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3D Acoustic and Elastic Modeling with Marmousi2

Neill P. Symons, David F. Aldridge,
and Matthew M. Haney
Geophysics Department
Sandia National Laboratories
Albuquerque, NM

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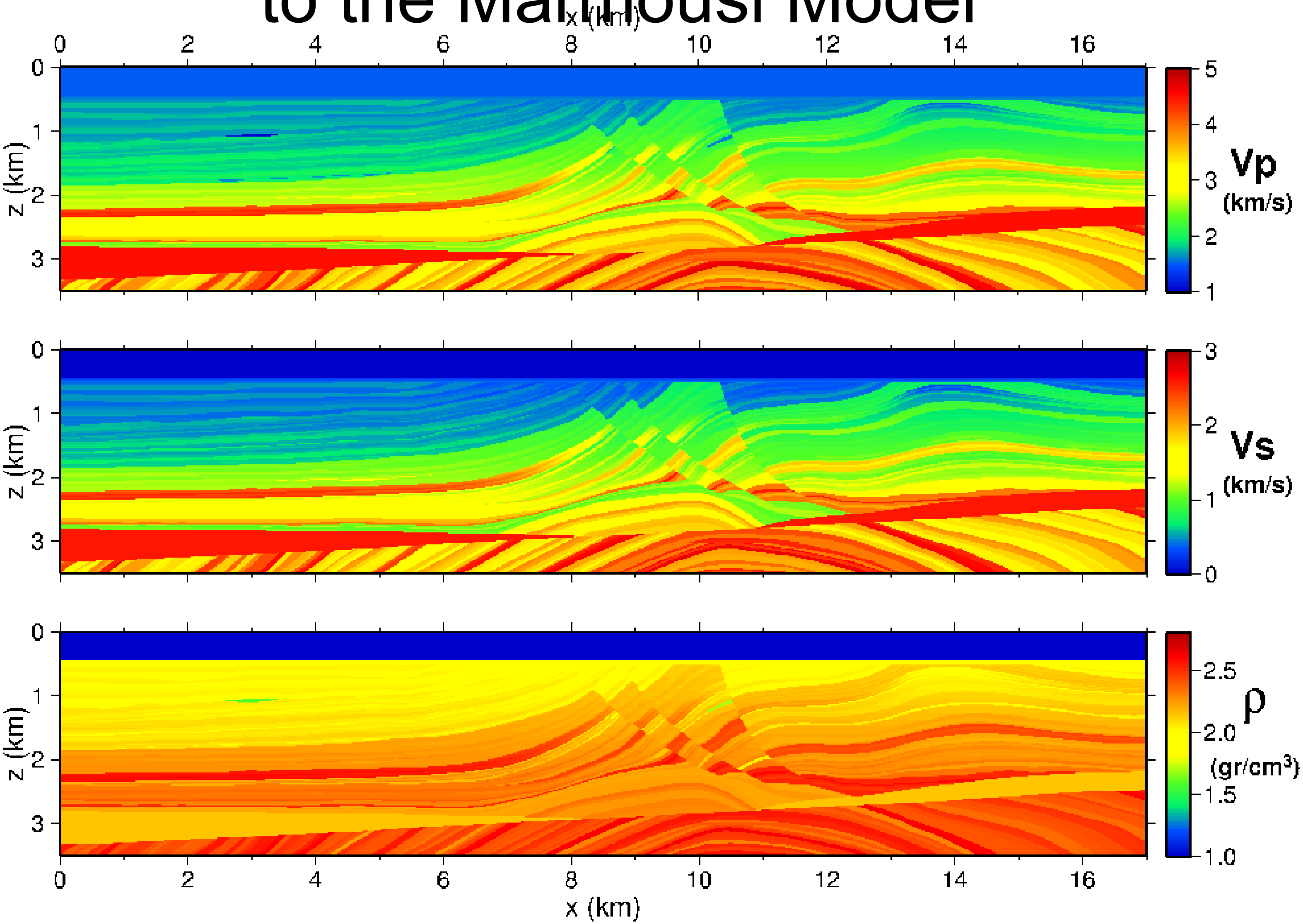
Marmousi2: Elastic Upgrade to the Marmousi Model



After **Martin et al.**,The Leading Edge, Feb. 2006. SNL 3D elastic modeling conducted with 5 m spatial grid interval ⇒ ~1.2 billion gridpoints

The Mathematical Basis:
Coupled Systems of Linear First-Order PDEs

Elastic Velocity-Stress System: 9 equations with 9 unknowns

$$\frac{\partial v_i}{\partial t} - b\frac{\partial \sigma_{ij}}{\partial x_j} = b\left(f_i + \frac{\partial m_{ij}^a}{\partial x_j} \right)$$

$$\frac{\partial \sigma_{ij}}{\partial t} - \lambda \frac{\partial v_k}{\partial x_k}\delta_{ij} - \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) = \frac{\partial m_{ij}^s}{\partial t}$$

Variables:

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

Parameters:

$b(\mathbf{x})$ - mass buoyancy
$\lambda(\mathbf{x})$, $\mu(\mathbf{x})$ -elastic moduli

Acoustic Velocity-Pressure System: 4 equations with 4 unknowns

$$\frac{\partial v_i}{\partial t} + b\frac{\partial p}{\partial x_i} = b\left(f_i + \frac{\partial m_{ij}^{dev}}{\partial x_j} \right)$$

$$\frac{\partial p}{\partial t} + \kappa \frac{\partial v_i}{\partial x_i} = -\frac{1}{3}\frac{\partial m_{ii}^{iso}}{\partial t}$$

Variables:

$v_i(\mathbf{x},t)$ - velocity vector
$p(\mathbf{x},t)$ - pressure

Parameters:

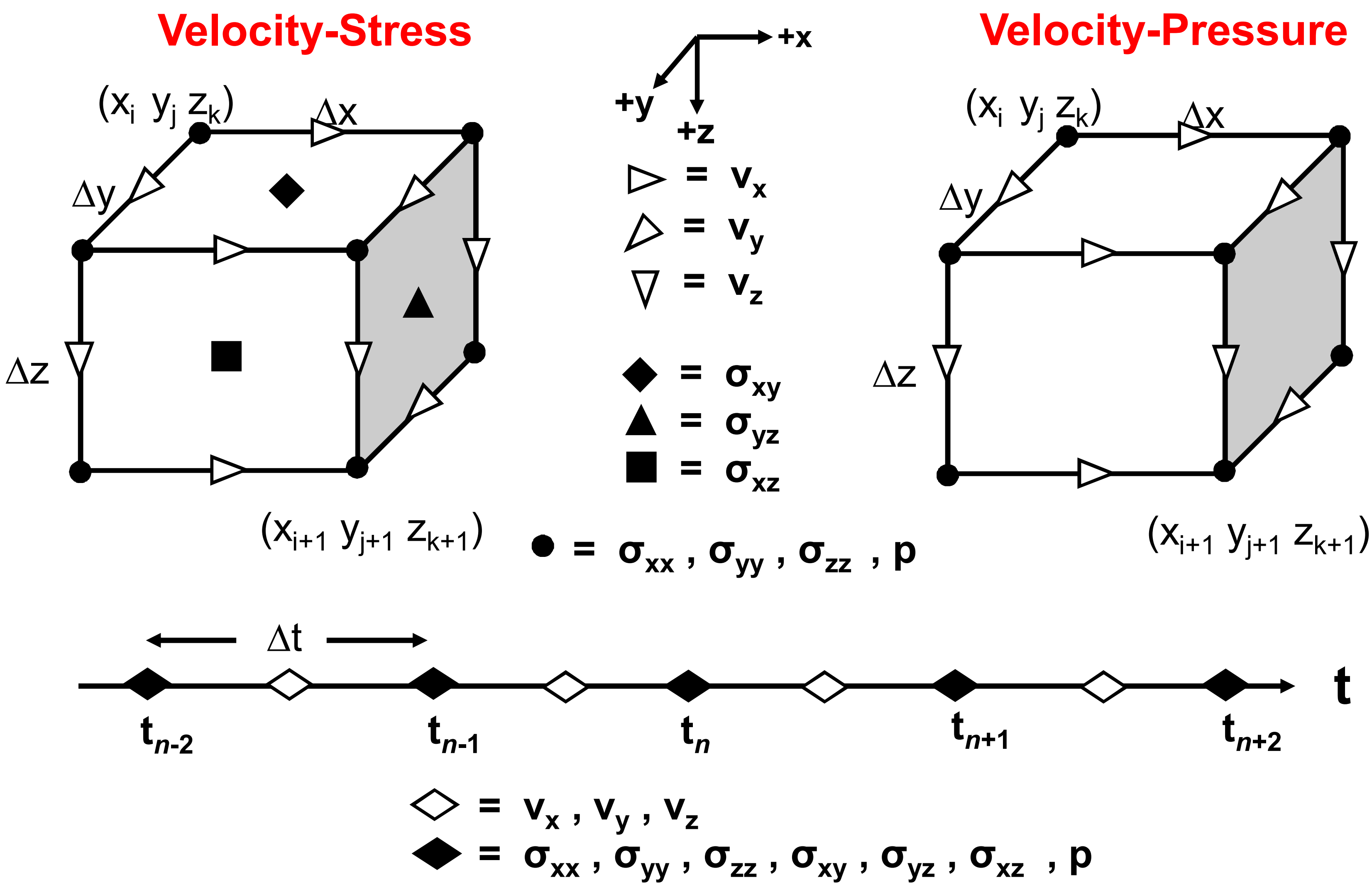
$b(\mathbf{x})$ - mass buoyancy
$\kappa(\mathbf{x})$ - bulk modulus

