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Distributed acoustic sensing observations and modeling of the DAG series of chemical explosions

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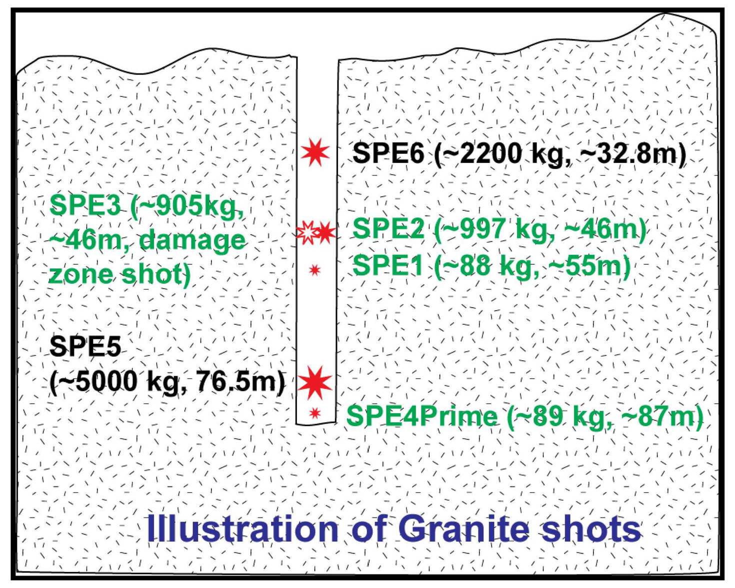
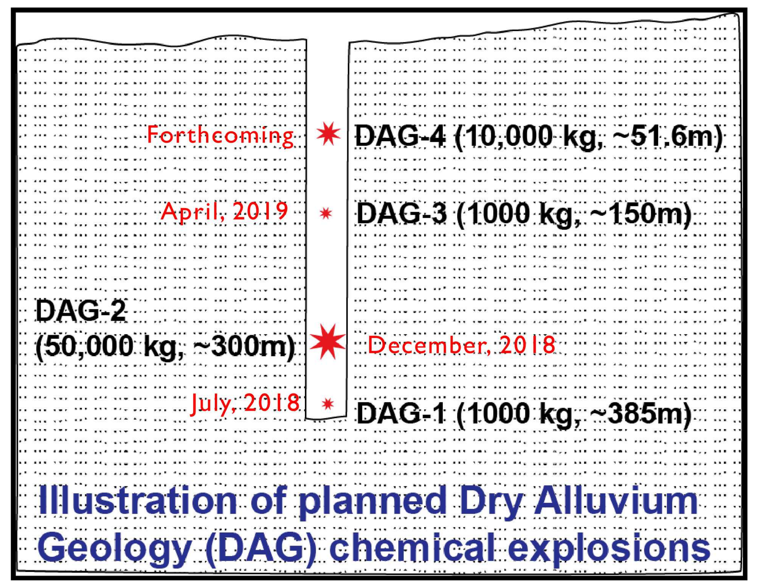
Abstract

The Dry Alluvium Geology (DAG) series of chemical explosions aim to increase our understanding of explosion-source seismic, acoustic, and electromagnetic phenomenology. The explosion series takes place on the Nevada National Security Site (NNSS) in an alluvium geology. As of December 2018, two of the planned four explosions have been detonated in a common borehole on Yucca Flat: 1,000 kg TNT-equivalent at 385-m depth-of-burial and 50,000 kg TNT-equivalent at 300 m. A component of the DAG diagnostic instrumentation consists of surface-laid and downhole fiber optic distributed acoustic sensing (DAS) cables. A helically-wound fiber installed in two vertical boreholes 80-m from ground zero (GZ) and a traditional surface-laid straight fiber extending from GZ to 2 km recorded the explosions. We present both modeling and observations of the explosions. Phenomenology observed thus far include near-source generated S waves, post-event microseismicity, and surface spall.

