Correlating Shear Content in Seismic Source Functions to Scaled Depth-of-Burial for a Series of Buried Chemical Explosions

David Steedman and Ryan Modrak

2.3-141

ORAL PRESENTATION

The authors thank the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (DNN R&D), and the SPE working group, a multiinstitutional and interdisciplinary group of scientists and engineers.
LA-UR- 21-24412

National Nuclear Security Administration

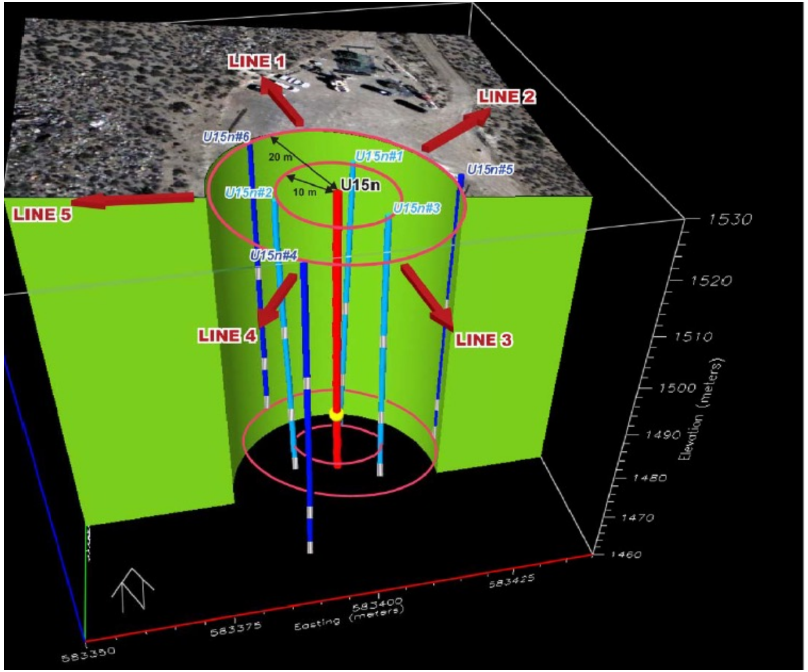
Los Alamos NATIONAL LABORATORY

Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Source Physics Experiment (SPE)

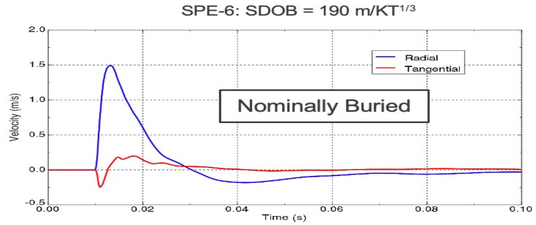
- SPE Phase I consisted of six chemical explosions at different scaled depth-of-burial (SDOB)
- A major goal was to identify sources of "excess" shear, which complicate discrimination criteria
- Another goal was to understand how seismic data vary with respect to scaled depth-of-burial, especially for deeply overburied events

