SAND2019-4290C

Nonlinear Effects on Linear Seismic Source Inversions from Simulations of Underground Chemical Explosions

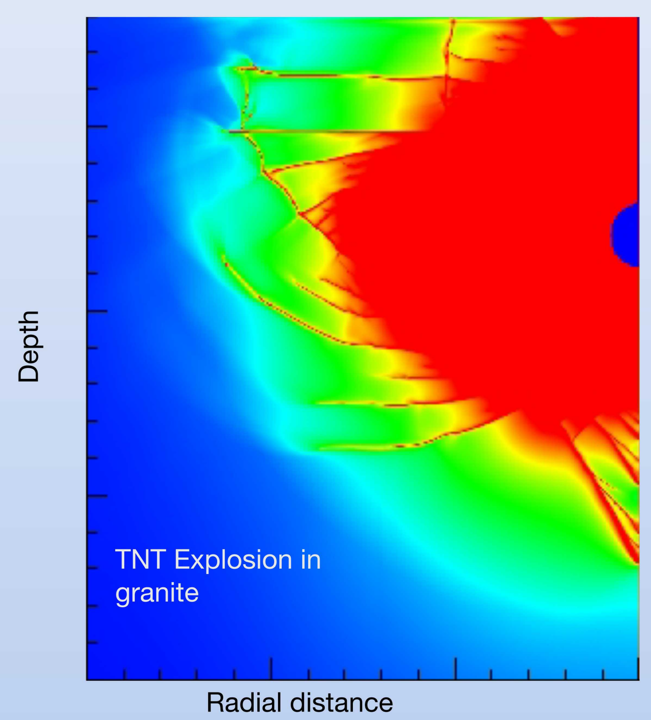
Leiph Preston (lpresto@sandia.gov), Mehdi Eliassi, Arne Gullerud, and Christian Poppeliers
Geophysics Department, Sandia National Laboratories, Albuquerque, NM

