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Seismic Investigation of the WIPP Site "Brine Pod" Problem

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Seismic and Acoustic Wave Propagation R&D In SNL's Geophysics Department

Principal Research and Development Thrust:

Development and application of advanced numerical algorithms for simulating 3D seismic and acoustic wavefields propagating within realistic geologic and atmospheric environments.

Customers:

- Petroleum exploration/production industry (small, intermediate, and large companies).
- Geophysical services industry.
- DoE, DoD, and DoHS agencies.
- Academia and Professional Societies.

Funding:

- SNL: LDRD, NMSBAO
- DoE: BES, NGOTP, NETL, EMSP.
- DoD: DARPA, DTRA, SERDP.
- WFO: Other government agencies or private enterprise.

Seismic and Acoustic Wave Propagation R&D In SNL's Geophysics Department

Numerical Algorithms Appropriate for:

- fixed and moving ideal fluid (acoustic) media.
- isotropic solid elastic media.
- isotropic anacoustic and anelastic (i.e., attenuative/dispersive) media.
- poroelastic (two-phase fluid-saturated solid) media.
- *anisotropic (both elastic and anelastic) media under development.*

Preferred Numerical Solution Methodology:

Explicit, time-domain, finite-differencing of coupled systems of first-order partial differential equations, representing "full physics" mathematical characterization of continuum-mechanical wave propagation problems, in the linear (i.e., infinitesimal deformation) limit. Issues include:

- staggered spatial and temporal grids.
- high-order finite-difference operators.
- parallelization via spatial domain decomposition.

Why Compute Synthetic Seismic and Acoustic Data?

1) **Fundamental research:** study scientific issues associated with wave propagation in earth and atmosphere environments (radiation, reflection, refraction, scattering, attenuation, dispersion, etc.).

2) **Applied research:** understand practical issues related to remote sensing and imaging with seismic and/or acoustic waves (detection, resolution, sensitivity, parameter estimation accuracy, etc.).

3) Engage in **prediction**, hypothesis testing, or simulation (ground motion, CO_2 sequestration, monitoring, fluid inclusion effects, etc.).

4) Enhance **interpretation** of field-recorded seismic/acoustic data.

5) **Validate** data processing, analysis, interpretation, imaging, or inversion **algorithms** with *realistic* synthetic data generated from known earth and atmosphere models (Marmousi Model, SEG/EAEG Salt Model, SEAM project).

6) **Design** field or laboratory data acquisition **experiments** or **equipment** (survey planning, illumination studies, borehole tools, core sample apparatus).

7) Develop and **enhance numerical computation** capabilities (algorithm parallelization, memory reduction, execution speedup, FD operators, absorbing boundary conditions).

8) Improve **seismological education** via modern visualization capabilities.

Elastodynamic Velocity-Stress System

$$\frac{1}{\rho}\frac{\partial v_i}{\partial t} - \frac{\partial \sigma_{ij}}{\partial x_j} = f_i + \frac{\partial m_{ij}^a}{\partial x_j}$$ (3 equations)

$$\frac{\partial \sigma_{ij}}{\partial t} - \lambda \frac{\partial v_k}{\partial x_k}\delta_{ij} - \mu\left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right] = \frac{\partial m_{ij}^s}{\partial t}$$ (6 equations)