Seismic Body Sources:

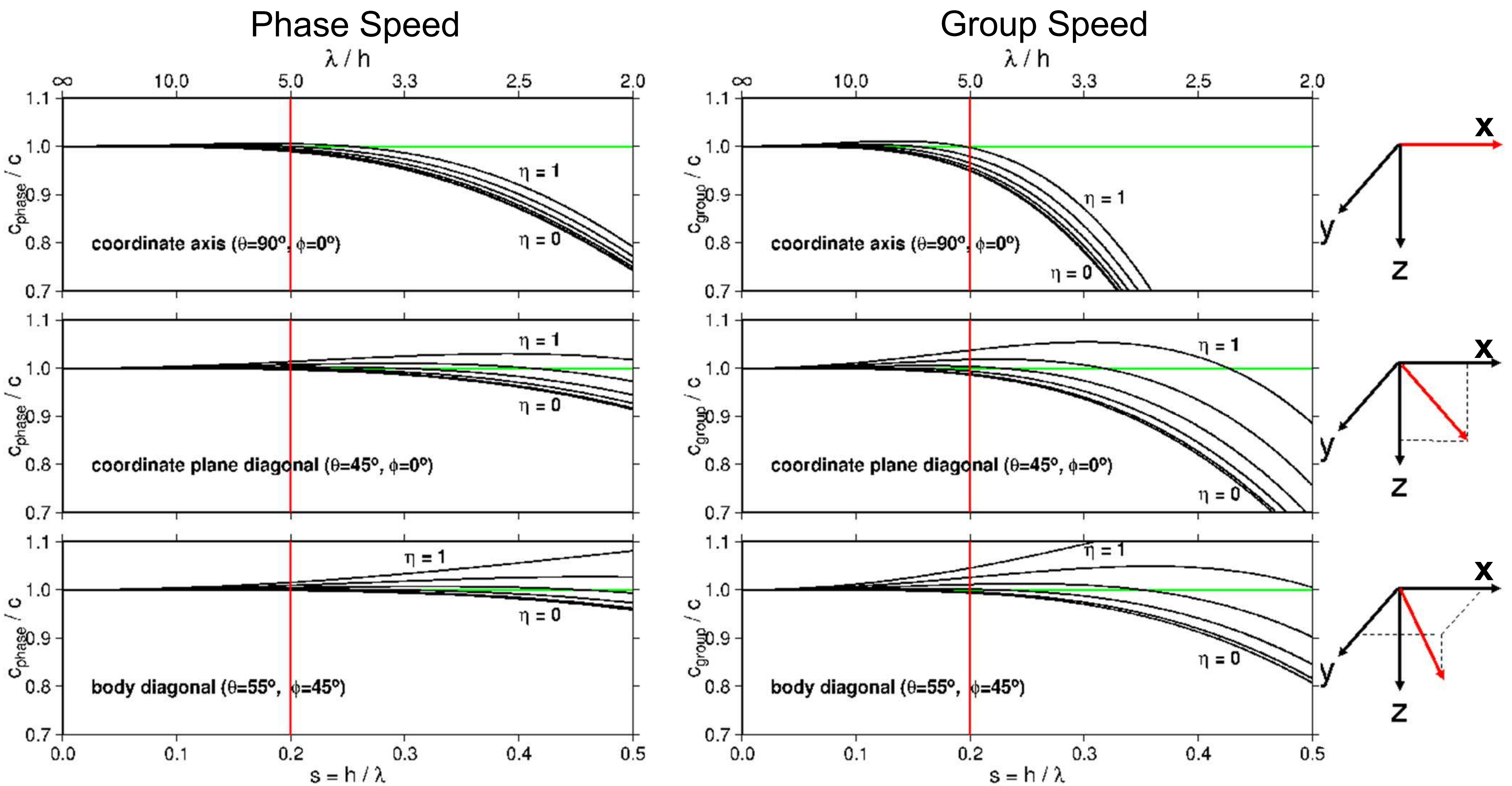
$f_i(\mathbf{x},t)$ – force density vector
$m_{ij}(\mathbf{x},t)$ – moment density tensor

Systems derived from fundamental principles of continuum mechanics (conservation of mass, linear, and angular momentum), and linear, time-invariant and local stress-strain constitutive relations.

The Algorithmic Basis: Explicit, Time-Domain, Finite-Difference Solution on Staggered Spatial and Temporal Grids

