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Uncertainty Propagation and Stochastic Interpretation of Shear Motion Generation due to Underground Chemical Explosions in Jointed Rock

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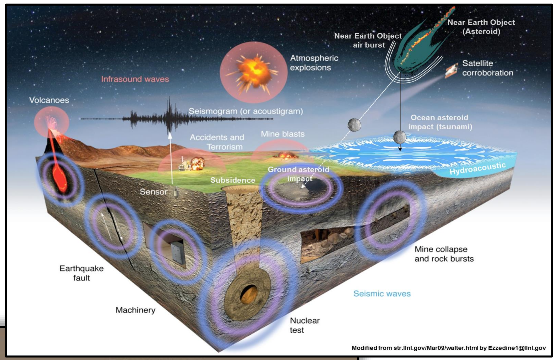
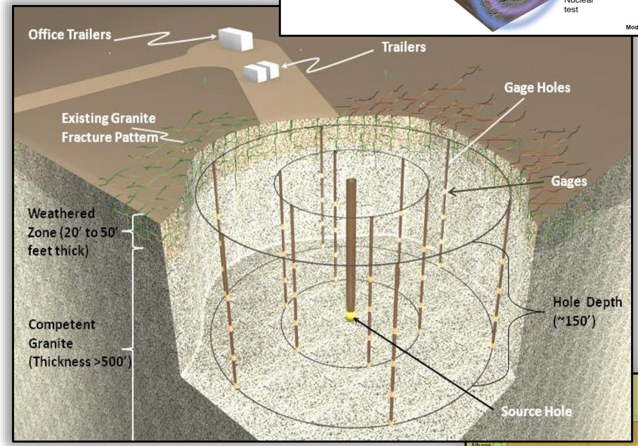
Outline

- **SPE Modeling framework [MF]**
  - Statement of the problem
  - Modeling flowcharts
  - Adaptation of SPE MF to DAG
- **Near Field**
  - Source
  - Wave propagation
  - SPE lessons learned
  - DAG-1 & -2 lessons learned
- **Findings & lessons learned**
  - Near-Field
  - Far-Field
  - Discrimination

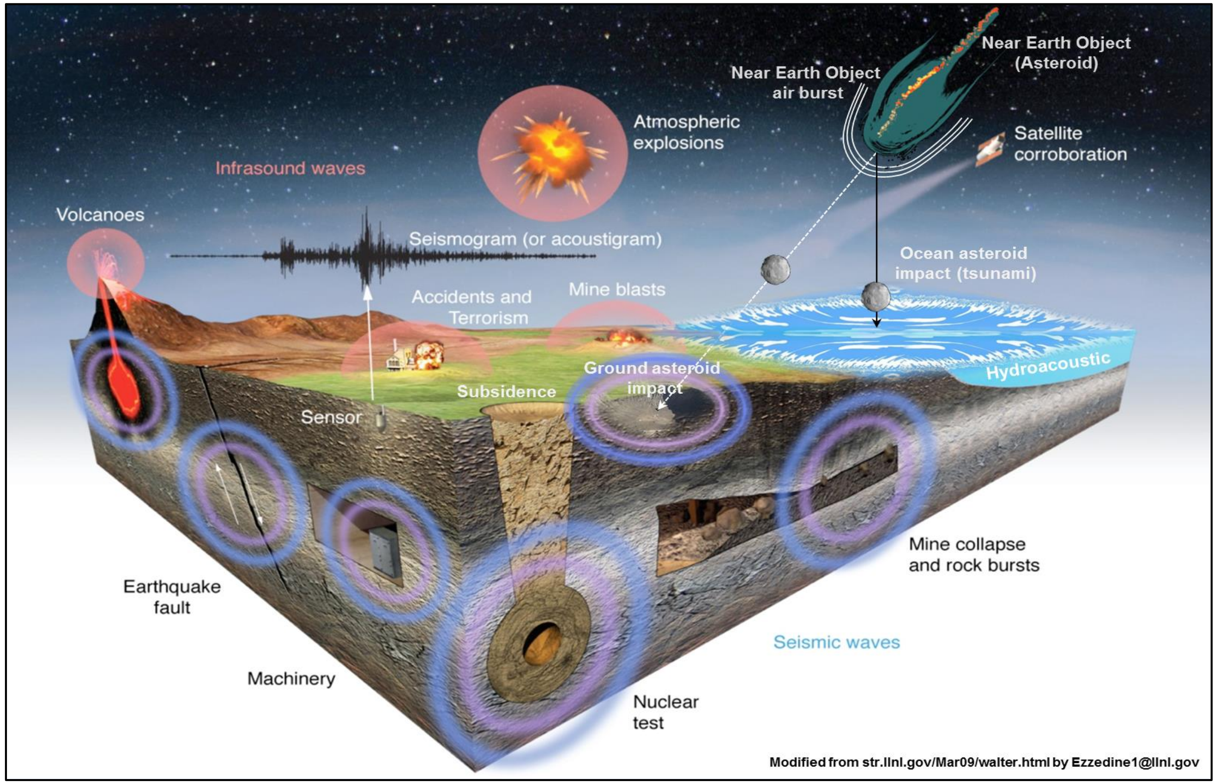




Motivation of current efforts: Discriminate between anthropogenic, natural & nuclear sources

- 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

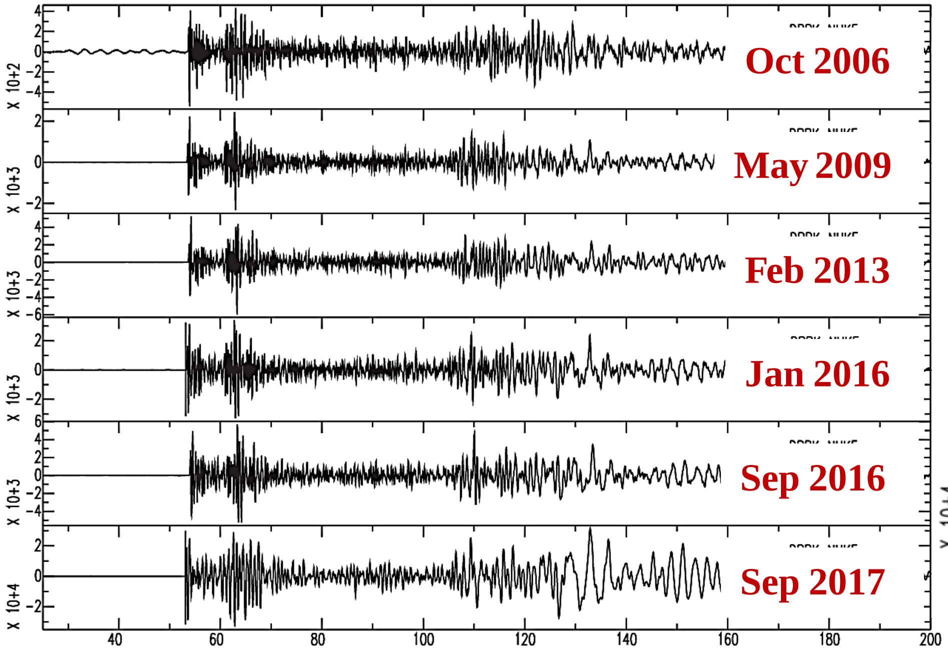


Cutaway view depicting many of the different disturbances recorded by sensors worldwide. Sources of disturbances include: volcanic eruptions, earthquakes, machinery vibrations, nuclear tests, mining and rock bursts and blasts, terrorist acts, atmospheric explosions, and asteroid ground and ocean impacts.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

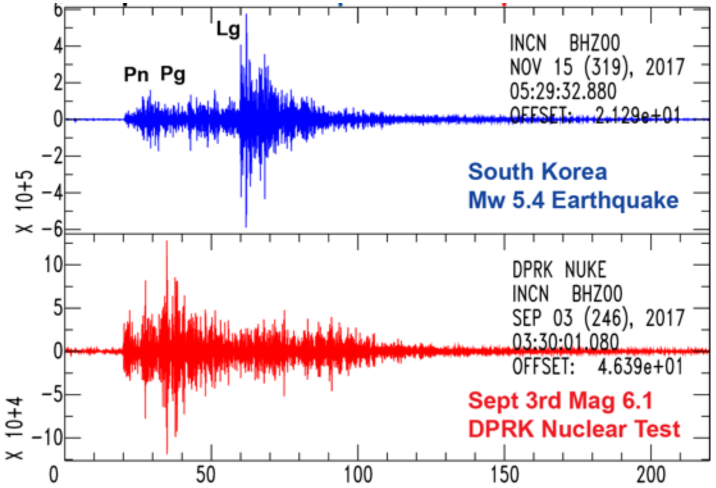
Motivation of current efforts: Discriminate between anthropogenic, natural & nuclear sources

Seismic measurements of historic nuclear tests have some limitations.
How do P/S ratios separate explosions from earthquakes and can we model this?

Declared DPRK nuclear test seismic signals at publicly available seismic station MDJ about 350 km north

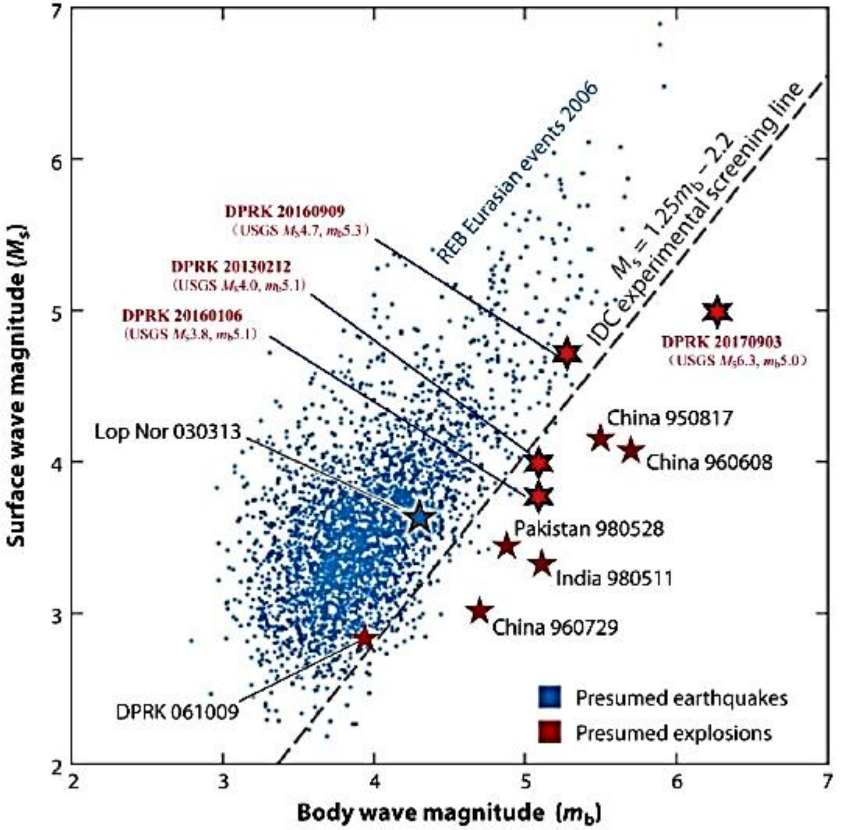


Comparison of Earthquake and Explosion at ICNCN



[Courtesy from William Walter]

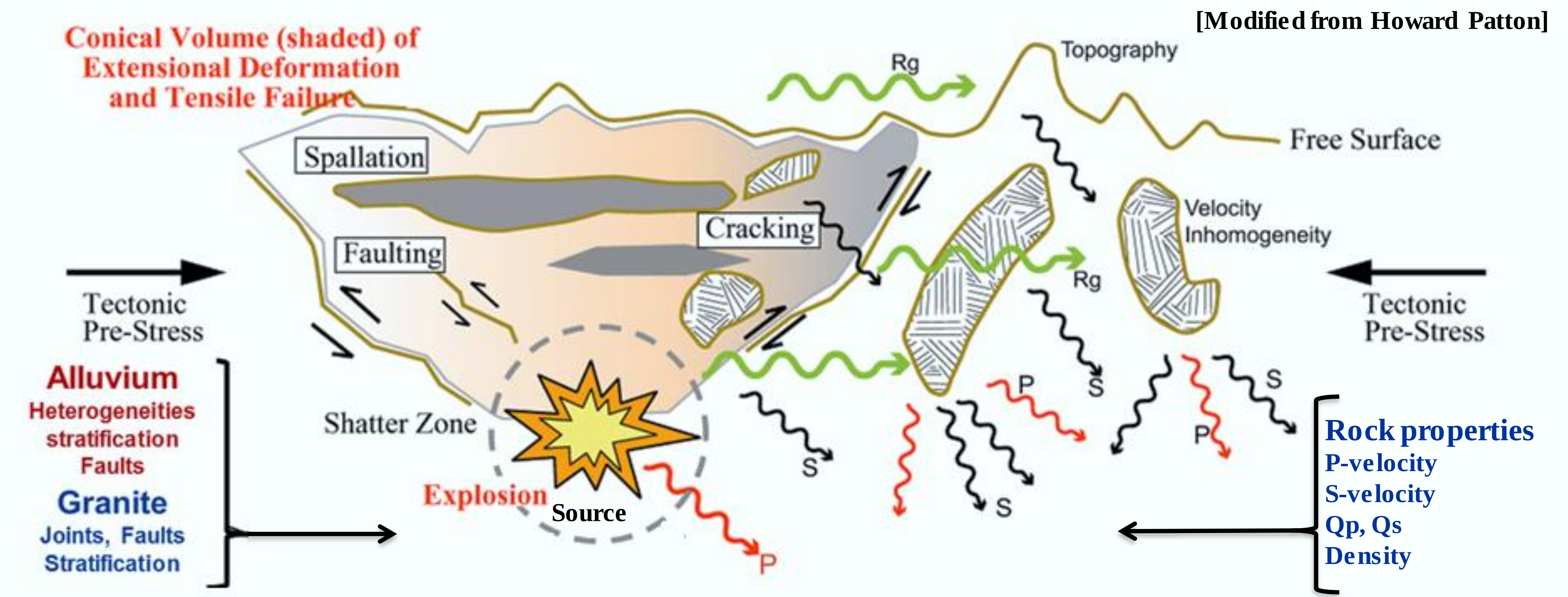
Properties of 3 seismic events in 09/2017 in the north Korean Peninsula from moment tensor inversion [Han et al. undated]



Continue exploring methodologies to improve earthquake-explosion discrimination using regional amplitude ratios such as P/S. Understand shear motion generation is a essential to building source models that predict P- & S- waves and their ratios.