National Nuclear Security Administration

Sandia National Laboratories

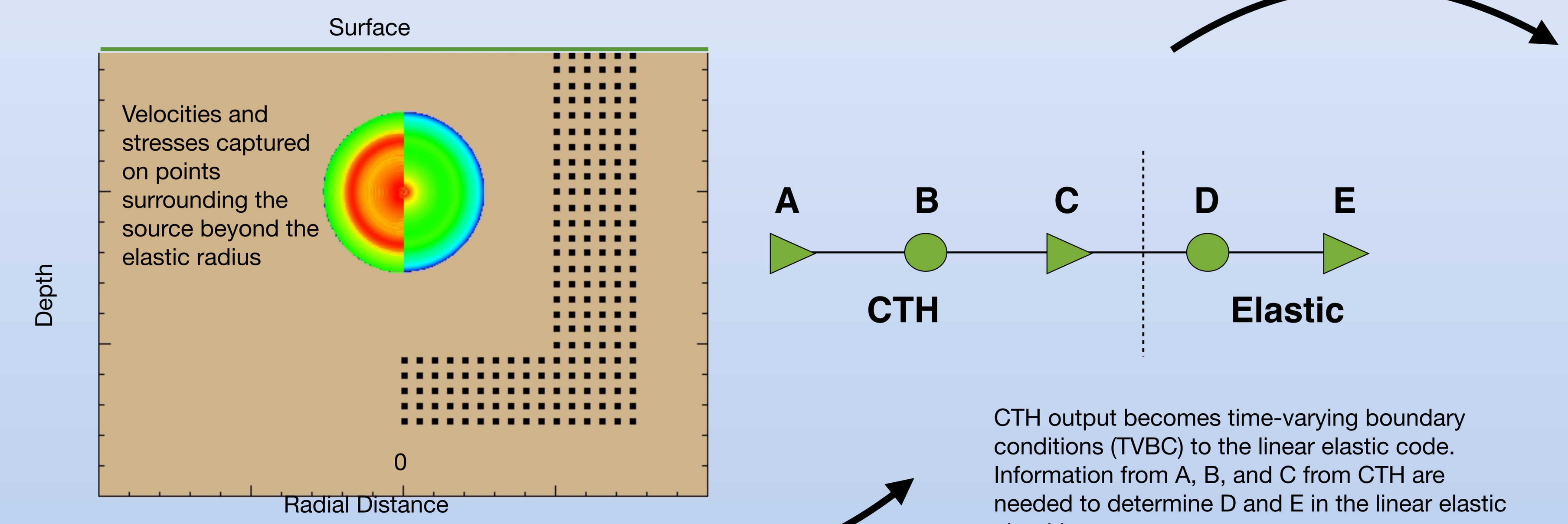
Abstract

Linear moment tensor inversion is a common method used in seismology to understand the characteristics of the seismic source model. However, underground explosions nonlinearly affect the surrounding earth materials through plastic deformation, breaking rocks, and spall. Although nonlinear algorithms can accurately simulate very near field ground motions, they are computationally expensive and unnecessary for far field wave simulations. Linearized seismic wave propagation codes, on the other hand, are computationally efficient and can accurately model the far-field linear wavefield, despite their simplification of the seismic source. Thus, it is advantageous to understand the conditions under which a purely linear analysis of far-field seismic waveforms is sufficiently accurate and when nonlinear analysis is critical. We have coupled Sandia's nonlinear algorithms to a linearized elastic wave propagation code using time-varying boundary conditions, to pass information from the nonlinear domain to the linear one. We find the purely linear seismic moment tensor and source time functions that optimally fit the waveforms produced by the nonlinear source and investigate how well these purely linear methods can adequately fit the synthesized data from nonlinear sources. We present results showing the effects of geological materials, the free surface, and explosive yield on linear source parameters for earth models with simulated chemical explosions at various scaled depths of burial. We also discuss how well the linear source models are able to reconstruct the waveforms from the nonlinear source in the various scenarios.

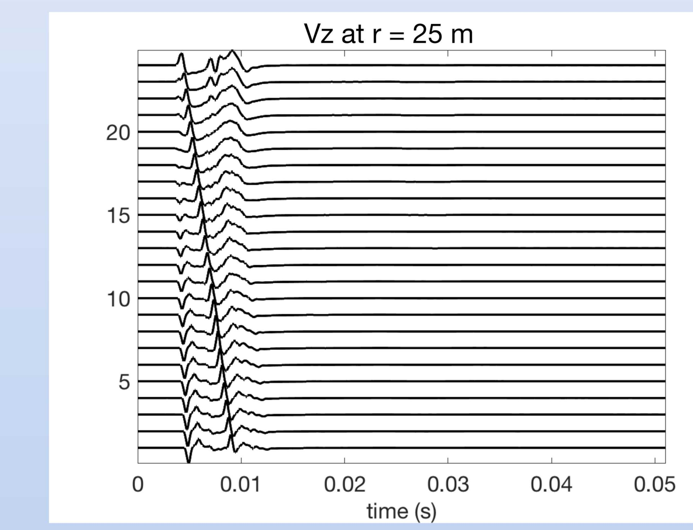


Method

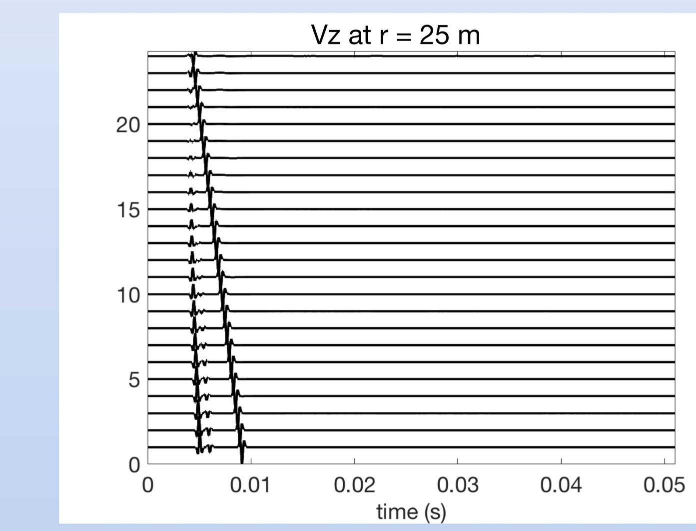
CTH is a large-deformation, strong-shock physics, massively-parallel code that can simulate shock through multiple materials in 1D, 2D (rectangular or cylindrical), or 3D (Schmitt et al., 2016).



CTH output becomes time-varying boundary conditions (TVBC) to the linear elastic code. Information from A, B, and C from CTH are needed to determine D and E in the linear elastic algorithm.