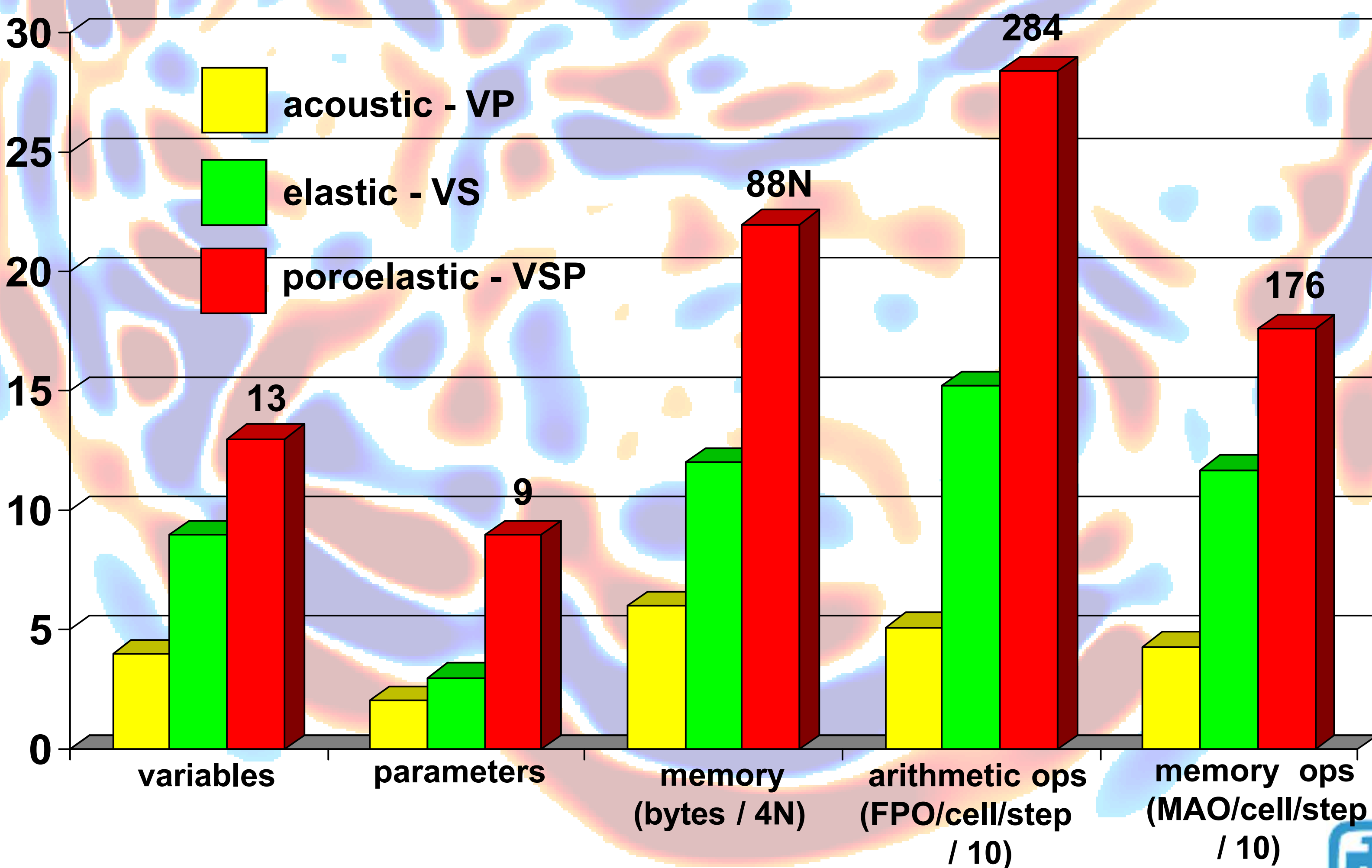


Numerical Dispersion: Phase and Group Speed Curves



3D O(2,4) FD solution of 1st order velocity-stress elastic *and* velocity-pressure acoustic systems on staggered temporal/spatial grids. Stability parameter η ranges from 0 to 1. **Vertical red line:** conventional "5 grid intervals per wavelength" rule of thumb for for minimal dispersion. **Horizontal green line:** ideal (no dispersion) case.

TDFD Algorithm Comparisons: 3D O(2,4) Temporal / Spatial Staggered Solution of 1st-order Coupled PDE Systems



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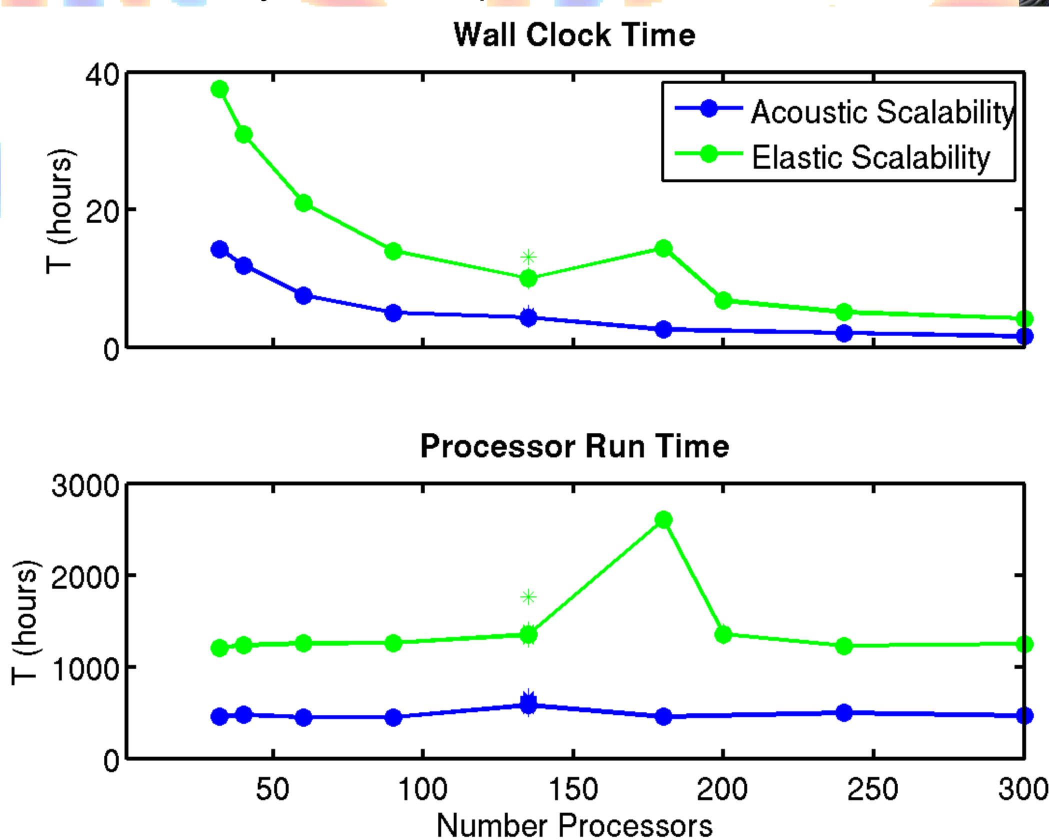
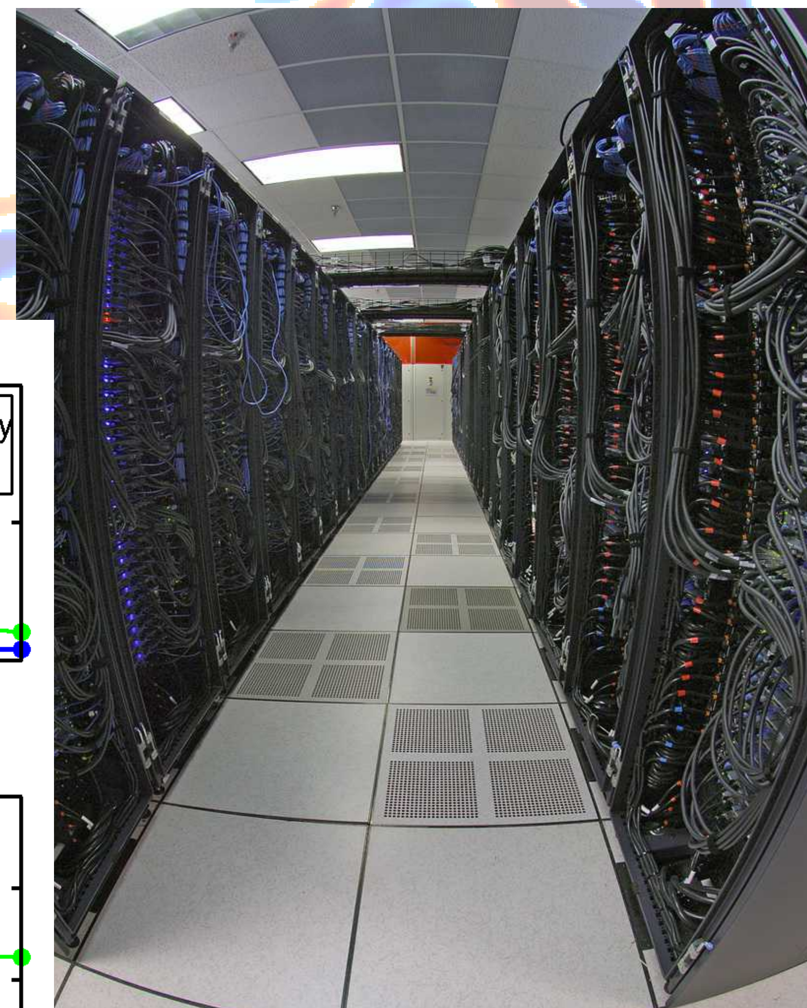
Run Time Comparison/Scalability

- Thunderbird
  - Dell PowerEdge cluster
  - 4480 compute nodes
    - Dual 3.6 GHz Intel EM64T processors
    - 6 GB RAM
  - 3.6GHz Infiniband interconnect
  - Currently 6 on the Top500