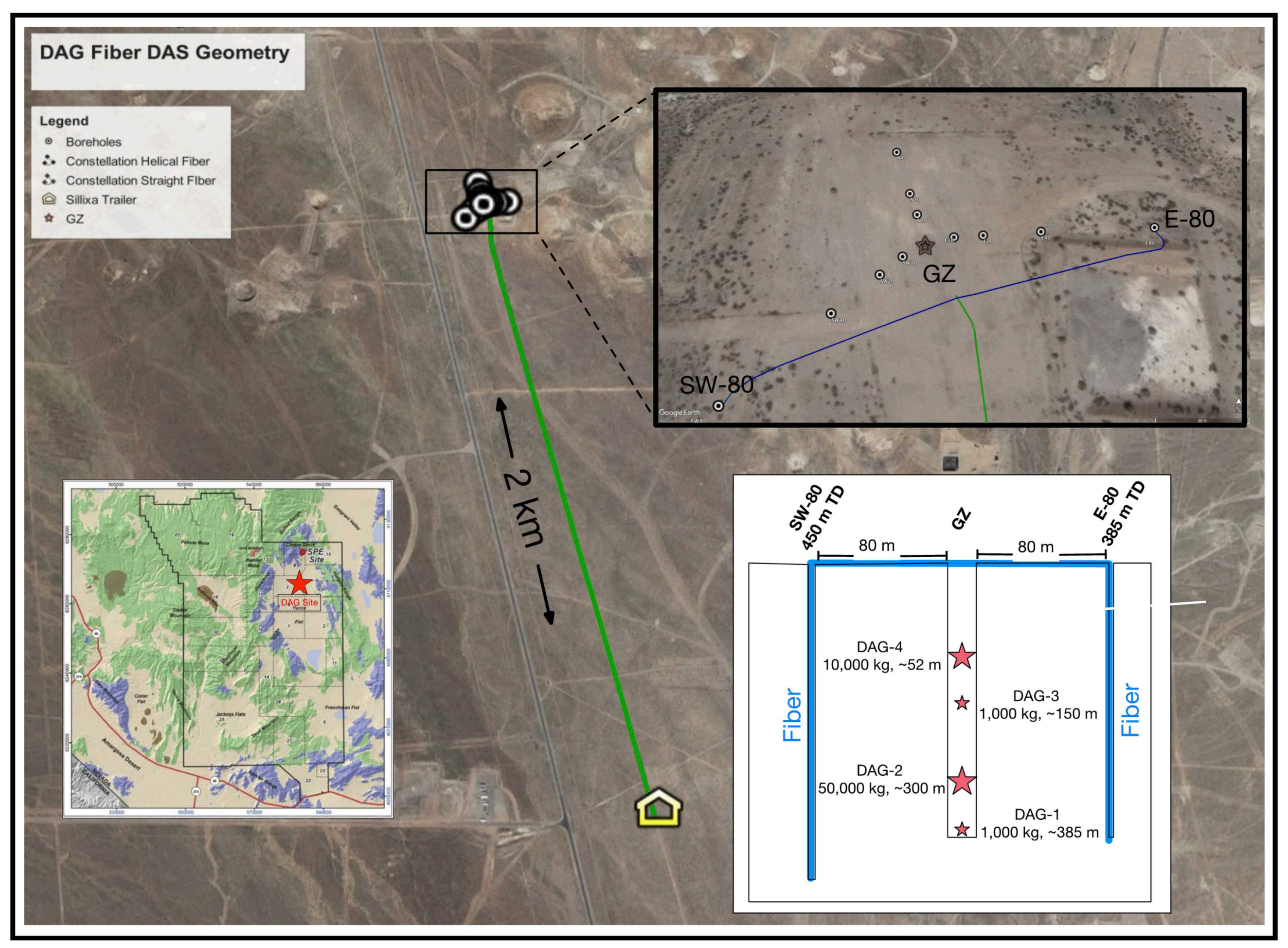
SPE Chemical Explosions

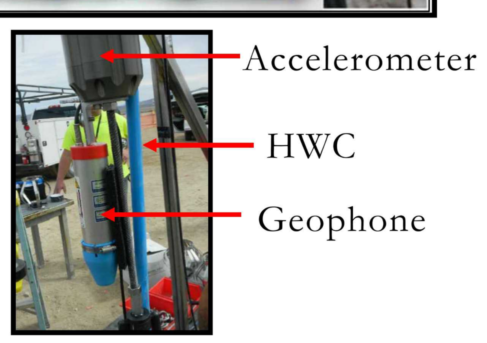




Two dissimilar geologies (granite and alluvium) have hosted the two phases of the Source Physics Experiment. The fiber optic data presented here are for the first two explosions in alluvium. No DAS data was acquired in granite.

