



Data analysis and simulations of the Source Physics Experiments (SPE): impact on explosion discrimination & monitoring

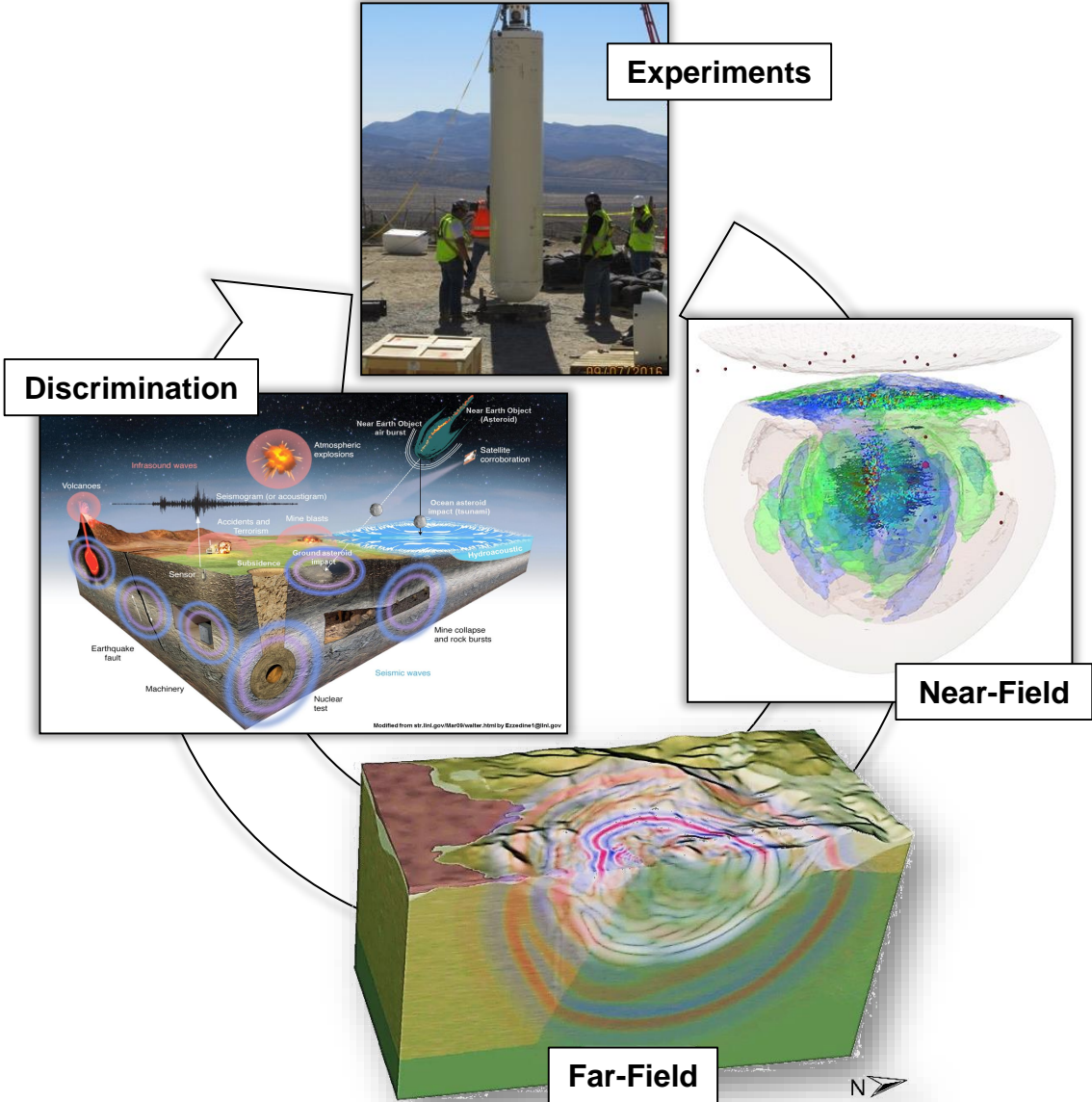
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Outline

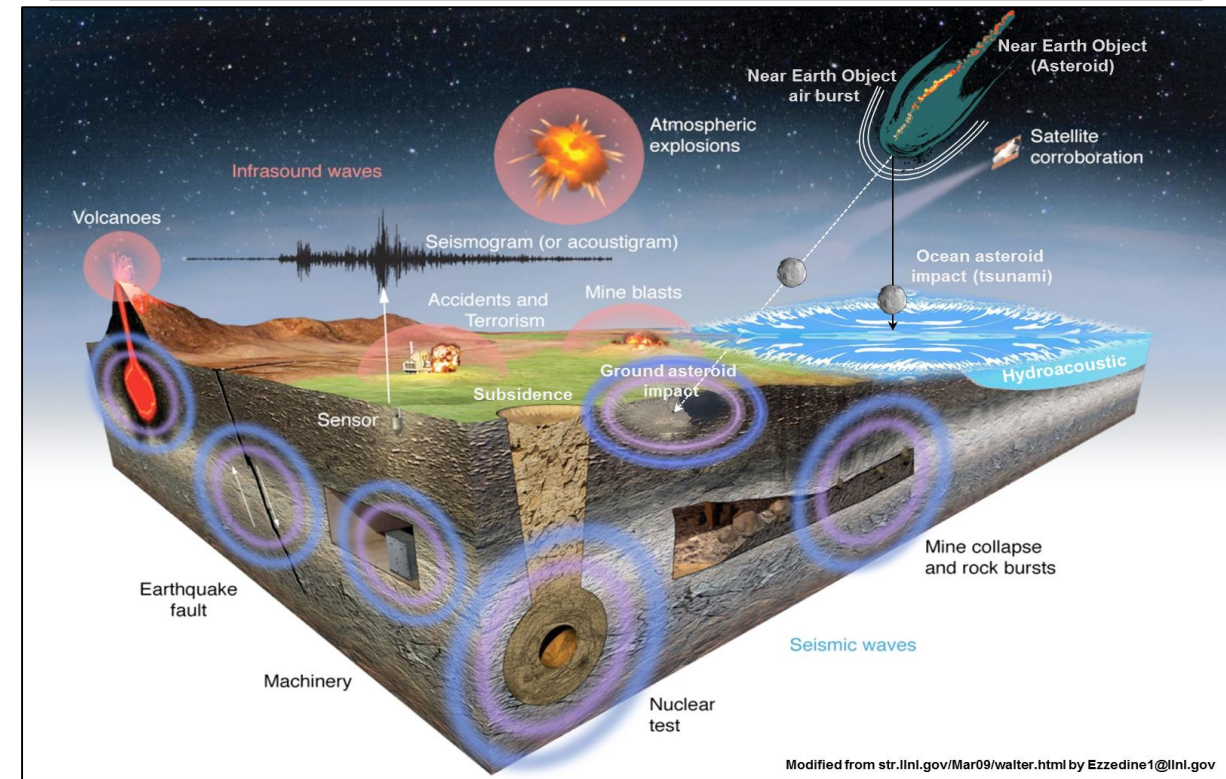
- Motivations
- SPE/DAG Experiments
- SPE Modeling framework
- Near/Far-Field observations & simulations
- Implications for source discrimination
- Summary



Motivation of current efforts: Discriminate between anthropogenic, natural & nuclear sources

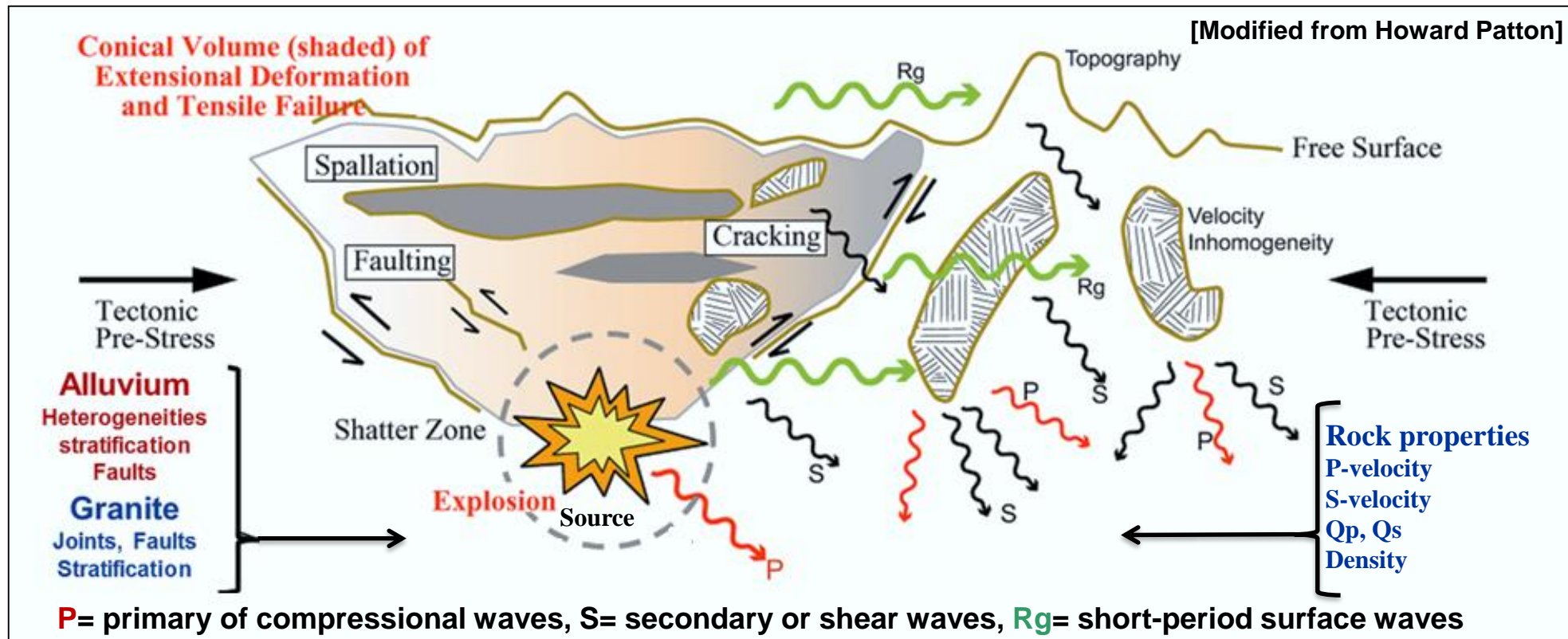
- NRC released in 03/12 a report on CTBT technical issues for USA:
 - Finding 2-4: “Technical capabilities for seismic monitoring have improved substantially in the past decade...”
 - Finding 2-6: “Seismic technologies for nuclear monitoring have the potential to improve event detection, location, and identification substantially over the next years to decades.”
- **Recommendation 2-4: “The United States should renew and sustain investment in seismic R&D efforts to reap the rewards of ... source models ... to enhance underground explosion monitoring ...”**
- **NEED: capability to predict observed signals from an arbitrary source to arbitrary receivers**
 - Understand shear motion generation
 - Build source models that predicts P- & S- waves (end-to-end)
 - Assess geological and physical uncertainty on earth response
 - Discriminate between sources for monitoring
- **NAS’s 2006: Computational seismology has entered a new era**
 - Focused efforts to develop validated documented software for seismological computations should be supported, with special emphasis on HPC
 - Education of seismologists in HPC
 - Collaborations between seismologists & CSE should be strengthened
 - Infrastructure for archiving, disseminating, and processing large volumes of seismological data should be expanded.

Spatiotemporal scales and real-time data require HPC & big data storage



Cutaway view depicting many of the different disturbances recorded by sensors worldwide. Sources of disturbances include: volcanic eruptions, earthquakes, machinery vibrations, nuclear tests, mining and rock bursts and blasts, terrorist acts, atmospheric explosions, and asteroid ground and ocean impacts. [Modified from William Walter]

Near- & Far-field processes: We are dealing with very daunting and complex non-linear & linear phenomena

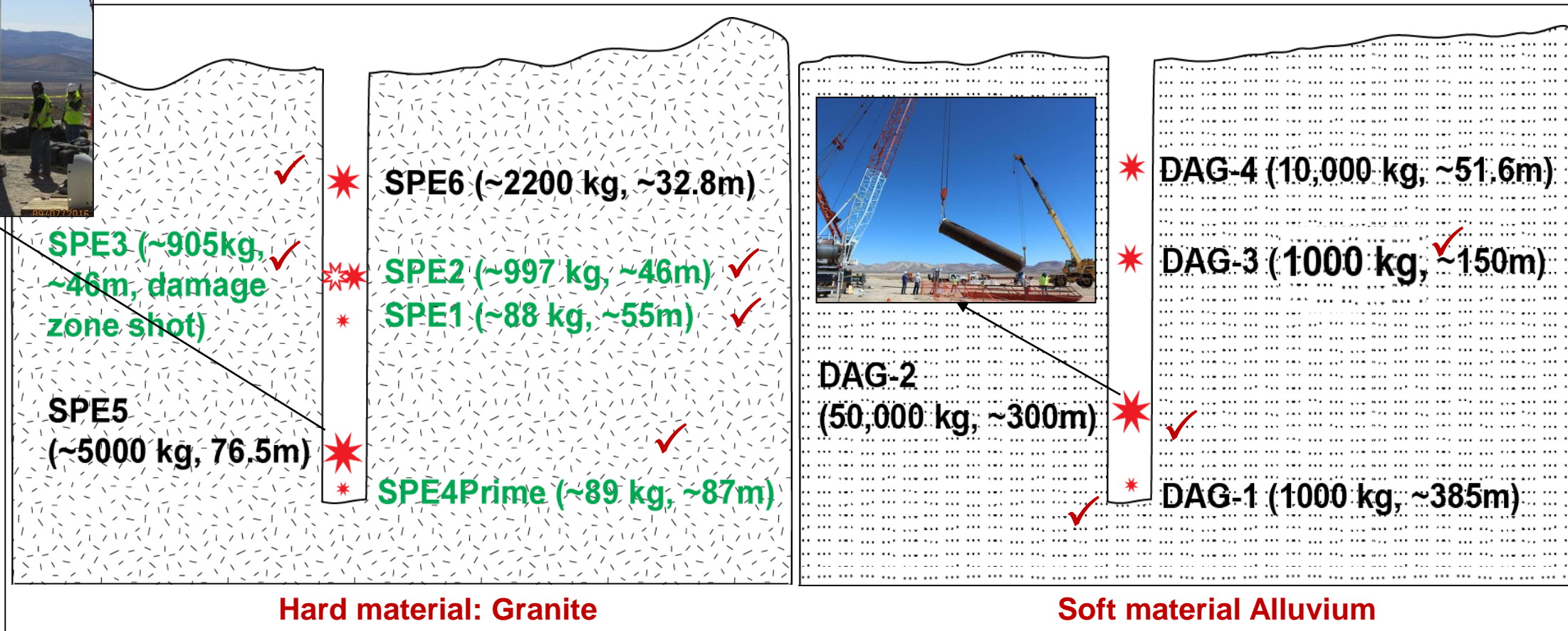


Far-field observations = Source Region Effects + Free Surface Effects + Path Effects
(monitoring distances) = (Rock fabric & properties) + (Spall, damage) + (Conversions)

Our goal is to understand the genesis of shear motions in jointed media (granite) and porous media (alluvium) using state-of-the-art HPC numerical models and data obtained from the Source Physics Experiments conducted at NNSS.