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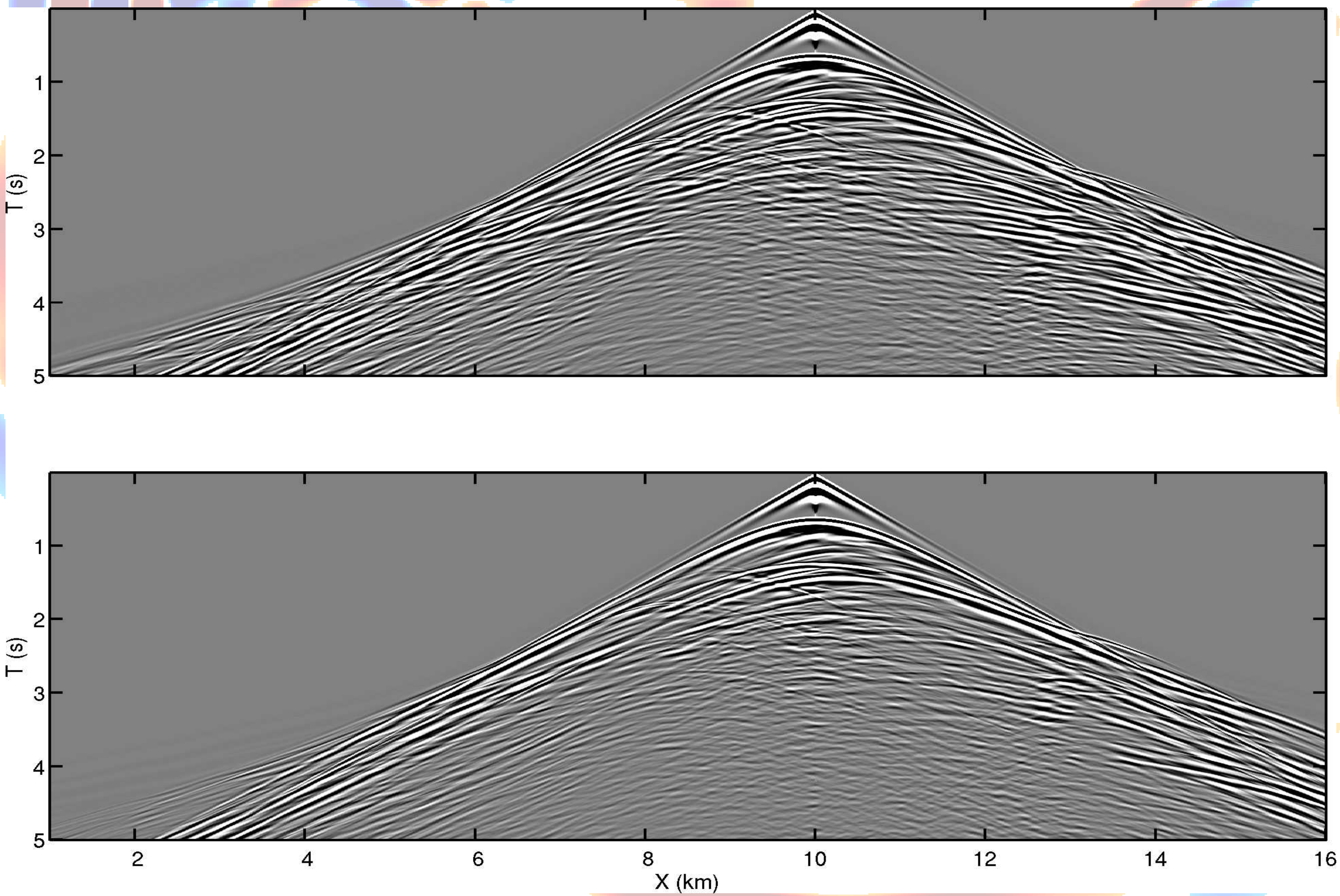
Pressure Trace Comparison



Velocity-pressure (acoustic) algorithm

Velocity-stress (elastic) algorithm

1501 hydrophones, 5 m below sea-surface, arrayed from x = 1 km to x = 16 km. Note strong similarity of calculated responses.

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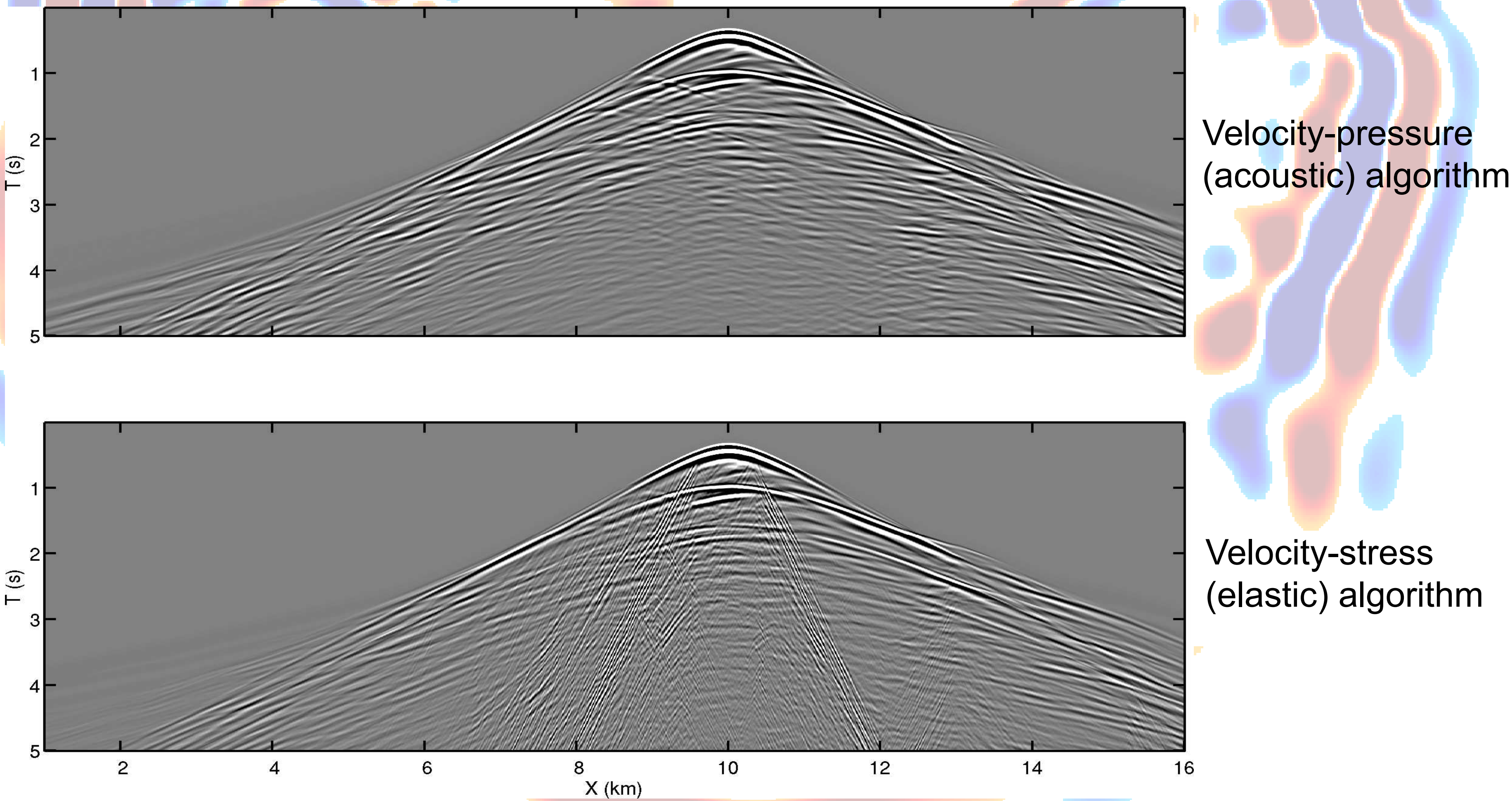
Ocean Bottom Seismometer Trace Comparison



1501 vertical component (Vz) ocean bottom seismometers, located 450 m below sea-surface, arrayed from x = 1 km to x = 16 km. Note strong differences in calculated responses.

