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3D Orthorhombic Elastic Wave Propagation Pre-Test Simulation of SPE DAG-1 Test

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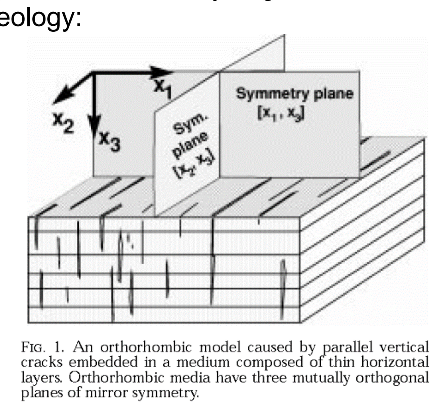
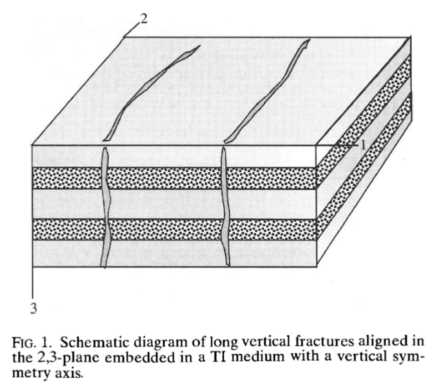
Summary

Many geophysicists concur that an ***orthorhombic*** elastic medium, characterized by three mutually orthogonal symmetry planes, constitutes a realistic representation of seismic anisotropy in shallow crustal rocks. This symmetry condition typically arises via a dense system of vertically-aligned microfractures superimposed on a finely-layered horizontal geology:

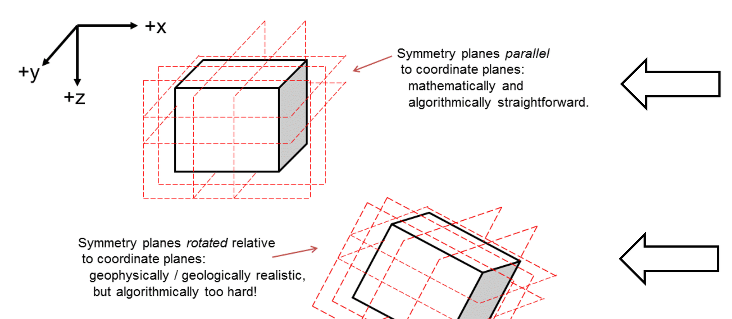


From Tsvankin, 1997, *Geophysics*.



From Schoenberg and Helbig, 1997, *Geophysics*.

However, various geological deformation processes will rotate the symmetry planes away from alignment with the global XYZ coordinate planes:

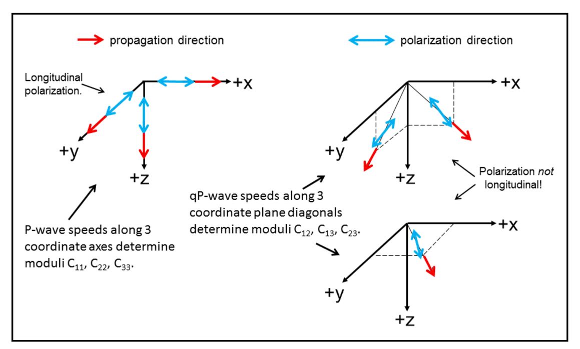


Present algorithmic assumption: 3 principal axes of orthorhombic elastic modulus tensor aligned with global XYZ coordinate axes.

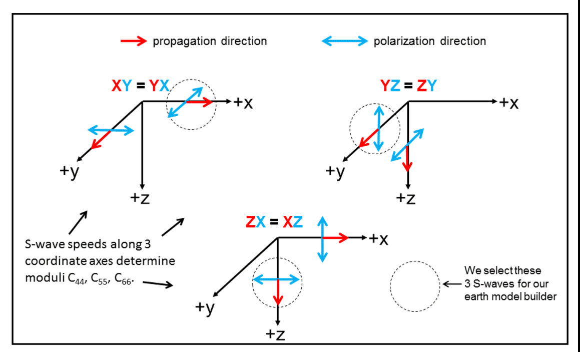
Rotated principal axes lead to significant algorithmic complications! Subject of future R&D.