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

[Modified from Howard Patton]



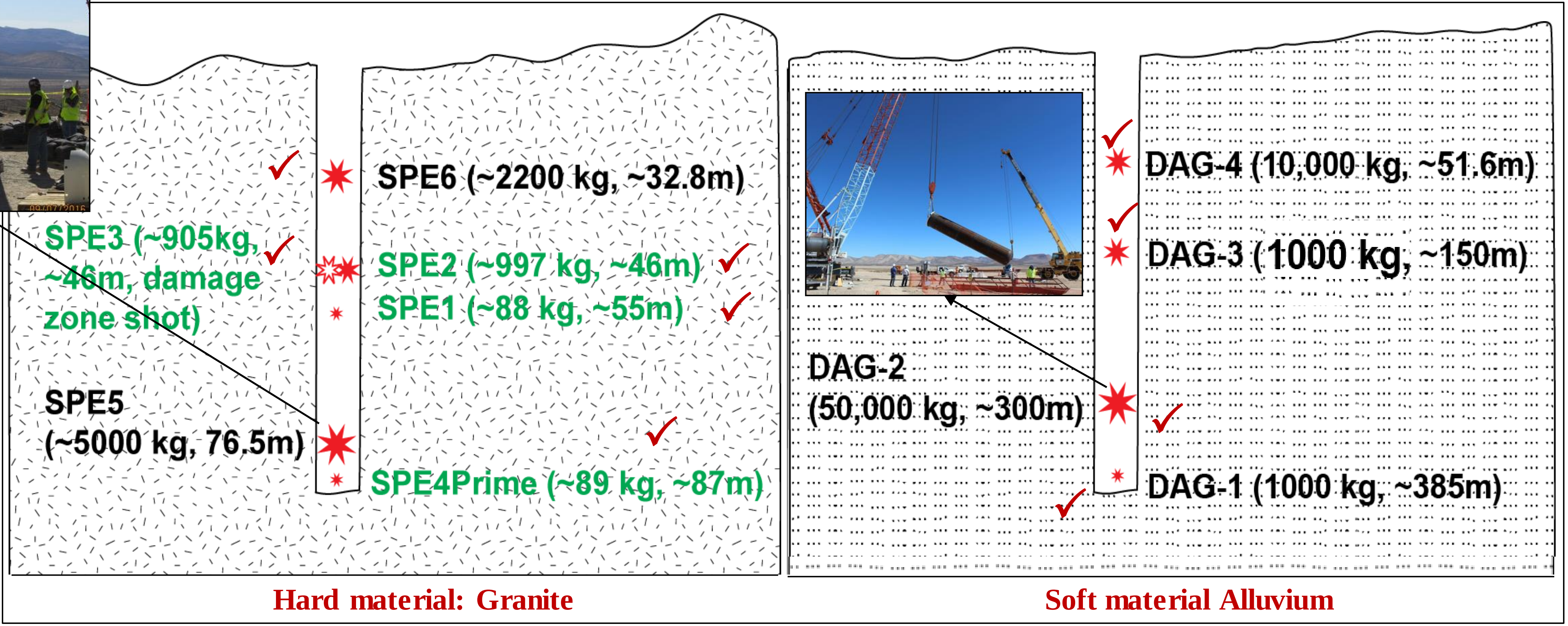
P= primary of compressional waves, S= secondary or shear waves, Rg= short-period surface waves

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).

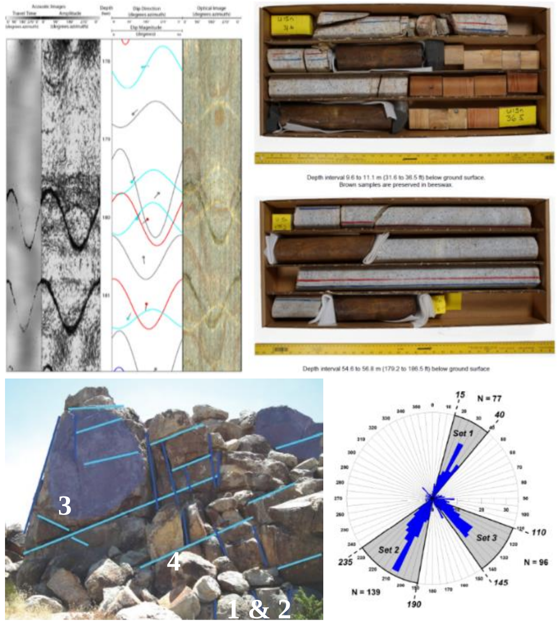
There 9 nuclear tests within 1 km of emplacement hole which is 96" diameter, 1400' deep drilled in 1983

Building Block: Structural, geomechanical & geophysical characterization of uncertainties

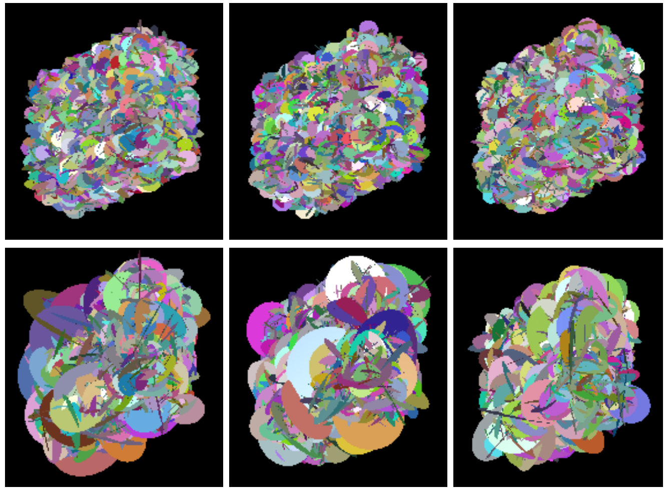
SPE Phase I (SPE) site characteristics ⟵ VS ⟶ SPE Phase II (DAG) site characteristics

- **Granite**
  - Fractures discontinuities
  - Fracture size
  - Density
  - Orientation…
  - Spatial variability of properties

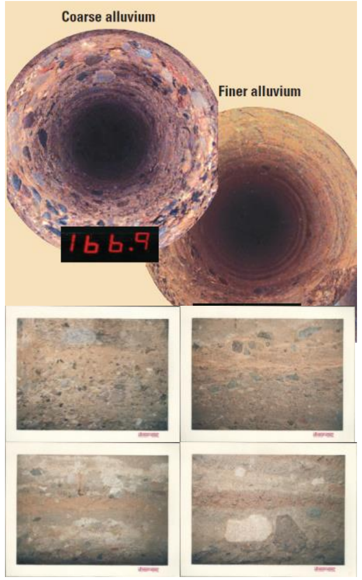
- **Alluvium**
  - Porous inclusions
  - Inclusion size
  - Connectivity (continuity)
  - Stratification…
  - Spatial variability of properties

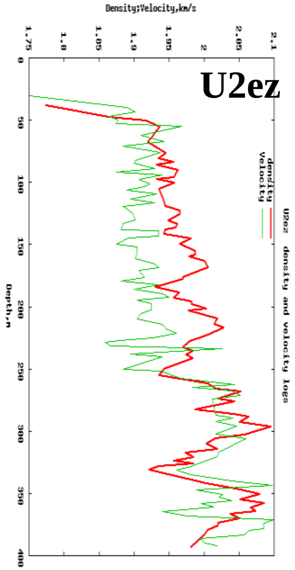


SPE I, geological observations

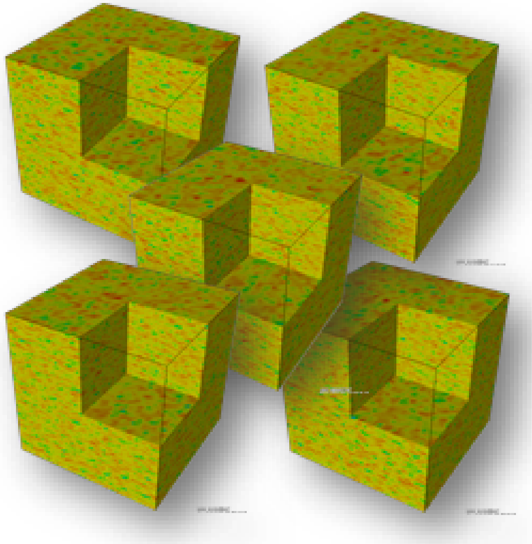


Synthetic fractured (jointed) media





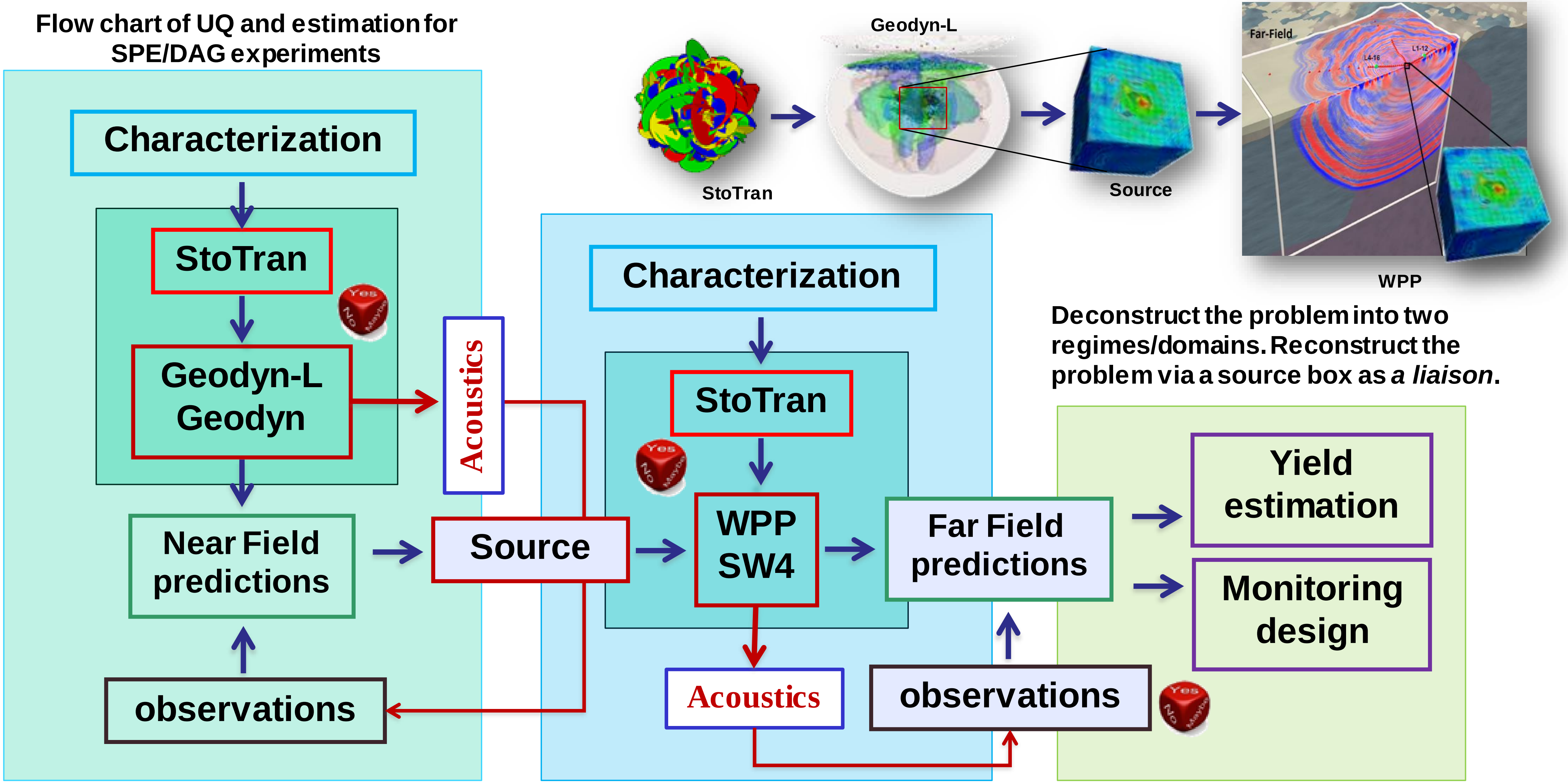
SPE II, Legacy U2EZ observations



Synthetic porous alluvial media

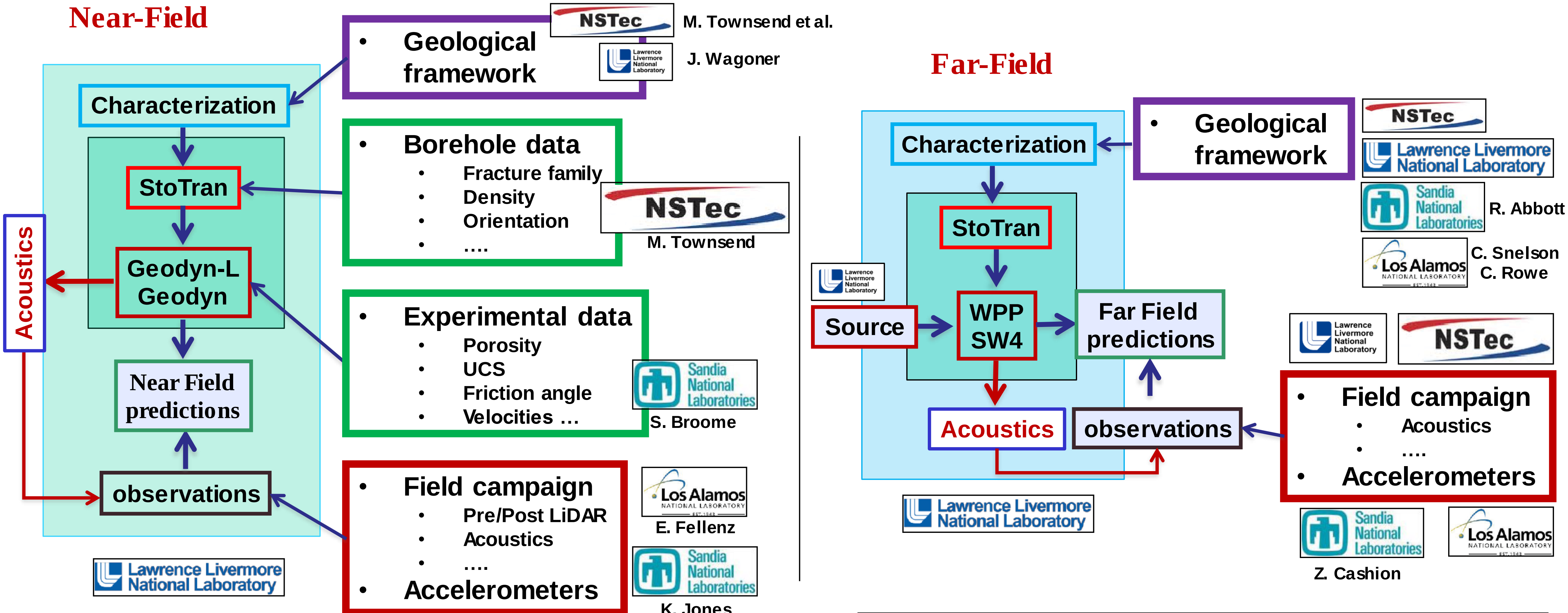
SPE modeling framework to simulate & predict under conditions of uncertainty

Flow chart of UQ and estimation for SPE/DAG experiments



Deconstruct the problem into two regimes/domains. Reconstruct the problem via a source box as *a liaison*.