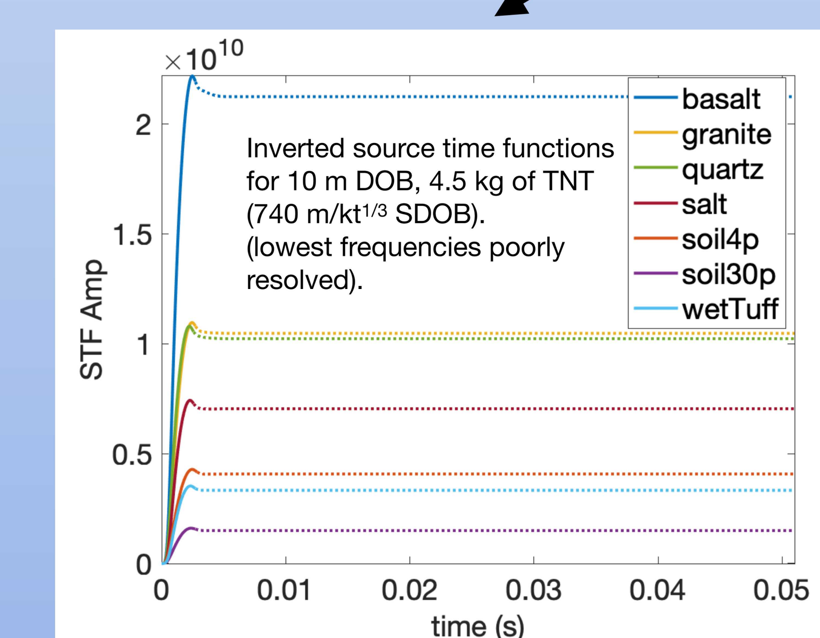


Far-field seismograms from linear elastic algorithm driven by CTH TVBC's.



Isotropic explosion Green's Function (convolved with 2000 Hz Gaussian for visualization)