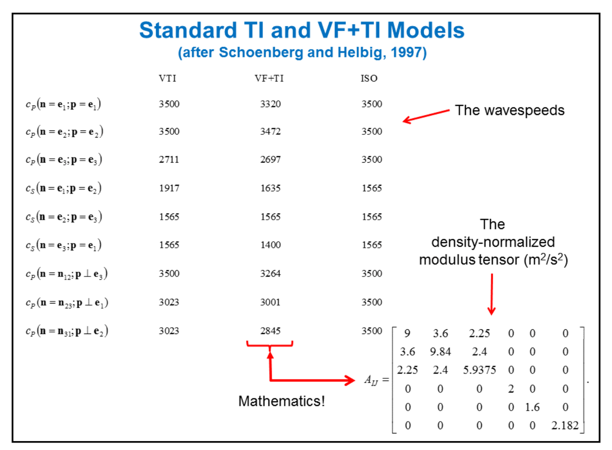
Mathematically, the elastic stress-strain constitutive relations for an orthorhombic body contain nine independent moduli. In turn, these moduli can be determined by observing (or prescribing) nine independent P-wave and S-wave phase speeds along different directions (Brown, 1989):

6 P-Wave Speeds / Directions:



6 S-Wave Speeds / Directions:





Our initial test modeling utilizes the "standard model" of a VF+TI (vertical fractures + transverse isotropic) elastic model of Schoenberg and Helbig (1997), plus its TI and isotropic counterparts.

The anisotropic elastic ***velocity-stress system***, a set of 9 coupled, first-order, linear, inhomogeneous PDEs forms the mathematical basis for our explicit time-domain finite-difference (FD) numerical algorithm. All partial derivatives are discretized with centered and staggered FD operators that are 2[nd]-order in time and 4[th]-order in space:

Governing PDE System:
Anisotropic Elastic Velocity-Stress System

$$\rho \frac{\partial v_i}{\partial t} - \frac{\partial \sigma_{ij}}{\partial x_j} = f_i + \frac{\partial m^a_{ij}}{\partial x_j}$$ 3 equations of motion

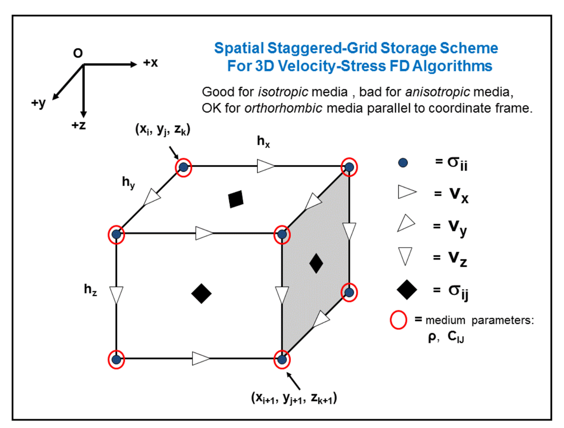
$$\frac{\partial \sigma_{ij}}{\partial t} - c_{ijkl} \frac{\partial v_k}{\partial x_l} = \frac{\partial m^s_{ij}}{\partial t}$$ 6 stress/strain constitutive relations

Nine, coupled, first-order, linear, non-homogeneous partial differential equations.

Wavefield variables:
$v_i(\mathbf{x},t)$ - velocity vector
$\sigma_{ij}(\mathbf{x},t)$ - stress tensor

Earth model parameters:
$\rho(\mathbf{x})$ - mass density
$c_{ijkl}(\mathbf{x})$ – modulus tensor
$(c_{ijkl} = c_{jikl} = c_{ijlk} = c_{klij})$

Body sources:
$f_i(\mathbf{x},t)$ - force vector
$m_{ij}(\mathbf{x},t)$ - moment tensor