SPE involves coordinated team efforts & model updates as data become available



The process of model updates as data become available has been proven fruitful when we executed DAG1, DAG2 etc

SPE ≤ 5

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

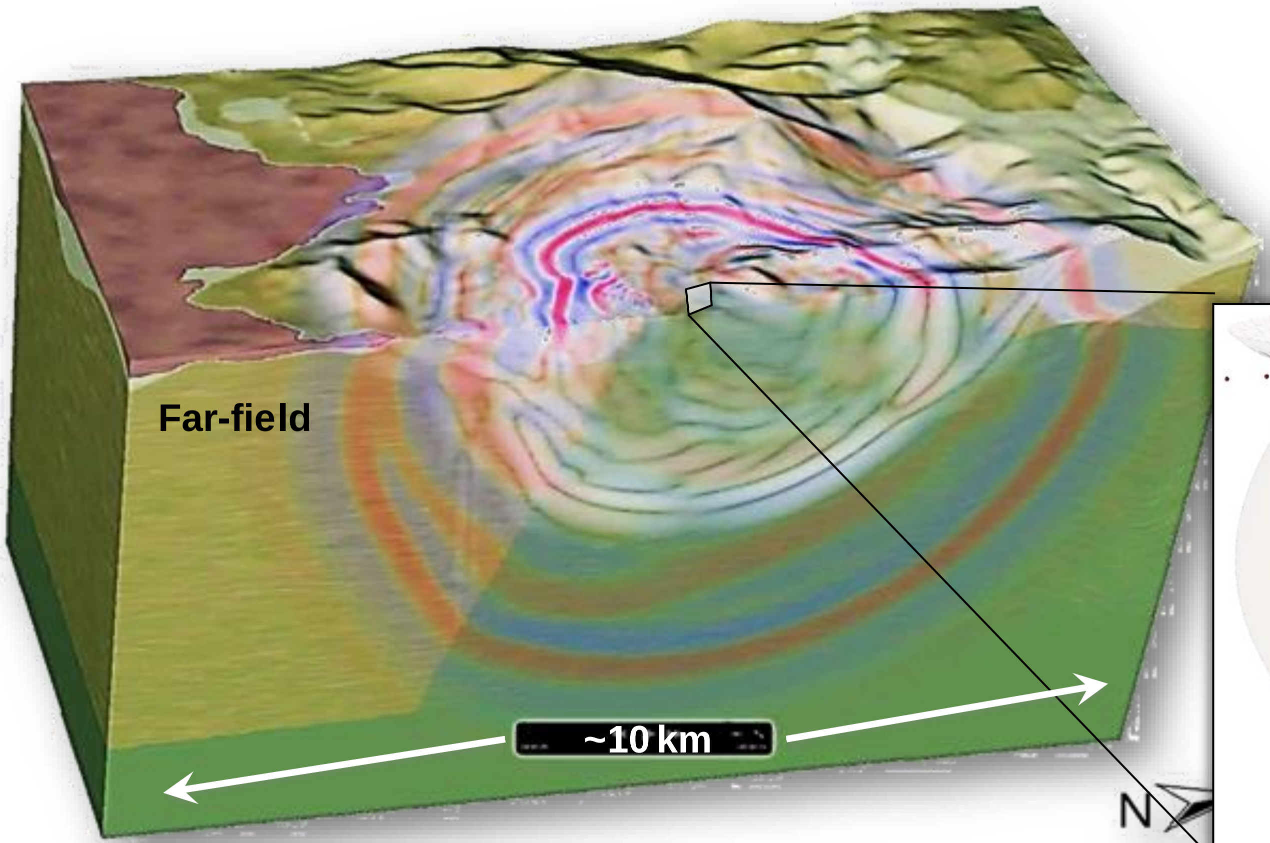
Typical dimensions
- joint aperture ~1 mm
- joints spacing ~1 m
- source size ~1 m

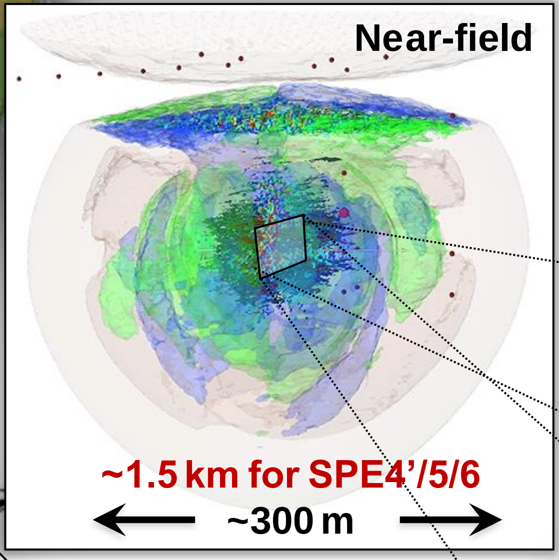
Resolution requirements
- ~ 20-50 million elements
- ~ 100-200 million zones

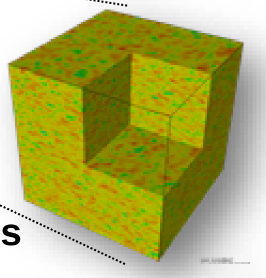
Uncertainty propagation
- ~ 500s runs a set
- ~ 10s of parameters

HPC requirements
- ~ 10% of one cluster
- ~ 17% of temp storage
- ~ 3.5 Million CPU-Hrs

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







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

SPE4'/5/6

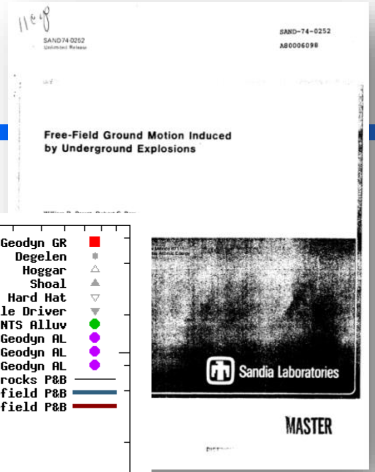
2200 CPU x 12 HRS = 26,400 CPU-HRS

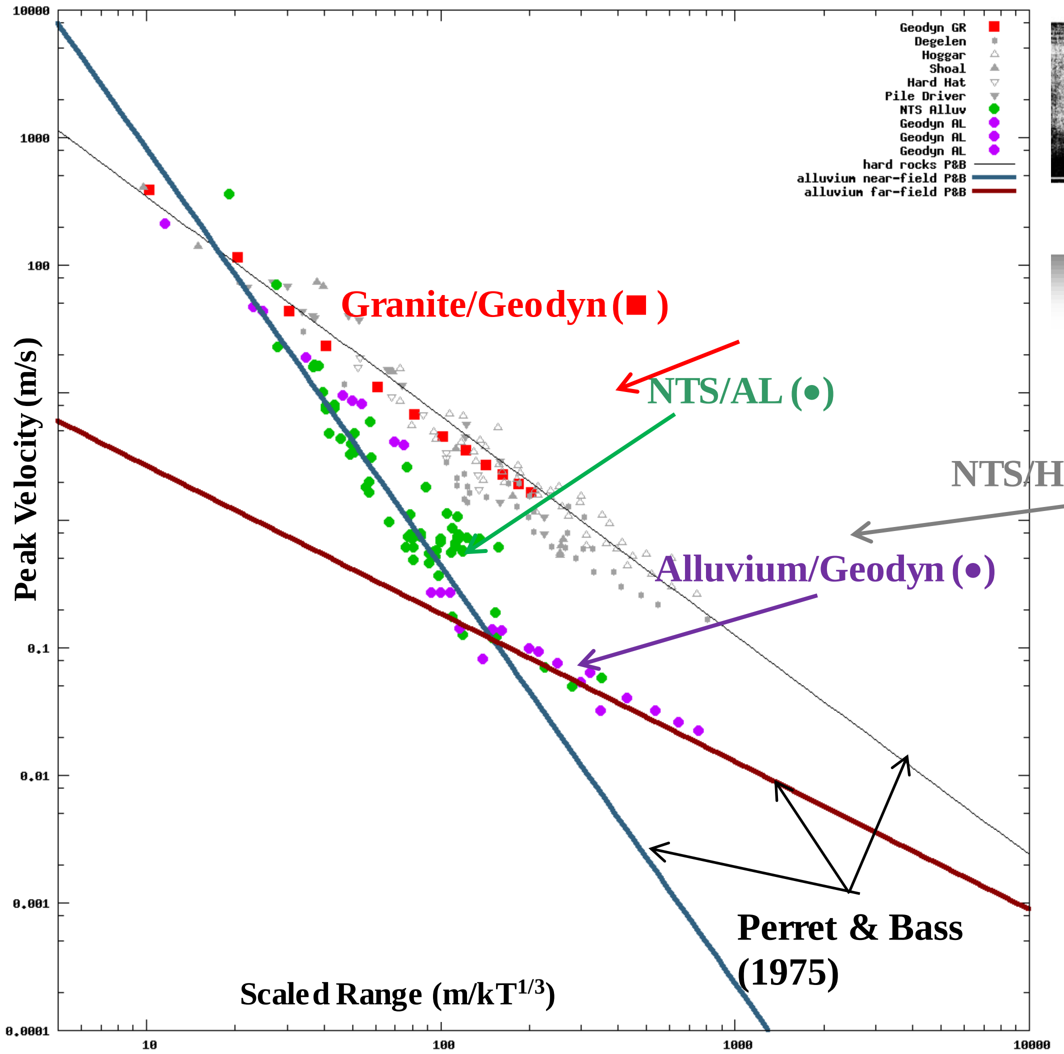
3200 CPU x 16 HRS = 38,400 CPU-HRS

Repeated several times for uncertainty quantification

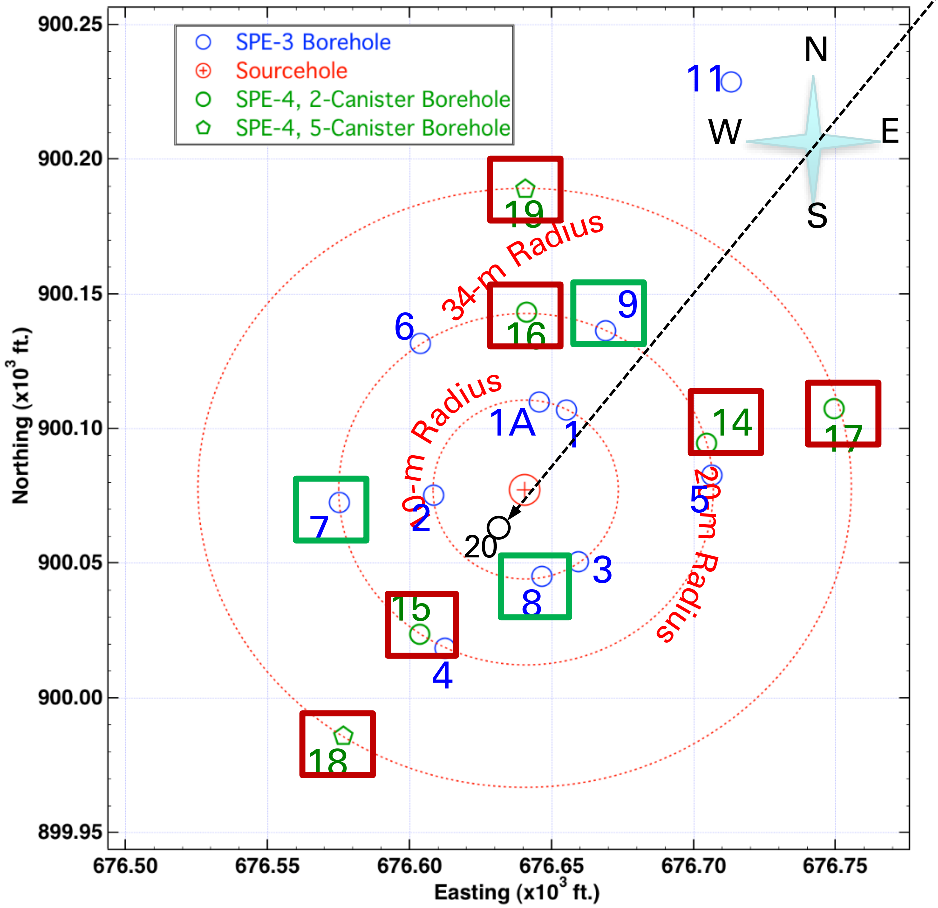
Geodyn MM calibration to NTS (NNSS)