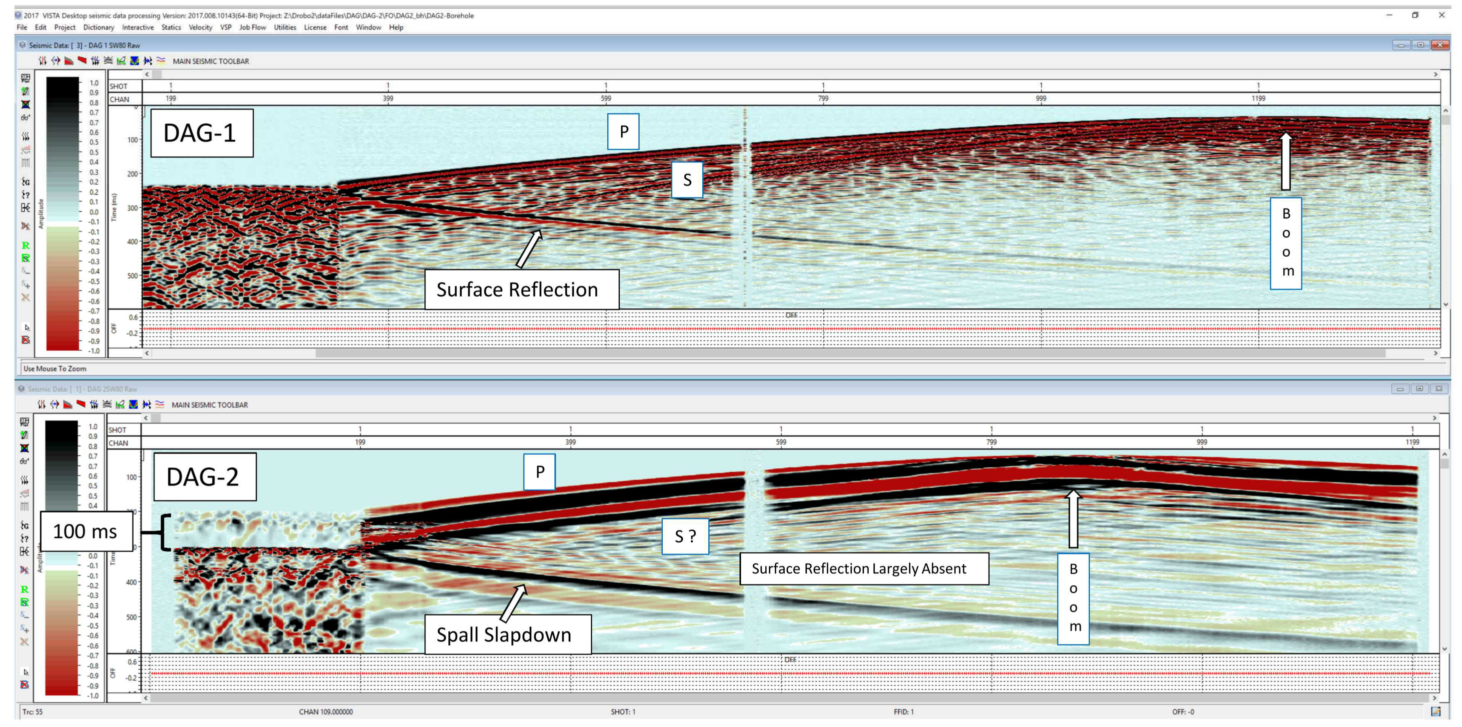
Acquisition Geometry



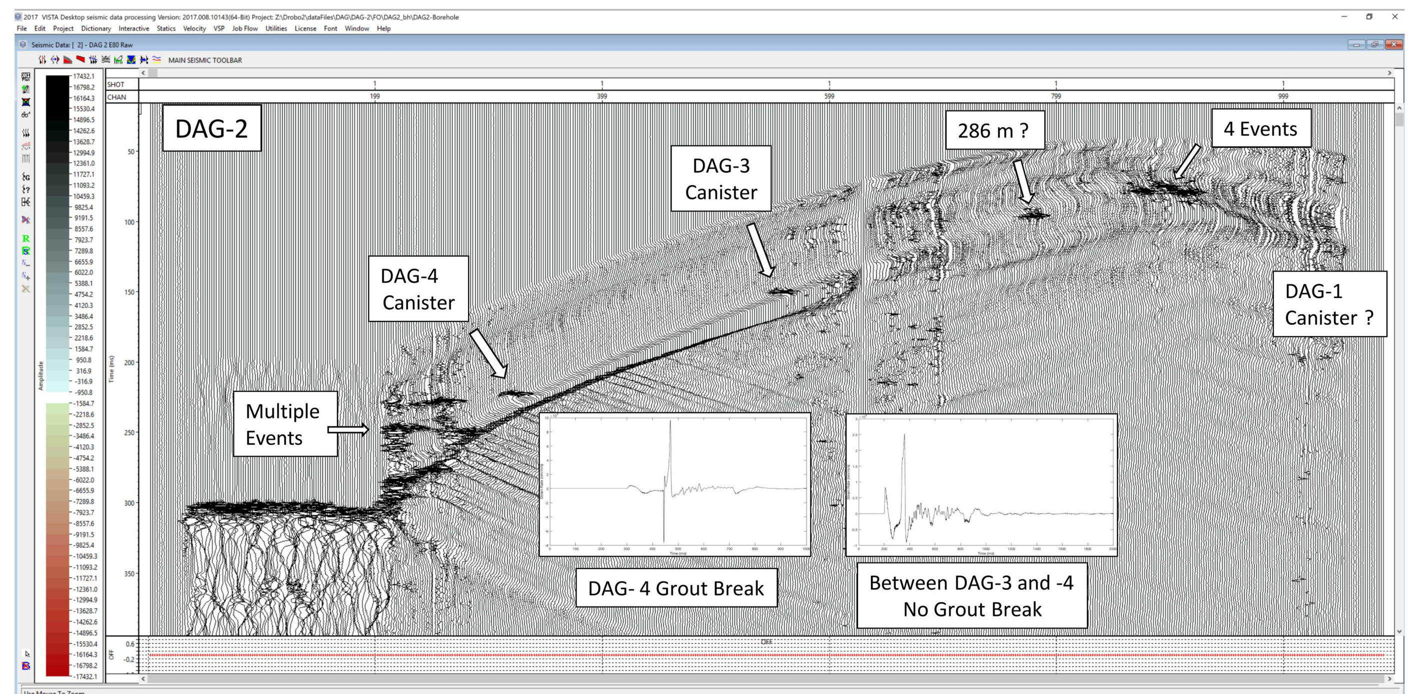


- 1 km of helically wound cable (HWC)
  - HWC cable grouted in two boreholes 80 m from GZ
  - HWC surface-trenched cable between the two boreholes
- 2 km of straight Constellation cable
  - Straight cable runs in trench to recording trailer ~ 2 km from GZ
- Triaxial accelerometers at level of each explosion in 12 surrounding boreholes
- Single triaxial geophone