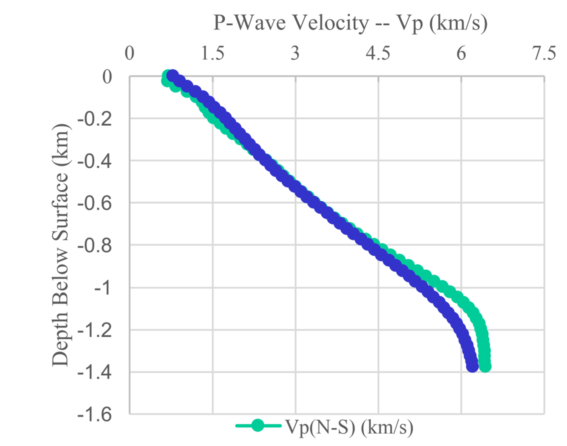
Model Creation

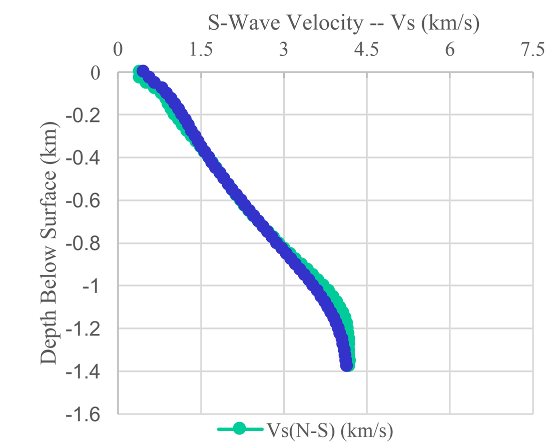
Model
•1051 x 1051 x 353 grid points.
•4 m grid point spacing.
•Free-surface boundary along X-Y plane at z=0 m.
•40 m thick CPML on all boundaries except free surface.
•Explosion source at z = 388 m.
•Source is Error Function (3rd integral of Ricker wavelet), 5 Hz frequency shifted 100 ms.
•No published anisoptrophy models of site

Two Cases
•Unmodified data from THOR I and II.
•Modified data with Z-axis wave speeds reduced 10 % to see effect of greater wave speed differential.

Assumed Model Wave Speeds

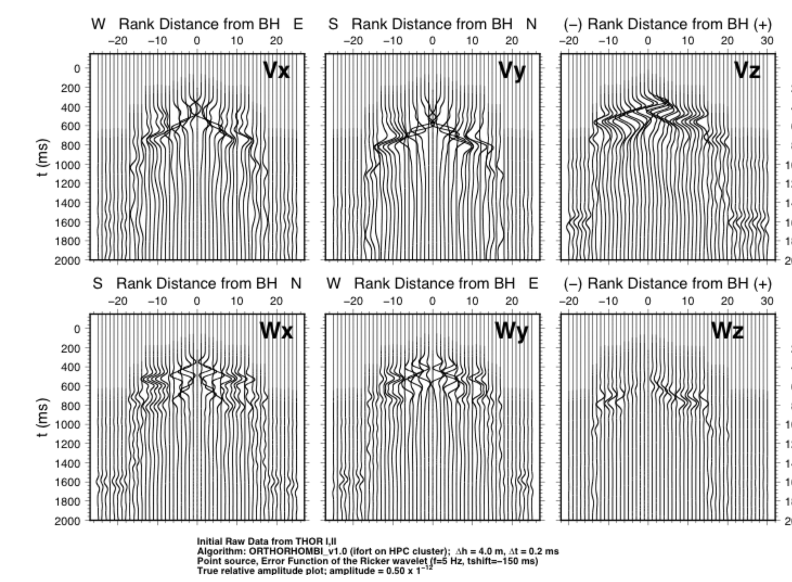
- **Existing anisotropic wave speed data for dry alluvium deposits were not located in literature search**
- **P- and S-wave speeds were adapted from preliminary Seismic Hammer Project (THOR 1 and THOR 2) results.**
- **Velocity model comprises a 1-D series of constant velocity layers**