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

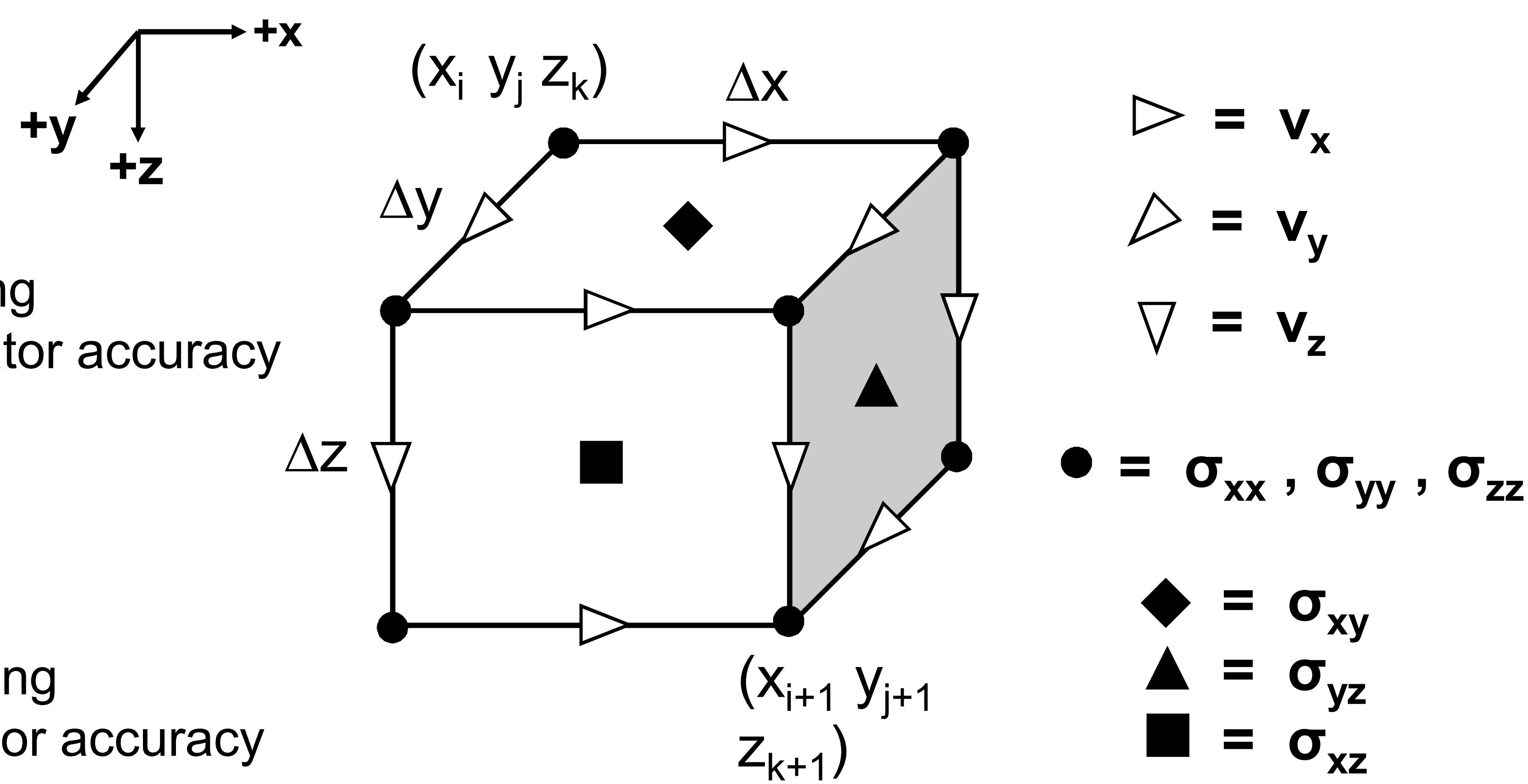
Body sources:

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

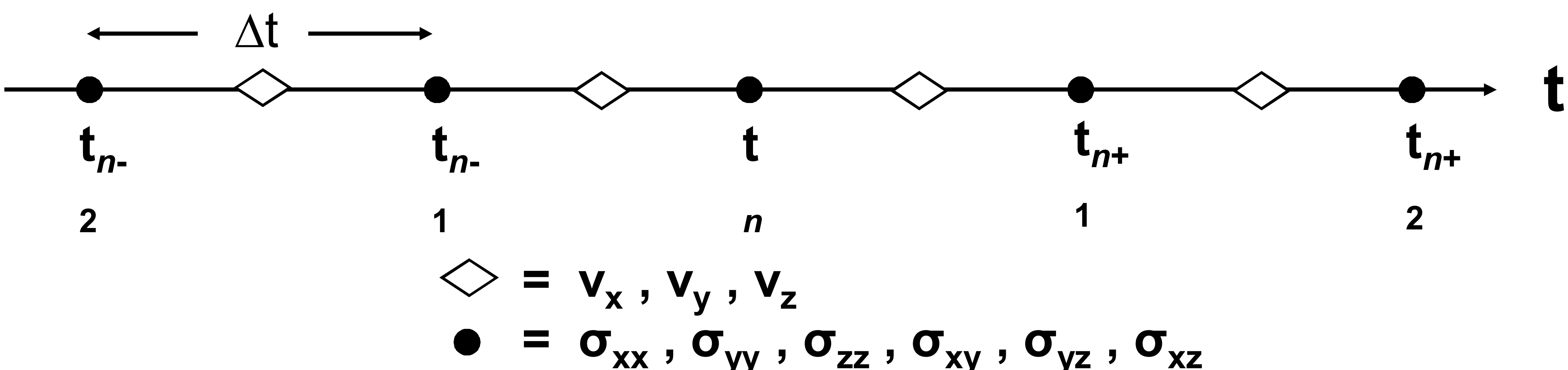
Derived from fundamental principles of continuum mechanics (conservation of mass, balance of linear and angular momentum), an isotropic elastic stress-strain constitutive relation, and linearization to the infinitesimal deformation regime.