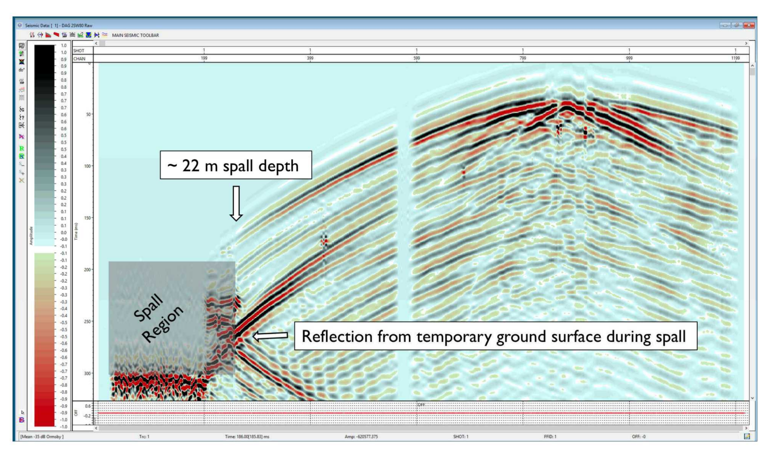
DAG-1 and DAG-2 Observations

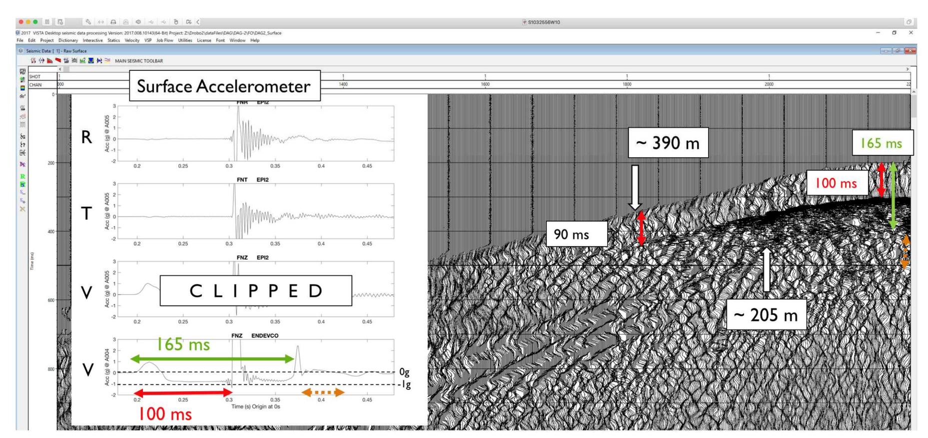


DAG-1 and DAG-2 Recording in hole SW80. Deeper portions of the hole is to the right. The abrupt change in character to ground surface where the fiber transitions to laying on the surface. Notice the immediate reflection from the surface for DAG-1 which delayed 100 milliseconds for DAG-2. We interpret this to be related to surface spall.

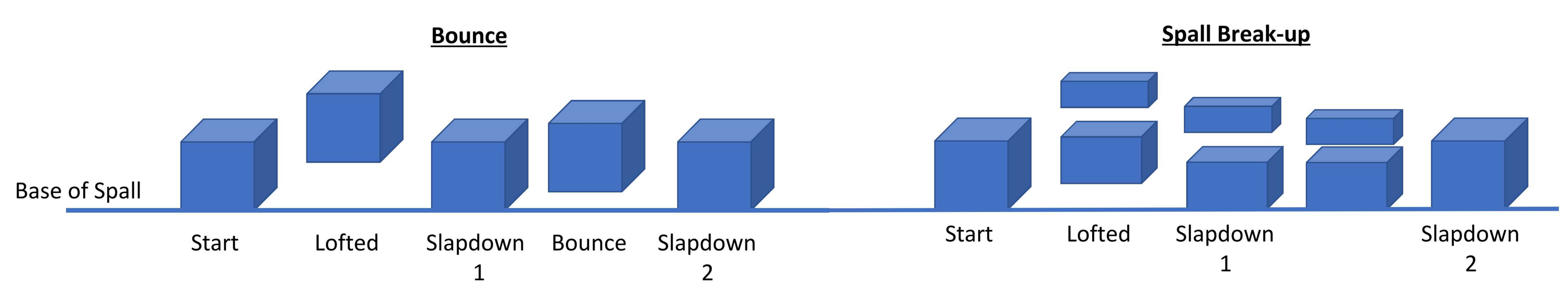


DAG-2 in SW80: Spurious high-amplitude, high-frequency signals were observed in the co-located accelerometer data. Examination of the DAS data reveals that these signal are local to the accelerometer packages ("Canisters" in above figure) and located along a wavefront of maximum dilation. We interpret this to be grout damage caused by grout separating from the smooth packages. This was not observed for DAG-1 with lower ground motion. Additional grout damage was seen in the spalled region near the surface ("Multiple Events", above).