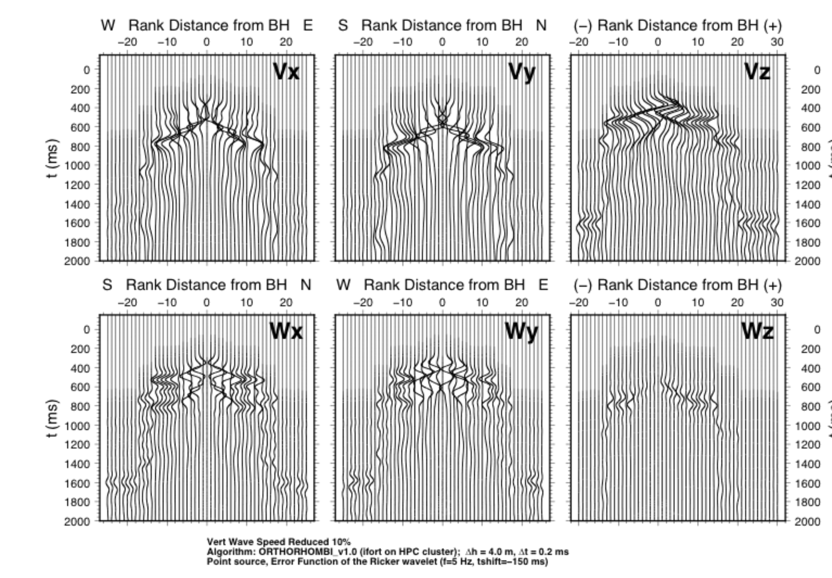


True Relative Amplitude Trace Plots

Initial Wave Speed Inputs

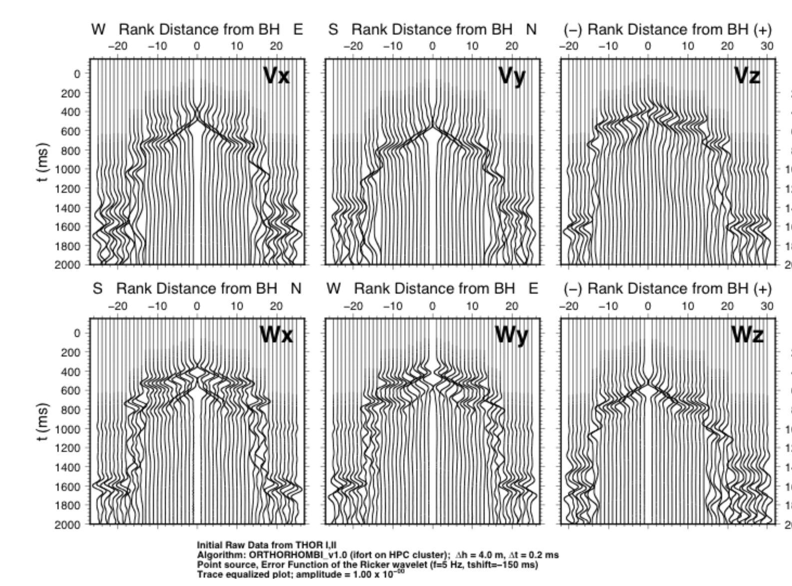


10% Reduction of Initial Vertical Axis (Z-axis) Wave Speed Inputs

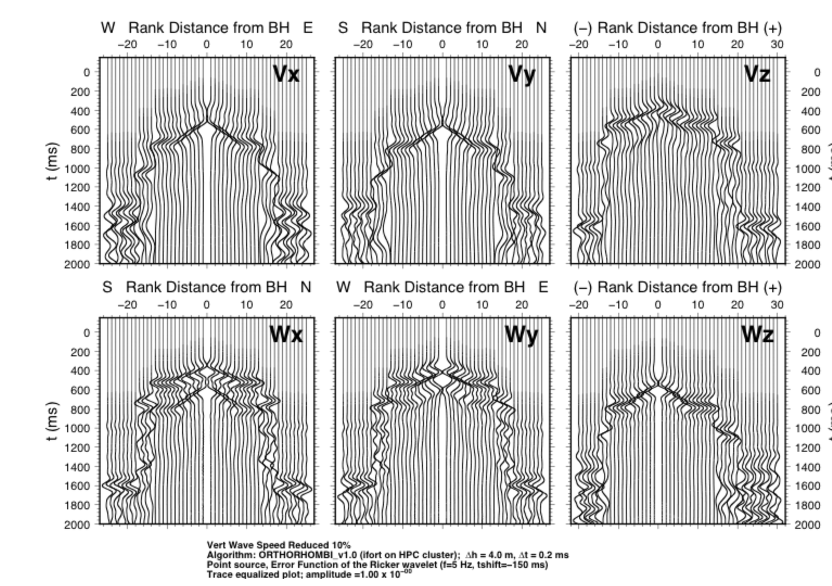


Trace Equalized Trace Plots

Initial Wave Speed Inputs

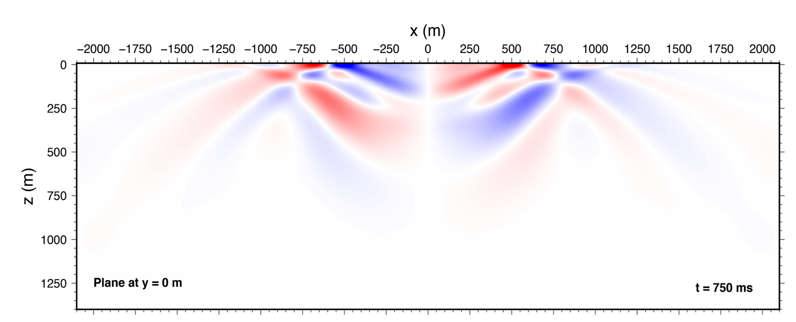


