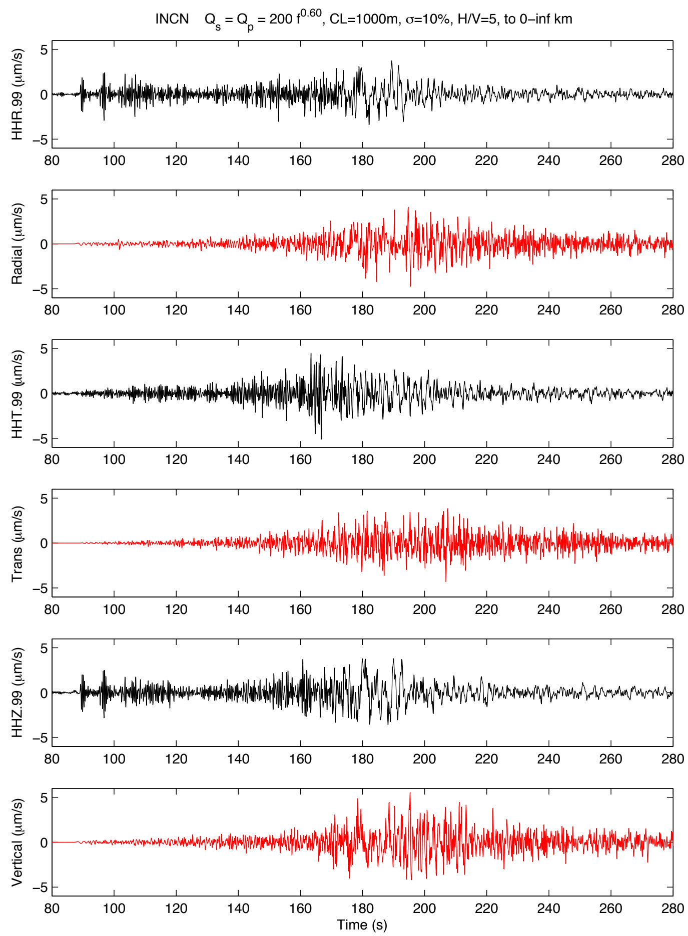
SALSA3D + CL1000m, H0.1, σ10%, upper 10km



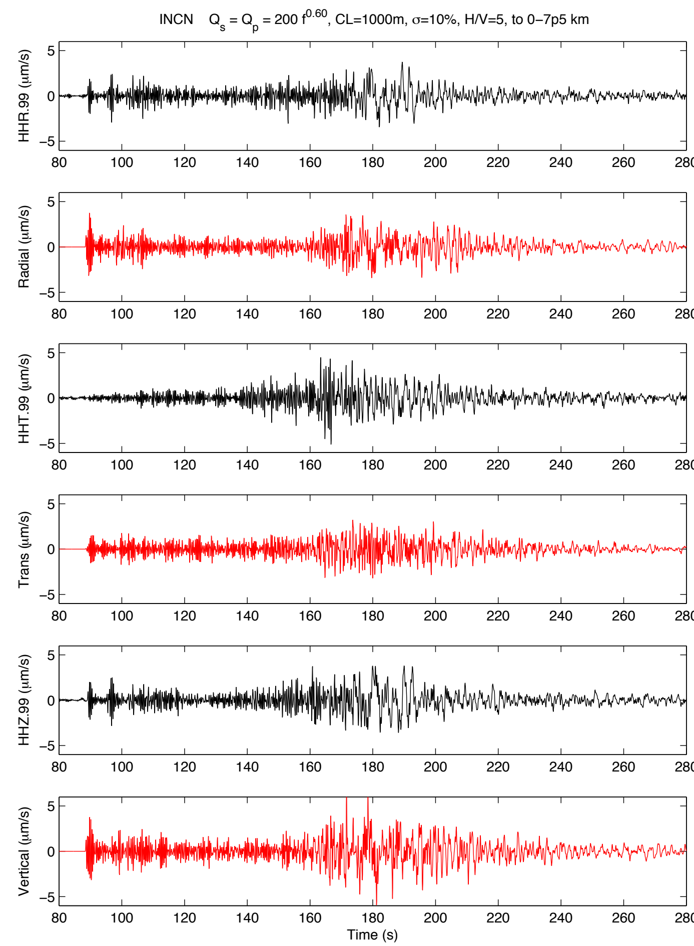
Depth–dependency of Heterogeneities

If small-scale heterogeneities are added to the entire model column, scattering wipes out the initial P waves, in disagreement with data. Thus, the bulk of the scattering appears to be limited to the top 7.5-10 km of the crust