The Multi-Institutional Source Physics Experiments (SPE) Phase I (Granite) vs. Phase II (Alluvium)

SPE initially focuses on granite, a relatively strong media with foreign analogs, and where there are still unexplained results from U.S. 1960's tests – site of 3 nuclear tests.



SPE Phase II focuses on dry alluvium: no pre-existing joints and a relatively weak media with foreign analogs and a natural reduction of seismic signals by up to an order of magnitude (hence shots are an order of magnitude larger).

There 9 nuclear tests within 1 km of emplacement hole which is 96" diameter, 1400' deep drilled in 1983

Building Block: Structural, geomechanical & geophysical characterization of uncertainties

SPE Phase I (SPE) site characteristics

← VS →

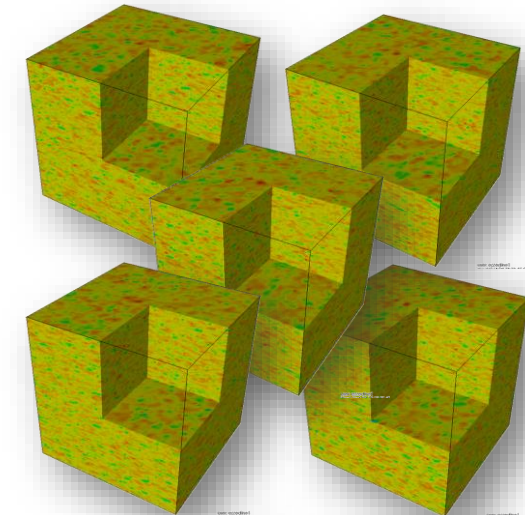
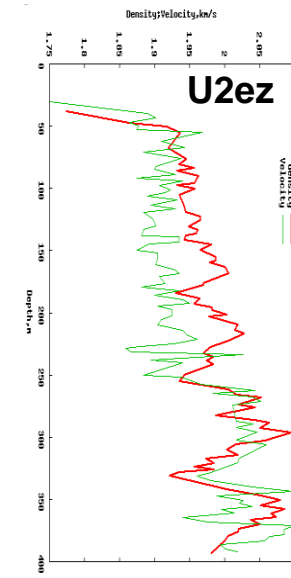
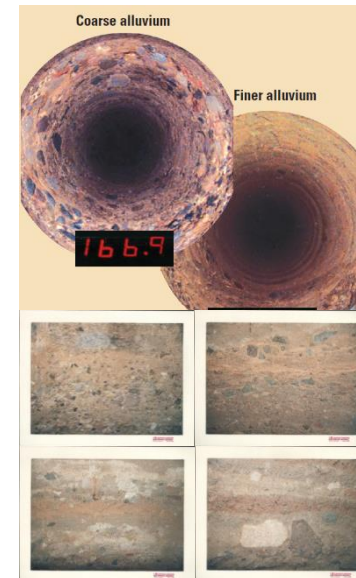
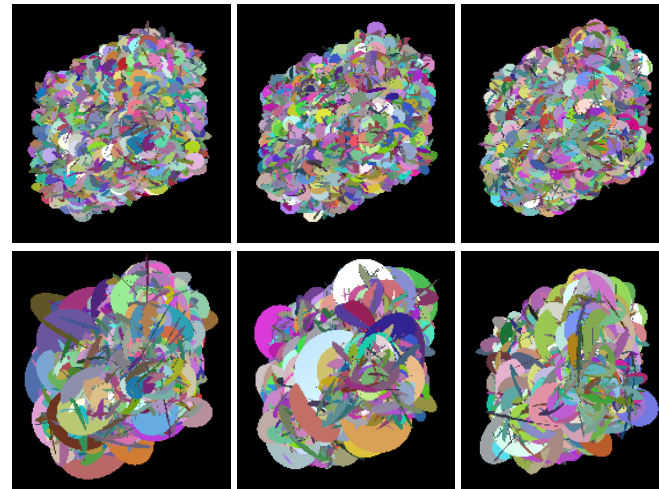
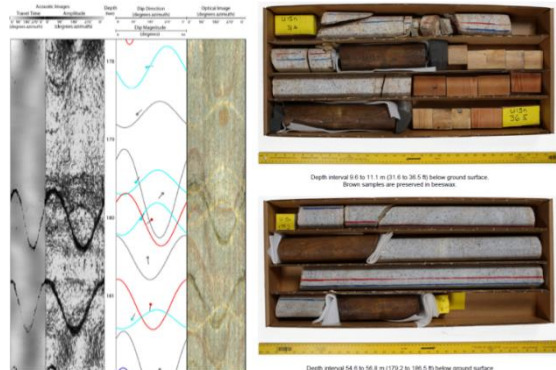
SPE Phase II (DAG) site characteristics

➤ Granite

- Fractures discontinuities
- Fracture size
- Density
- Orientation...
- Spatial variability of properties

➤ Alluvium

- Porous inclusions
- Inclusion size
- Connectivity (continuity)
- Stratification...
- Spatial variability of properties



SPE I, geological observations

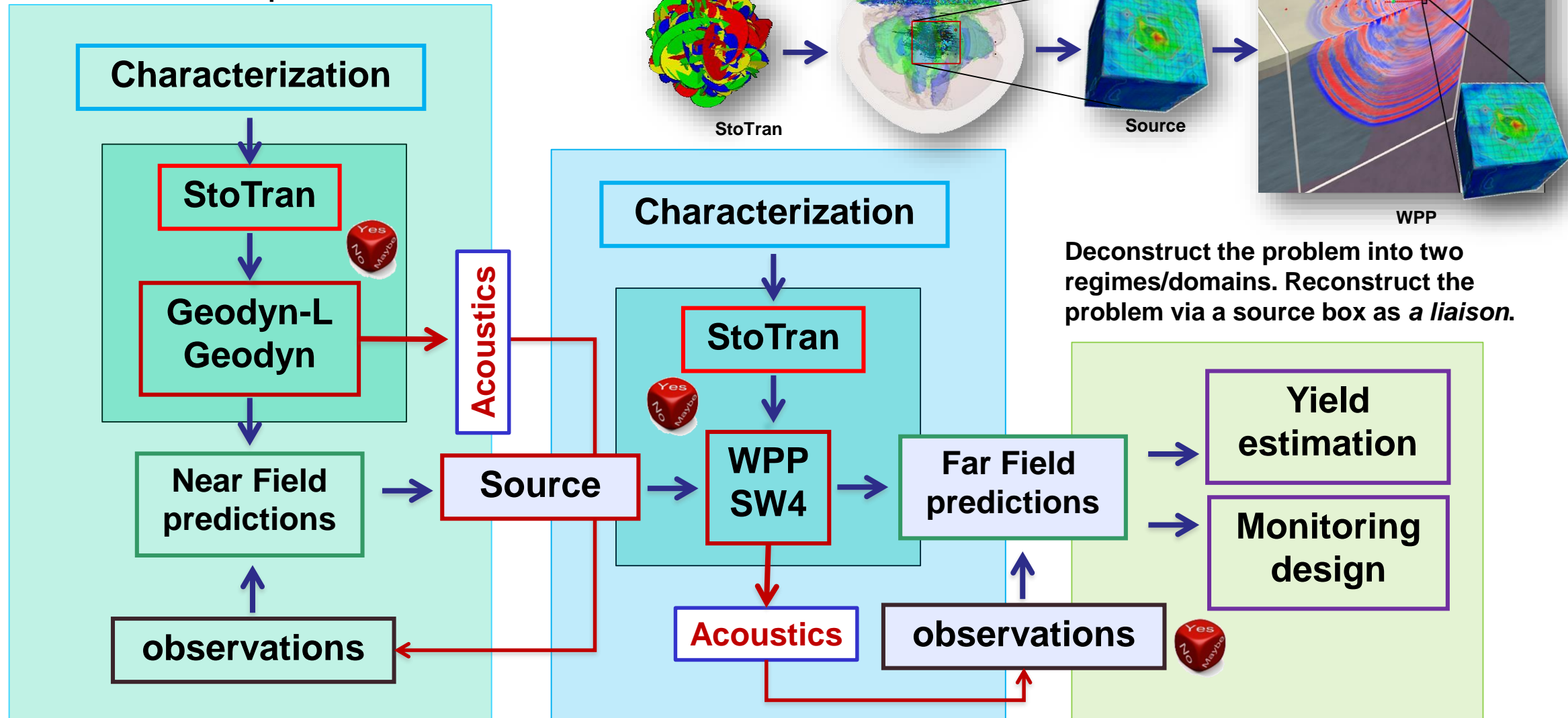
Synthetic fractured (jointed) media

SPE II, Legacy U2EZ observations

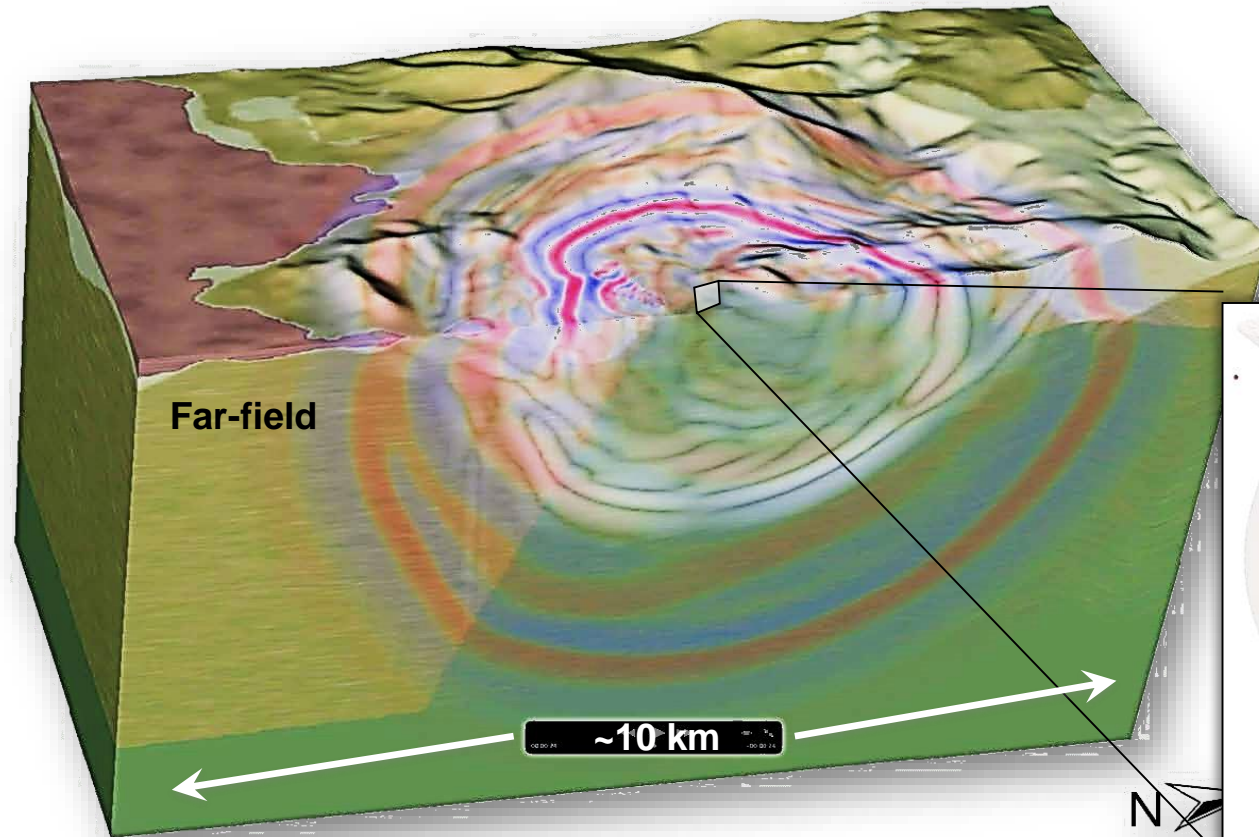
Synthetic porous alluvial media

SPE modeling framework to simulate & predict under conditions of uncertainty

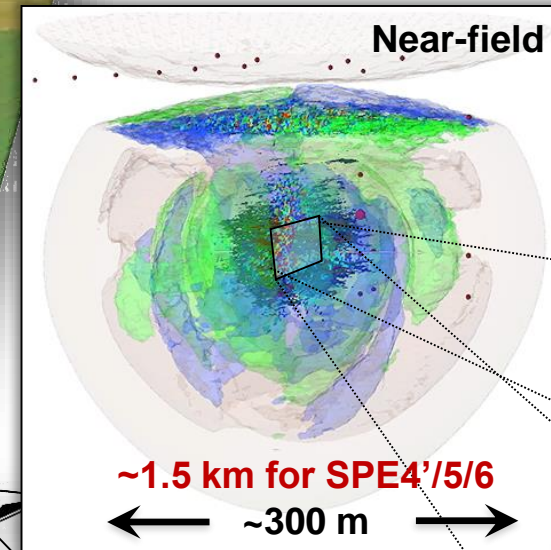
Flow chart of UQ and estimation for SPE/DAG experiments



Our unique E2E, S2R, coupled wave propagation capabilities is being adapted to DAG



NF: SPE4'/5/6 is 50x SPE3
250K joints vs 15K joints



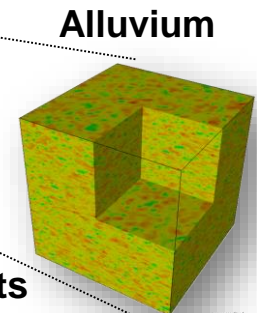
- Typical dimensions**
 - joint aperture ~1 mm
 - joints spacing ~1 m
 - source size ~1 m
- Resolution requirements**
 - ~ 20-50 million elements
 - ~ 100-200 million zones
- Uncertainty propagation**
 - ~ 500s runs a set
 - ~ 10s of parameters
- HPC requirements**
 - ~ 10% of one cluster
 - ~ 17% of temp storage
 - ~ 3.5 Million CPU-Hrs

HPC enables quantifying the effects of geologic heterogeneities on material response during wave propagation under conditions of uncertainties.