10% Reduction of Initial Vertical Axis (Z-axis) Wave Speed Inputs

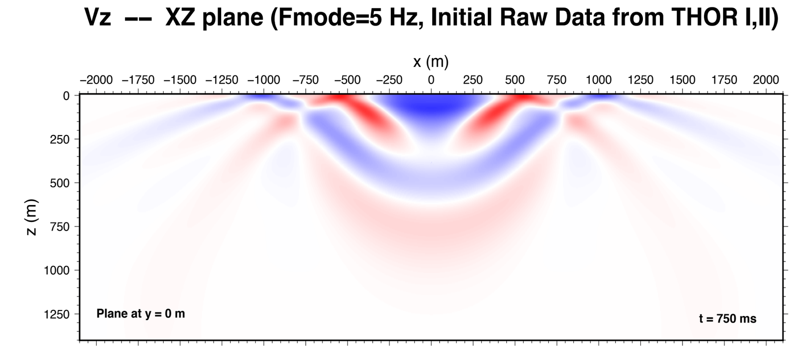


Particle Velocity Results

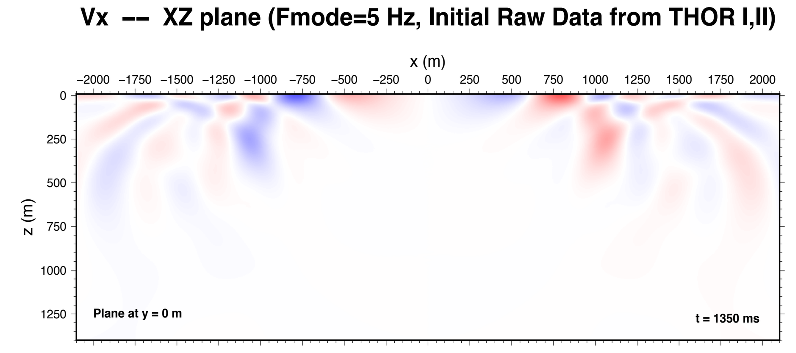
Vx — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)



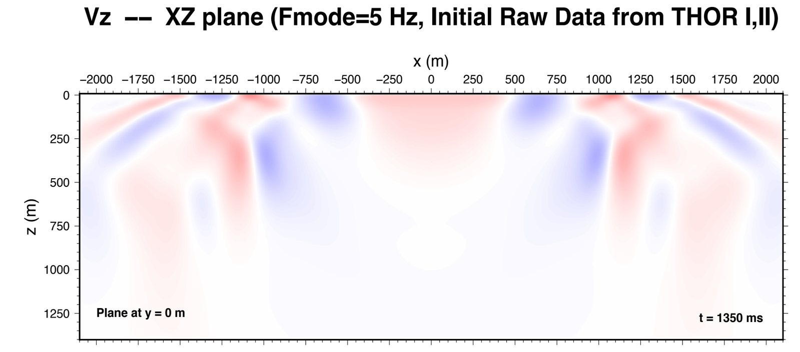
Vz — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)



Vx — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)