Finite Difference Staggered Spatial and Temporal Storage Schemes

3D spatial staggering
⇒ high centered FD operator accuracy



1D temporal staggering
⇒ high centered FD operator accuracy



Plan for Full Waveform Modeling Investigation of the Brine Pod Problem

1) Calculate full waveform seismic reflection/scattering responses for a suite of candidate brine pods inserted within a background geophysical model of the WIPP site (and including the WIPP facility as an air-filled void).

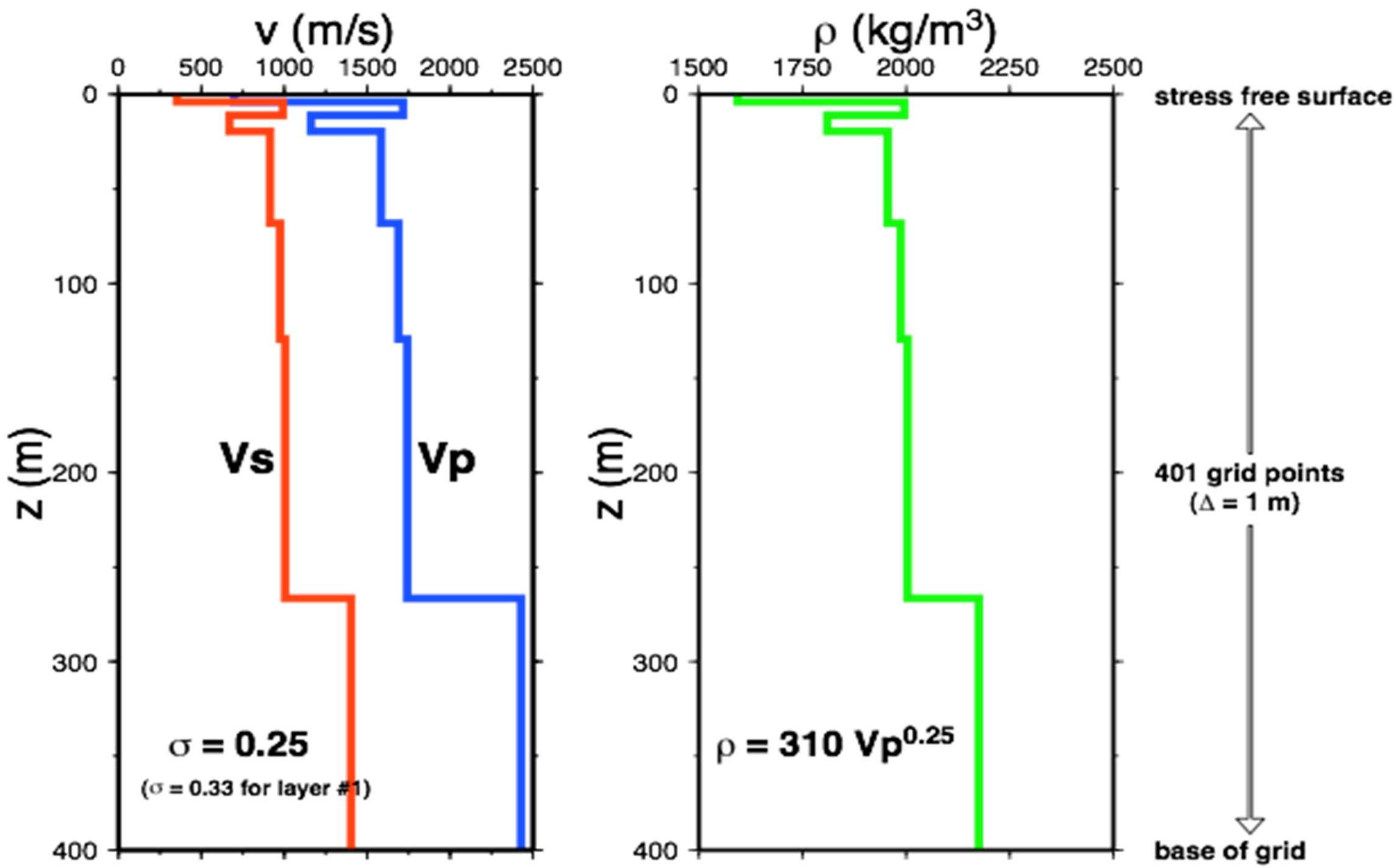
2) Examine effect on responses of varying brine pod size, shape, orientation, contrast with background, edge definition, spatial distribution, etc. Also consider variations in data acquisition geometry, spectral bandwidth, ambient seismic noise, etc.