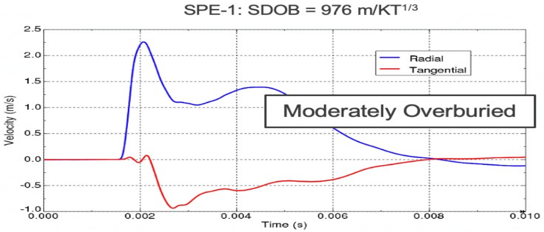


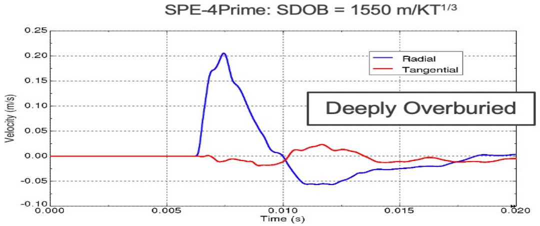
SPE Granite Testbed

Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov







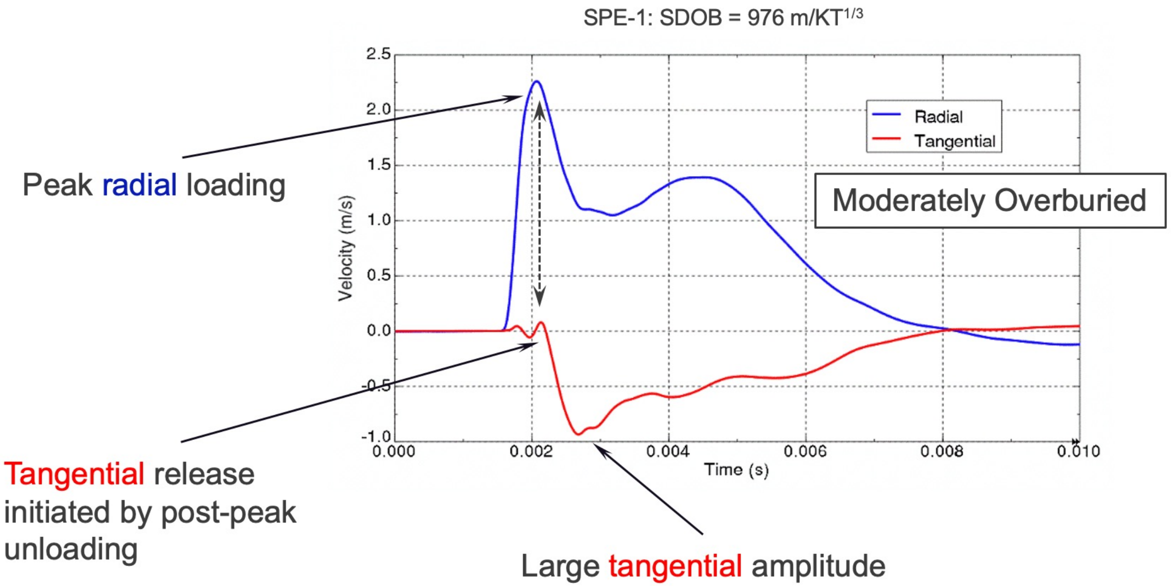
SPE near-field accelerometer records

- Accelerometers were placed ~15 m from the explosion borehole
- Interesting patterns emerge with respect to scaled depth-of-burial
- Radial motion corresponds to compressional waves (P-SV)
- Tangential motion corresponds to shear waves (SH)

Steedman et al., 2016, BSSA

Correlating Shear Content to Scaled Depth-of-Burial

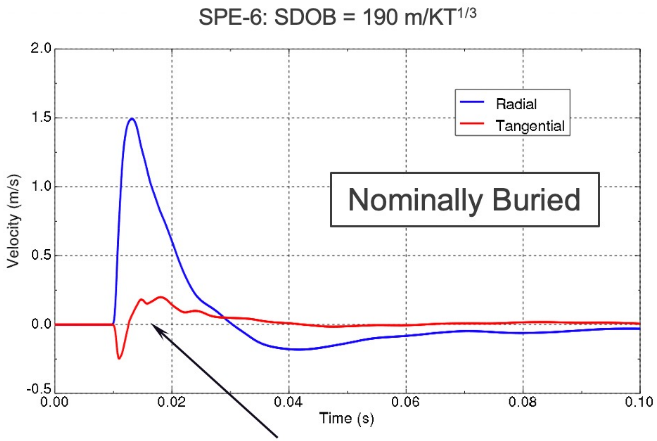
David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov



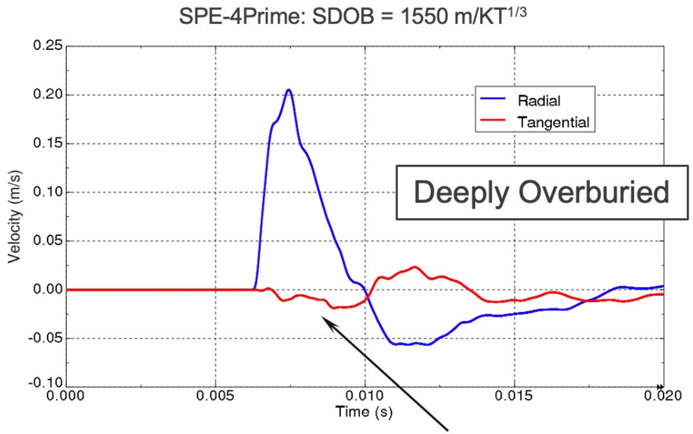
Takeaway: a lot of shear wave release from moderately overburied explosions

Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov



Small tangential amplitude



Small tangential amplitude

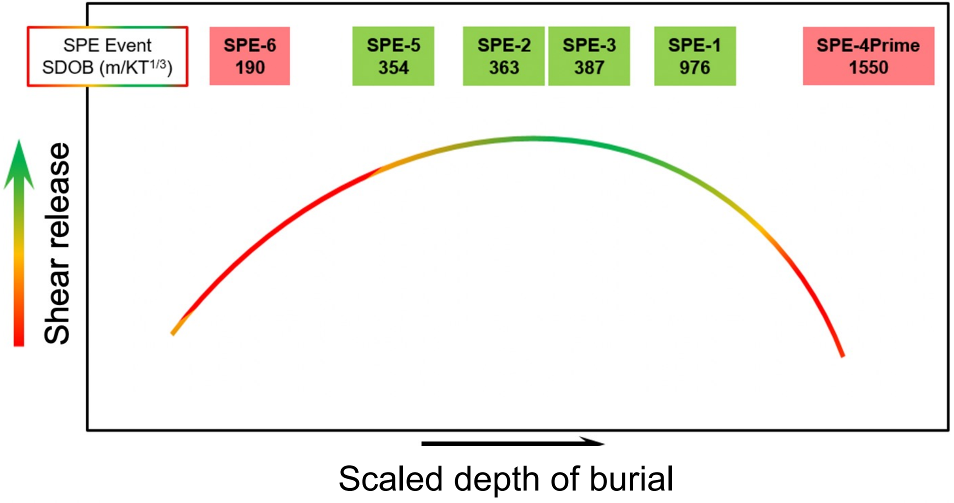
Takeaway: very little shear wave release from nominally- and deeply-buried explosions

Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Proposed shear release mechanism and relationship with scaled depth-of-burial

- *Mechanism*: shear release occurs from pre-loaded joints due to passage of explosion-generated shock wave
- Shear release is a function of
  (1) overburden stress
  (2) shock wave amplitude
- This dependence results in a distinctive SDOB pattern, shown in the notional model at right



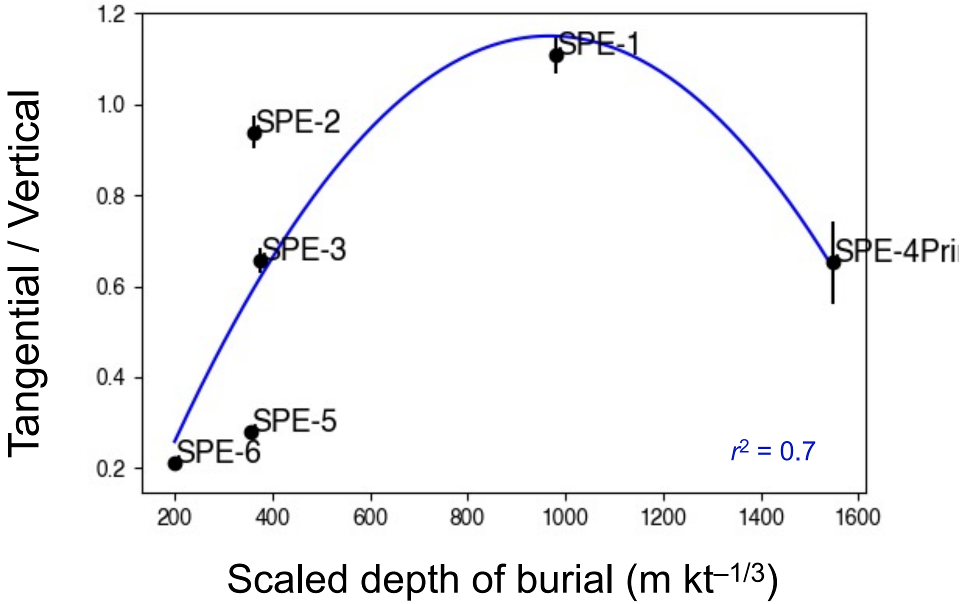
Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Analysis of far-field geophone records supports notional SDOB model

- Plotted at right is L2 norm of transverse velocity trace divided by L2 norm of vertical velocity trace, with σ/N error bars and 2nd order polynomial fit

- Using all available geophones between 100 m – 500 m from source



Correlating Shear Content to Scaled Depth-of-Burial

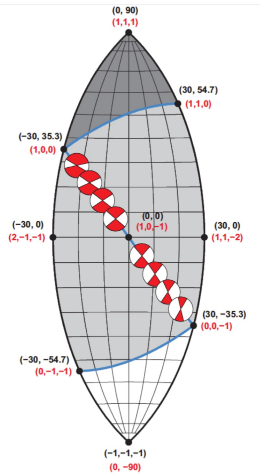
David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Moment tensor preliminaries