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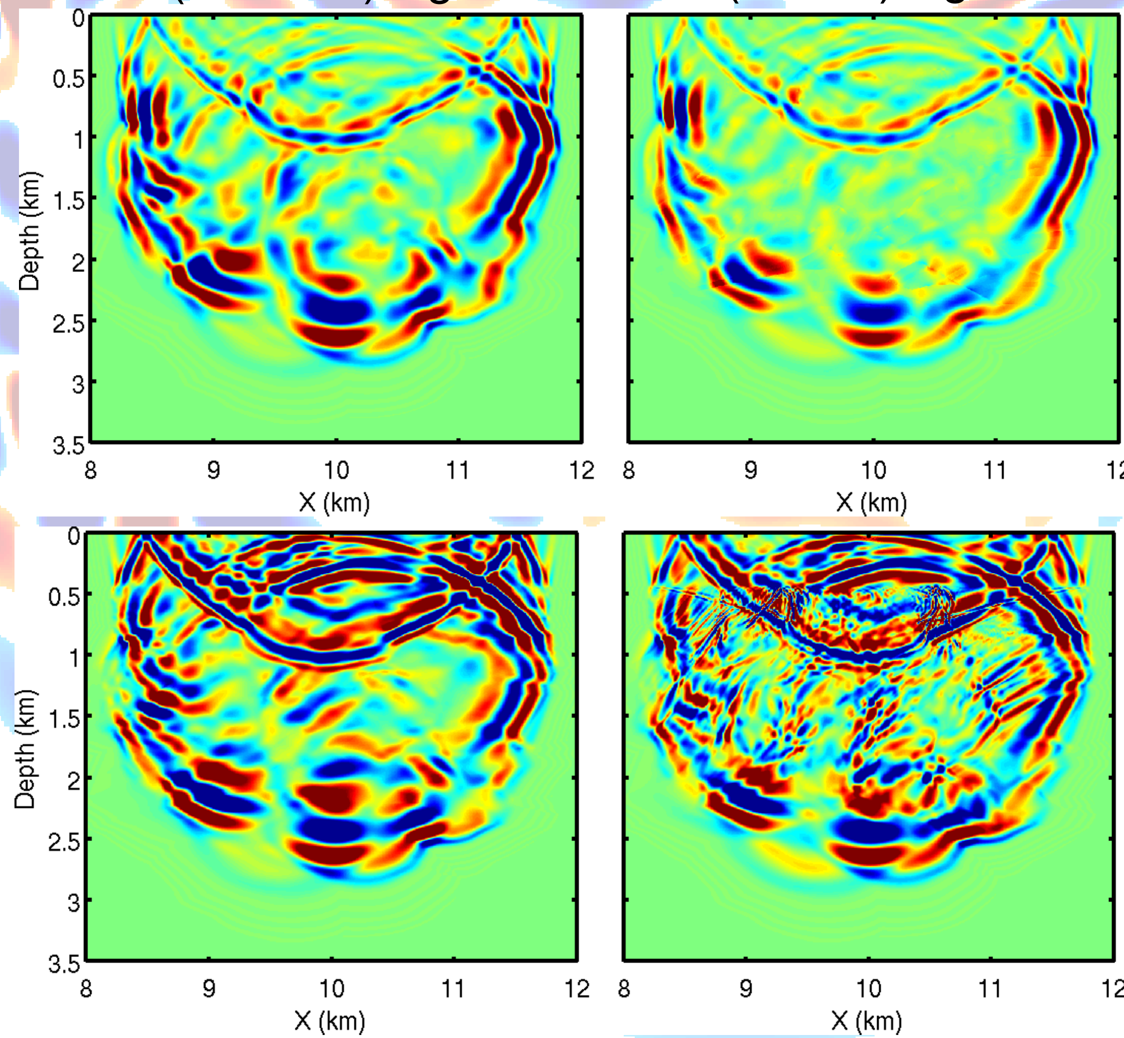
Timeslice Comparisons: Pressure and Vz Particle Velocity

VP (acoustic) algorithm VS (elastic) algorithm



Pressure timeslices;
t = 1.37 s.

(note similarity)

Vz Velocity Timeslices;
t = 1.37 s.

(note difference)