2200 CPU x 12 HRS =
26,400 CPU-HRS

3200 CPU x 16 HRS =
38,400 CPU-HRS

Repeated several times for uncertainty quantification



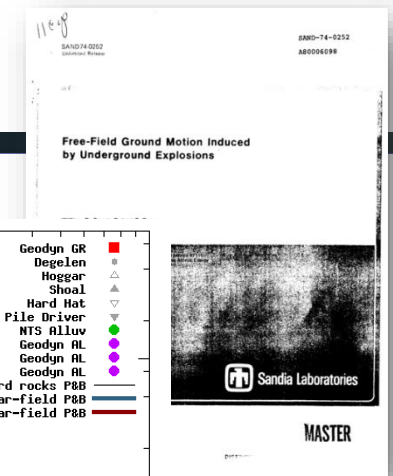
~50m



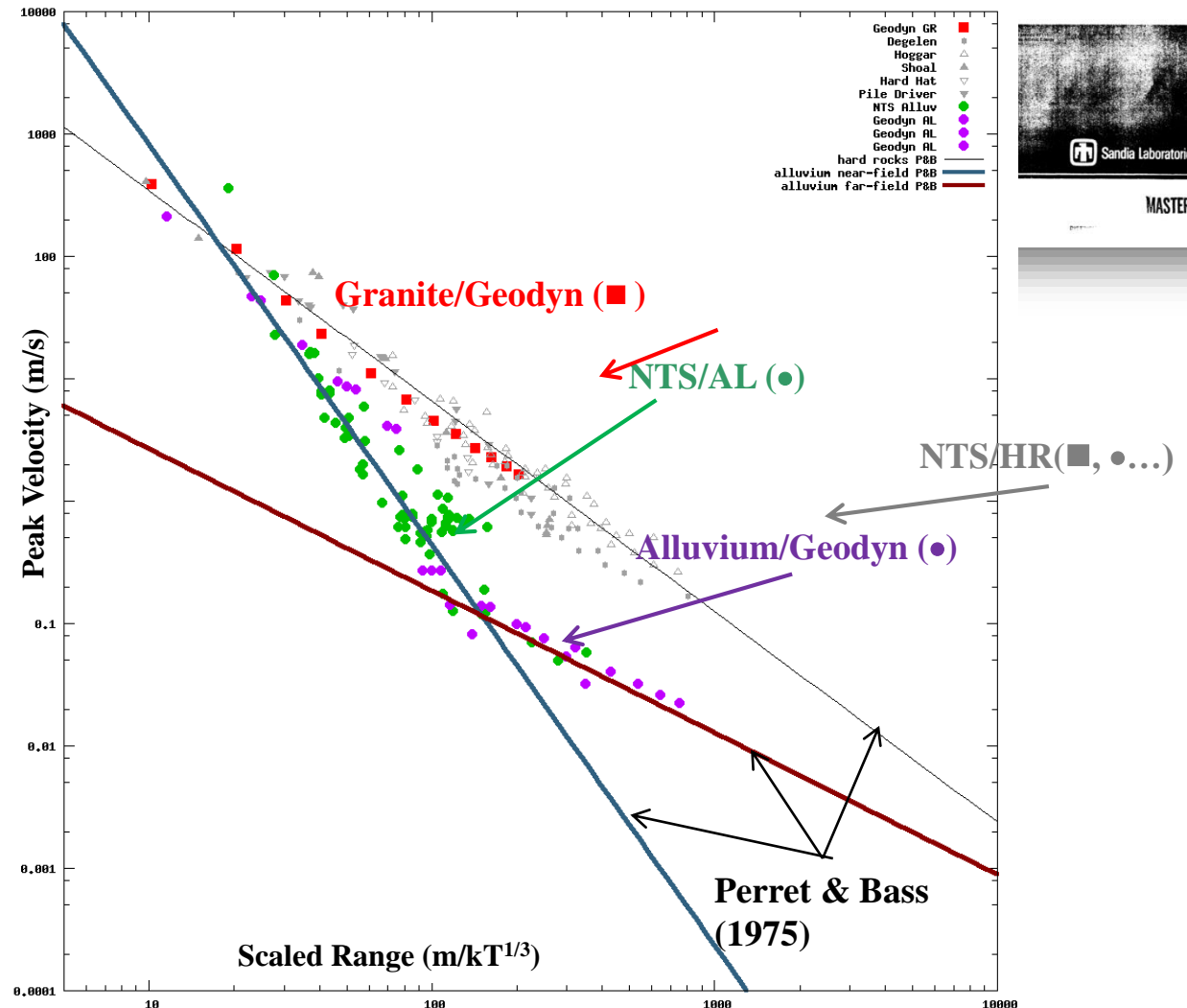
~10m

Granite

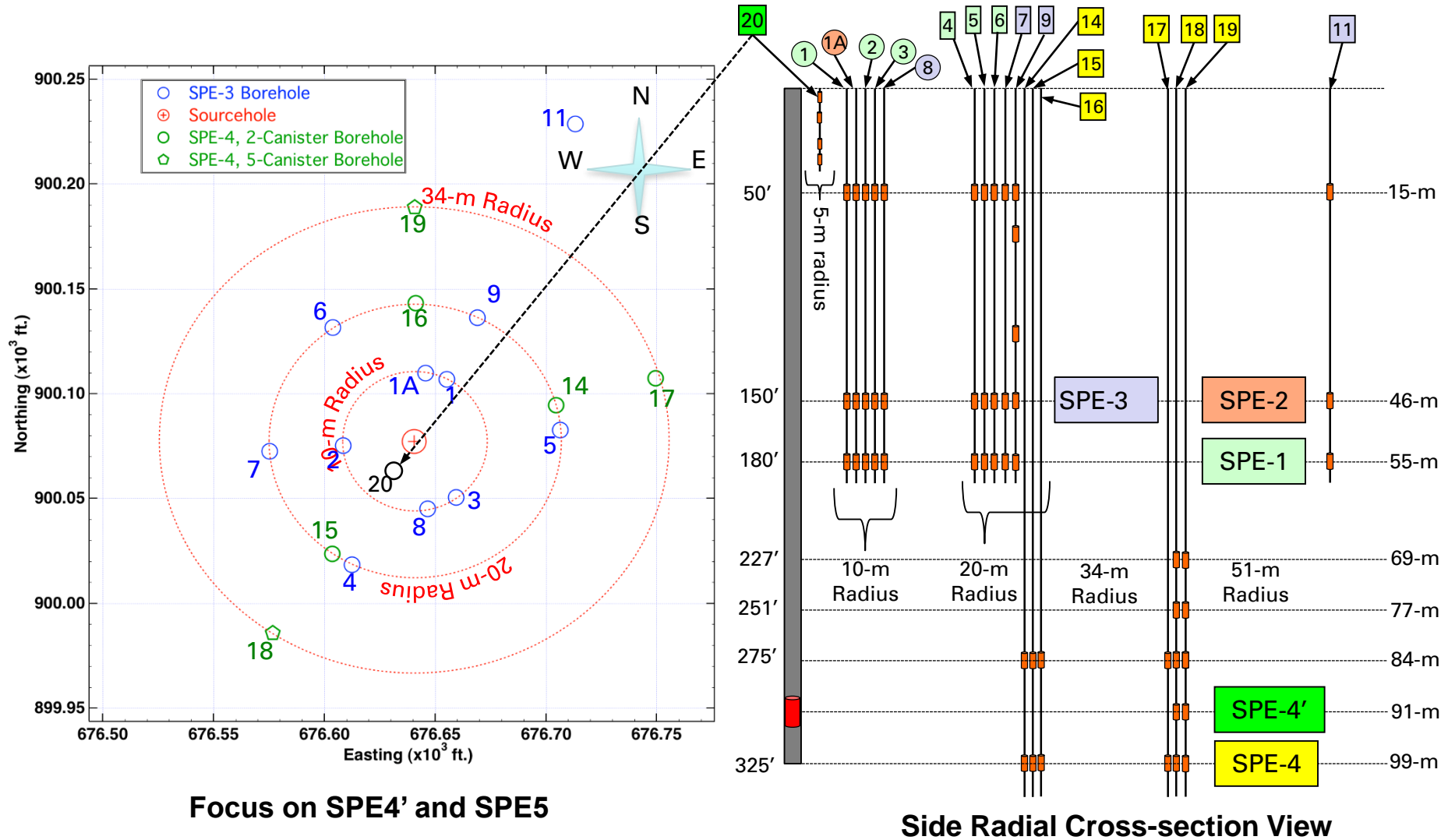
Geodyn Material Model calibration to NNSS (formaly NTS)



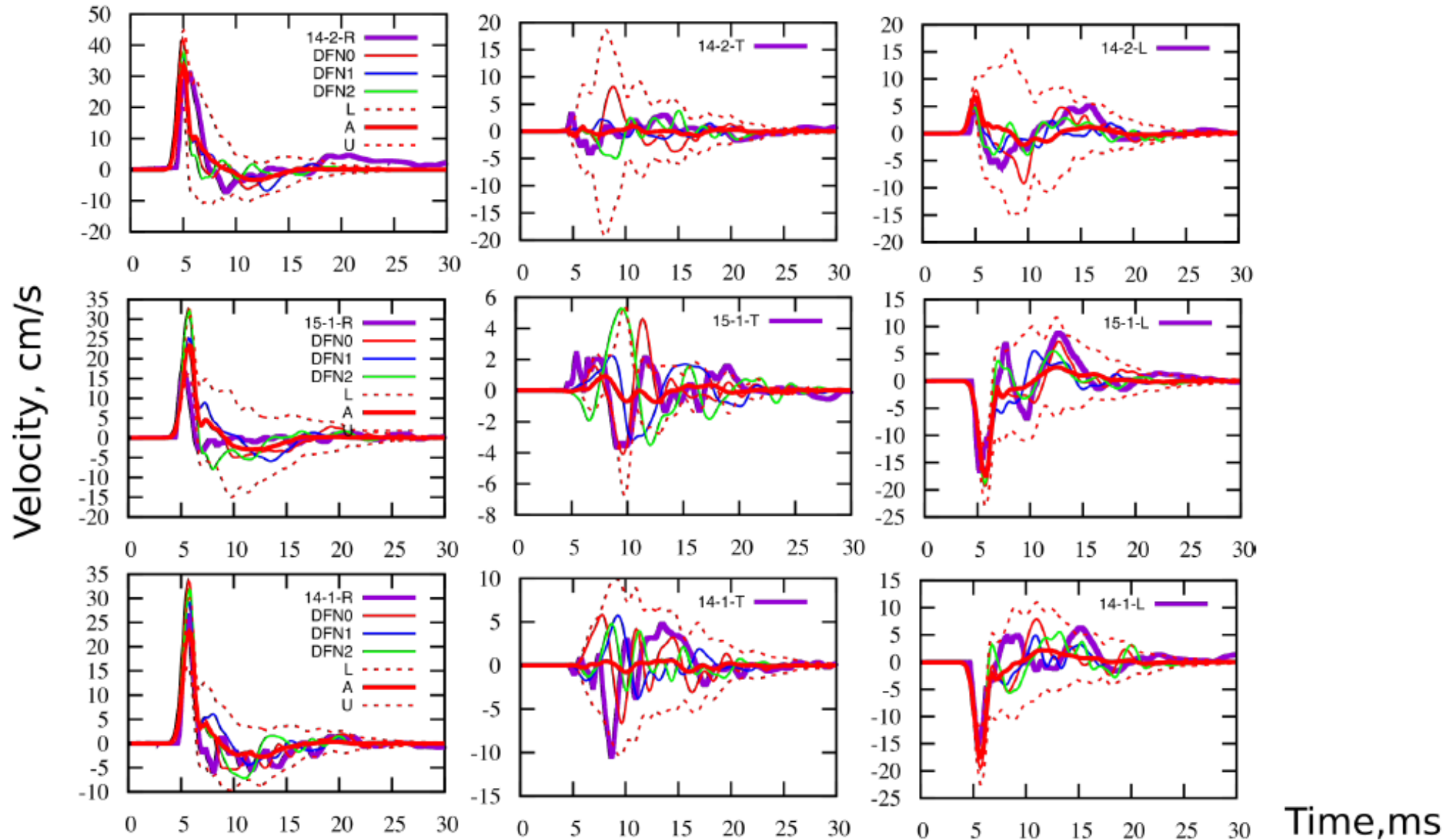
- Compiled several hardrocks and alluvium shots conducted at NTS
 - Scooter, Fisher, Hognose, Haymaker, Merlin, Vulcan, Hupmobile, Packard...Hardhat, Pilerrive, Horad, Degelen...
- Single regime for hard rocks
- Two main regimes when dealing with alluvium:
 - Nonlinear (near ranges)
 - Linear (far ranges)
- We recovered Peak-Velocity vs. Scaled-Range correlations
- We have seen similar behavior for Peak-Pressure vs. Scaled-Range
- Alluvium model is ready for DAG simulations



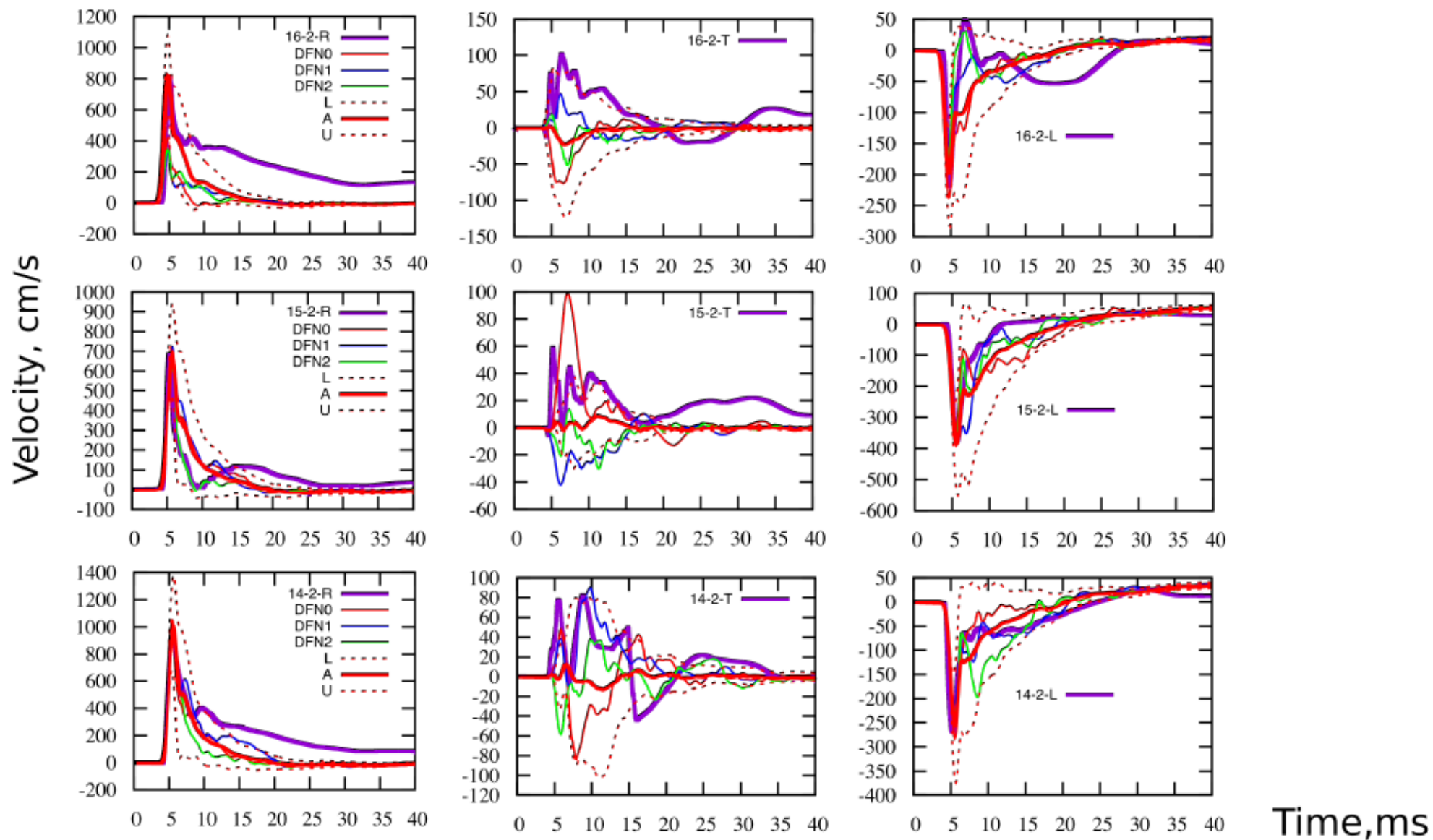
SPE1-6 instrumentation and gage locations