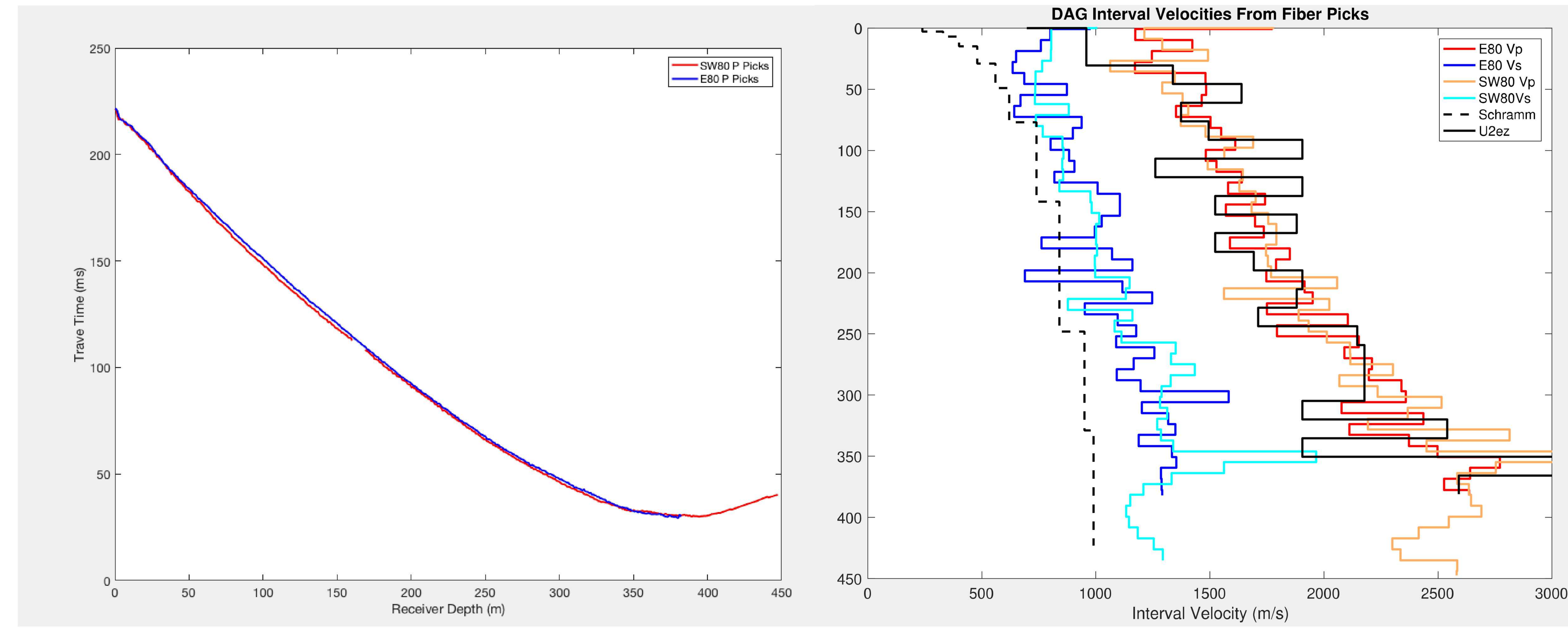




Downhole and Surface Fibers Constrain Both Depth and Width of Spall Zone:
Top Left. High-passing the SW80 data at 75 Hz accentuates a late arriving wave package as it reflects of the base of the spalled region at 22 meters depth.
Top Right. Surface fiber shows distinct spall signatures out to at least 390 meters from ground zero. Co-located surface accelerometers show multiple slapdown phases that are confirmed in the fiber data
Below. Two models of spall that can explain the data