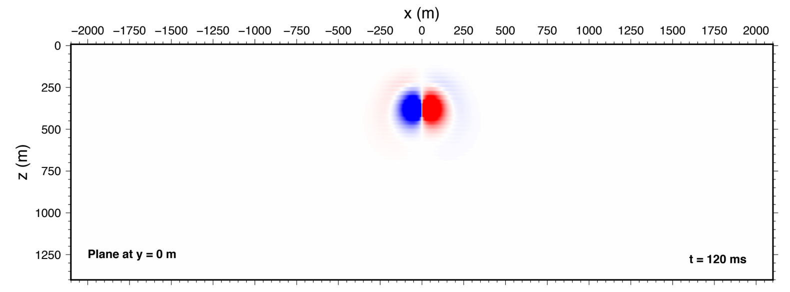


Vz — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)

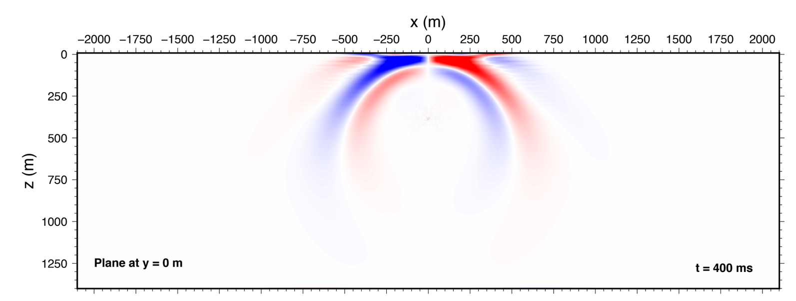


Particle Rotation Rate Results

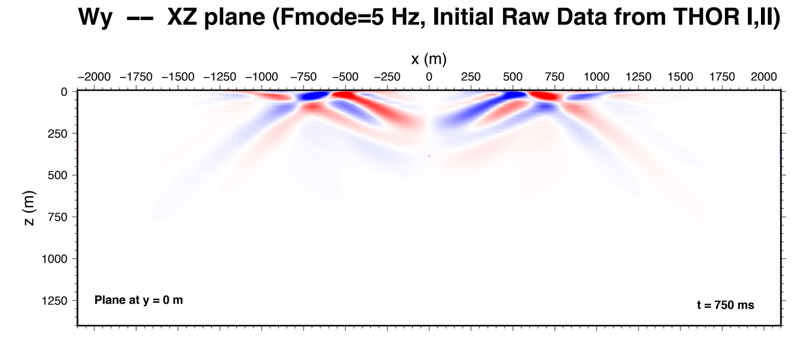
Wy — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)



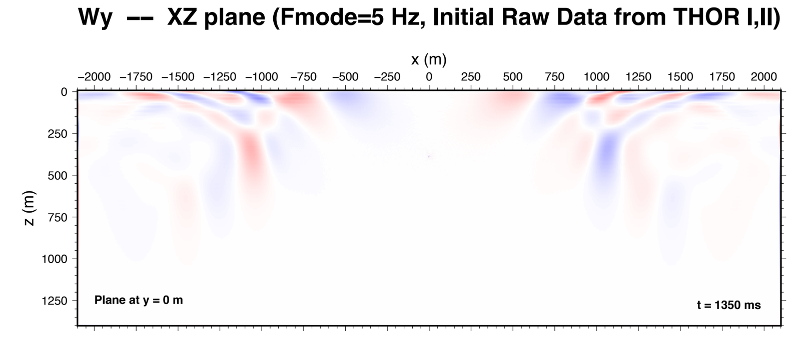
Wy — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)



Wy — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)

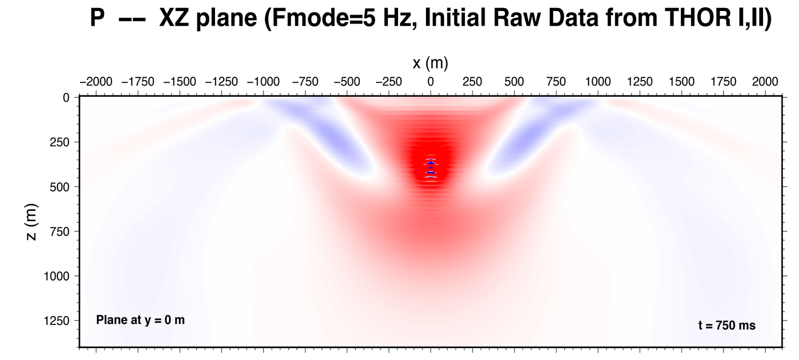


Wy — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)