A **moment tensor** is a weighted sum of force couples that together represent a seismic source; can be written as a symmetric matrix with 6 independent elements

$$\begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$

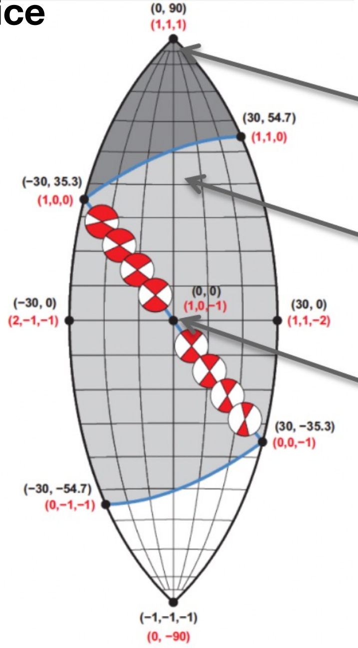
Visualizing over 6D space is nontrivial; the recently-developed **lune plotting device** allows for meaningful 2D visualization



Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Lune plotting device



Strongly isotropic
(low shear release)

Weakly isotropic
(moderate shear release)

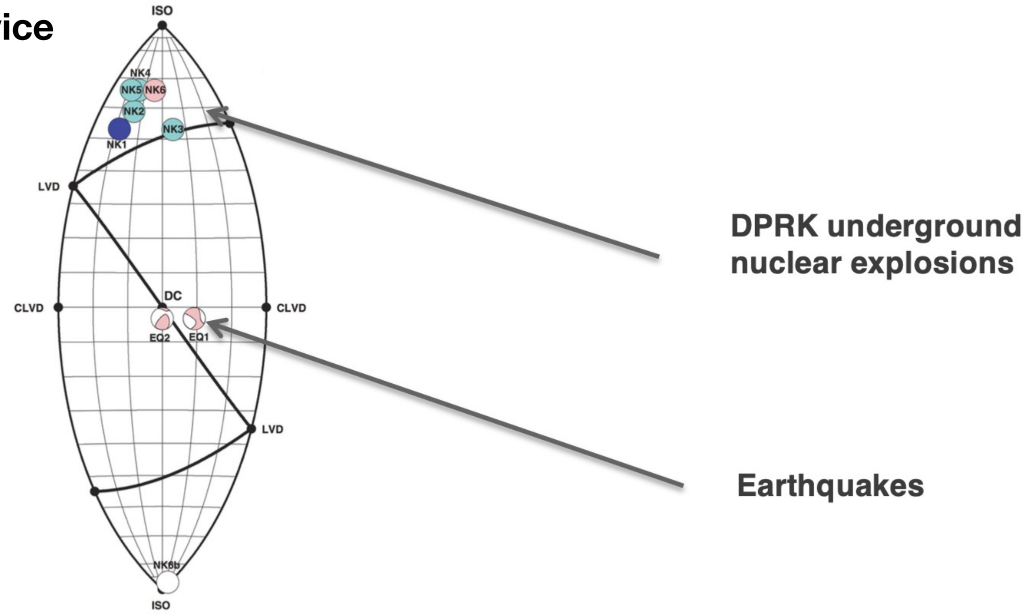
Strongly deviatoric
(high shear release)

Mathematically, the location of a given moment tensor on the lune is determined by the eigenvalues of its symmetric matrix

Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Lune plotting device



In practice, the location of an individual seismic event on the lune represents a moment tensor solution obtained by comparing observed and synthetic seismic waveforms

Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

$$\text{misfit}(m) = \sum \int \left| dat(t) - syn(t - t_{off};\, m) \right|^2 dt$$

summation over stations and components (Z,R,T)