Combined with

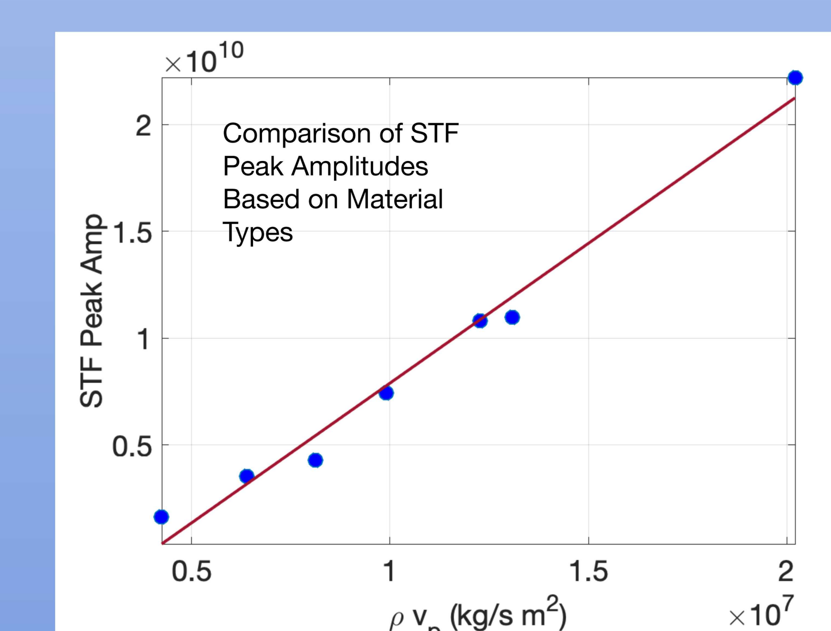


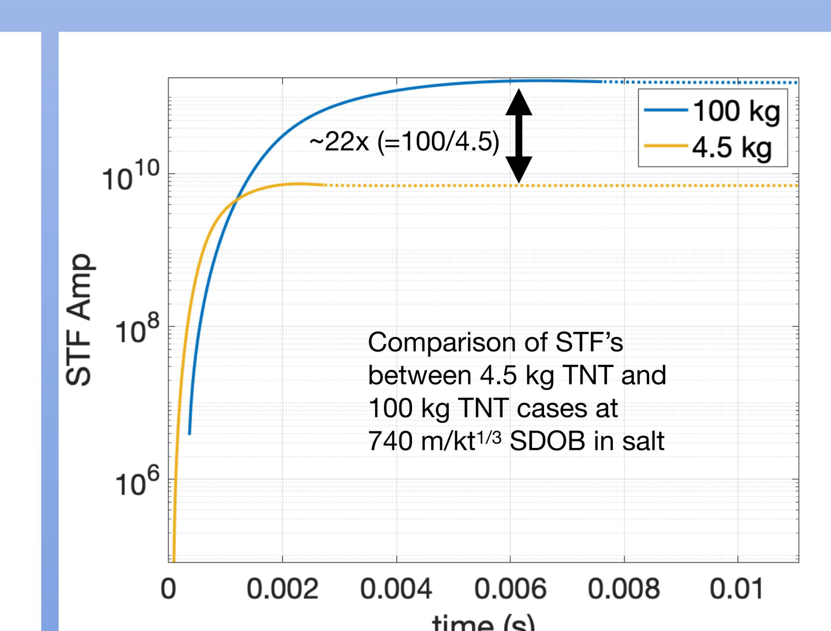
Source Time Function Inversion

$$D(t) = S(t) * G(t)$$
$$D(f) = S(f)G(f)$$
$$S(f) = \frac{D(f)}{G(f)}$$