- 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

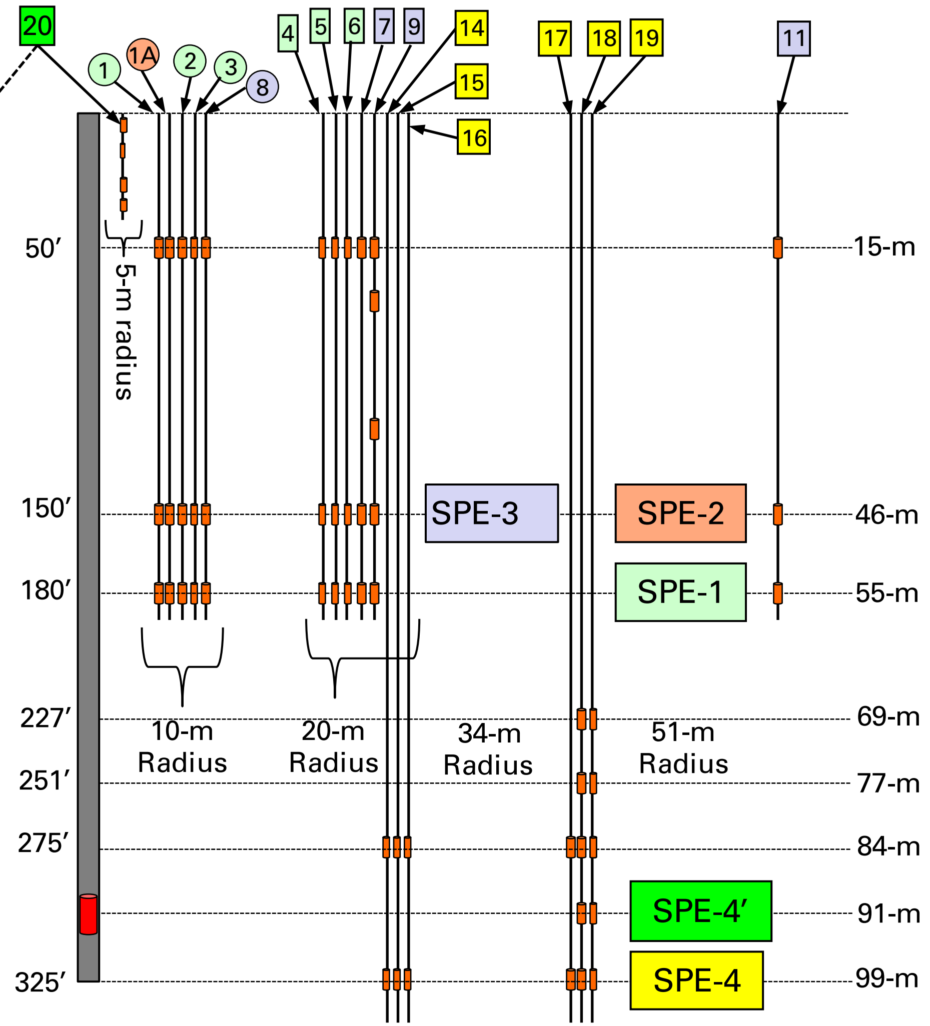




SPE1-5 instrumentation and gage locations



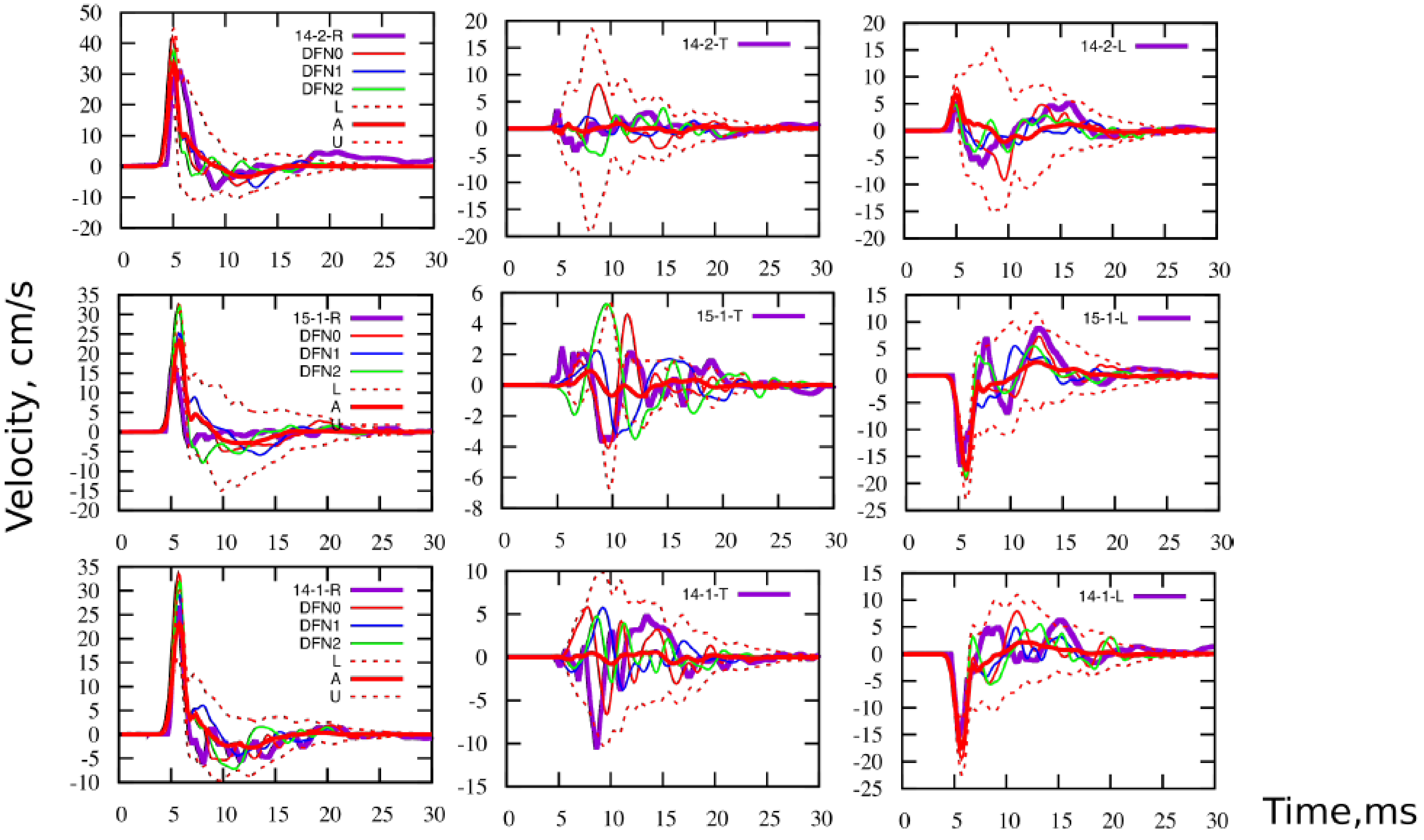
Focus on SPE4' and SPE5



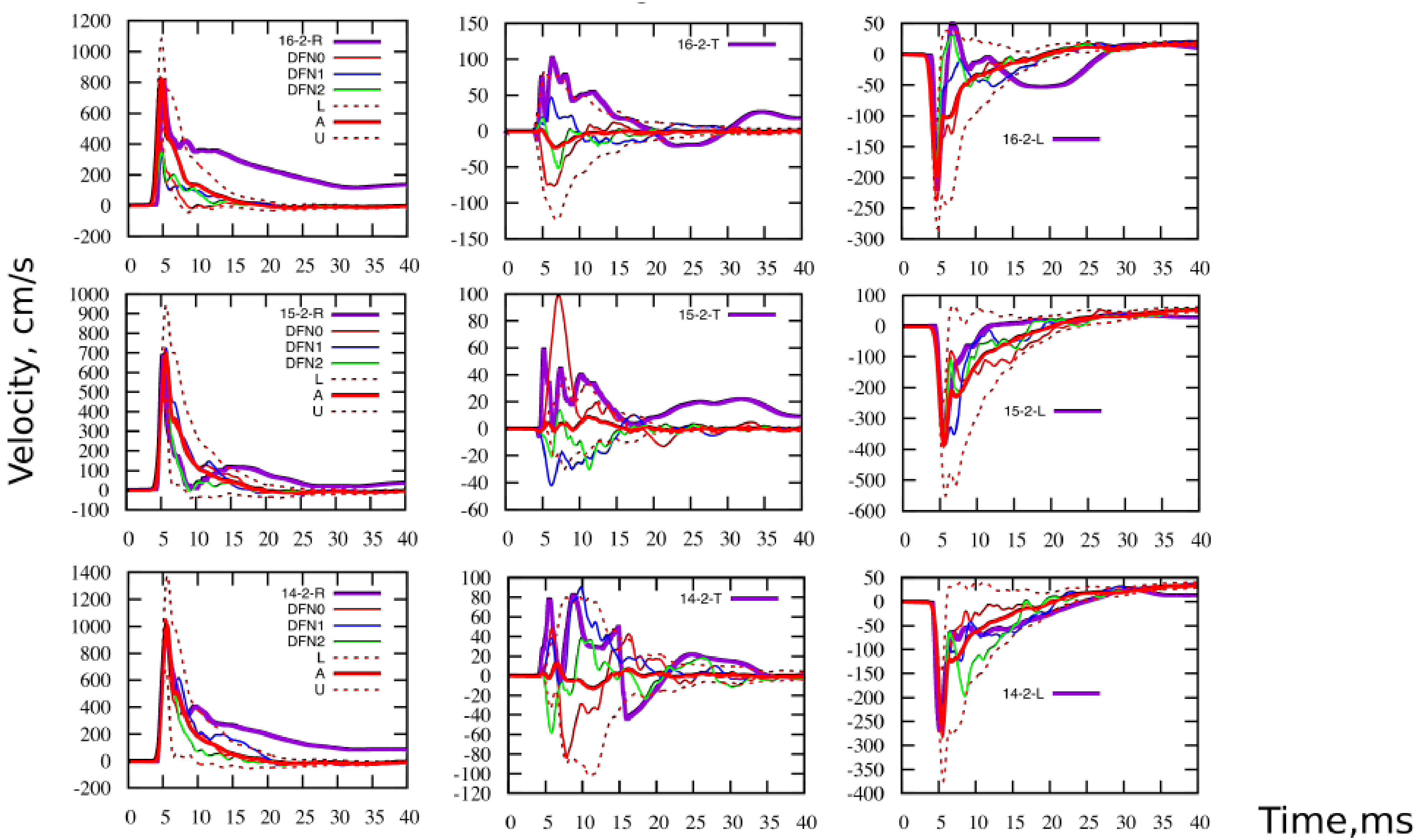
Side Radial Cross-section View

Courtesy of NSTEC, DTRA & LANL

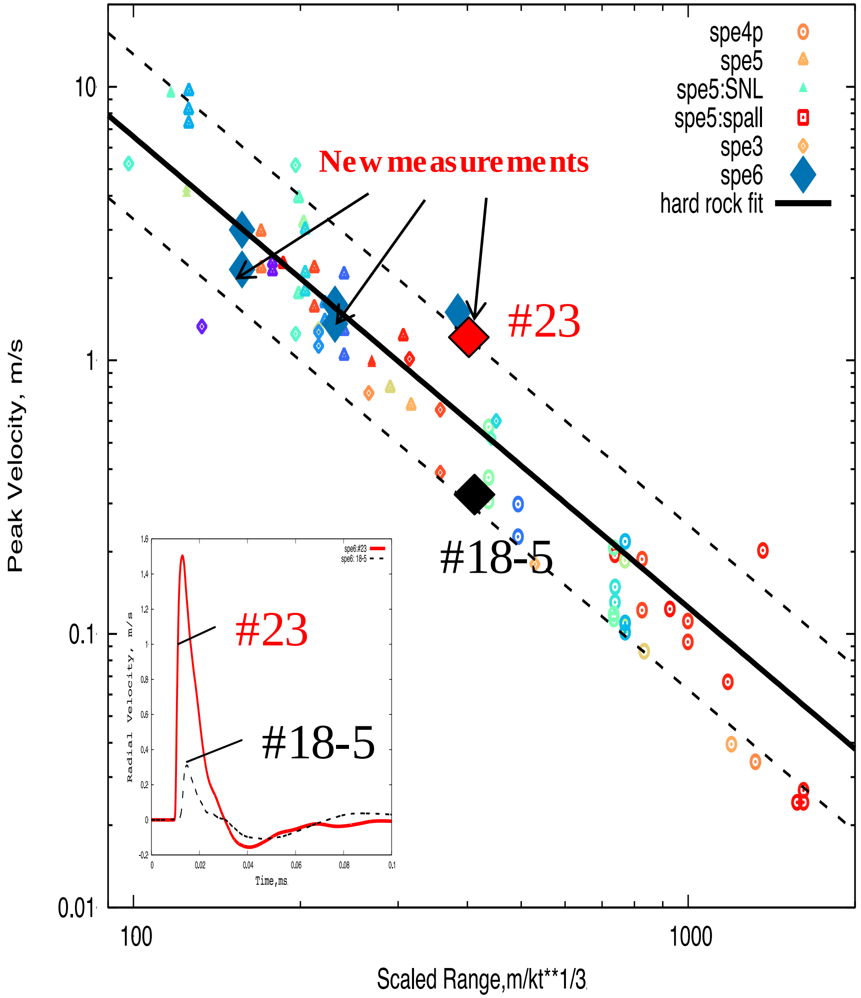
Example of SPE4P predictions complete data sets



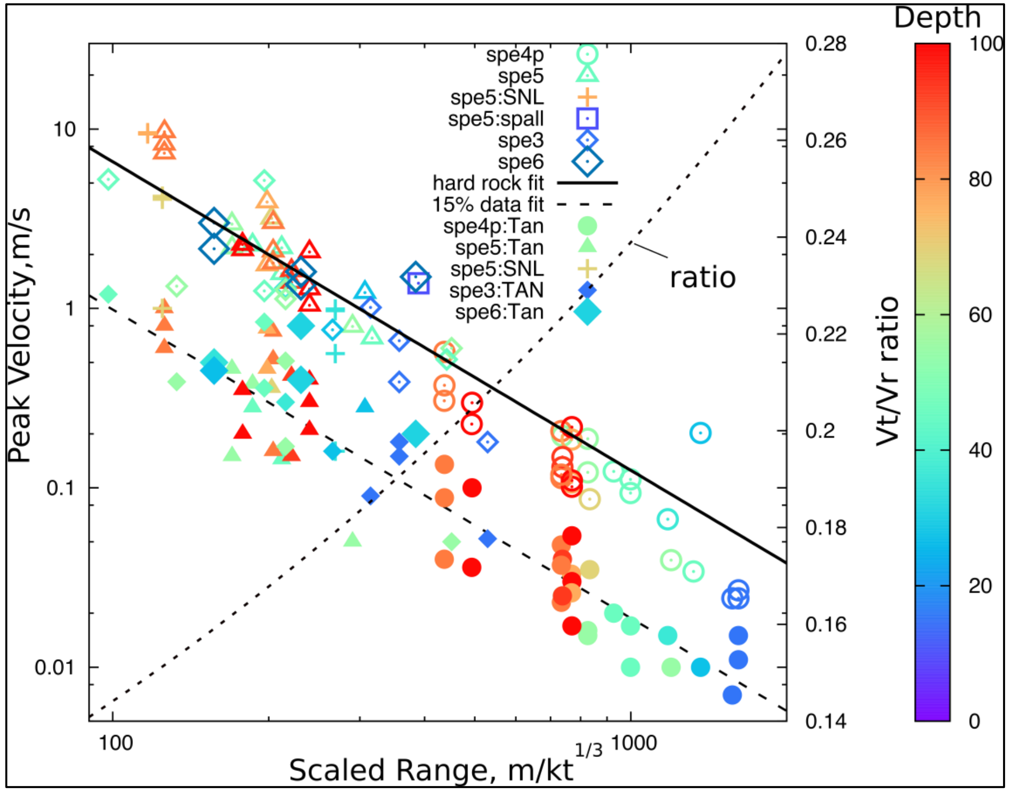
Example of SPE5 predictions complete data sets