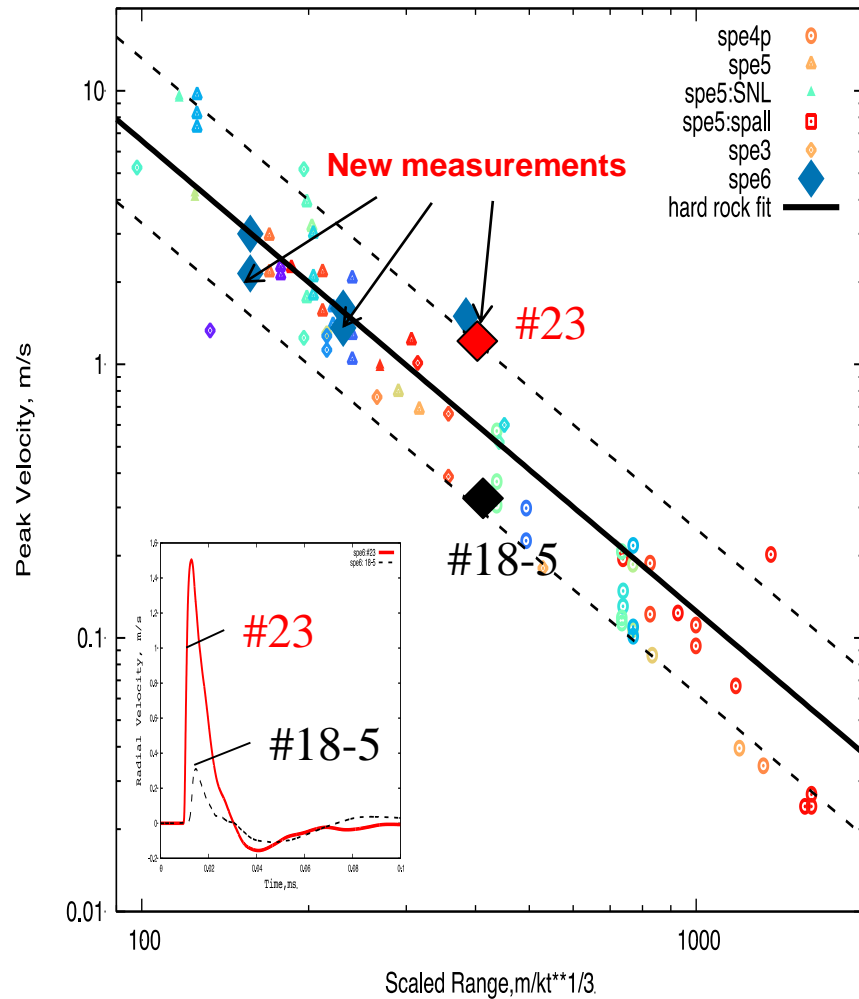
Example of SPE4P observed & predicted near-field data sets



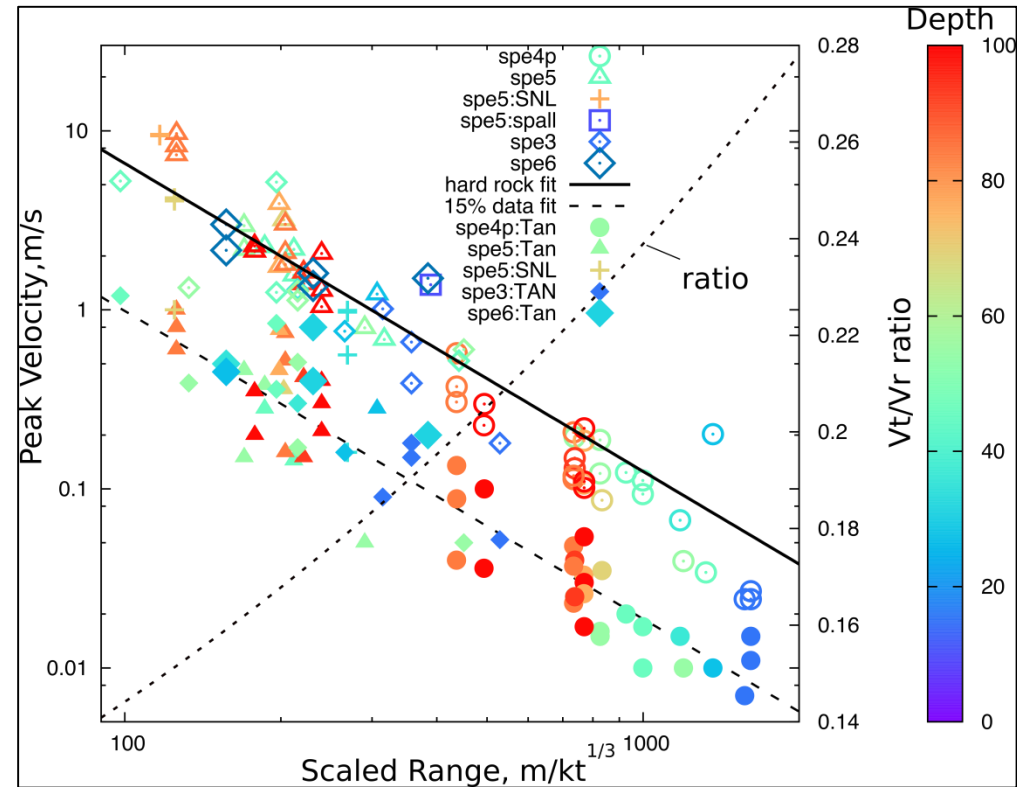
Example of SPE5 observed & predicted near-field data sets



SPE6 Peak velocity attenuation in agreement with previous SPE shots



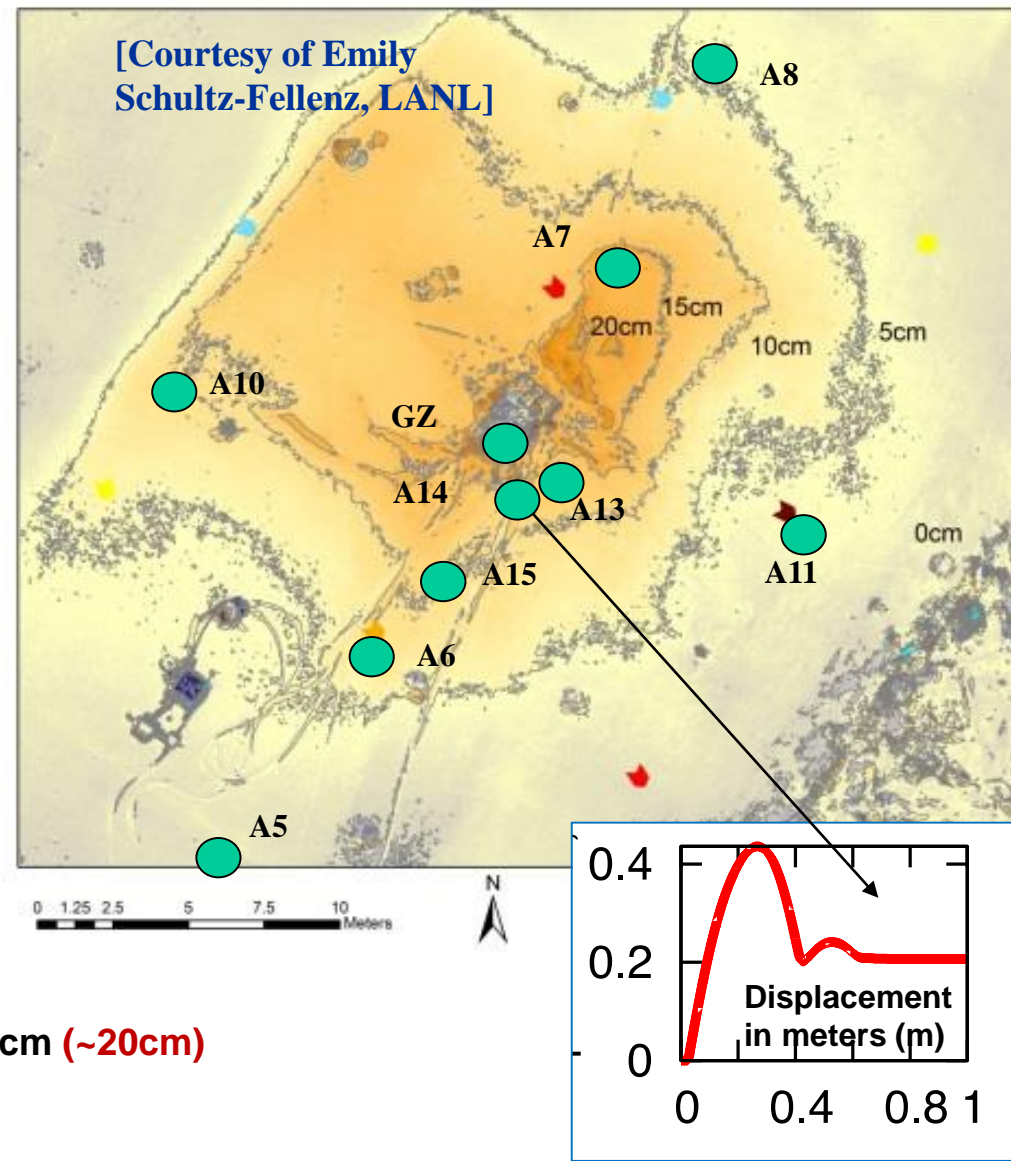
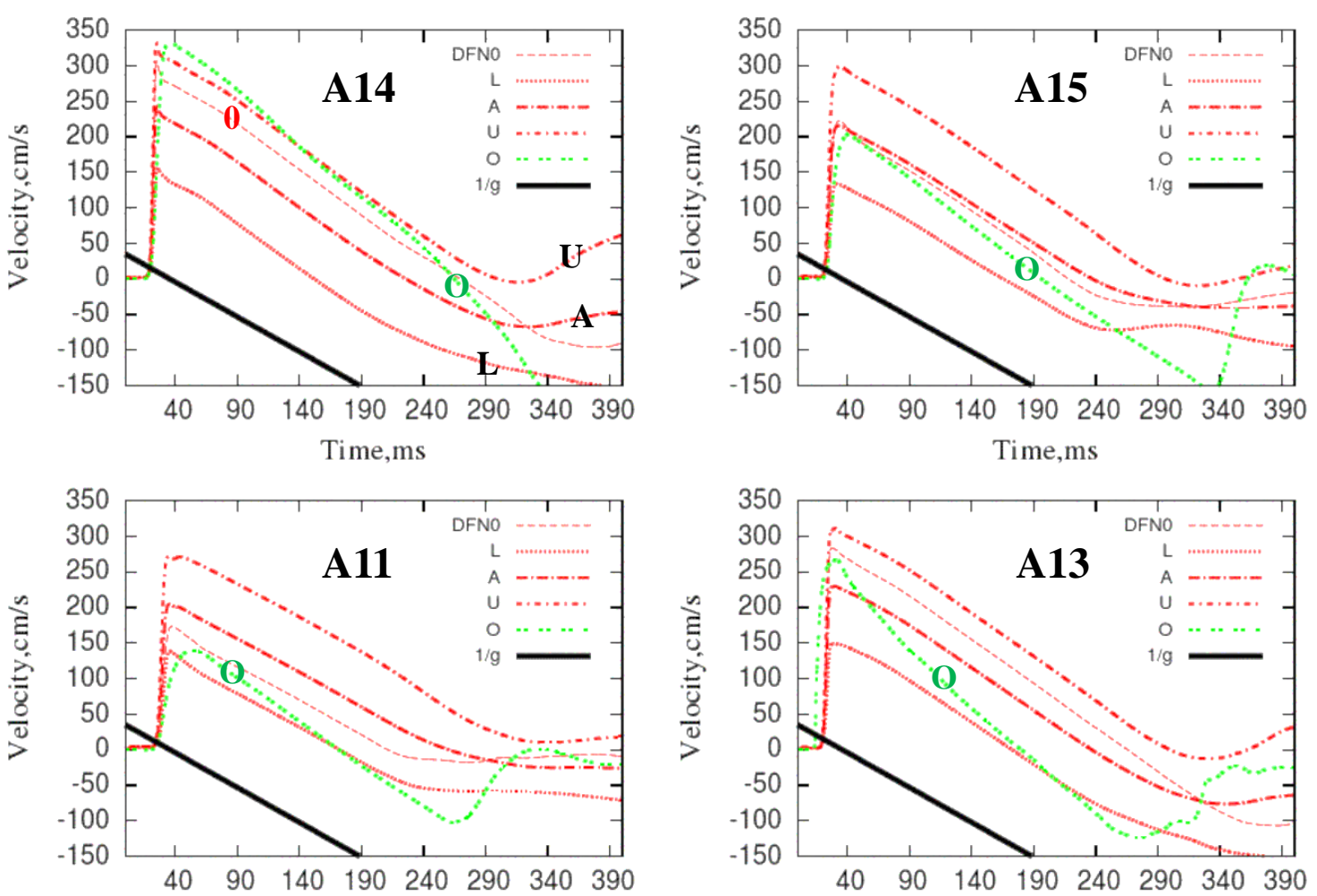
Radial & tangential motions



T/R ratio increases with scaled range

Higher radial velocity in direction #23 (similar to #9,#11 direction focusing for SPE3/SPE5)