data and synthetics have been filtered and windowed

compensates for un-modeled 3D structure

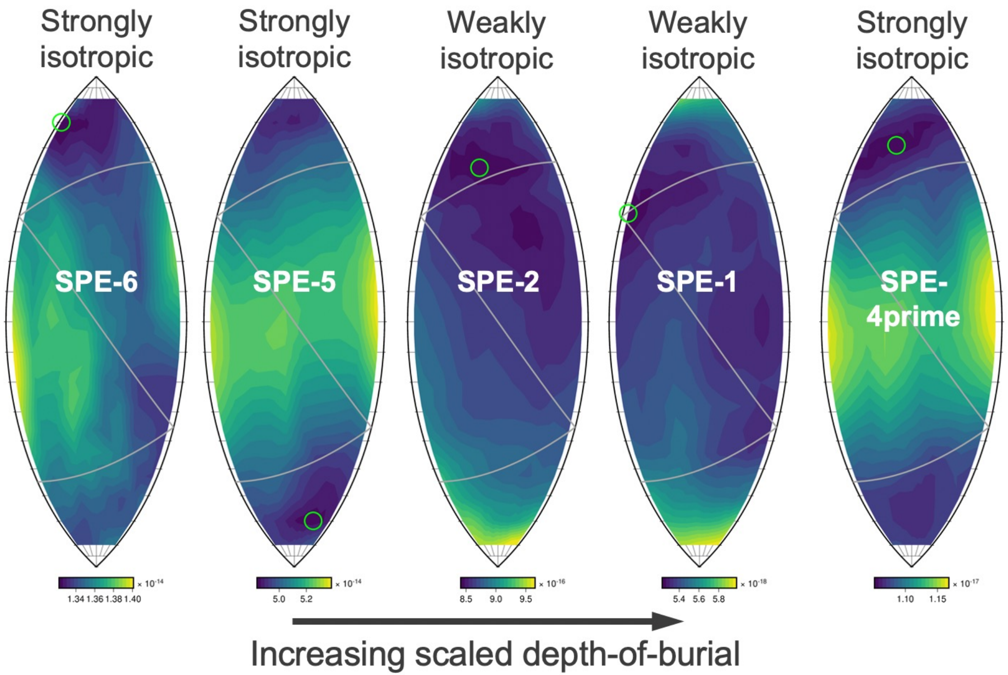
By evaluating this function over moment tensor space, we can get a visual sense of how uncertainty varies over moment tensor space…

Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Far-field moment tensor inversions supports notional SDOB model

- Using all available geophones within 2 km from source
- Color bar shows misfit variation; green circles mark maximum likelihood estimates



Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

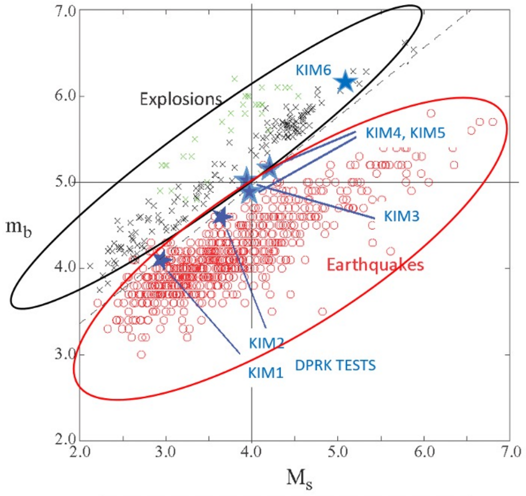
Summary

- Understanding shear release from underground explosions is important because many traditional discriminants involve shear-wave amplitudes
- Activation of pre-existing joints is one possible shear release mechanism, which would produce a distinctive pattern of shear-wave amplitude versus scaled depth-of-burial
- We have found patterns consistent with the above in SPE near-field records, far-field records, and moment tensor inversions
- These results establish the importance of joint unloading at distances of several kilometers from the source, further than previously known

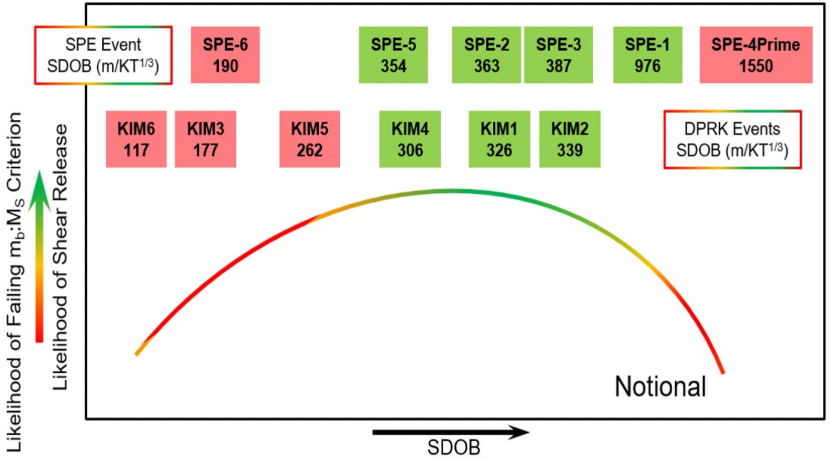
Correlating Shear Content to Scaled Depth-of-Burial

David Steedman and Ryan Modrak, Los Alamos National Laboratory, rmodrak@lanl.gov

Implications and future work – By showing that joint unloading effects persist further than previously known, these results raise possible nuclear explosion monitoring implications



Six DPRK Events in Relation to a m_b:M_S Discrimination Plot



Notional Trend in SPE Shear Release and DPRK m_b:M_S Indicating SDOB

Steedman and Bradley, 2020, ARMA