SPE6 Peak velocity attenuation in agreement with previous SPE shots



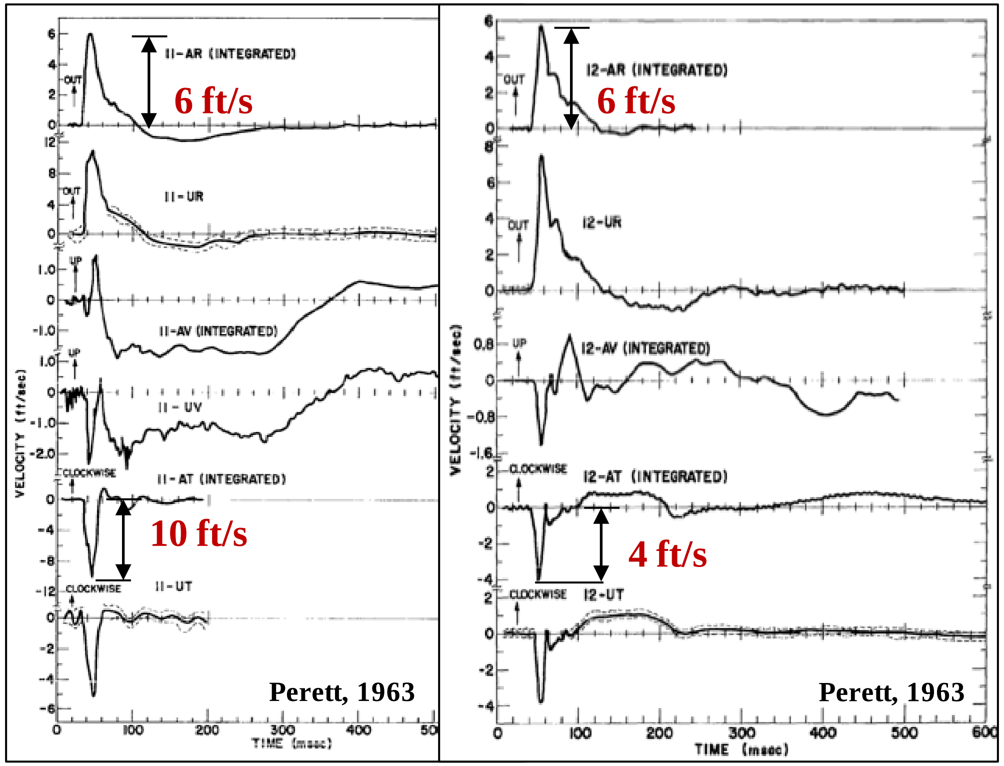
Radial & tangential motions

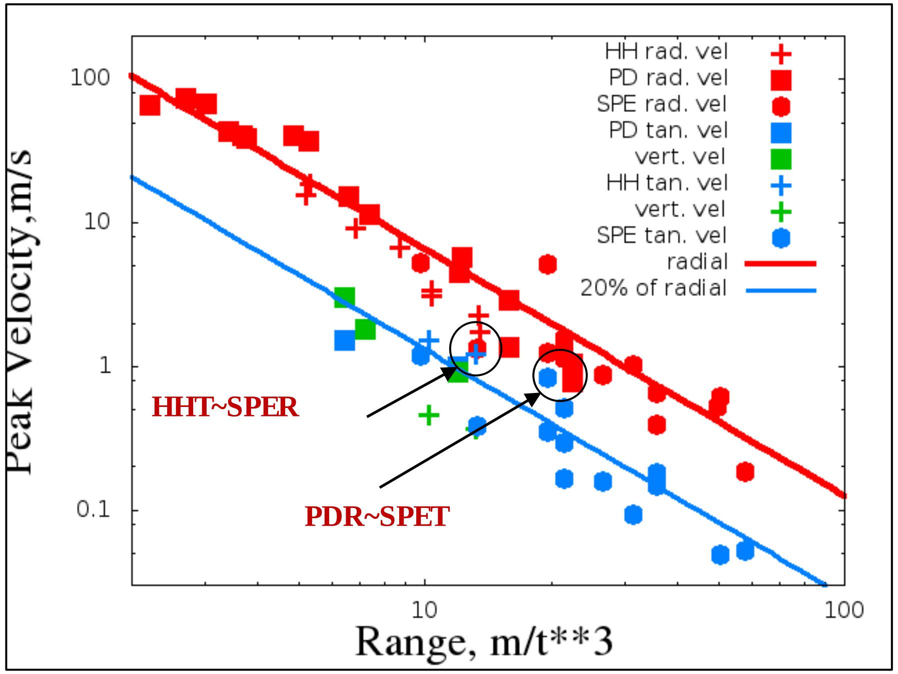


T/R ratio increases with scaled range

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

SPE6 is the shallowest shot in the SPE-I series.
SPE6 compares well with Legacy shots

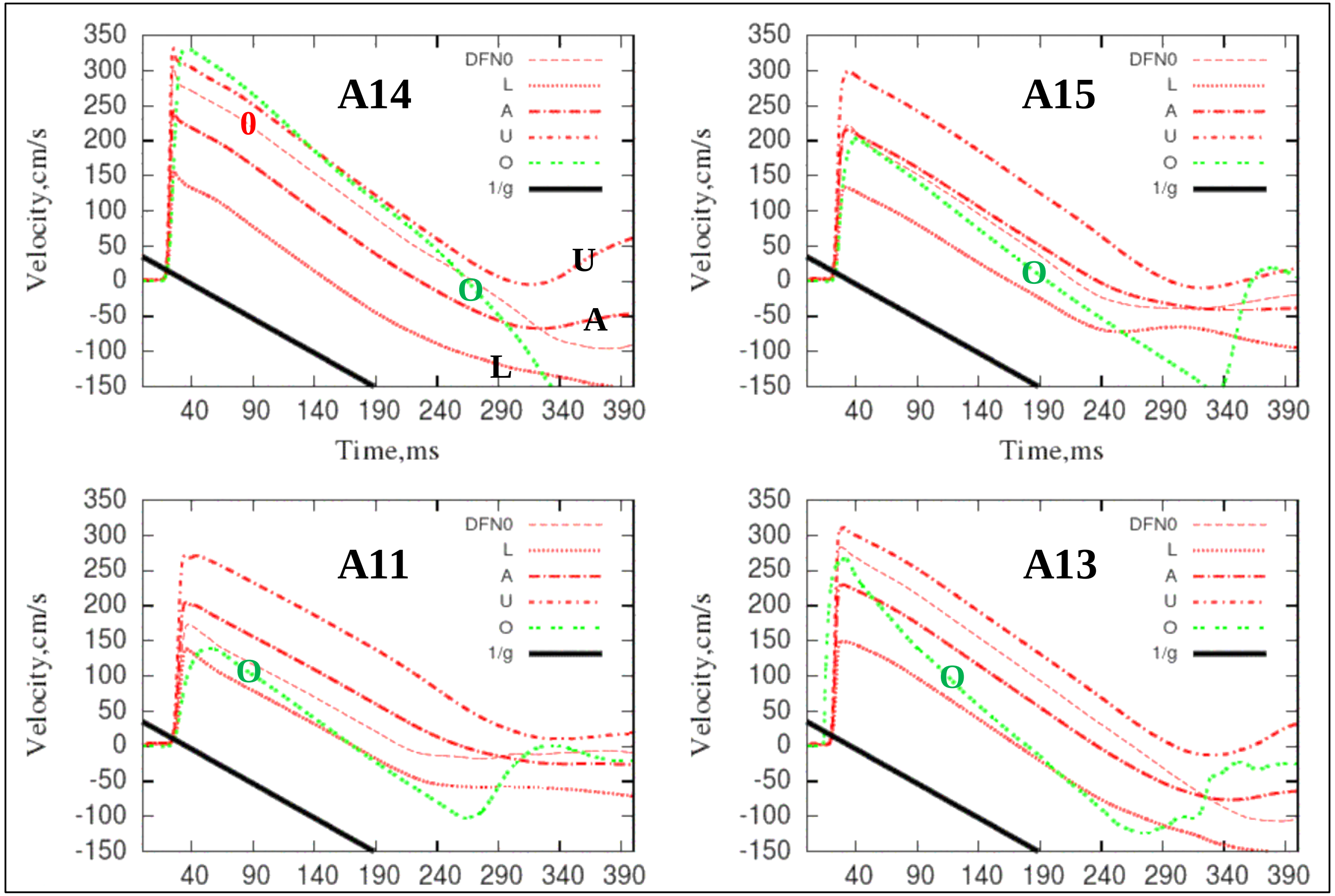


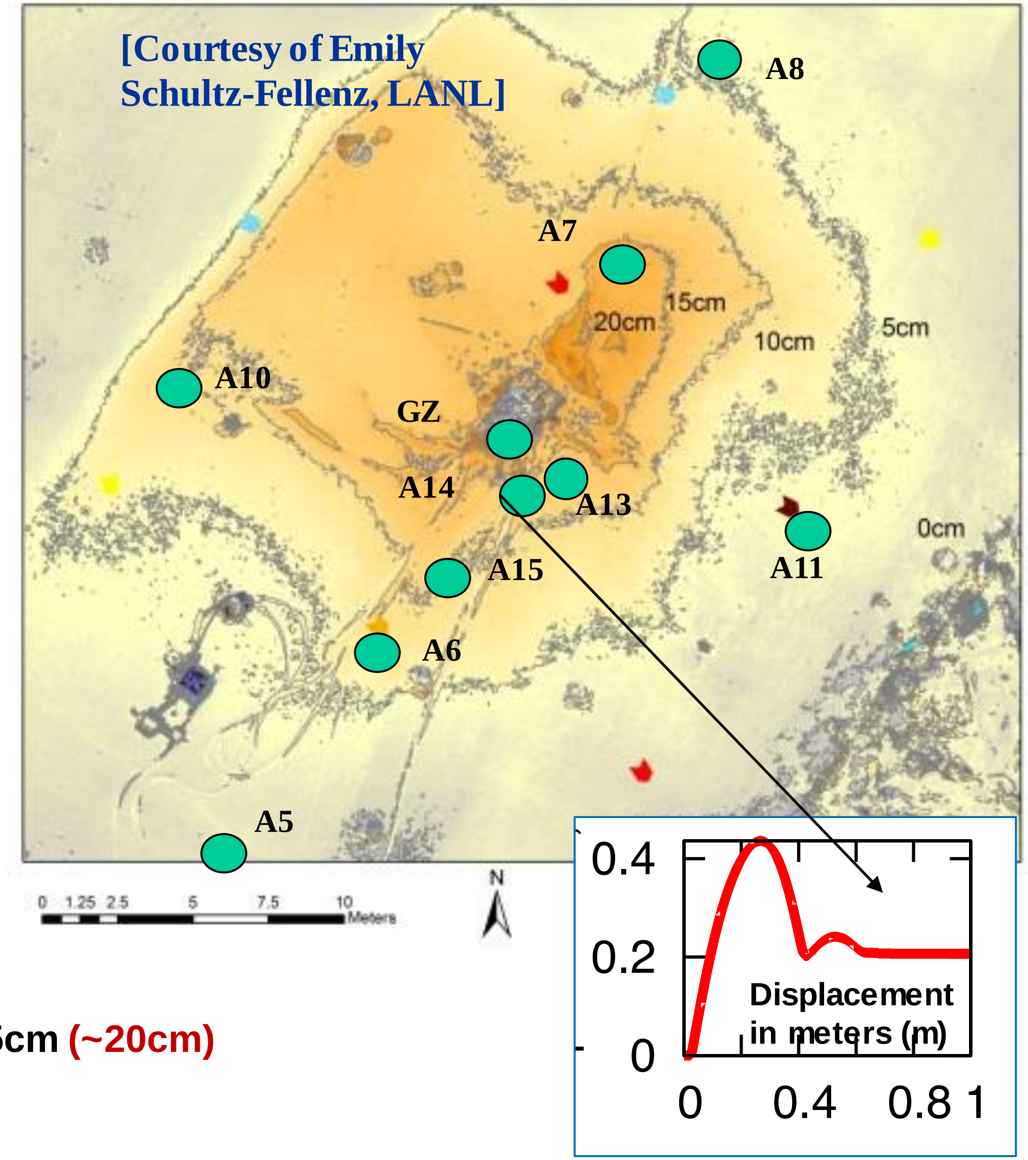


PD ~12m/kT$^{1/3}$; HH ~16m/kT$^{1/3}$ & SPE6 24m/kT$^{1/3}$

Historical data (e.g. HH B11 & B12) shows T motions ~ R motions
Similar high T-motions where observed in other geological settings
SPE6 is the 'only' shallow shot in the series, we ought to conduct more shallow shots to:
a) explore the unusual observations,
b) challenge scaling laws and, more importantly,
c) explore effects of weathering and layering on the overall response of the system