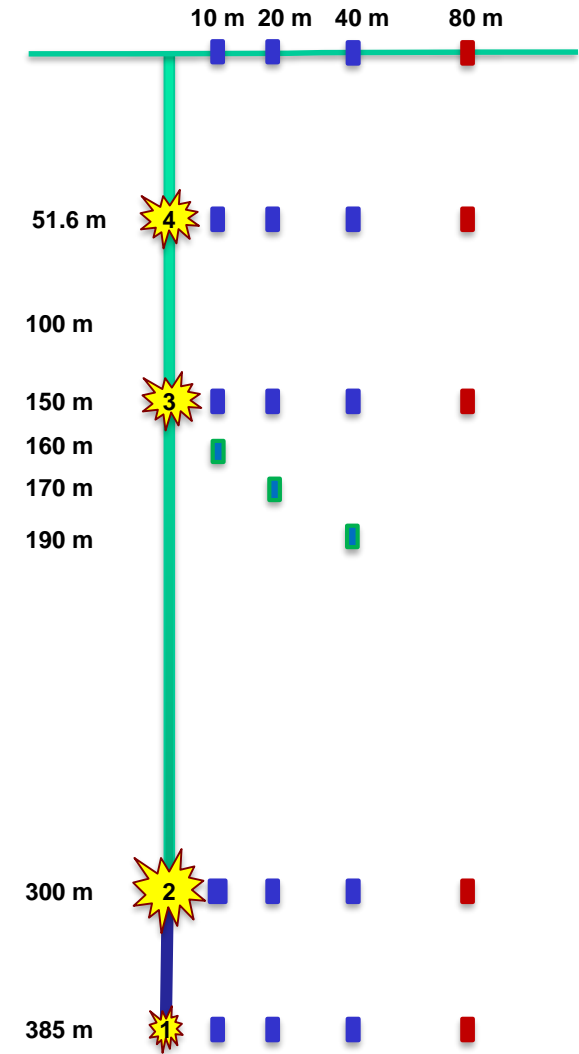
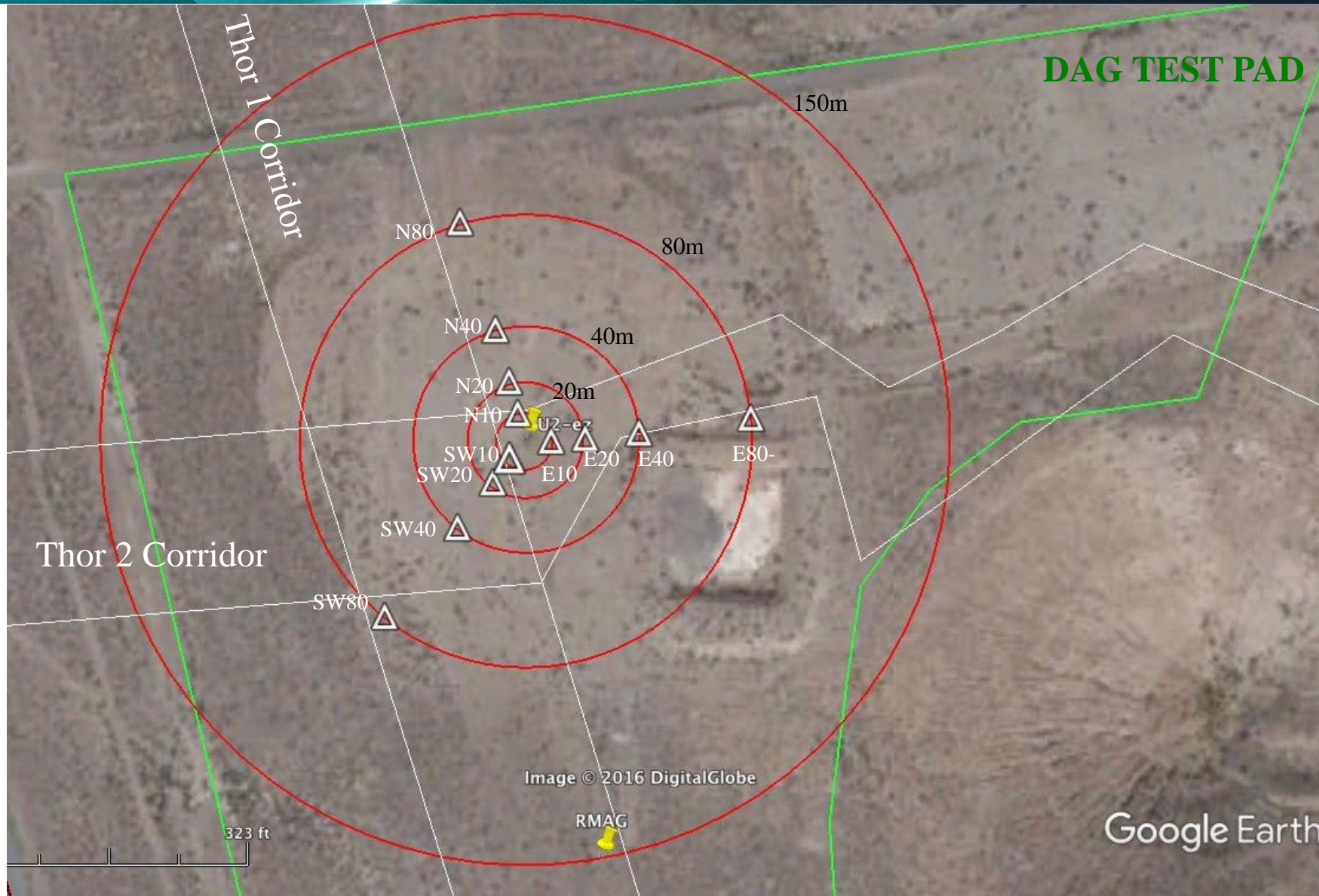
SPE6 Surface gauges around GZ are expected to exhibit ~2.5m/s (1m/s for SPE3/5) vertical velocity with clear spall



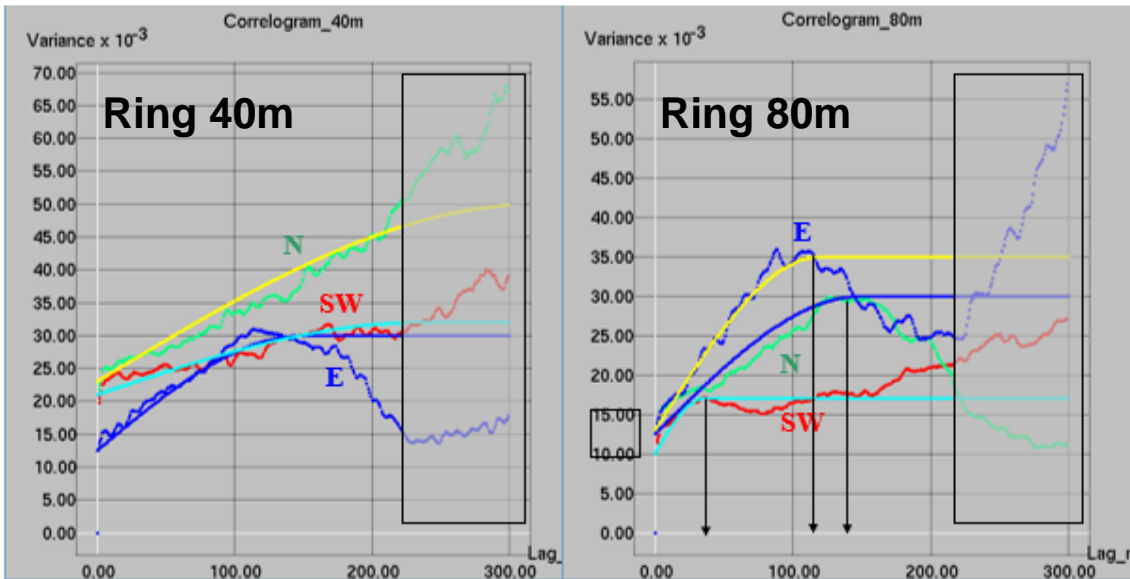
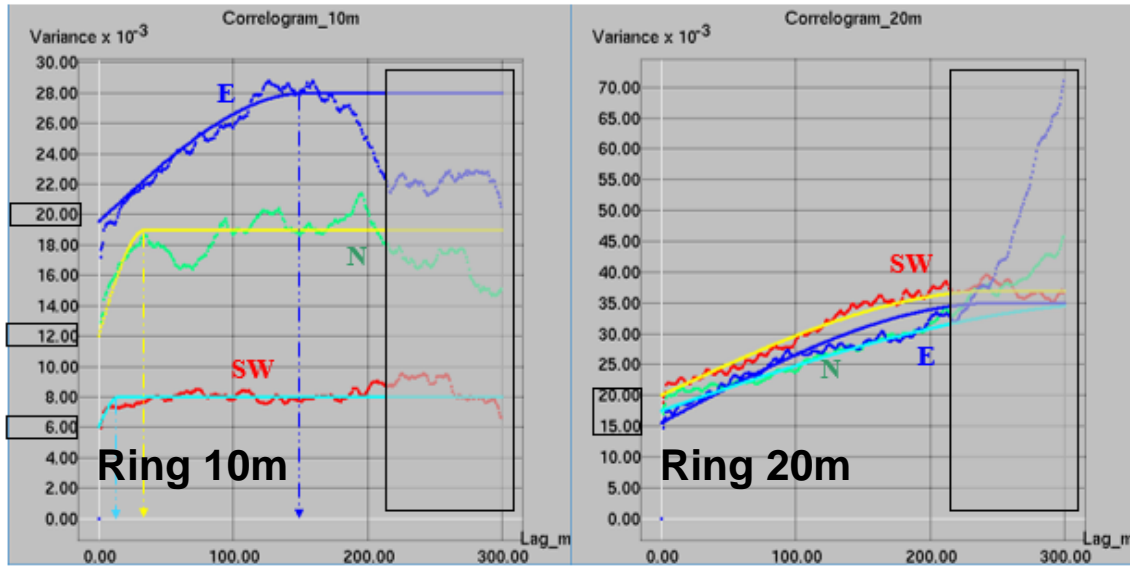
- Peak acceleration is ~100 Gs +/- ~30 Gs
- Peak velocity is 3.5 m/s +/- 1.25 m/s
- Peak displacement 27 cm +/- 9 cm (~40cm)

- Residual displacement 15 cm +/- 5cm (~20cm)
- Spall zone ~ 40-100 m (<60m)

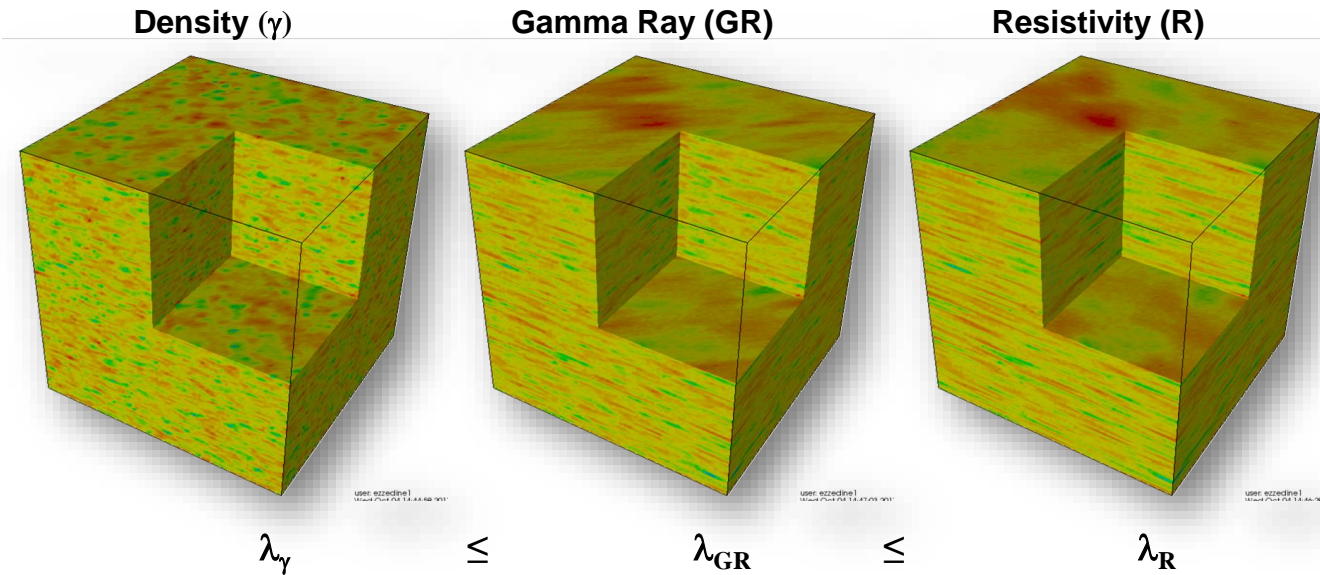
DAG Final Drilling PLAN: as of DEC 24, 2016



Vertical spatial correlation of Density : Hierarchy of scales & non stationarity

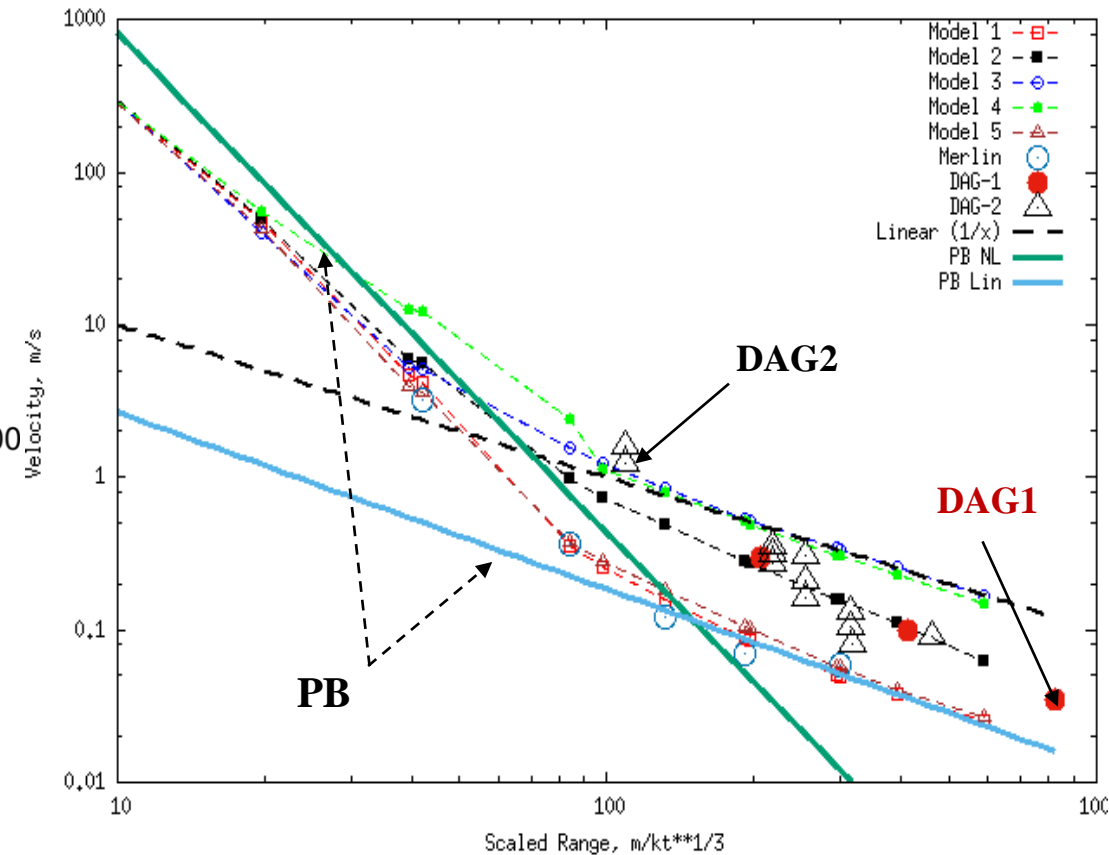
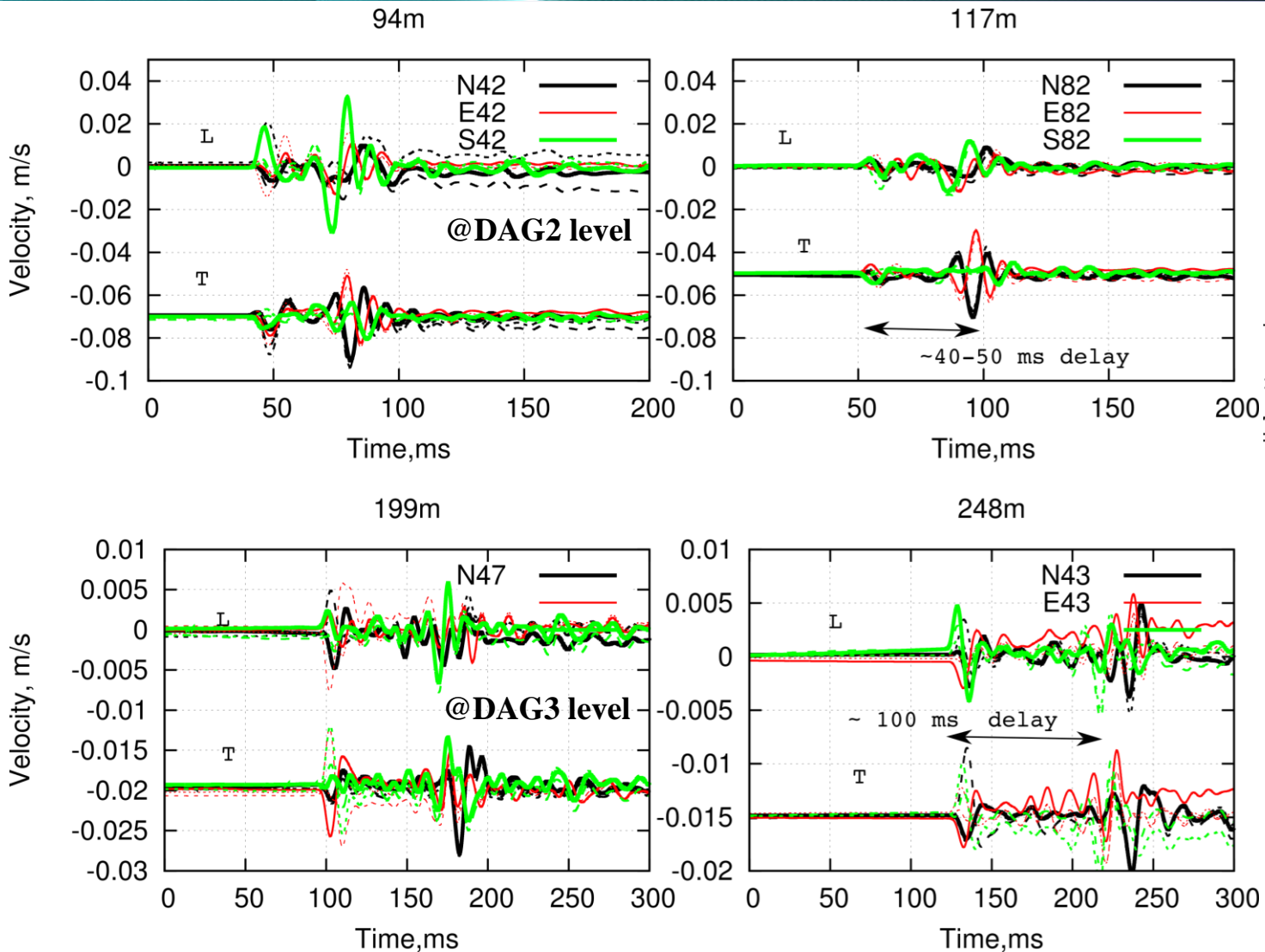