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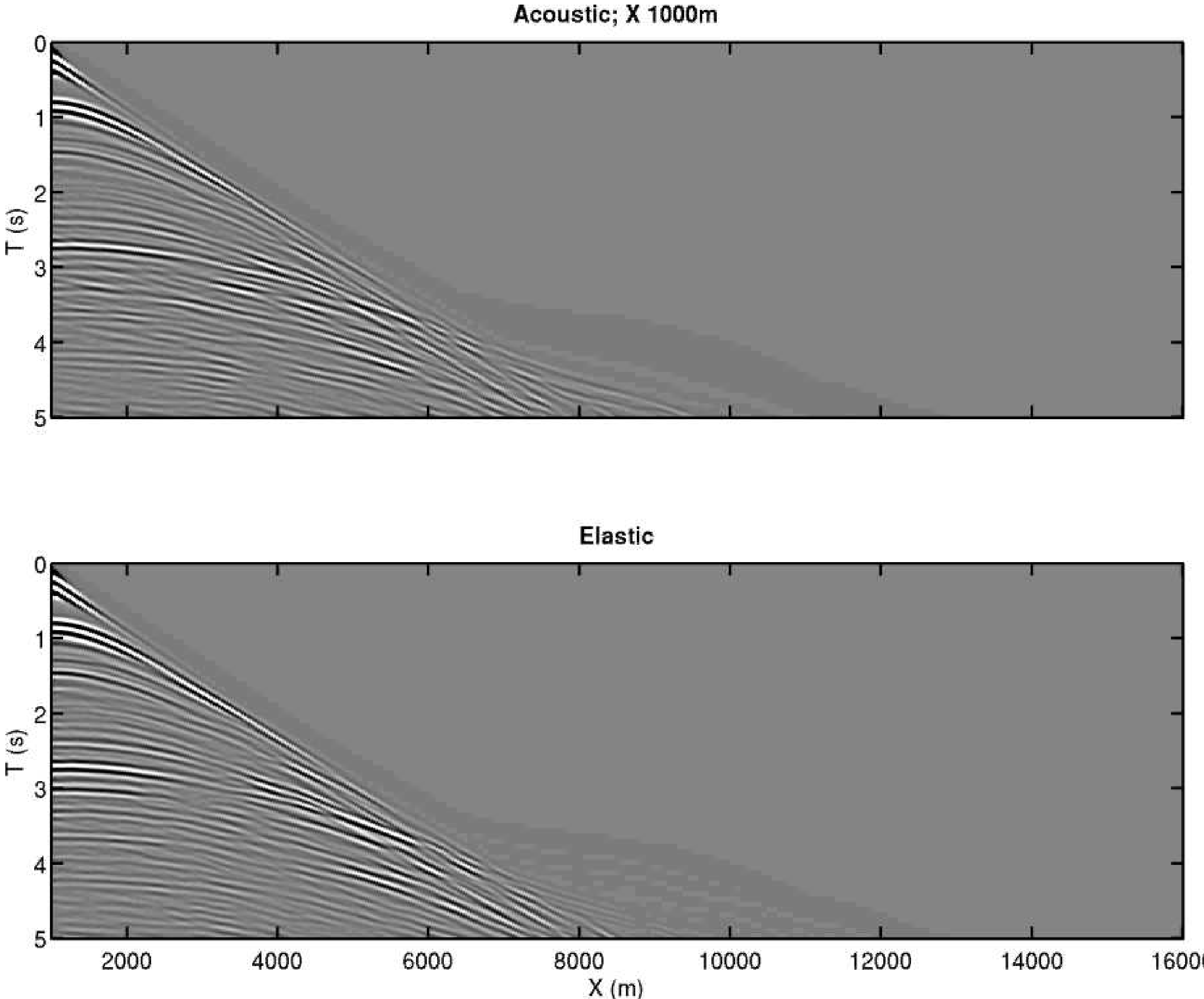
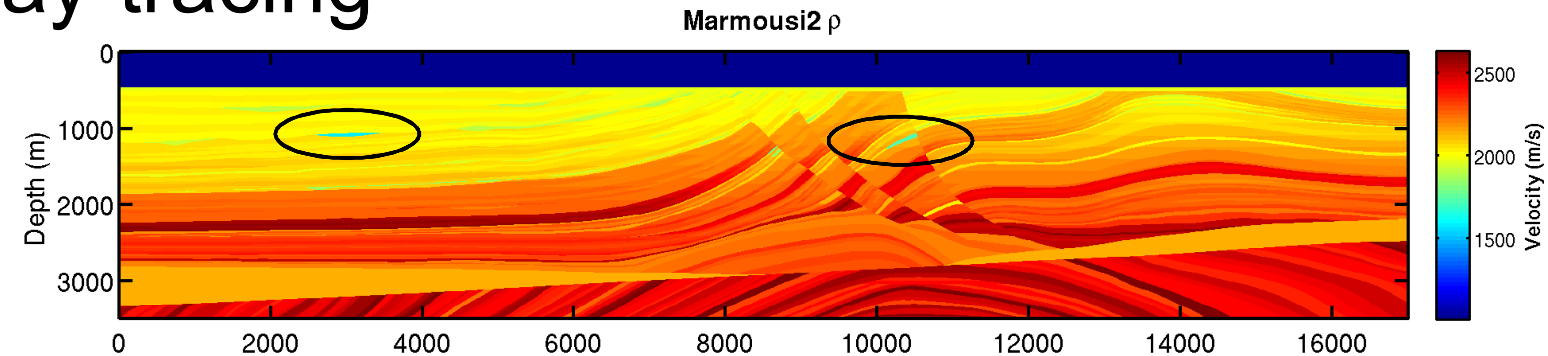
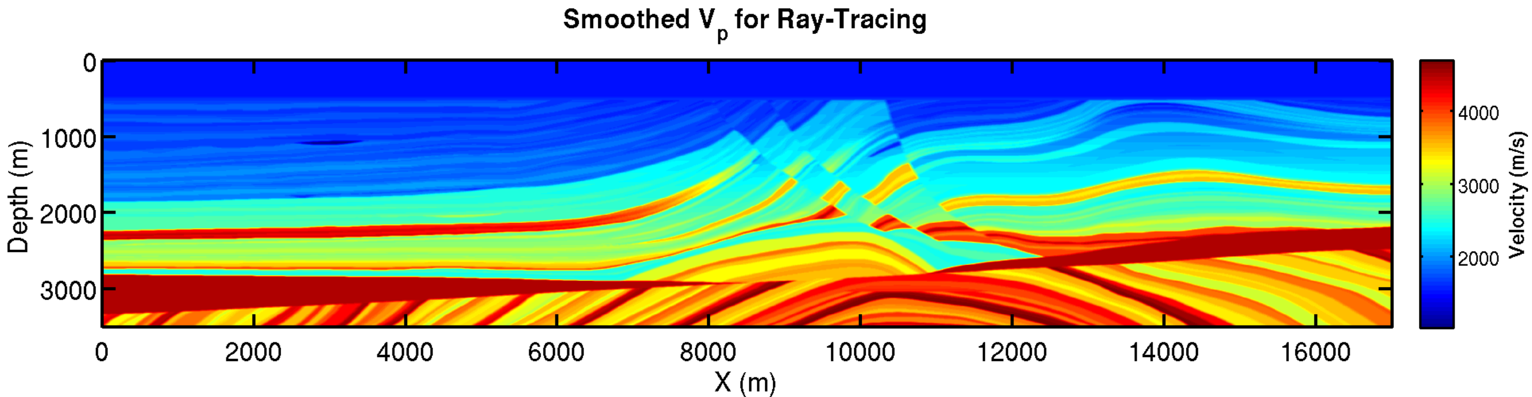
Acoustic/Elastic Record Sections



AVO Comparisons

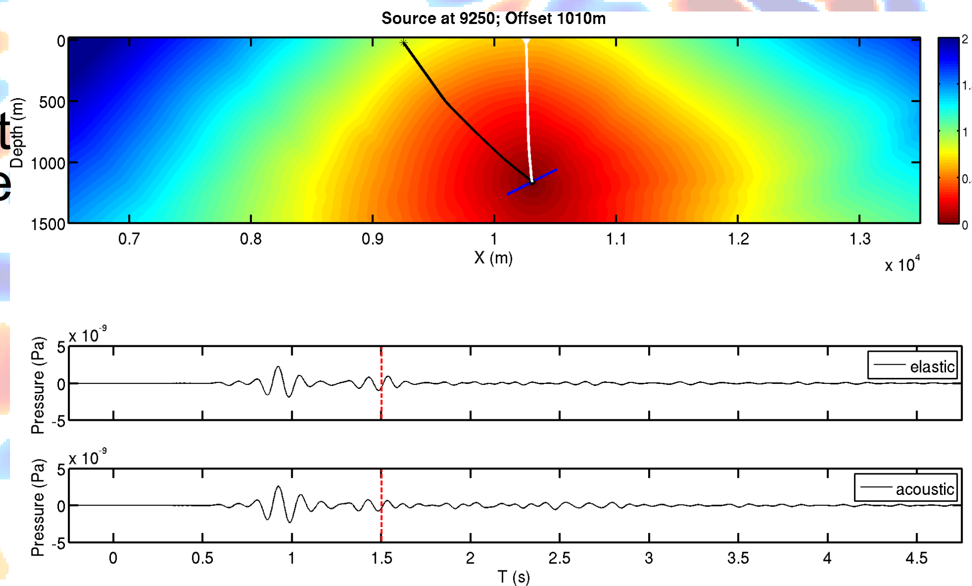
- Select 2 target regions
- Create a smooth version of the model for ray-tracing





Ray-Tracing and Amplitude Extraction

- Calculate travel-times outward from the CRP
  - Follow the steepest-descent travel-time gradient from the source to CRP
  - Determine the angle of incidence to the target
  - Calculate the specular reflection angle
  - Determine which receiver generates a ray with this angle to the target



  - Trace from that receiver to the target
  - Add times on source and receiver rays to get the primary PP reflection travel-time
    - Index into the trace that corresponds to the receiver and calculated travel-time
    - Amplitude is the mean of 0.1s window around this time