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

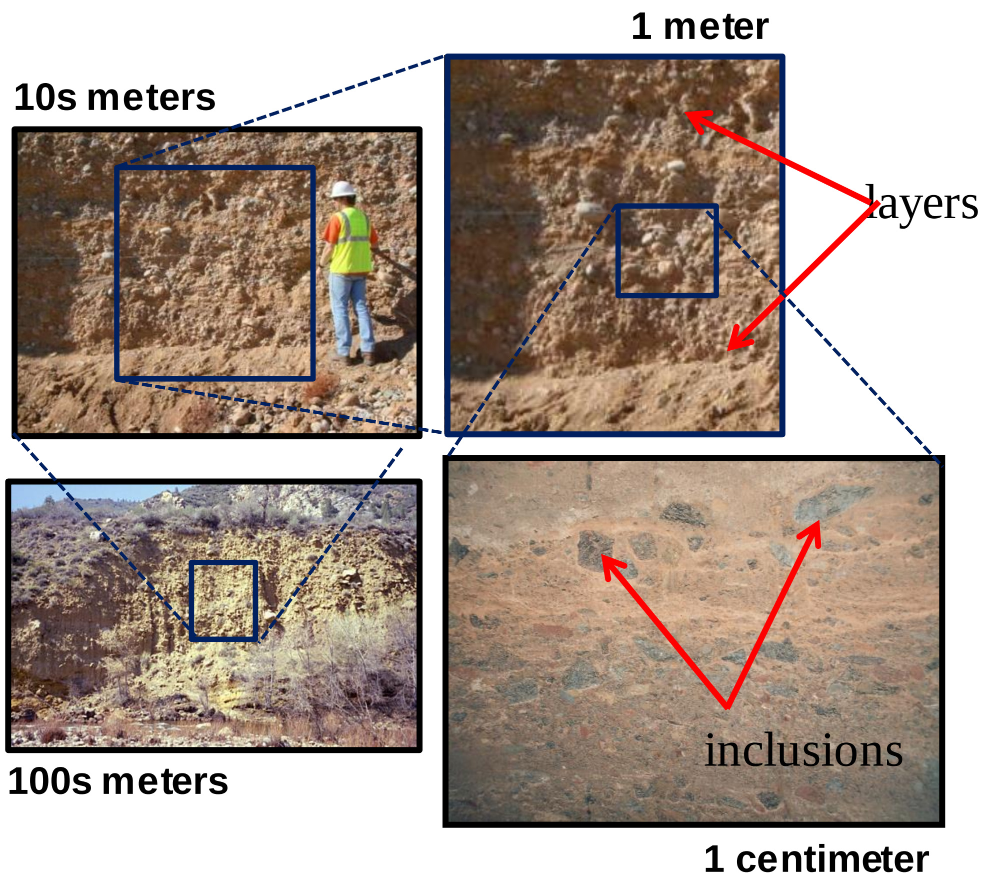




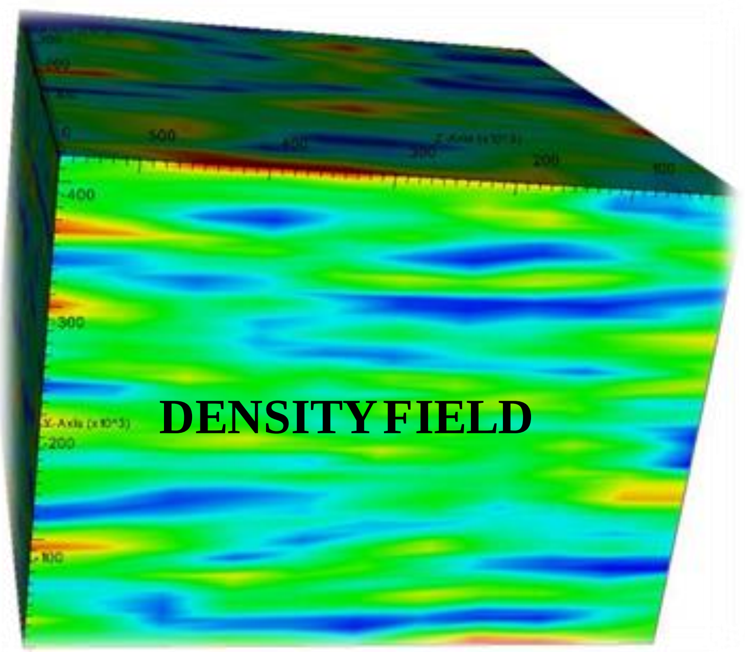
- Peak acceleration is ~100 Gs +/- ~30 Gs
- Peak velocity is 3.5 m/s +/- 1.25 m/s
- Peak displacement 27 cm +/ 9 cm (~40cm)
- Residual displacement 15 cm +/- 5cm (~20cm)
- Spall zone ~ 40-100 m (<60m)

Alluvium displays a hierarchy of scales of variability of the geophysical attributes

Alluvium encompasses a hierarchy of scales of variability

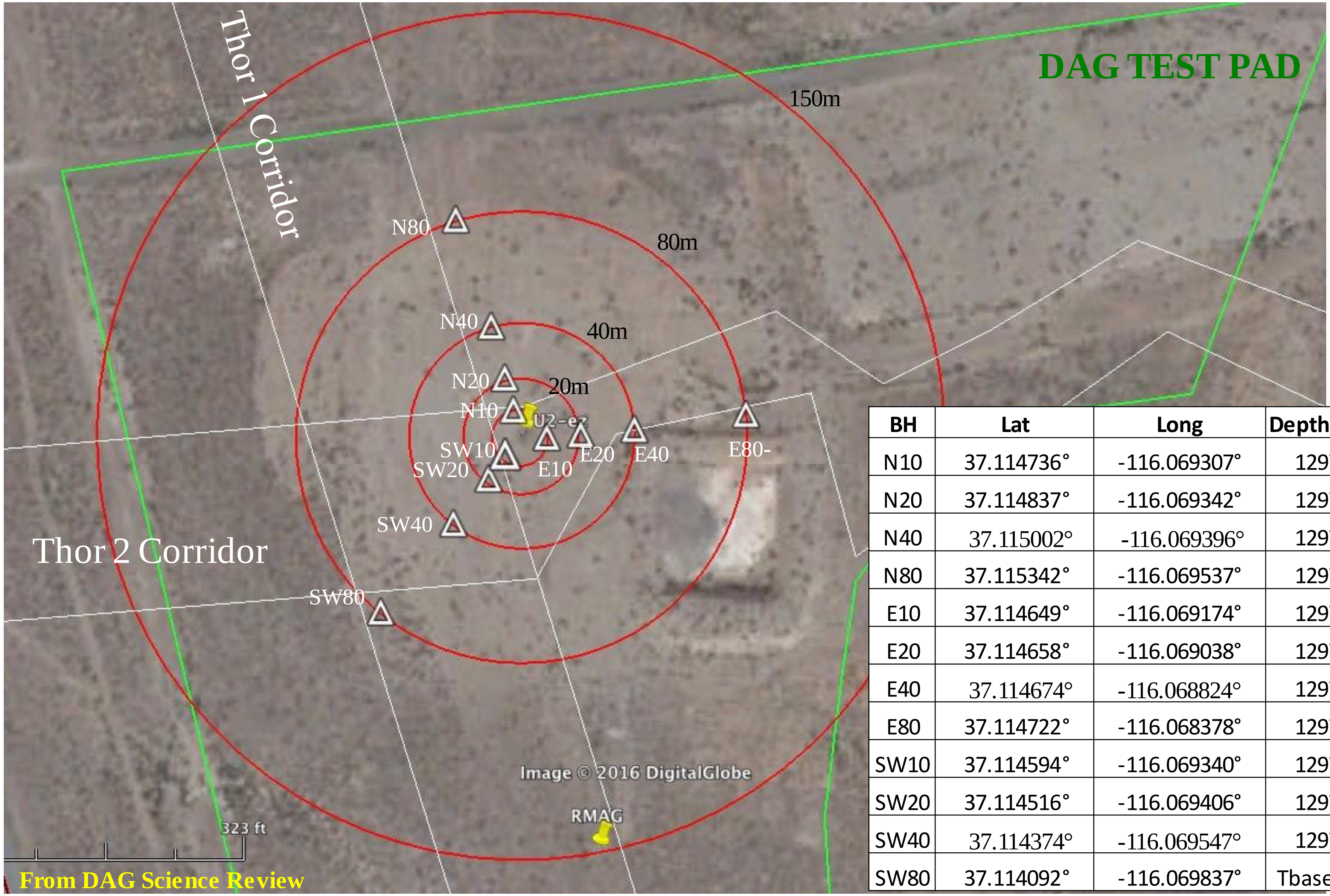


Example of a Geodyn parameterization of density in the vicinity of U2EZ

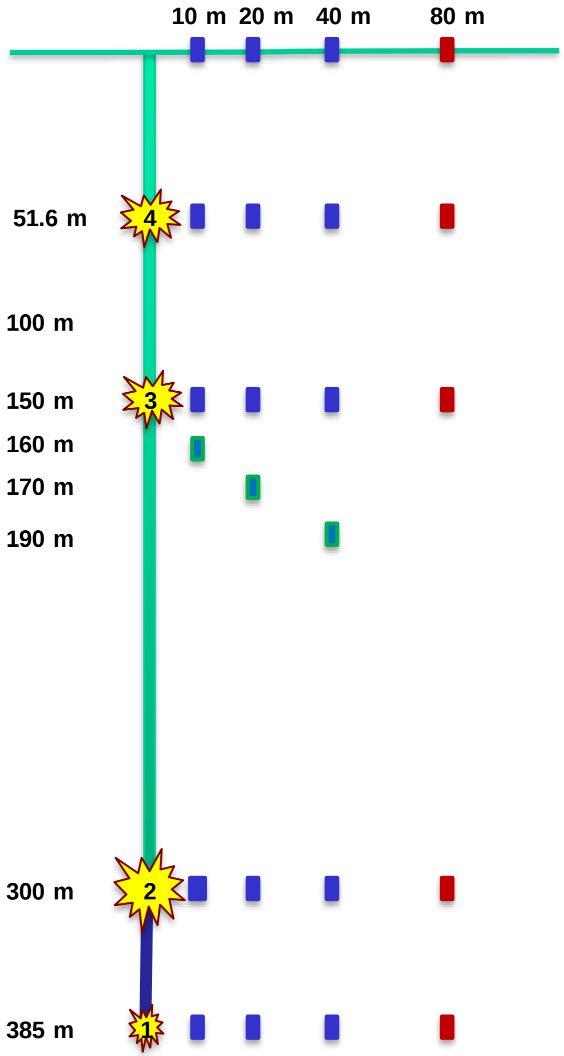


Simple approach: two materials, one is weak alluvium (A) the other one is strong (B)
Realistic approach: continuum parameterized alluvium model which describes both A and B and everything in between

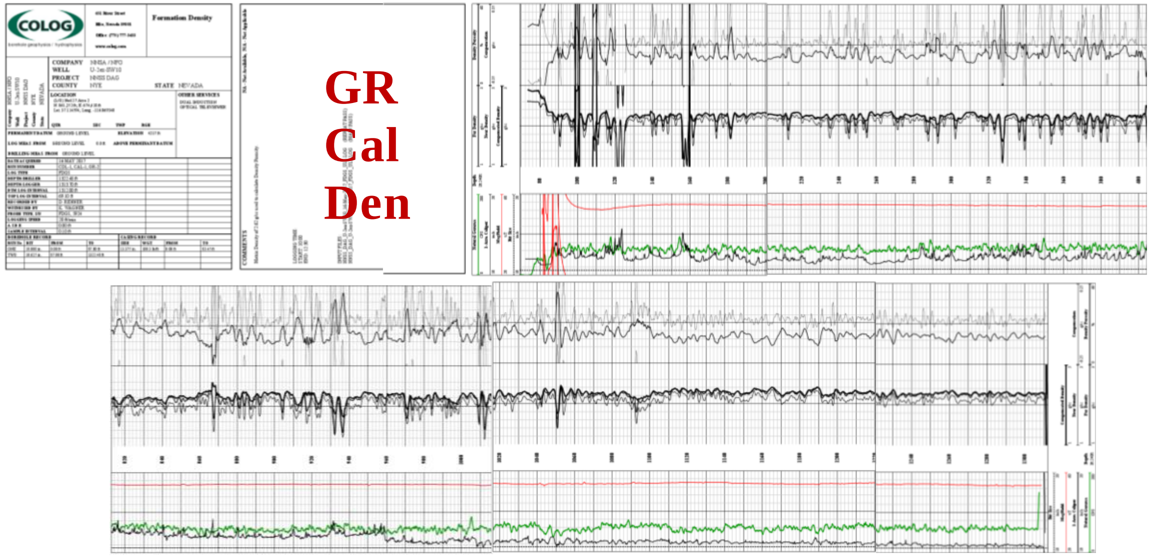
Final Drilling PLAN: as of DEC 24, 2016

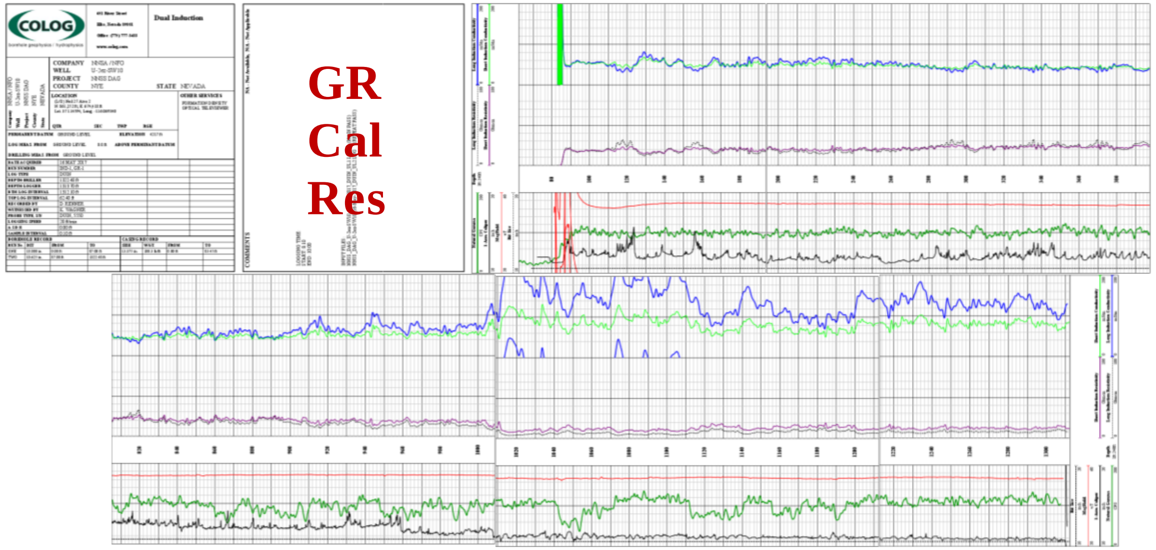


BH	Lat	Long	Depth (ft)
N10	37.114736°	-116.069307°	1297
N20	37.114837°	-116.069342°	1297
N40	37.115002°	-116.069396°	1297
N80	37.115342°	-116.069537°	1297
E10	37.114649°	-116.069174°	1297
E20	37.114658°	-116.069038°	1297
E40	37.114674°	-116.068824°	1297
E80	37.114722°	-116.068378°	1297
SW10	37.114594°	-116.069340°	1297
SW20	37.114516°	-116.069406°	1297
SW40	37.114374°	-116.069547°	1297
SW80	37.114092°	-116.069837°	Tbase..*