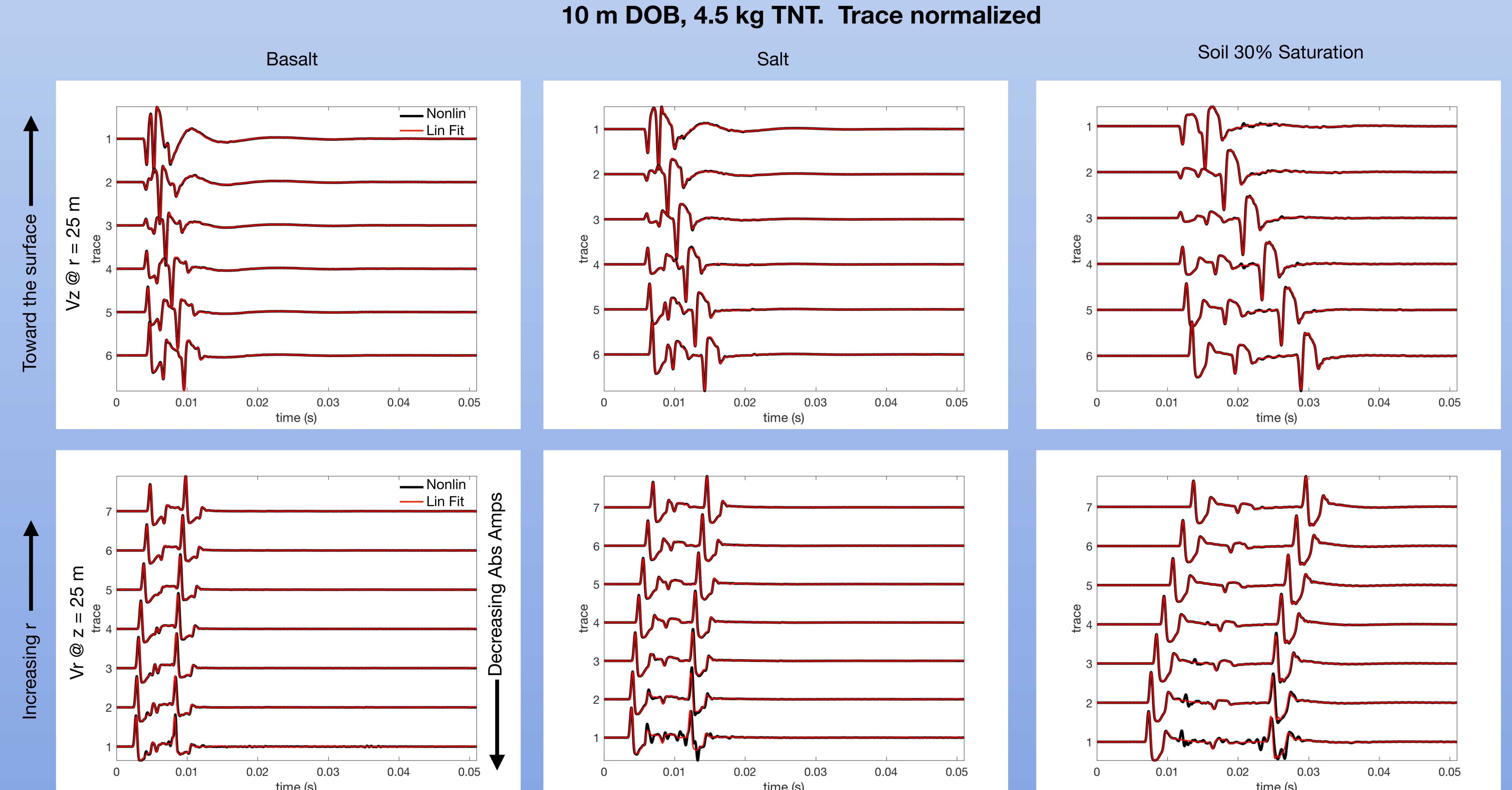
Observations, $D(t)$, are inverted for the source time function, $S(t)$, using Green's Functions, $G(t)$. Here, "observations" are coupled CTH-linear elastic simulated output.