10m Ring: Strong anisotropy between directions (spherical to affine-like)
 20m Ring: Isotropy between directions (strong affine-like)
 40m Ring: Isotropy between N/SW affine-like in E direction
 80m Ring: Almost isotropy between N/E spherical in SW direction



- There is a hierarchy of scales between Density, Gamma Ray and Induction Resistivity
- Nested scale $\lambda_g \leq \lambda_{GR} \leq \lambda_R$: higher continuity between R lenses than GR lenses than density
- We use Joint PDF (of all 3) to generate conditional simulations for NF wave simulations and predictions
- Data is honored at each location: reduces the number of realizations

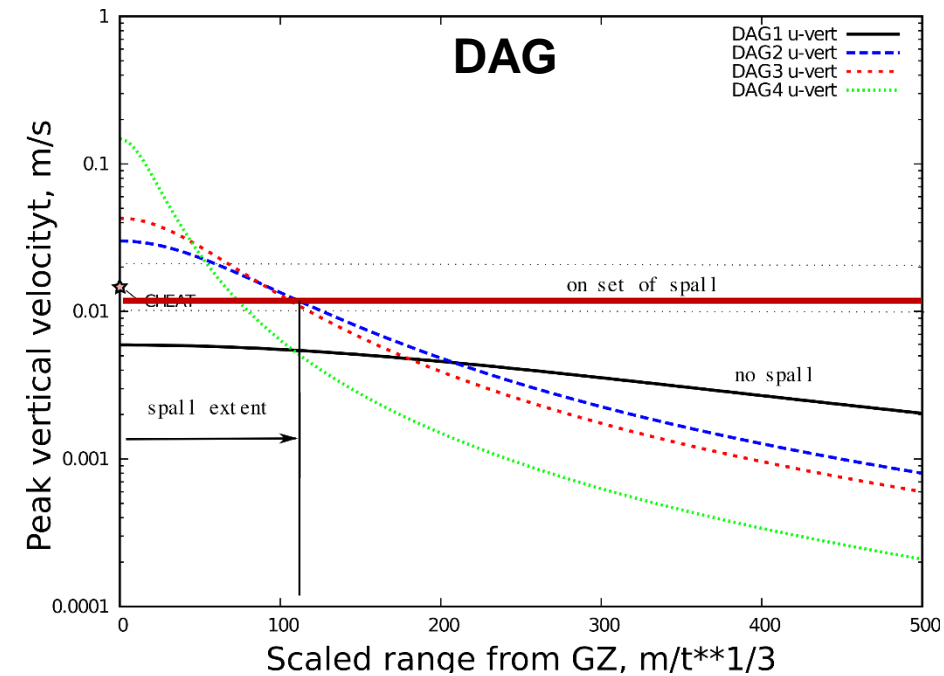
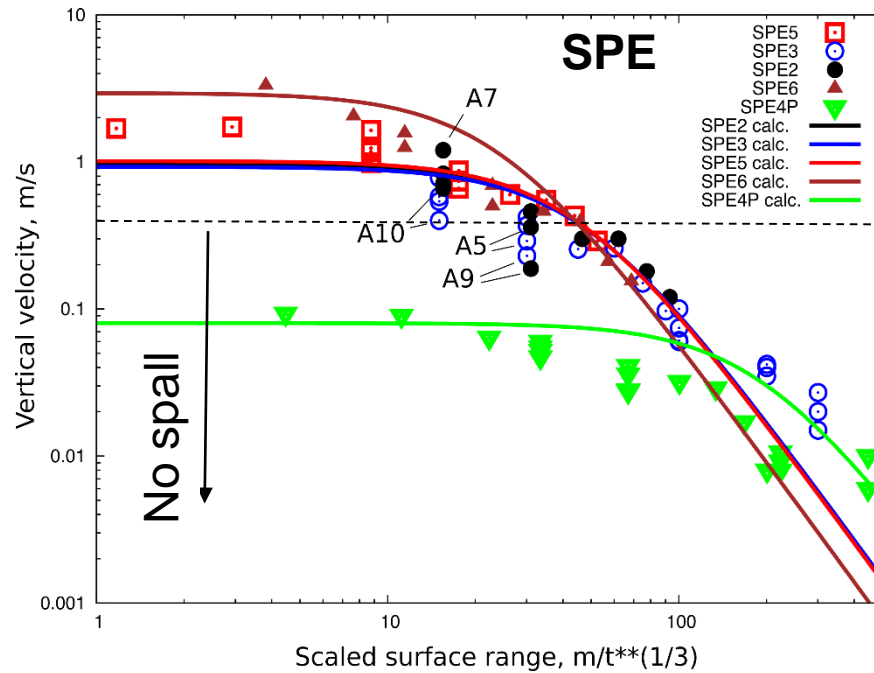
Motions recorded above DAG-1 showed delayed arrivals of shear waves in all directions (N, E, SW). We are moving beyond Perret & Bass 'EOS'.



DAG1 measurements cluster well along the new material model prediction. DAG2 however has a larger scatter than expected (canisters may not be properly gauged, residual movement from DAG1, weak grout)

DAG1 velocities registered at DAG2 & DAG3 shot levels showed delayed shear wave arrivals

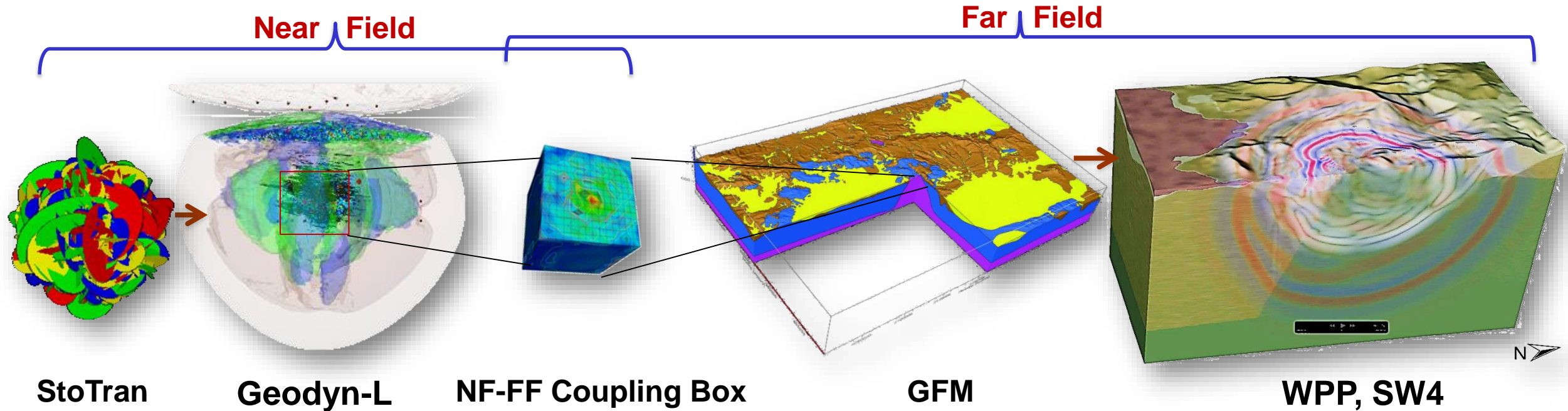
SPE & DAG Spall predictions vs. BLUF surface accelerometers



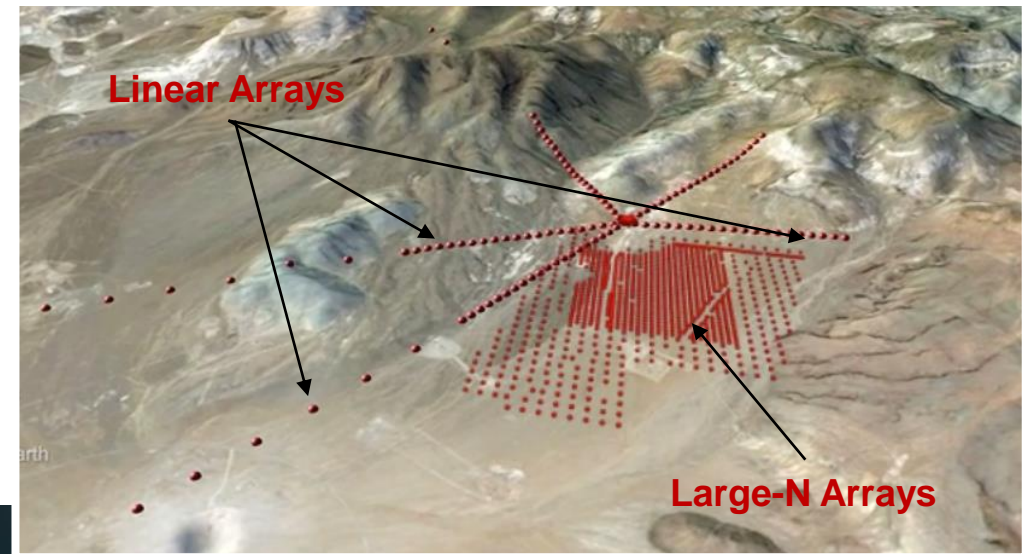
Blind predictions = 110 m spall

**BLUF surface accelerometers
The entire array (out to 90 m) spalled for about 0.14 s.
(Jesse Bonner, MSTs)**

Fully Coupled Source-to-Sensor 3D Physics-Based NF to FF Wave Propagation Modeling Capability

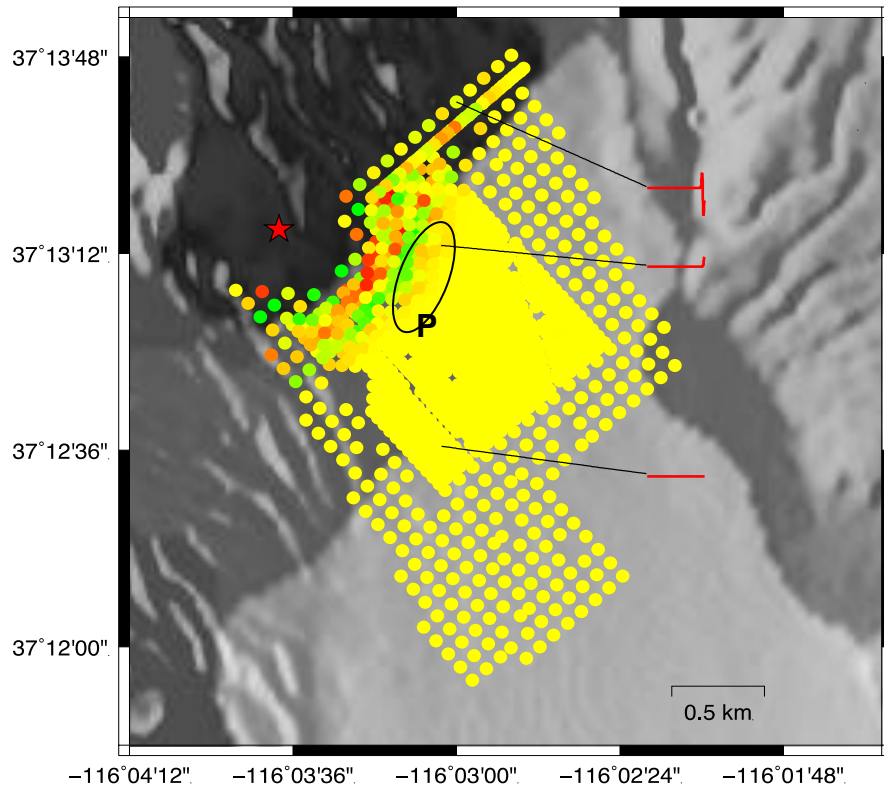


We will present the far-field
synthetic and observed signals
using both Linear and Large-N
arrays