3) ***Goals:*** Understand characteristic seismic signature of a of a brine pod, and quantitatively assess the conditions under which the signature can be recognized in seismic data. Has strong implications for subsequent design of a field seismic survey and effective interpretation of the recorded data.

4) ***Risks:*** Very little information exists about the pertinent geophysical/seismological properties of a brine pod. Hence, a large number of modeling scenarios must be examined. Also, characteristic signature may be too small to be recognized in field-recorded seismic data, under typical seismic data acquisition conditions. Finally, field recording conditions favorable to brine pod detection may never be achieved at the WIPP site (e.g., seismic sources within WIPP?).

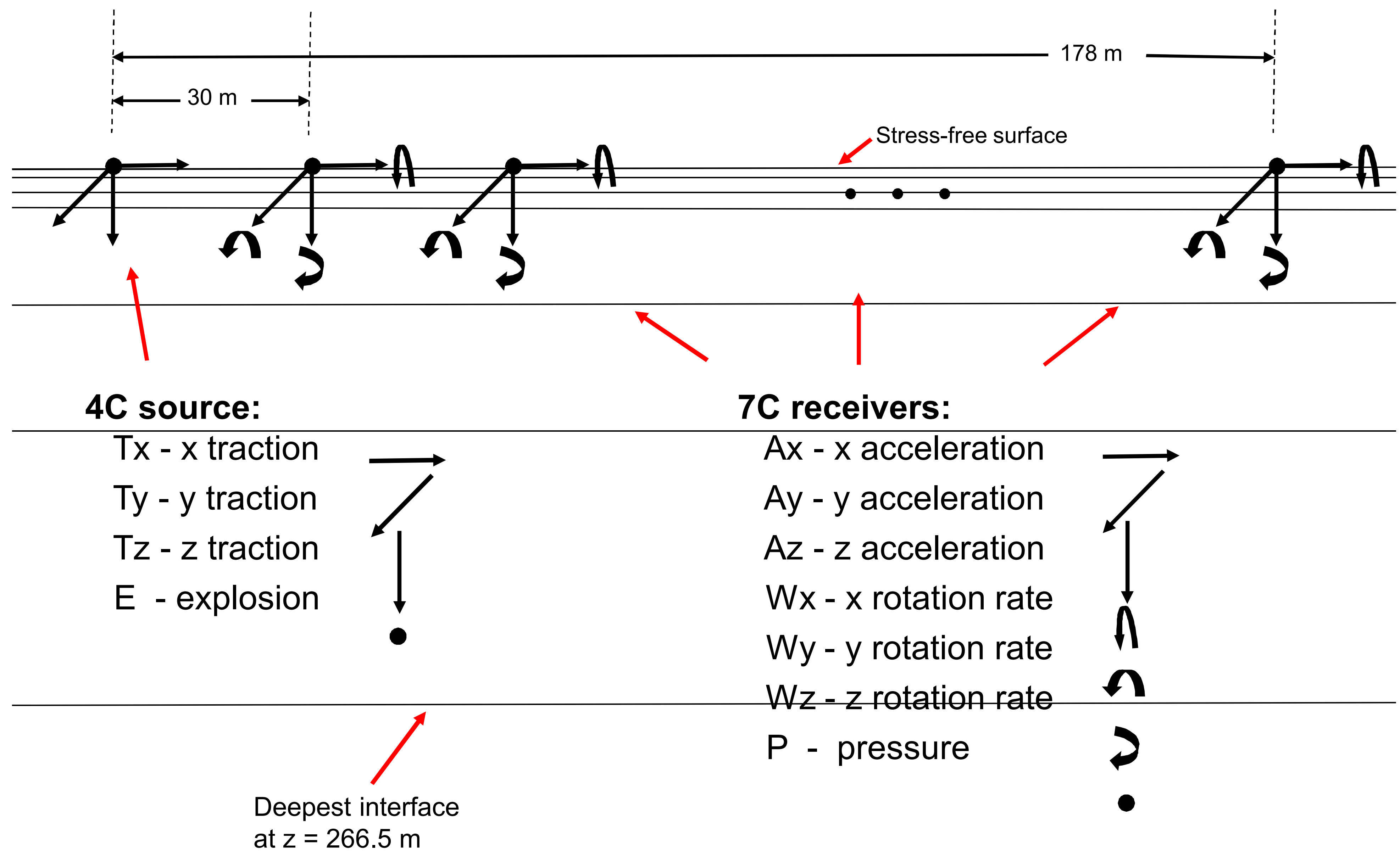
Note extreme low velocities/density of shallow subsurface layers, as well as velocity/density reversal.