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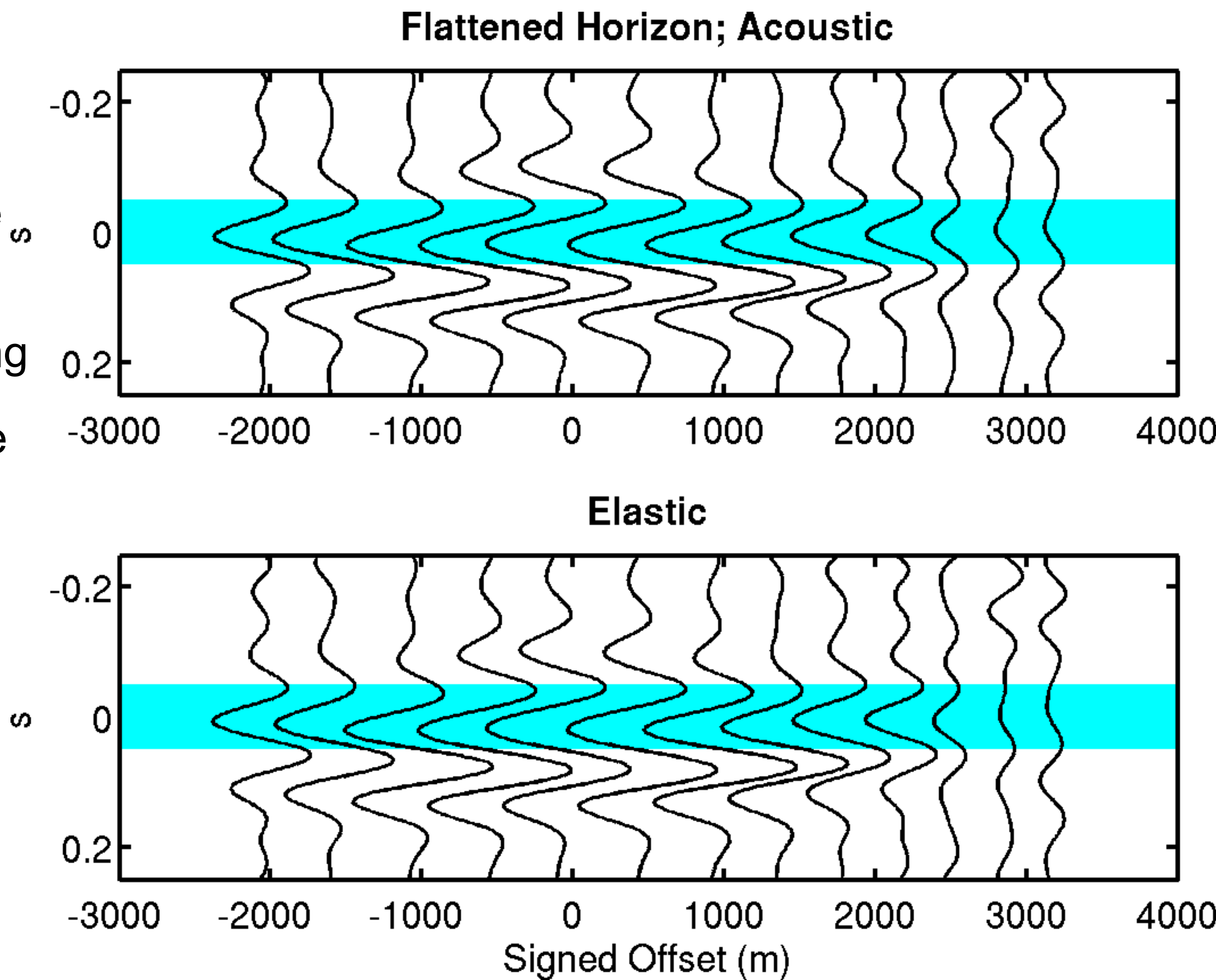
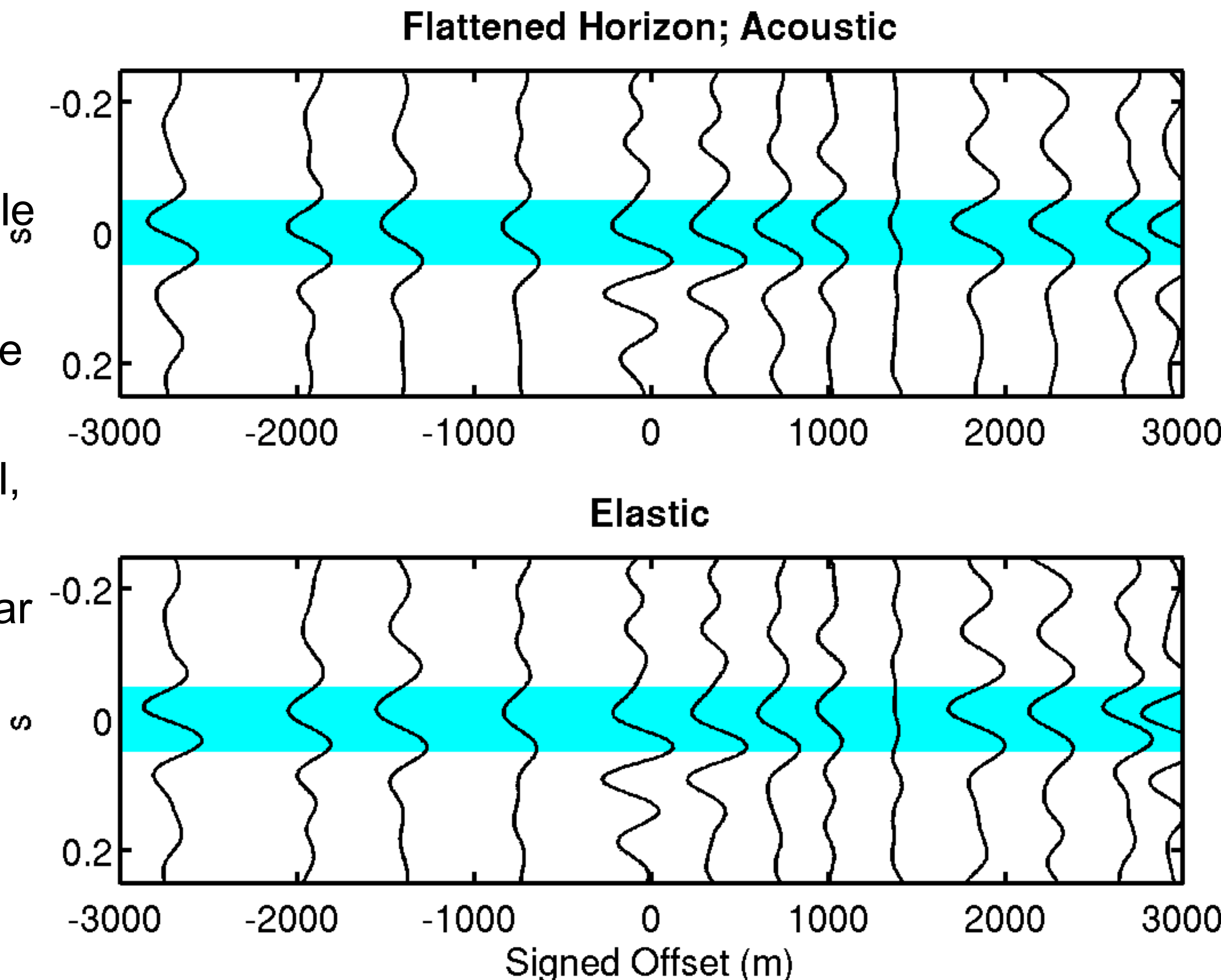
AVO Data Target 1

- This is the nearly horizontal target on the left side of the model
- Since we are only comparing the results we have not done any type moveout or spreading corrections