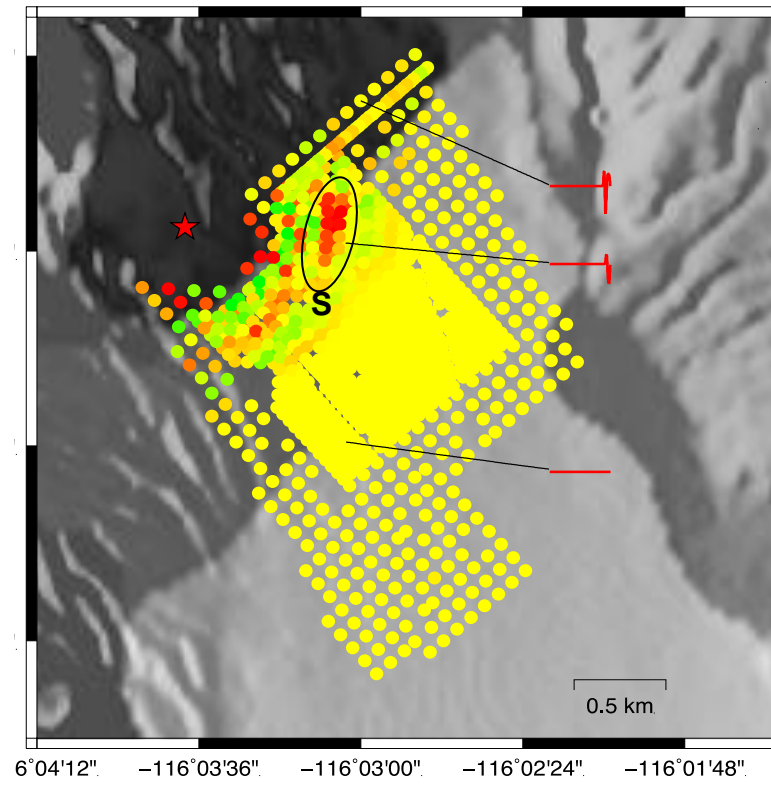


P-S, P-Rg, S-Rg Wave Conversions and Basin Induced Secondary S Waves Observed during SPE Phase I

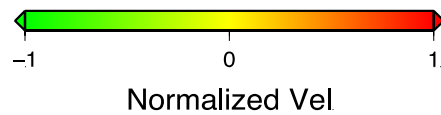
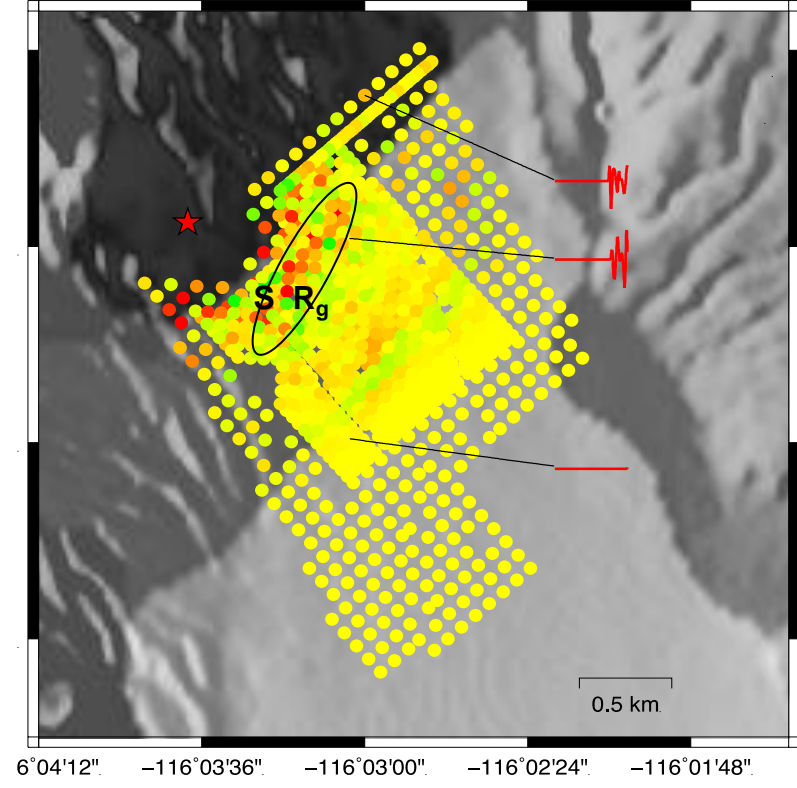
Source generated P waves



Converted P to S waves and S wave focusing

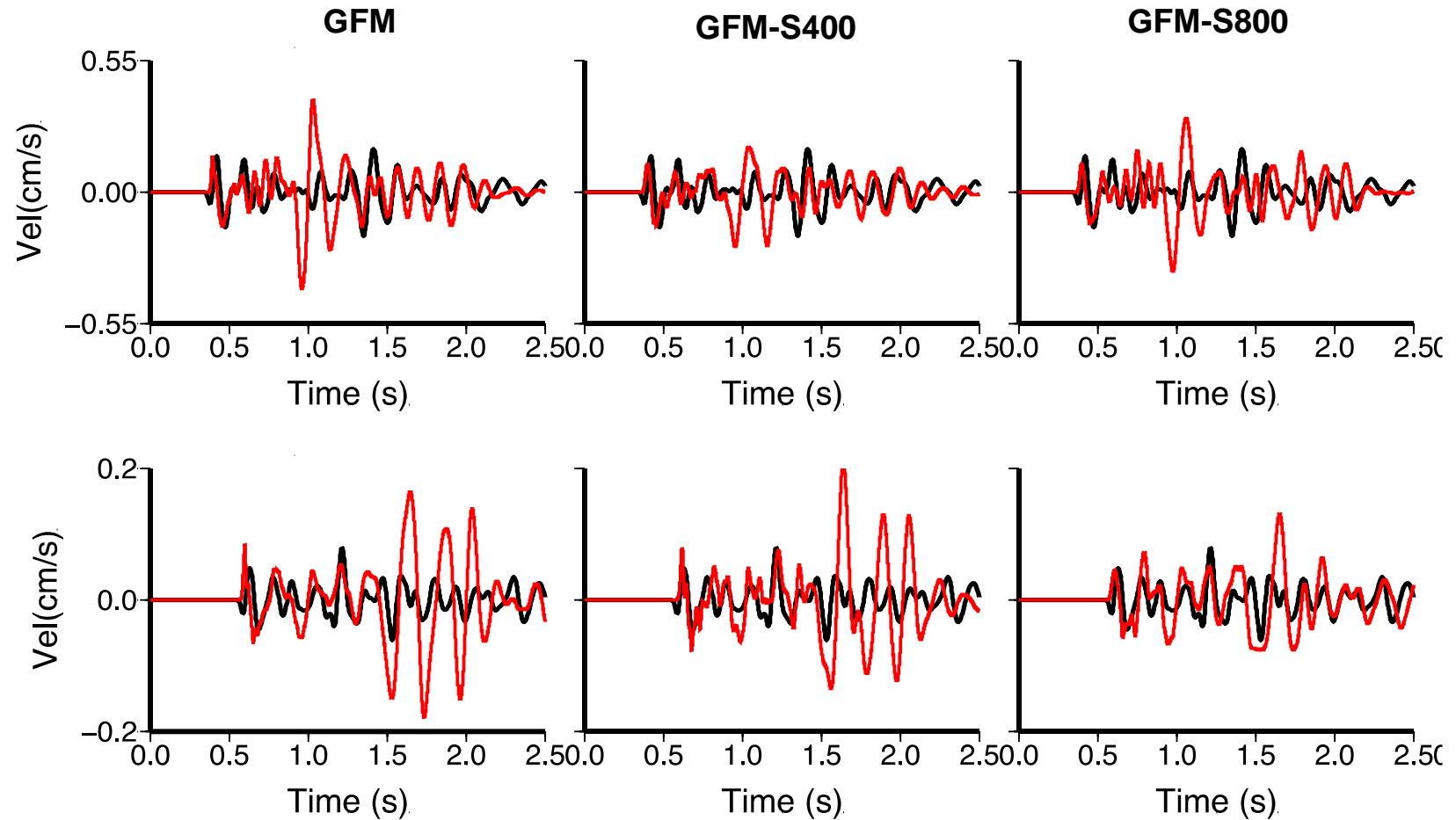
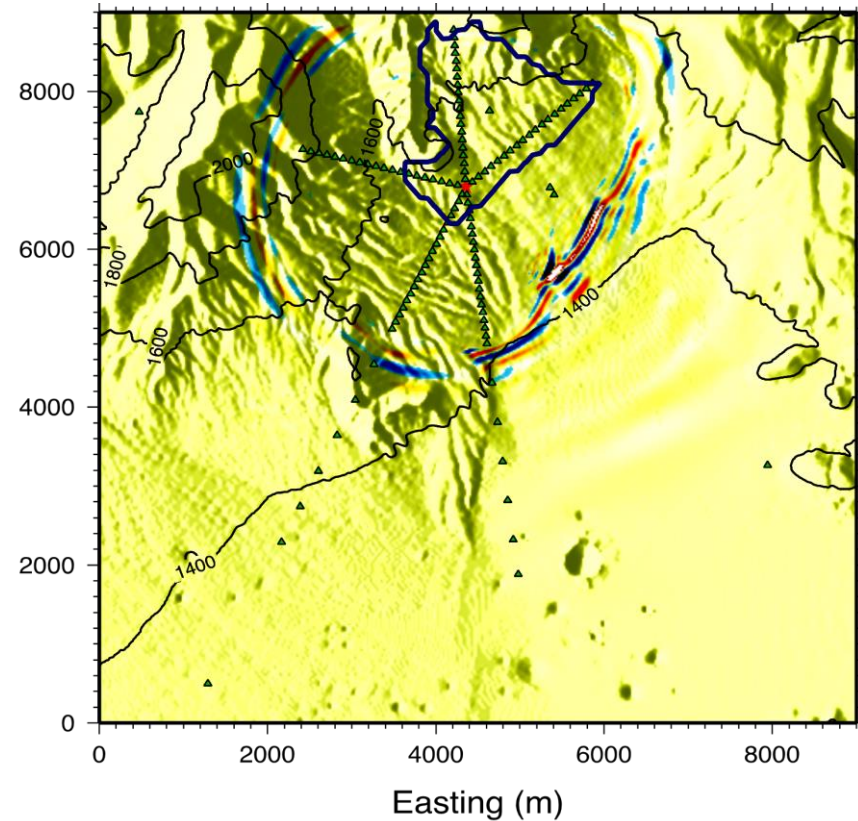


Basin generated shear and surface waves



Large-N array data show strong propagation effects on S waves generated in the source region and at structural boundaries, and Rg waves

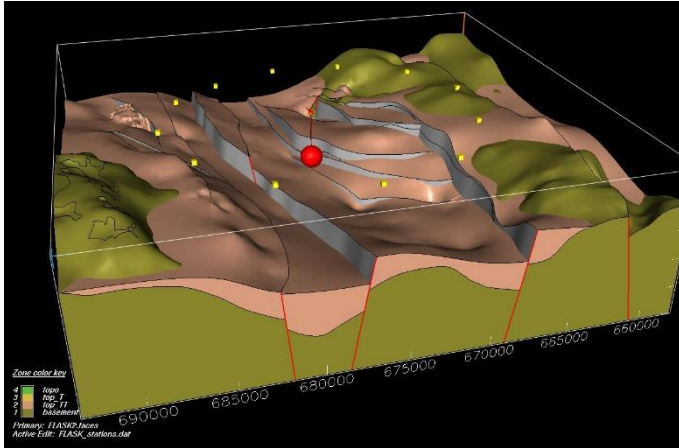
Simulated Far-Field motion up to 10 Hz using GFM & GFM-S



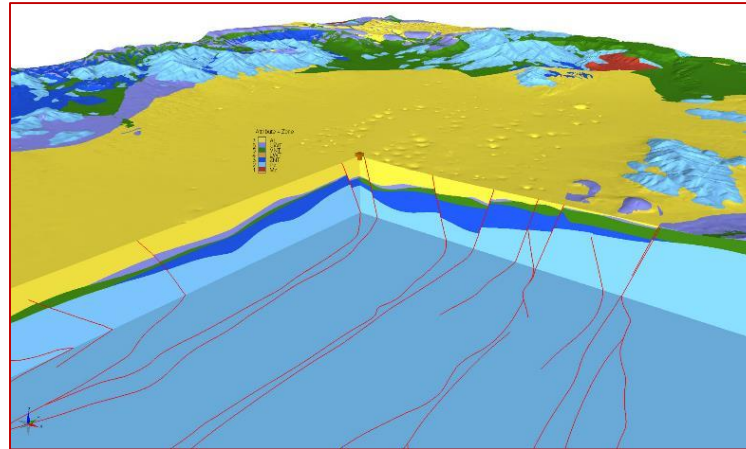
Inclusion of correlated stochastic variability in shallow layers improves the performance of GFM in reproducing observed wave scattering (GFM-S)

Phase II DAG-2 explosion P and S Waves Generation (1-8Hz)

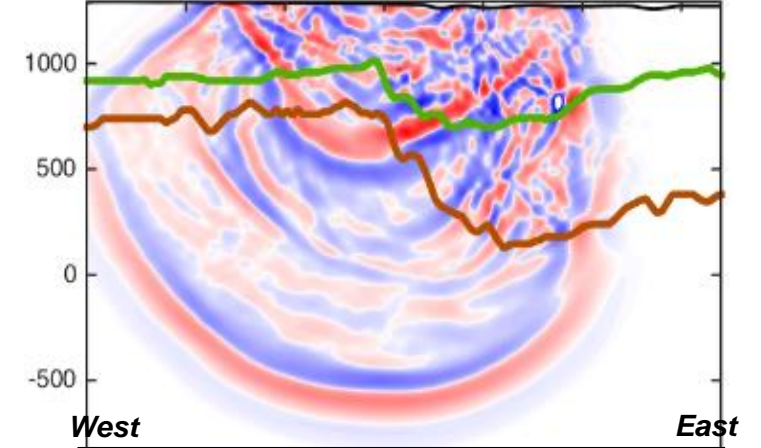
Structural Discontinuities in GFM



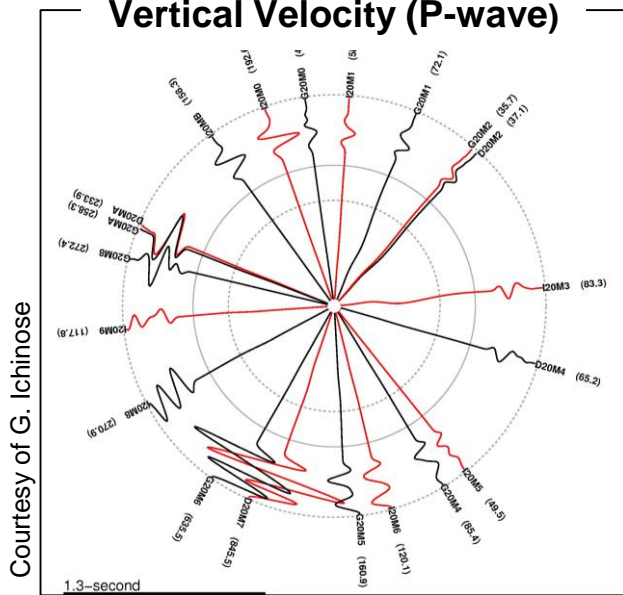
DAG-GFM



3D Simulated Waves (Vert. Comp)