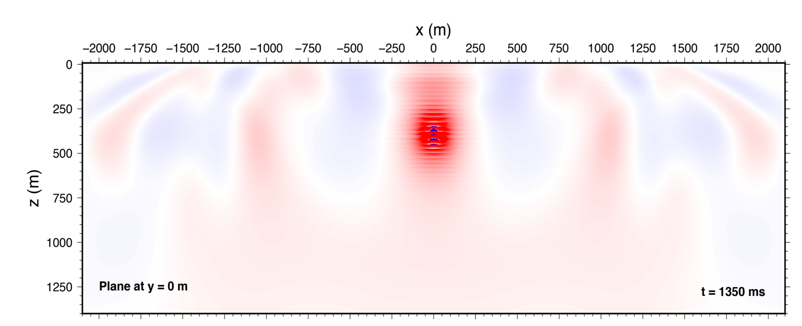


Pressure Wave Results

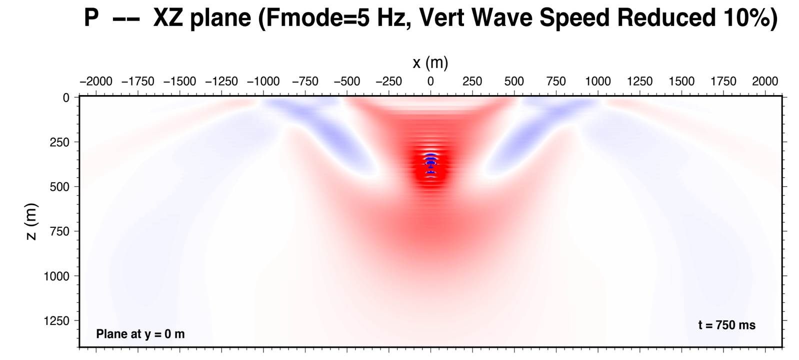
P — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)



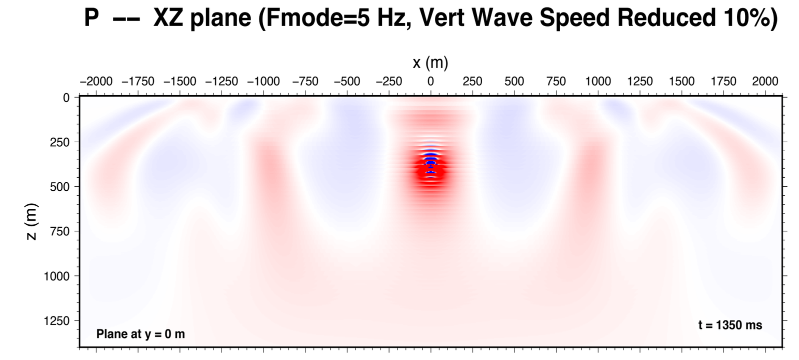
P — XZ plane (Fmode=5 Hz, Initial Raw Data from THOR I,II)



P — XZ plane (Fmode=5 Hz, Vert Wave Speed Reduced 10%)



P — XZ plane (Fmode=5 Hz, Vert Wave Speed Reduced 10%)



Conclusions

Explicit time-domain finite-difference numerical algorithm demonstrates known anisotropic seismic phenomena of:

1) Complex wavefront shapes, 2) Pressure / rotation propagating with *both* P / S speeds, 3) Split (fast and slow) shear waves, 4) SH energy (W_z) is generated for an explosion source in this 1-D layered structure (in an isotropic medium, no SH energy would be seen

Completed synthetic predictions for DAG-1 azimuthally anisotropic and orthorhombic model of site.

Limitations
1) No published anisotropy models of site, 2) Used best estimated 1-D layered structure

Future work:
Source scaling will be estimated from prior SPE data and DAG

Acknowledgements

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References

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