Heterogeneities 0-80 km



Heterogeneities 0-7.5 km



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Summary and Conclusions

- We have run ~25 3D FD simulations of 0-4Hz regional wave propagationwith Q(f) for the 2009 North Korea nuclear explosion and compared to instrument-corrected records at INCN and TJN (500 km+) in South Korea using 2,500 GPUs on the ORNL Titan Supercomputer
- Synthetics in the LANL SALSA3D velocity model contain initial P and surface waves with too large amplitudes and too weak coda in between
- The addition of statistical distributions of small-scale heterogeneities to SALSA3D improves the fit at the 2 stations, with correlation lengths of ~1000m, H=0.1, σ=10%
- The best fits are obtained from scattering limited to the top 7.5-10 km of the crust. Deeper scattering tends to weaken the initial P wave amplitudes too much
- Optimal $Q(f)=Q_o f^\gamma$ with $Q_o=Q_s=Q_p$ ~200-300 and γ=0.3-0.5, apparently with lower Q_o and higher γ toward INCN, and higher Q_o and lower γ toward TJN
- Results demonstrate (for the first time) that state-of-the-art high-frequency 3D wave propagation simulations can reproduce the full records for stations 500km+ from the source, including the S/Love waves and coda on the transverse component, generated by P-S wave scattering in the upper crust
- Surface topography was not needed to obtain the satisfactory regional fits
- In light of conclusions, this pilot project was very much worthwhile funding

Why conduct the project?

- In order to examine whether state-of-the-art 3D finite-difference simulations can reproduce instrument-corrected records from nuclear explosions at regional distances (500 km +) using highly scalable codes on the fastest supercomputers
- The successful prediction of the full regional-distance wave forms will significantly improve the ability to detect, verify and characterize nuclear explosions, important objectives of Arms Control

How Did the PI execute the project?

- Dr. Kim Olsen (PI, SDSU) generated all statistical distributions of small-scale heterogeneities in the crust on the ORNL Titan supercomputer, and carried out all 3D regional simulations, the post processing and waveform comparisons
- Milestones met (examine whether regional waveforms for shallow explosions could be reproduced, and identification of associated crustal scattering and frequency-dependent attenuation parameters).
- Good collaboration with LANL on 3D model and waveform records

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What is new and innovative about the project?

- To my knowledge, this is the first time that the full high-frequency wave forms recorded from nuclear explosions at regional distances have been reproduced for timing, amplitudes and coda duration using state-of-the-art deterministic simulations on GPU-enabled supercomputers
- Simulations include physics-based Q(f) and crustal scattering, which are shown to be essential components needed to reproduce the high-frequency waveforms

What are the likely next steps in the project development?

- The encouraging results on modeling shallow explosions at regional scale will be used to generate averages of simulation ensembles of the statistical distributions of small-scale heterogeneities, in order to address the variation in the high-frequency synthetic time histories (nonuniqueness)
- Tests with depth-dependent strength of heterogeneities
- Additional North Korea nuclear explosions will be modeled
- The effect of the water column and continental shelf in the Sea of Japan will be studied, w/r to L_g blockage/leakage
- Validation of simulations for Japanese records
- Next steps will be supported by a pending award from ARFL

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Division of Work and Acknowledgements

- Dr. Kim Olsen (PI, SDSU) carried out the simulations
- The SALSA3D crustal model and instrument-corrected data for TJN and INCN were provided by LANL (S. Phillips and M. Begnaud)
- The computational resources were provided by ORNL at the Titan supercomputer
- Financial Support provided by US State Dept

Company Propriety

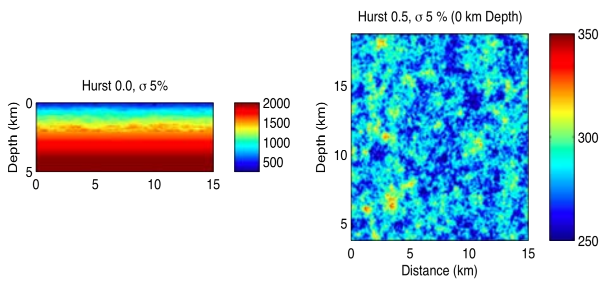
BAA Number: BAA-2014-DOS-AVC-VTRDN

Date: 06/15/2014

Document ID: KBO-1

Kim Olsen

Proposal Title: Regional Wave Propagation Including Small-Scale heterogeneities and Q(f)



((left) Vertical cross-section and (right) horizontal slice at z=0 of an S-wave model, for Hurst=0 and 5% σ)

Verification Technology R&D Need Objective

A more complete theoretical understanding of the impact of geology, soil type on regional seismic signals.

Technical Approach: **Finite difference simulations in 3D layered and heterogeneous media with Q(f) for shallow explosive sources, comparison to records from nuclear explosions in central Asia, and P-S wave conversion analysis.**

Phase 1 Tasks: Oct 1 2014- Mar 31 2015: Generation of earth models, FD simulations, parameter tuning, gather UNE data.

Phase 2 Tasks: Apr 1 – Sept 30 2015 FD simulations, gather UNE data, compare to synthetics, P-S wave conversion analysis, write final report.

Deliverables: Parameters of optimal statistical distributions of crustal heterogeneities and frequency-dependent anelastic attenuation, comparison of simulated and recorded UNEs, and regional P-S conversion analysis for central Asia.