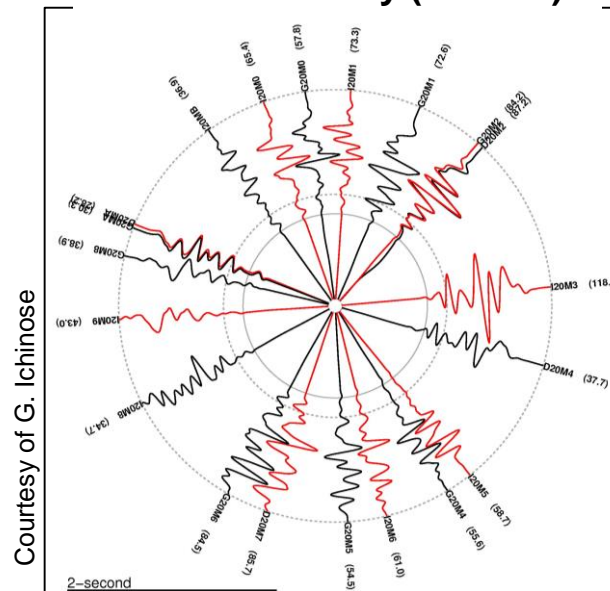


Vertical Velocity (P-wave)



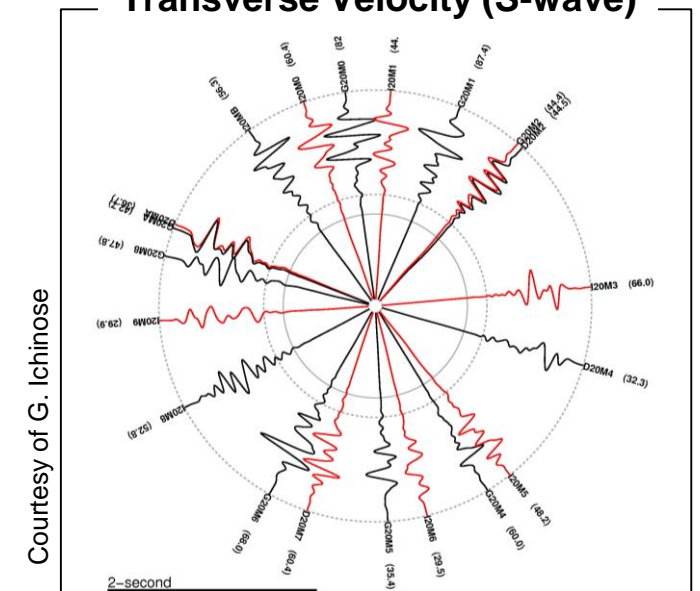
Courtesy of G. Ichinose

Vertical Velocity (S-wave)



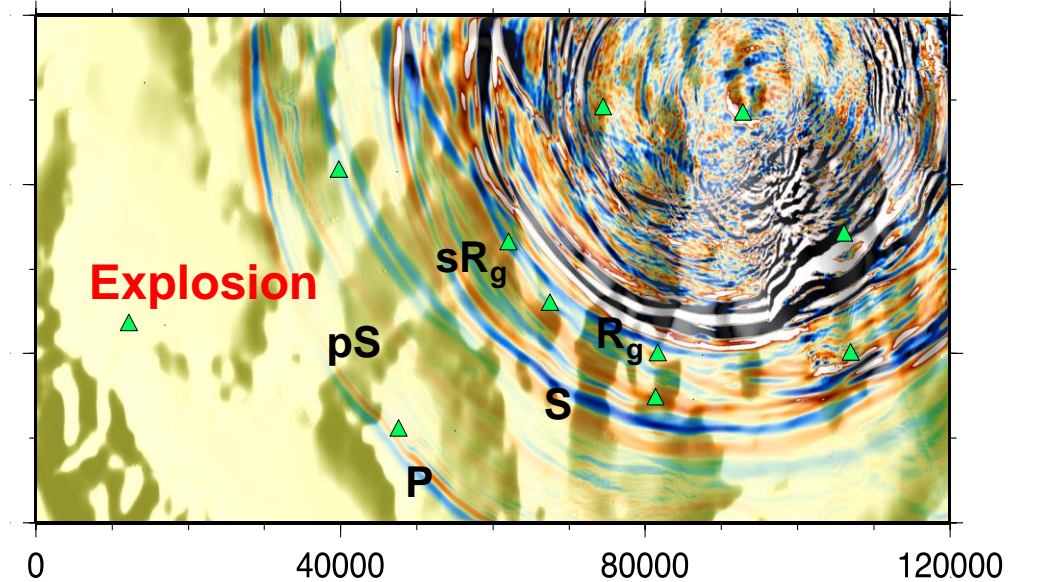
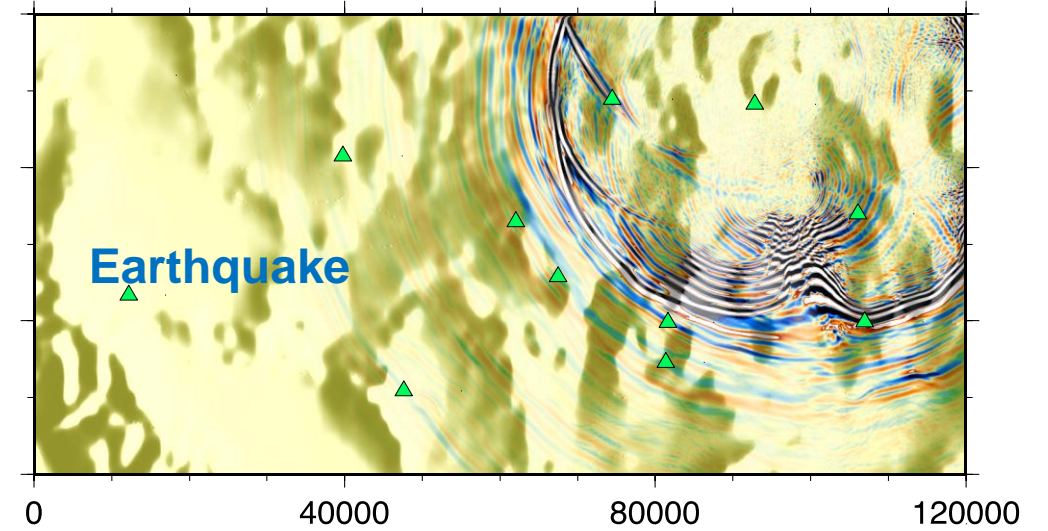
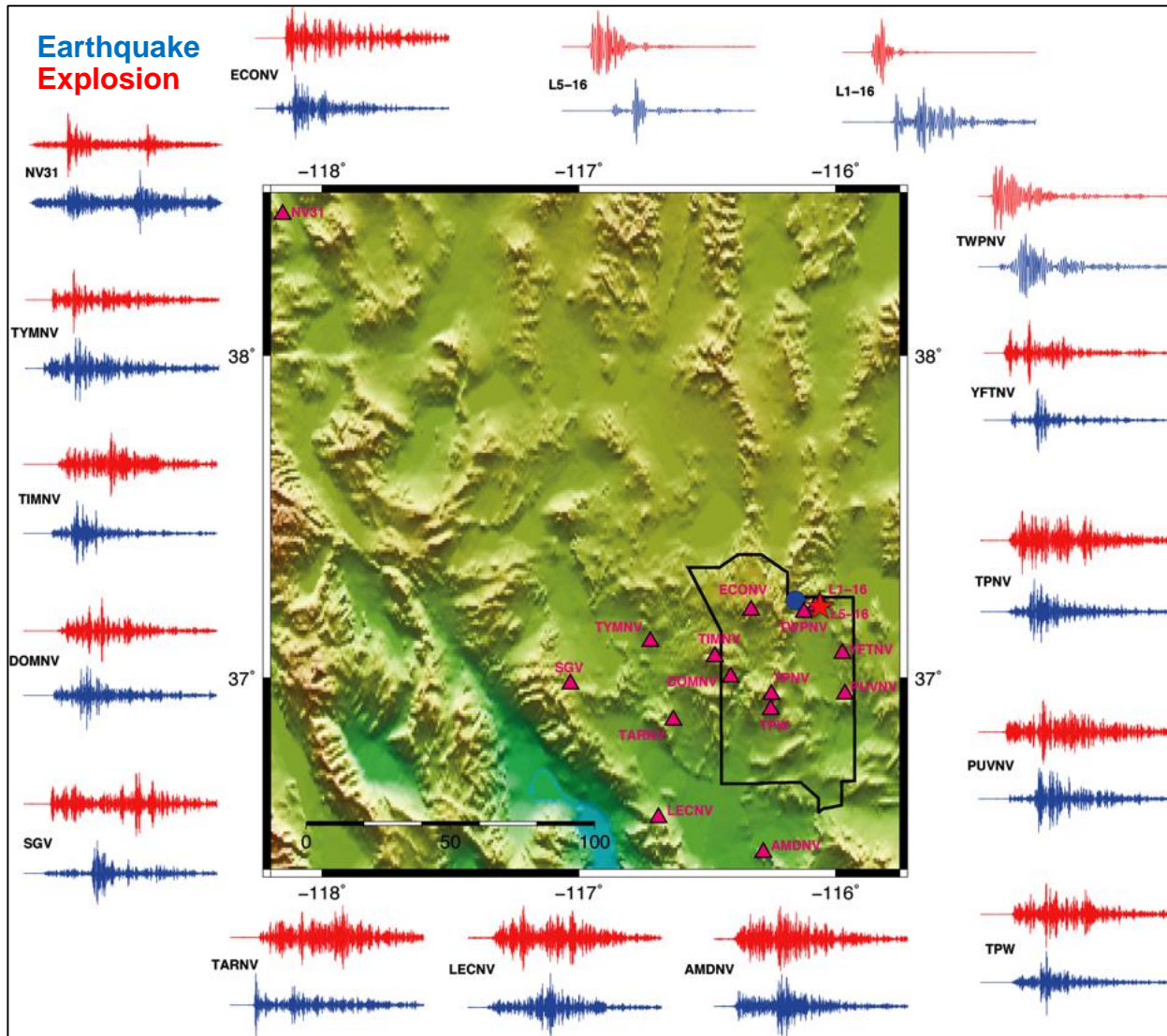
Courtesy of G. Ichinose

Transverse Velocity (S-wave)



Courtesy of G. Ichinose

SPE-5 Observed and Simulated Performance of P/S Ratio at Local Distances



Summary of the seismic monitoring implications being studied in the Source Physics Experiments

• Near-Field wave propagation:

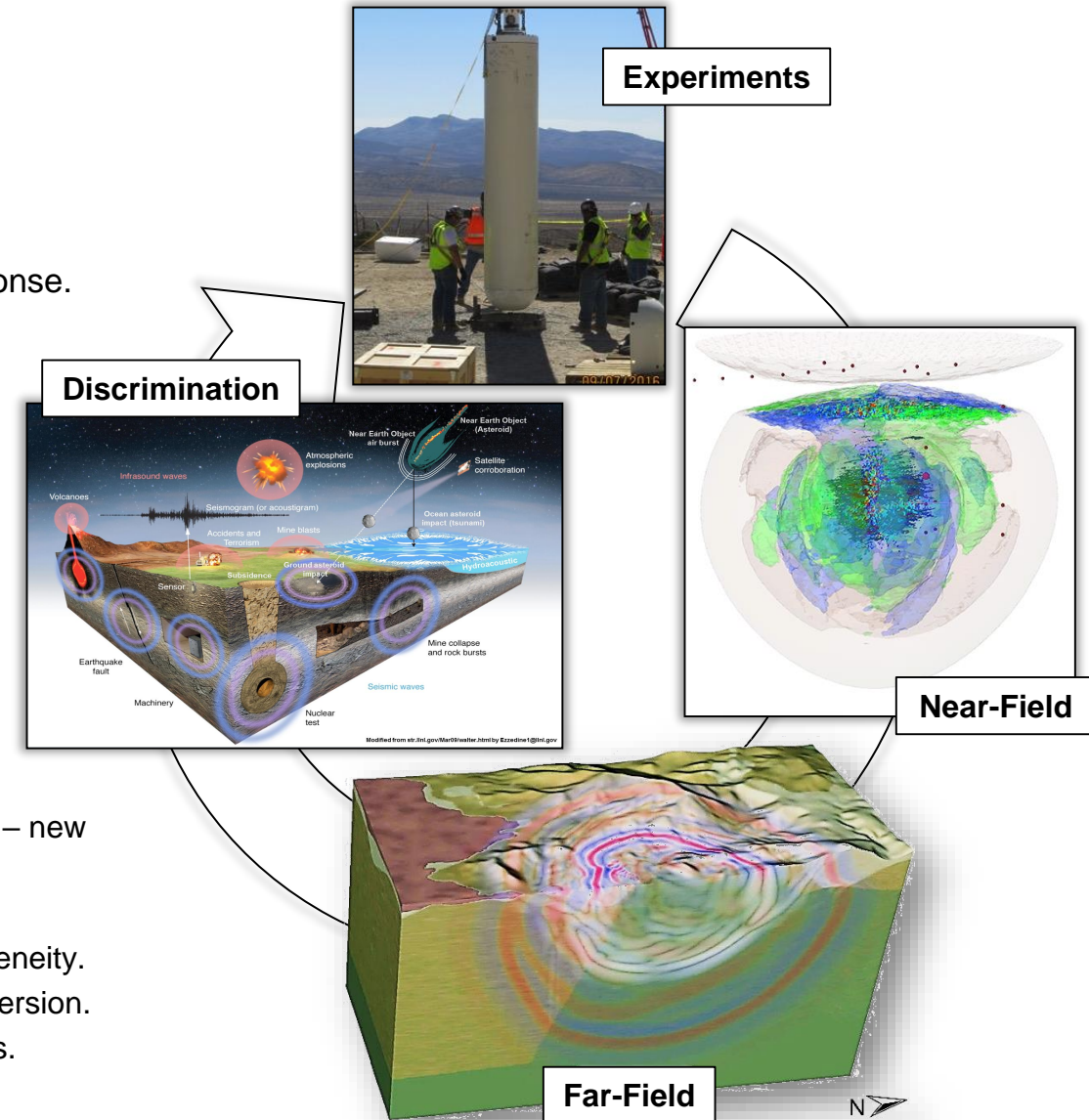
- Joints are the main cause of shear motion generation.
- SPE3 framework has been applied to SPE4', SPE5 and more recently SPE 6.
- Same framework has been adapted to DAGs and applied to DAG-1, -2 & -3.
- Several UQ & SA studies have been conducted (petrophysical, geological).
- We have conducted similar analyses for surface expression and acoustic response.

• Far-Field wave propagation:

- Source related effects are primary mechanisms of shear motion generation.
- Secondary sources of shear motions are:
 - Conversions (i.e. P-S & P-Rg) and
 - Path effects on basin generated S waves.
- Current model provides a platform for sensitivity analysis of ground motion.
- Local wave propagation effects are source-depth dependent.

• Implication for source discrimination / monitoring:

- P-wave spectra – affects yield estimation and discrimination.
 - Overall level, corner frequency, high-frequency roll-off affected by media.
 - Dry porous media, over-buried & small explosion not well fit by existing models – new ones underway.
- S-wave spectra – affects P/S discrimination.
 - Transverse waves in near-field/high frequency from joints and material heterogeneity.
 - S-wave generation in far-field, monitoring frequencies from scattering and conversion.
 - Physics-based modeling under development and starting to match observations.
 - Local P/S much less effective as a discriminant without azimuthal averaging.





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