Green's Functions are simulated with the linear elastic algorithm using a point isotropic moment tensor source at the source depth. All Vr and Vz receivers at ~25 m (~70 m) from the source for 4.5 kg (100 kg) TNT are used simultaneously in the inversion.

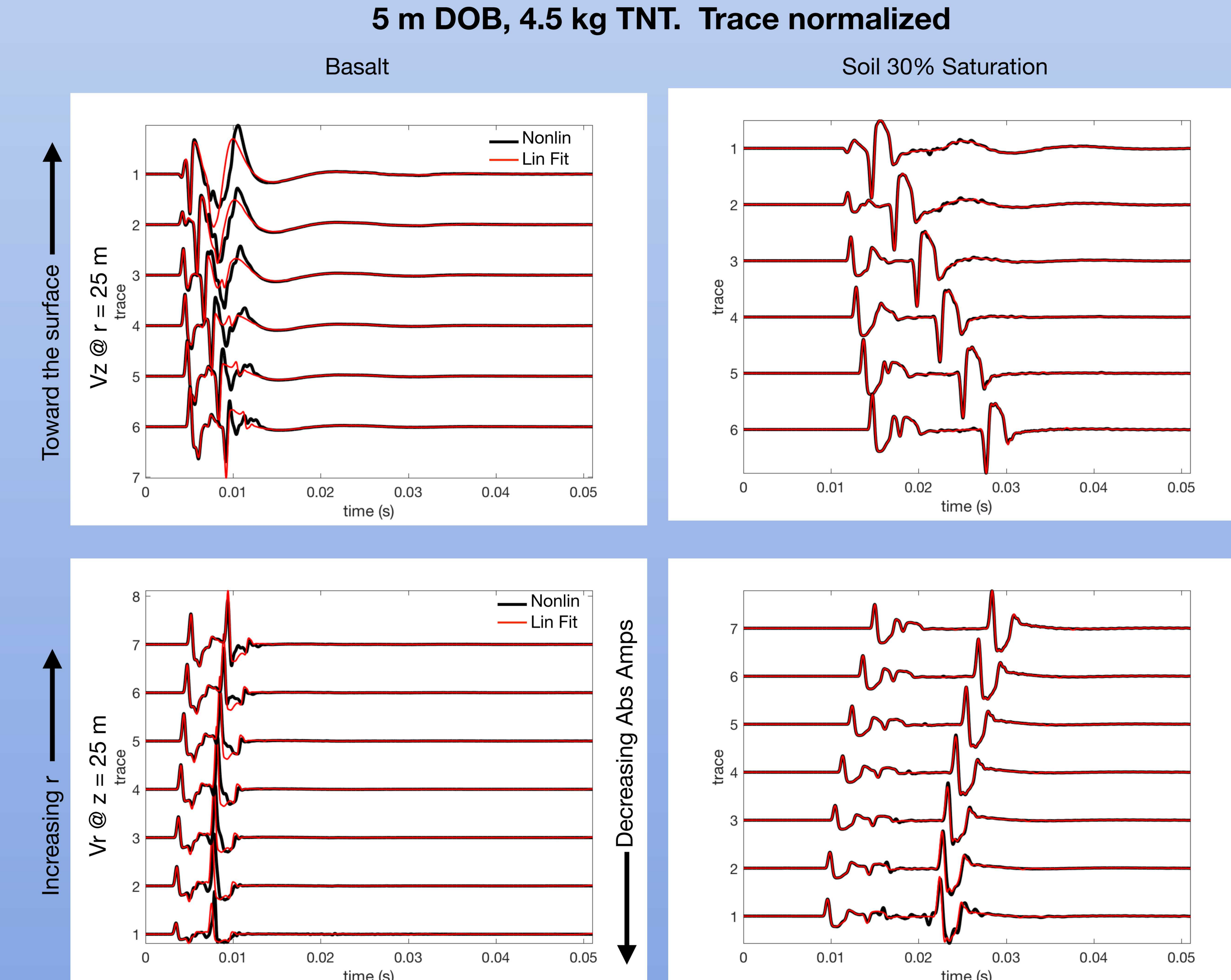




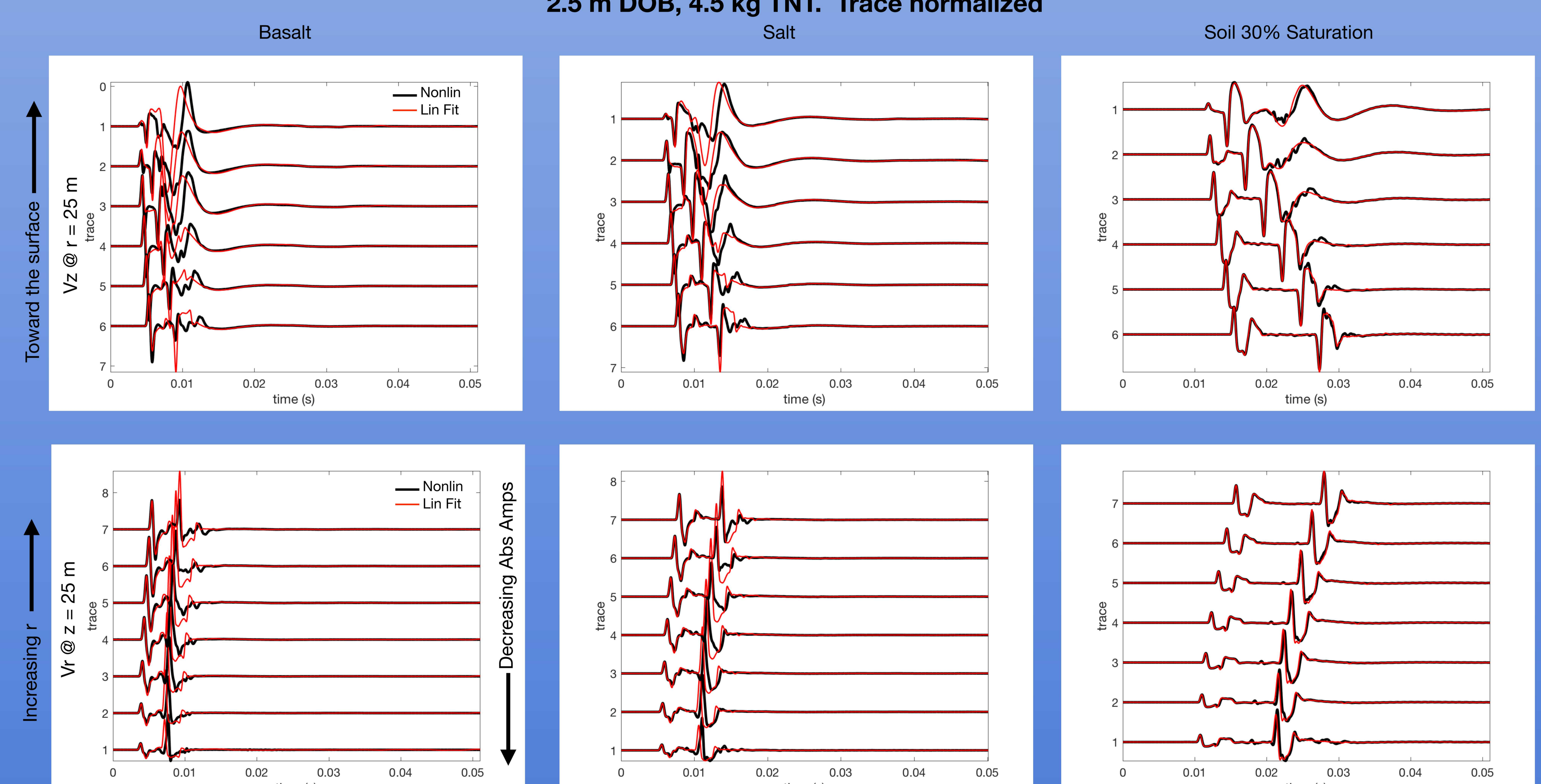
10 m DOB, 4.5 kg TNT. Trace normalized



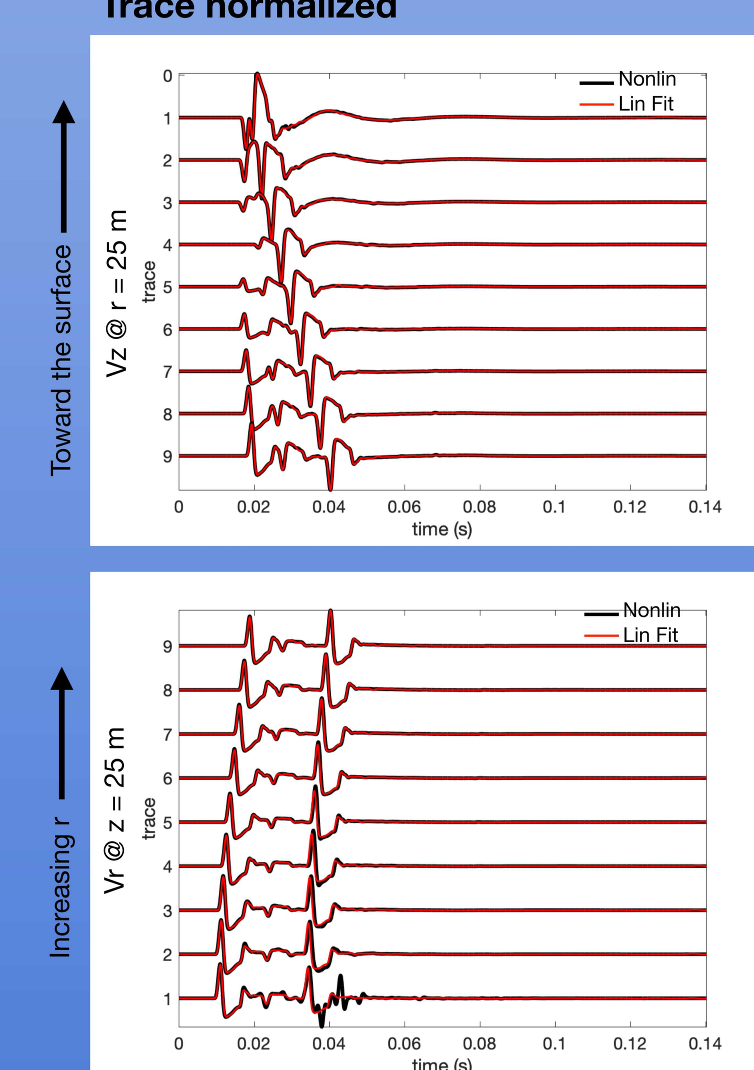
5 m DOB, 4.5 kg TNT. Trace normalized



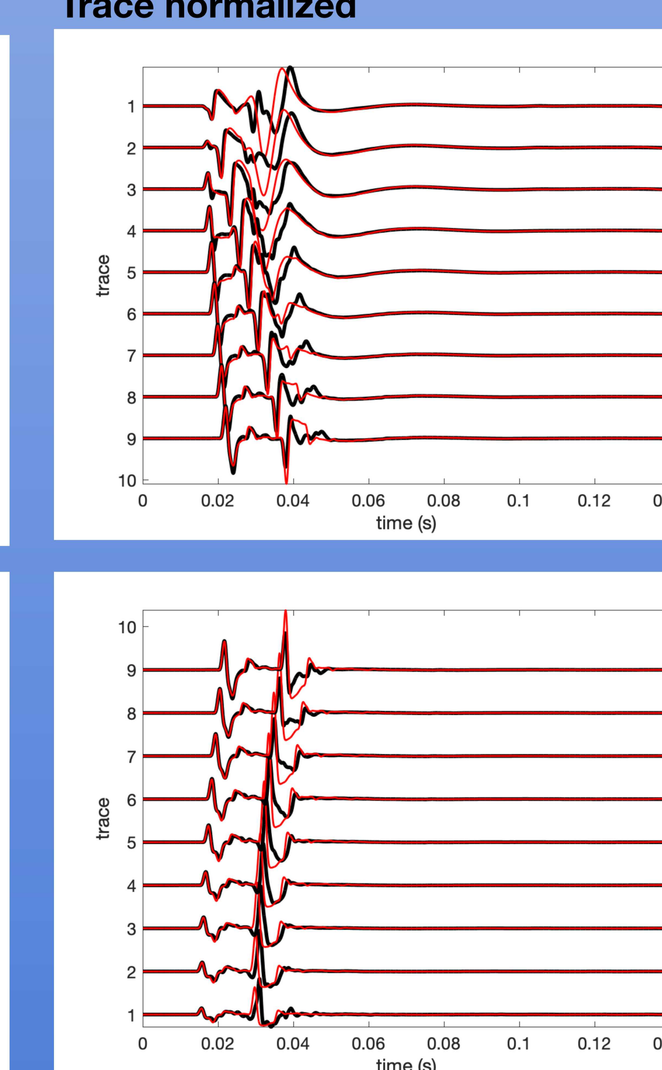
2.5 m DOB, 4.5 kg TNT. Trace normalized



28 m DOB, 100 kg TNT in salt. Trace normalized



7 m DOB, 100 kg TNT in salt. Trace normalized



Discussion

- Simulations used 4.5 kg or 100 kg TNT explosion sources in CTH
- Three different depths of burial (DOB): 10 m, 5 m, and 2.5 m for 4.5 kg TNT cases. Equivalent to a scaled depth of burial (SDOB) of ~740, 370, and 184 m/kt$^{1/3}$. 100 kg TNT cases used a DOB of 28 m and 7 m, or SDOB of 740 and 184 m/kt$^{1/3}$.