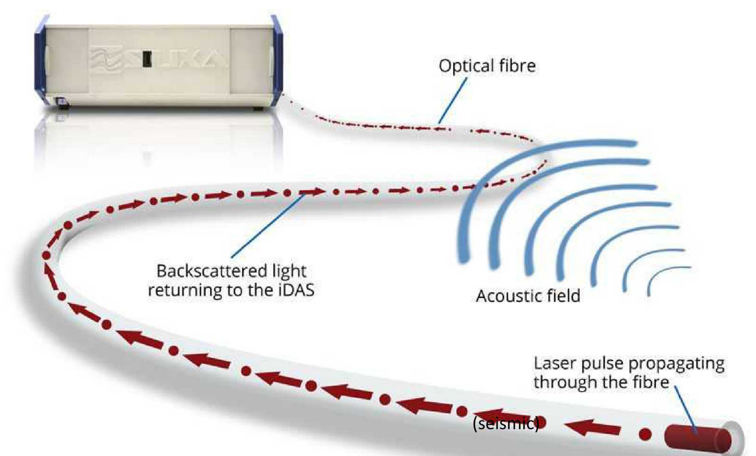


Velocity Model



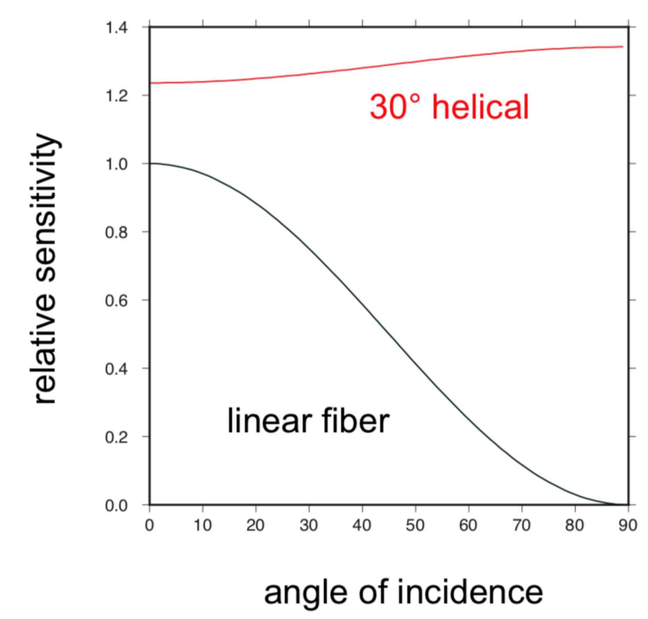
DAG-Vicinity P and S Velocity Model.
Top Left. The clean data with high signal-to-noise ratio allowed for very accurate and consistent travel time time picks. Notice the near co-incidence in travel times between SW80 and E80, indicating homogenous geology with 80 meters of the emplacement hole.
Top Right. The travel time picks for both P and S waves were used to create a 1-D velocity model. This model agrees with the original P-wave only model created (black line) in the 1980s when the emplacement hole was drilled.

Numeric Modeling

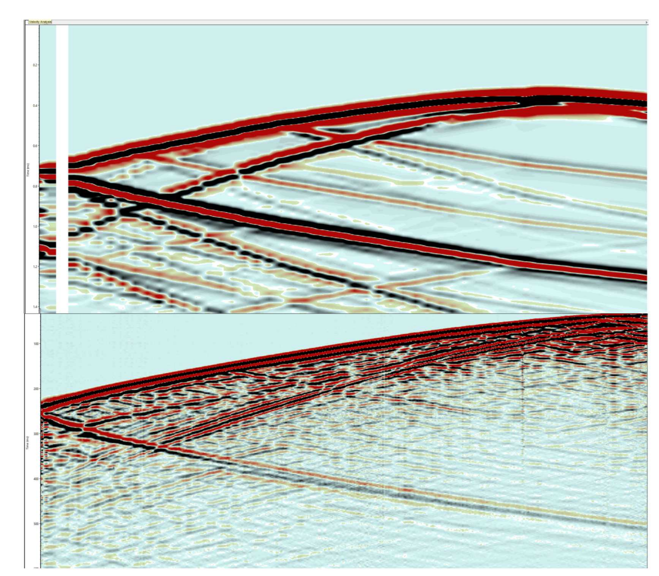


Schematic courtesy of Silixa, LLC. Silixa is subcontracted to Sandia to acquire the field data

Theory. Fiber Optic Distributed Acoustic Sensing operates by sending laser pulses of a certain duration and repetition rate down a fiber optic cable. An interrogator at one end of the fiber tracks the time of back-scattered laser pulses over time. If the fiber is coupled to a geologic media, seismic waves can be resolved as they strain the fiber, causing the back-scatter to vary in time. We can model this behavior.



Straight vs Helically-Wound. Since the strain-rate measurements are sensitive to the distance between the scatterers along the long axis of the fiber (the path of the laser pulses), for straight fibers the sensitivity to ground motion falls off rapidly with seismic angle of incidence. The helically-wound cable has a much less pronounced sensitivity variation with AOI and was better suited for our downhole application.



Synthetic Model of DAG-1 vs. Recording in SW80.
Left, Top. 3D finite difference model of DAG-1 in SW80 LLNL code *sw4*. Grid spacing was 1 m with a strain-rate extracted every 10 meters. Helically-wound cable was used for the simulation. As can be seen the synthetic matched many features seen in the field data **(Left, Bottom).** This includes P-waves, S-waves, as well as surface and intermediate-depth reflections. The synthetic over-estimates P-Wave and S-Wave mode conversions, and lacks some waveform complexity due the model's simple velocity structure without stochastic heterogeneity (future goal).

Summary

- Unqualified success in recording DAG-1 and DAG-2
  - Two orders of magnitude more data relative to traditional geophones/accelerometers
  - Recorded complete seismic wavefield instead of a few waveforms
  - Helical cable performed well in recording relevant phases
  - Greatly aids in interpreting primary diagnostics
- Evidence for multi-phase spall or spall bounce
  - Depth of main spall is approximately 22 m
  - Width of spall zone alt least 390 m
- Progress is being made in modeling the fiber response

The authors wish to express their gratitude to the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (DNN R&D), and the SPE working group, a multi-institutional and interdisciplinary group of scientists and engineers.

PUTTING AN END TO NUCLEAR EXPLOSIONS