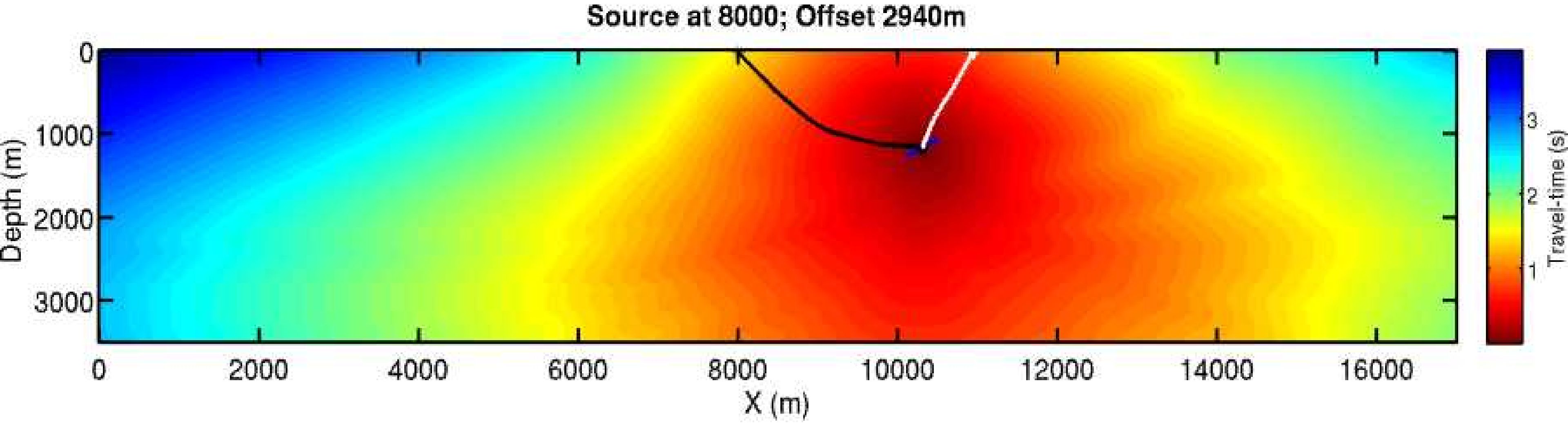


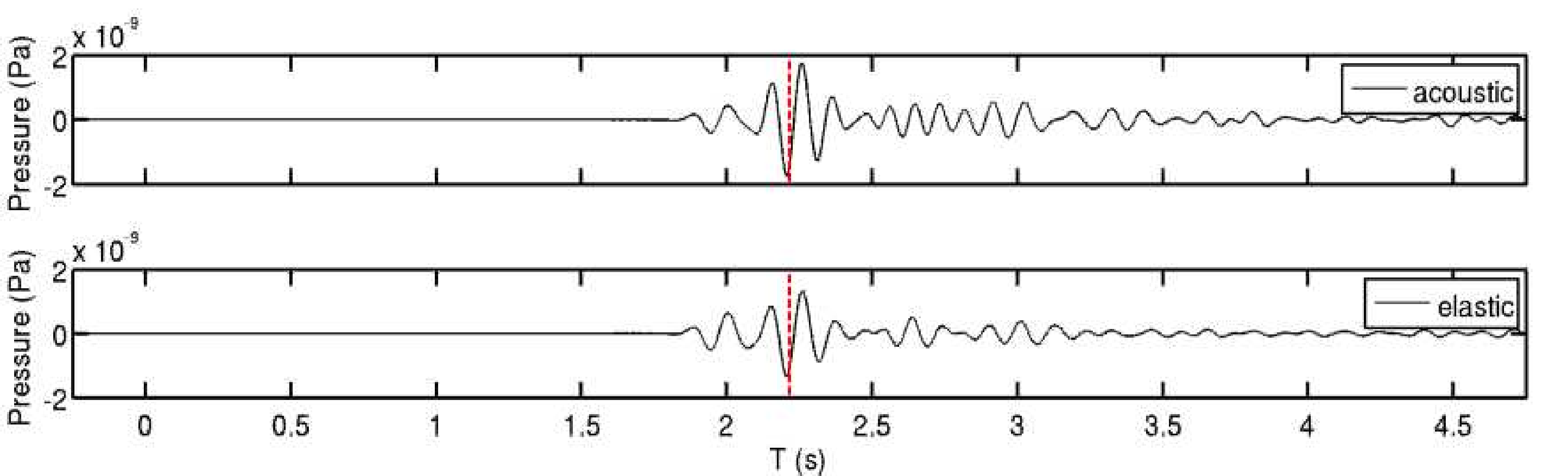
AVO Data Target 2

- This is the dipping target in the more structurally complex middle portion of the model
- Because of the dip, the complex velocity model, and the wide shot spacing we get irregular offsets



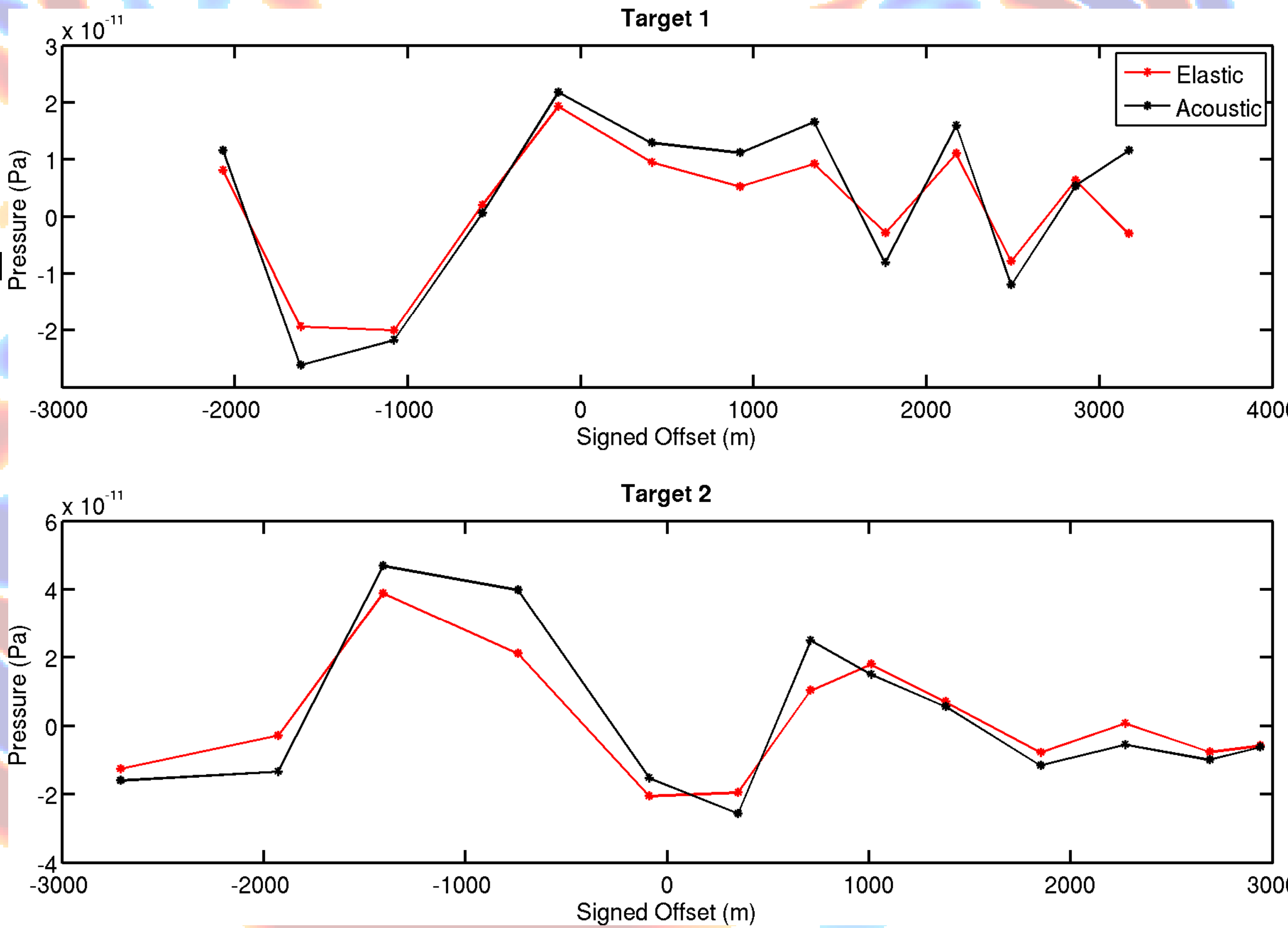
Target 2 Extraction





AVO Results

- Upper Plot
  - This is the nearly horizontal target on the left side of the model
- Lower Plot
  - This target is steeply dipping down to the left
  - Much more structurally complex part of the model



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Conclusions

- Modeling is a lot easier when someone else builds the model
  - Gary Martin, Robert Wiley, and Kurt Marfurt have put together an excellent model
  - Useful for a variety of algorithm/modeled data tests
- If we are interested in marine seismic hydrophone (pressure) data acoustic modeling is probably sufficient
  - Elastic modeling reproduces some fine details
  - AVO responses are very similar
    - Difference is probably below the noise floor for real data
- Acoustic models run much faster
  - The difference is greater than shown in our run-time comparison
  - We could have run the acoustic model with a higher-frequency source or a coarser grid spacing since the lowest velocities are higher
    - Frequency and grid spacing were limited by the need to keep numerical dispersion to a minimum

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