- Seven different materials tested: basalt, granite, quartz, salt, 4% saturation soil, 30% saturation soil, and wet tuff for 4.5 kg TNT case. Only salt has been evaluated thus far for the 100 kg TNT case.
- In all materials, at 740 m/kt$^{1/3}$ SDOB, a linear explosion point source is able to nearly perfectly fit the coupled CTH-linear elastic simulations
- The source time functions (STF) all have the same basic form, resembling a Meuller-Murphy source (Meuller and Murphy, 1971) (Note: low frequency components are poorly resolved).
- Peak amplitudes of the source time functions scale nearly linearly with the impedance (density * Vp)
- The other SDOB's use the explosion STF from 740 m/kt$^{1/3}$ SDOB convolved with the appropriate Green's Function at those depths
- At 370 m/kt$^{1/3}$ SDOB, the stronger materials (e.g., basalt) fit the P-wave well, but S/surface waves do not fit as well. Weaker materials are fit well with the explosion STF.
- At 184 m/kt$^{1/3}$ SDOB, the P-wave is not fit as well for the stronger materials, whereas weaker materials still fit the P-wave well, but the S/surface wave is more poorly fit
- The 100 kg TNT cases scale nearly perfectly with the 4.5 kg TNT cases in terms of explosion peak amplitudes and waveforms, with the peak amplitude of the 100 kg STF being almost exactly 100/4.5 times that of the 4.5 kg STF.

Acknowledgements

The authors acknowledge the support of the National Nuclear Security Administration Office of Defense Nuclear Nonproliferation Research and Development for funding this work. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

References

Mueller, R.A, and J.R. Murphy, Seismic Characteristics of Underground Nuclear Detonations. Part I. Seismic Spectrum Scaling, *BSSA*, 61(6), 1675-1692, 1971.
G. Schmitt, A.L. Brundage, D.A. Crawford, E.N. Harstad, K. Ruggirello, S.C. Schumacher and J.S. Simmons, *CTH User's Manual and Input Instructions, Version 11.2*, CTH Development Project, Sandia National Laboratories, Albuquerque NM, 2016.