Cost: $36,950

Schedule: 12-mo, starting October 1 2014

Proposer(s)/Partner(s): Kim Olsen

Principal Investigator(s): Same

Operational and Performance Capability Summary

We will investigate the effect of small-scale heterogeneities and Q_s(f) and Q_p(f) on regional seismic signals (0-1000 km, 0-4 Hz) using a parallel 3D visco-elastic staggered-grid finite difference method. Using shallow underground nuclear explosive sources (UNEs) and associated recorded data we will determine the parameterization of Q(f) and statistical distributions of small-scale heterogeneities (Hurst number, strength, correlation length) that can reproduce signal durations and the presence of S-waves in the records.

Corporate Contact Information

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Company Propriety

Effects of Surface Topography

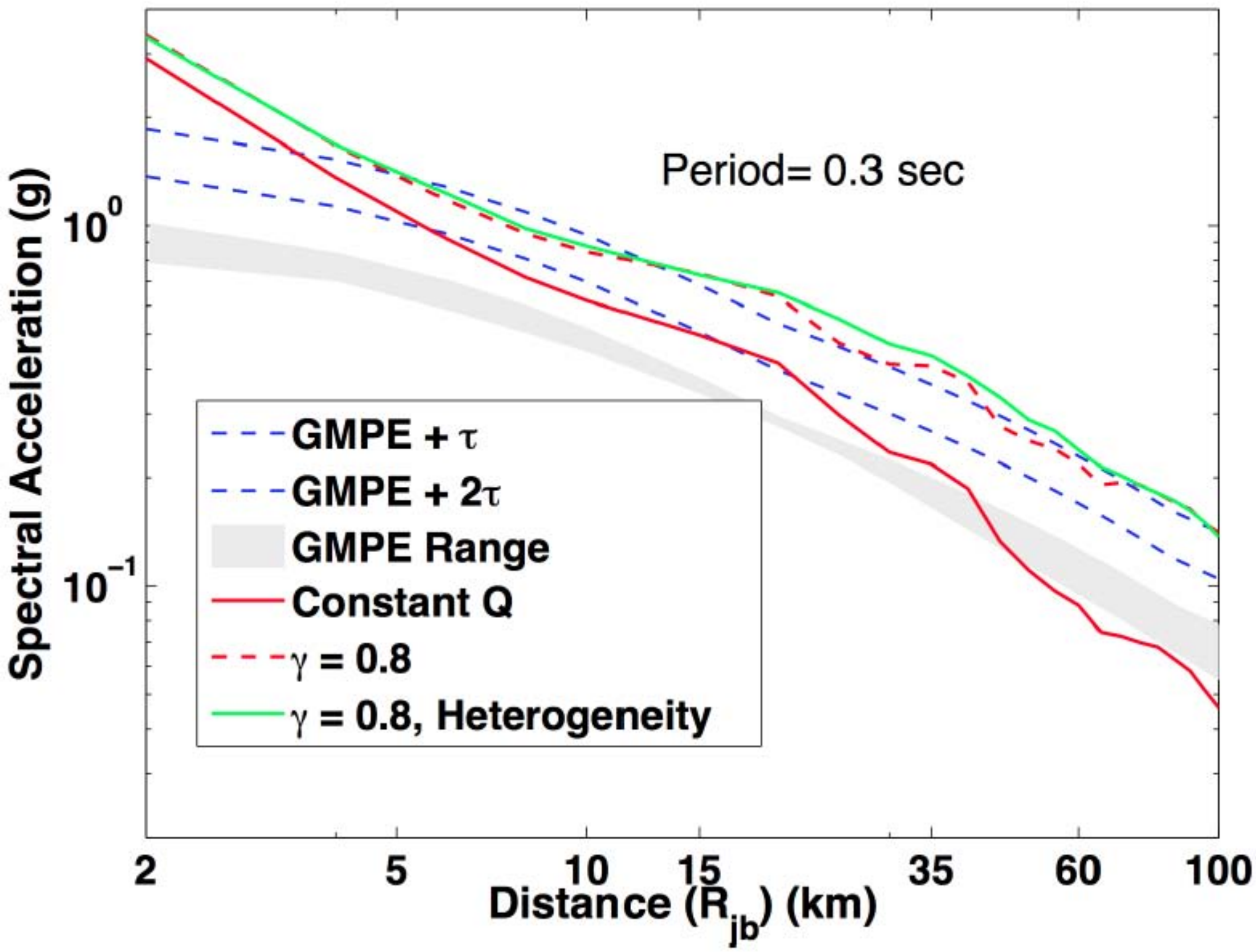
The simulations revealed that scattering due to irregular topography is significant only near the station and thus the topographic scattering effects do not accumulate as seismic waves propagate over long distances (~12% in SW Japan).

- Takemura, S., T. Furumura, and T. Maeda (2015). Scattering of high-frequency seismic waves caused by irregular surface topography and small-scale velocity inhomogeneity, *Geophys. Jour. Int.* **201**, 459-474.

VERIFICATION Assets Fund

SAN DIEGO STATE UNIVERSITY

Example of Q(f)



Results at INCN

H~0.1
CL_H~750m
CL_V~150m
σ=10% (top 7.5km)

Rayleigh Wave too energetic