Density, Gamma Ray & Resistivity (e.g. SW10)





Thanks to Maggie Townsend (MSTS)

- Full characterization of all 12 wells
- Caliper
- Gamma Ray
- Density
- Resistivity
- High resolution

Using the new well characterization

- Directional spatial variability
- Horizontal spatial variability
- Single variable vs. multiple

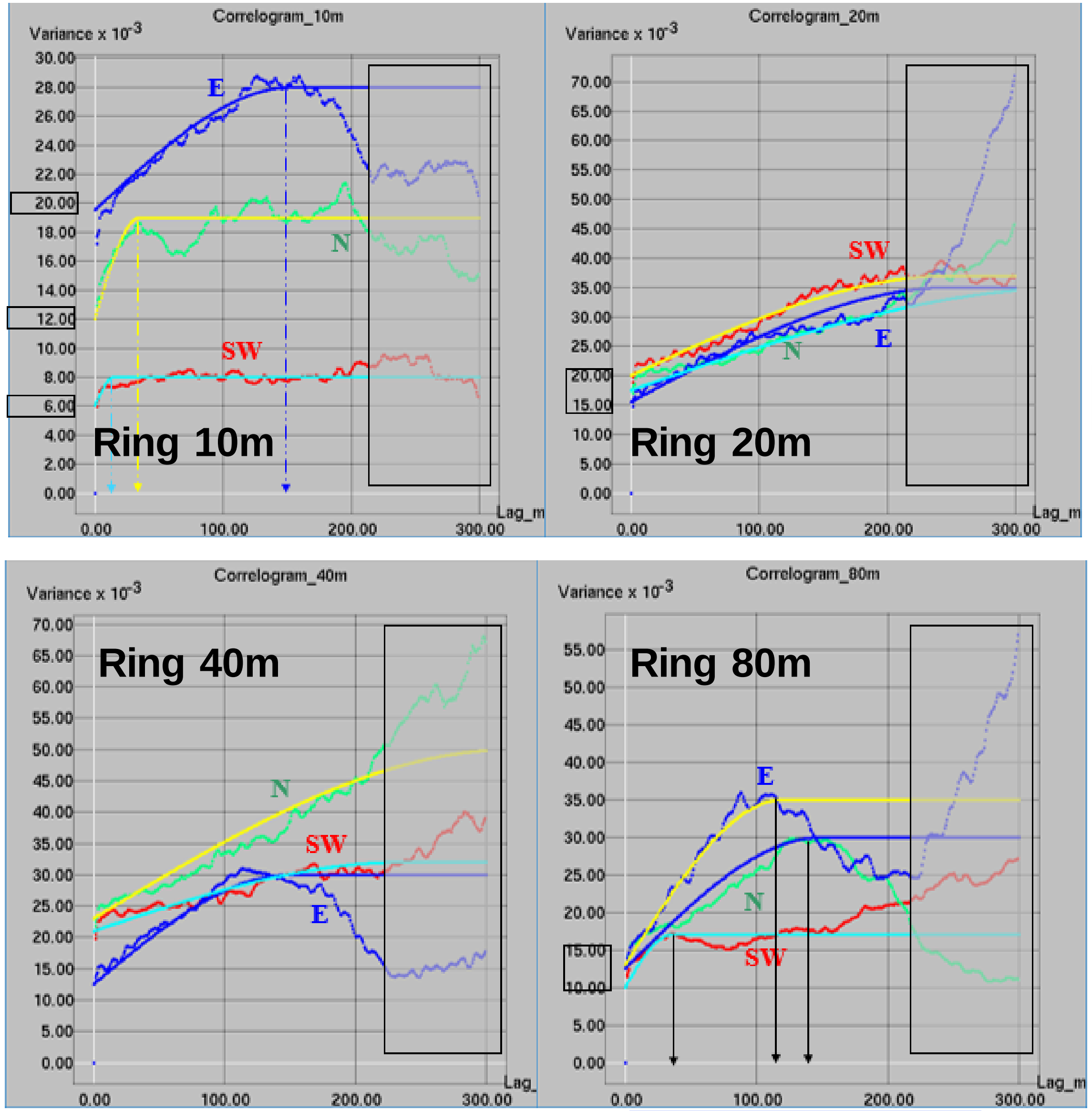
We started building the step stone of our simulation framework

- Bayesian stochastic generation of variable of interest (e.g. Ezzedine '90s, '00s)
- Judicious sampling methods of the probabilistic space
- Alluvium bring several challenges

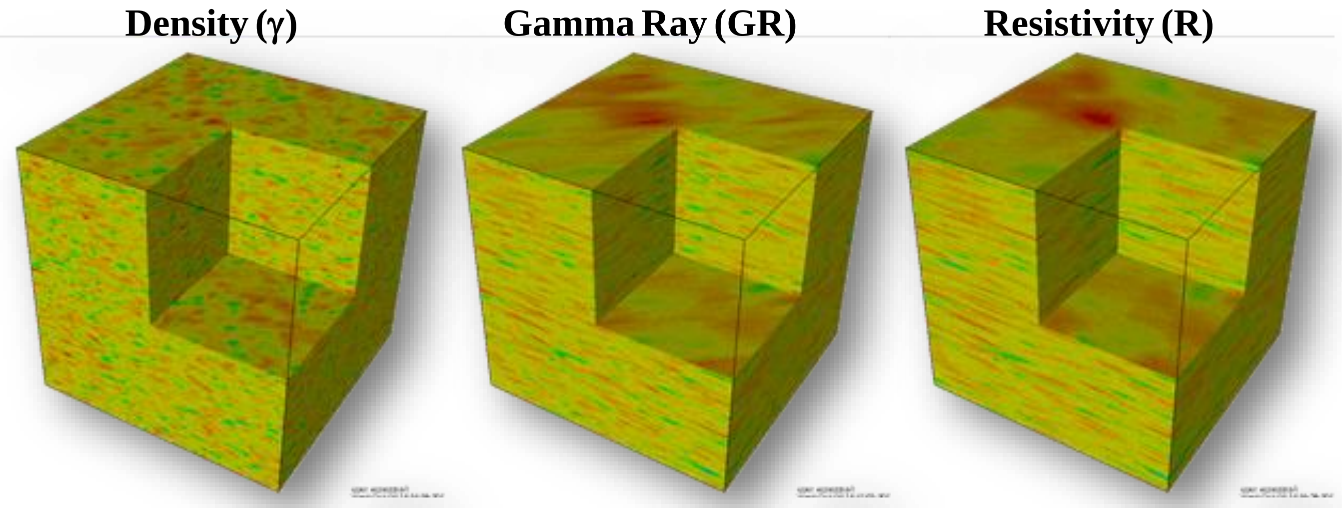
Our goals

- Minimize aleatoric uncertainties to single the epistemic ones
- Enhance codes for UNE monitoring

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



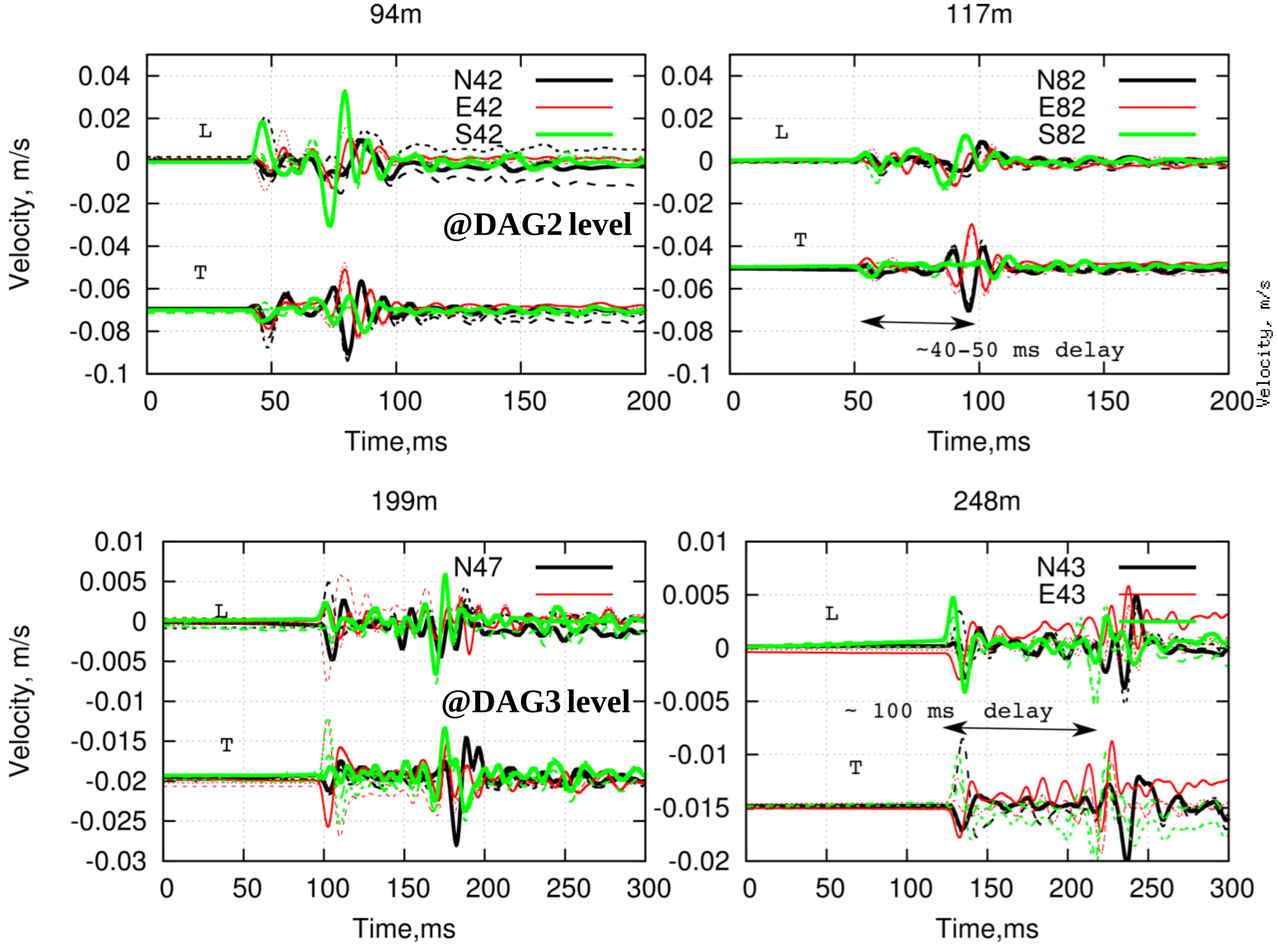
10m Ring: Strong anisotropy between directions (spherical to affine-like)
20m Ring: Isotropy between directions (strong affine-like)
40m Ring: Isotropy between N/SW affine-like in E direction
80m Ring: Almost isotropy between N/E spherical in SW direction



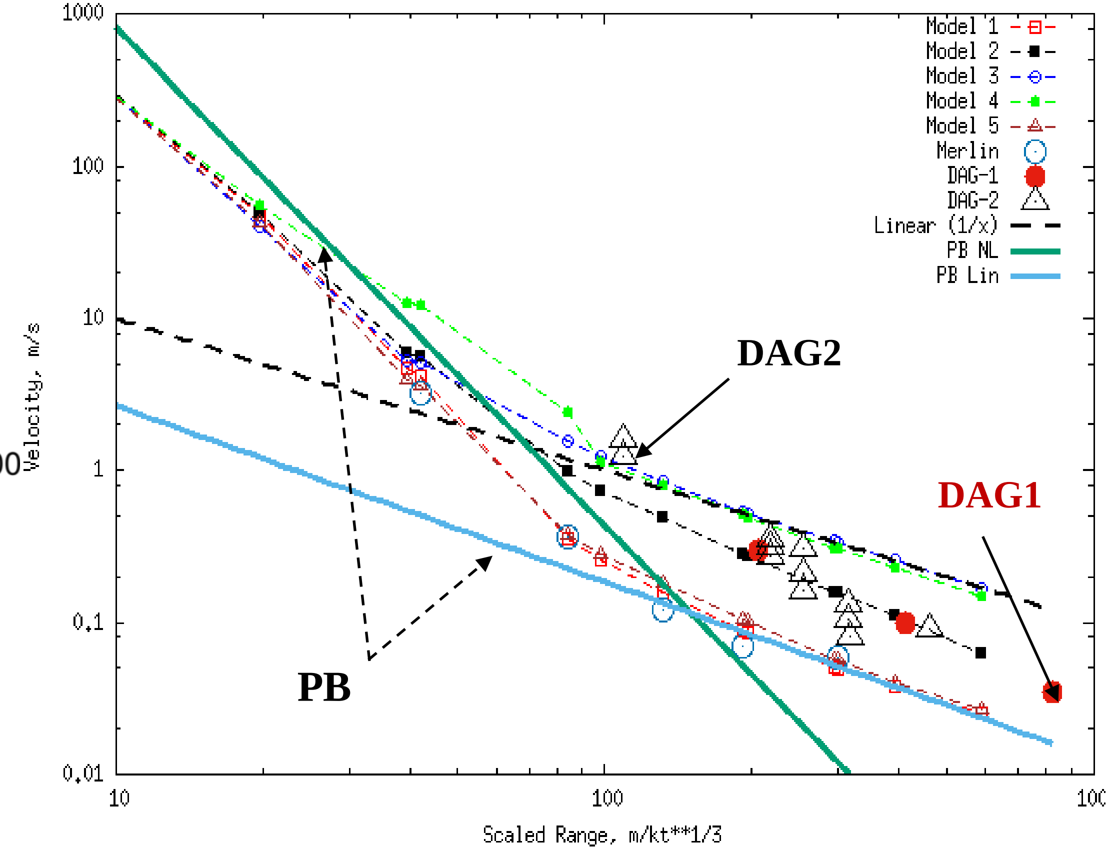
$\lambda_\gamma \leq \lambda_{GR} \leq \lambda_R$

- There is a hierarchy of scales between Density, Gamma Ray and Induction Resistivity
- Nested scale $\lambda_\gamma \leq \lambda_{GR} \leq \lambda_R$: higher continuity between R lenses than GR lenses than density
- We will use Joint Probability Distribution (of all 3) to generate conditional simulations (of all 3) for NF wave simulations and predictions
- All data is honored at each location which 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'.



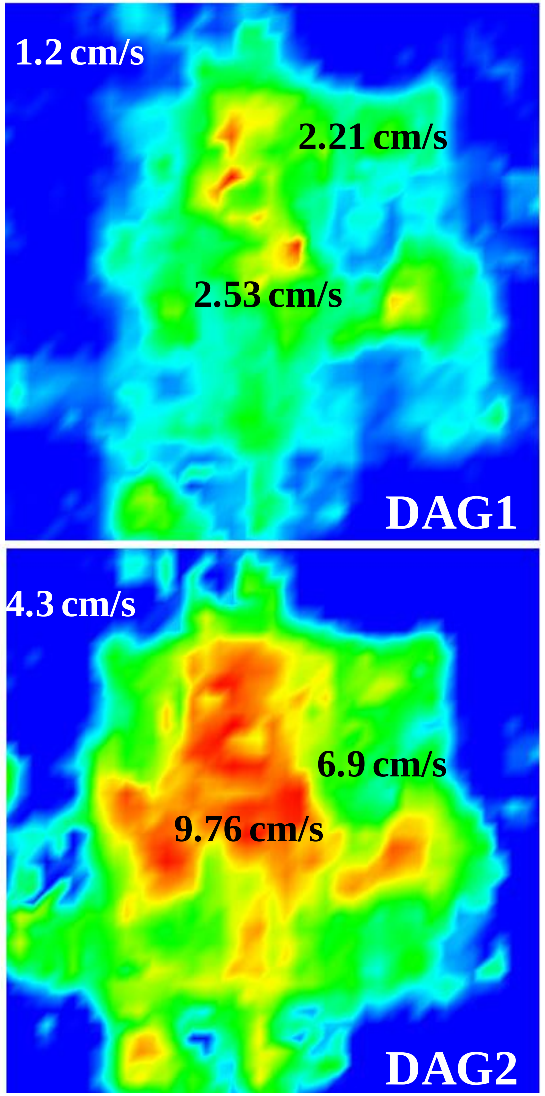
DAG1 velocities registered at DAG2 & DAG3 shot levels showed delayed shear wave arrivals



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)

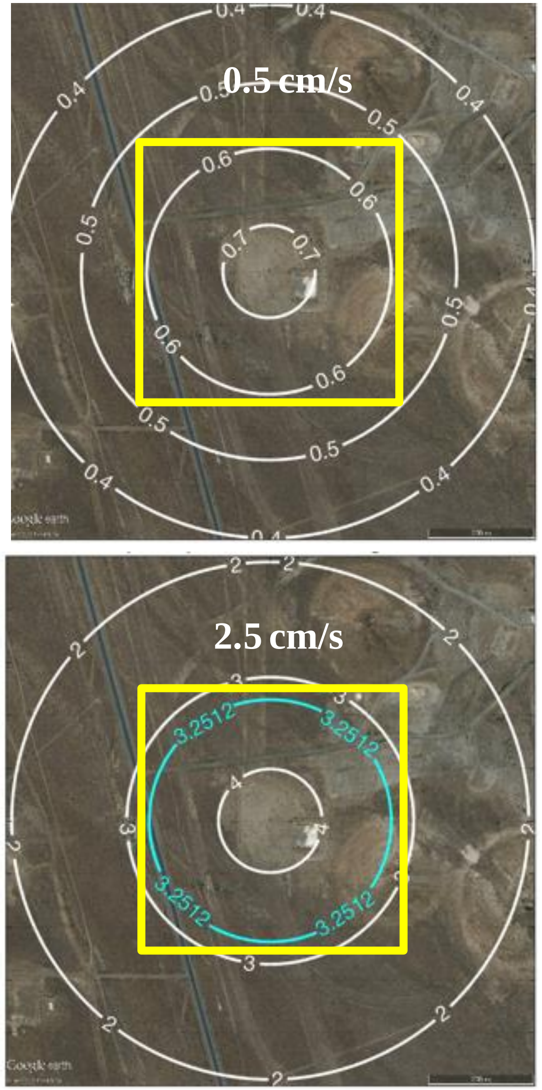
Peak Velocity and Peak Acceleration at SGZ for DAG1 & DAG2. DAG (stronger) alluvium favors the upper bound estimates.

Peak Velocity Image at all times

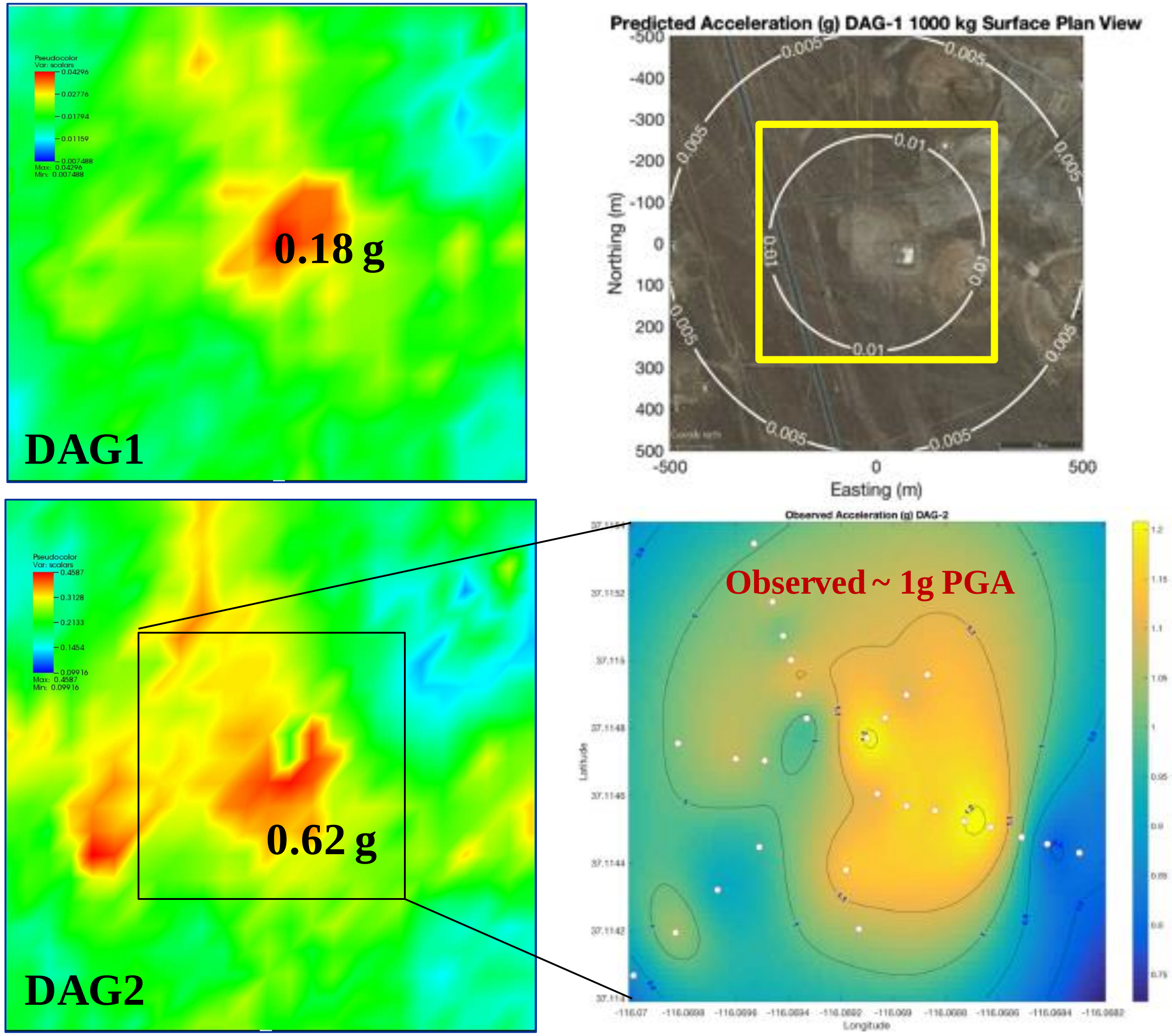


400m x 400m

Peak Velocity Image P&B by Jesse B.

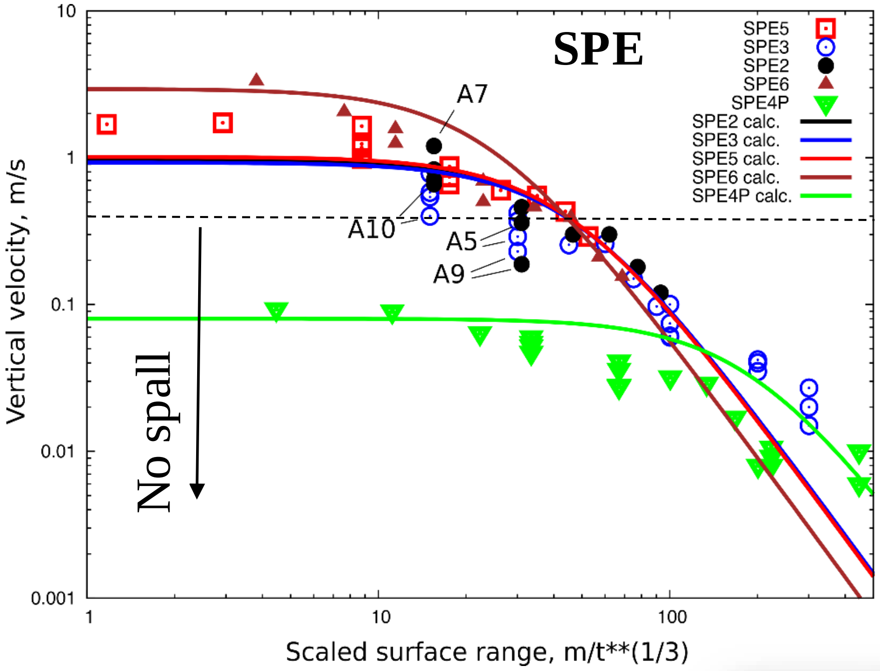


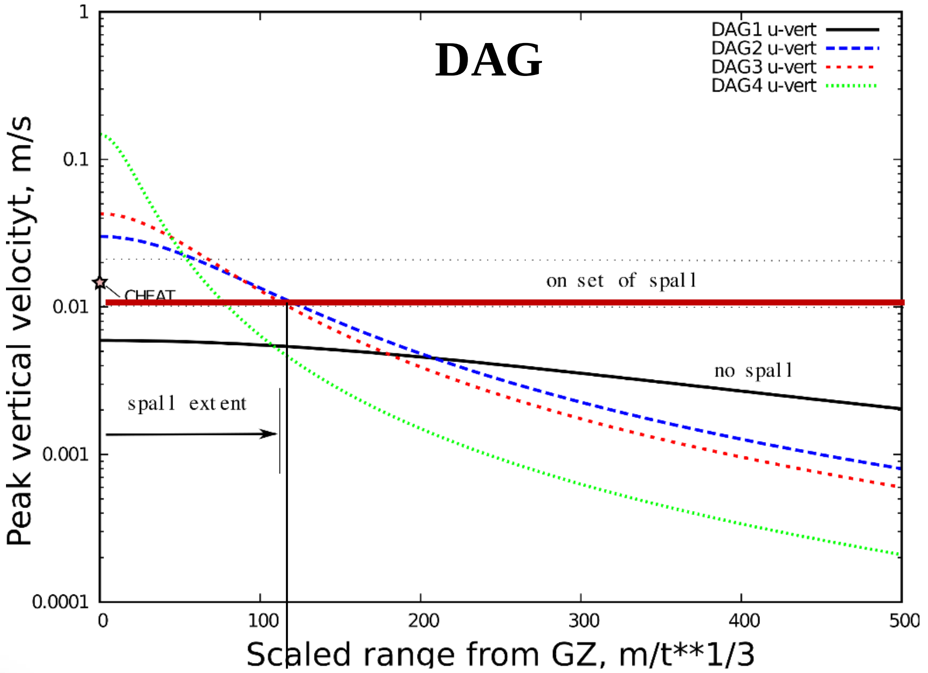
1km x 1km

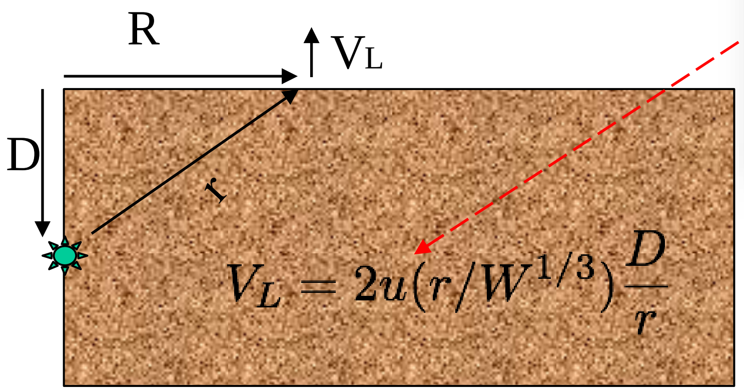


DAG1: average 18 times P&B +/- 5.5 ~ 23.5 times at most. DAG2: average 6.5 times P&B +/- 3.25 ~ 9.75 times at most (Obs 10x)

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)

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 through DAG-4.
  - Several UQ & SA studies have been conducted (petrophysical, geological).
  - We have conducted similar analyses for surface expression and acoustic response (not shown here).
- **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 performing sensitivity analysis of ground motion.
  - Local wave propagation effects are source-depth dependent.
- **Implication for source discrimination**:
  - P-wave spectra – affects yield estimation and discrimination.
    - Overall level, corner frequency, high-frequency roll-off affected by media.
    - Dry porous media, over-buried and 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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