A "Shallow" Synthetic Data Example: One-Dimensional Earth Model of YMP Site



Note extreme low velocities/density of shallow subsurface layers, as well as velocity/density reversal.

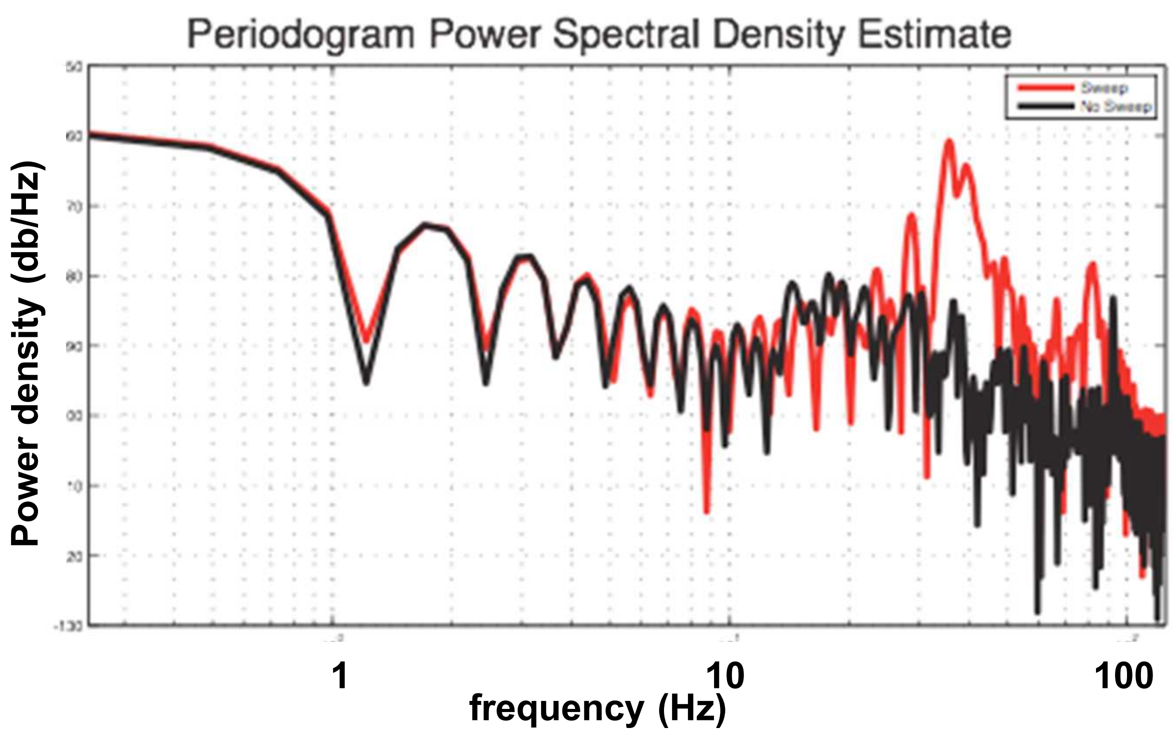
YMP Site Data Acquisition Geometry (Mimics Actual Field Deployment)



- a single line array of 6 7C receivers extending from 30 m to 178 m offset; receiver interval ~ 30 m

Surface Traction Seismic Energy Source

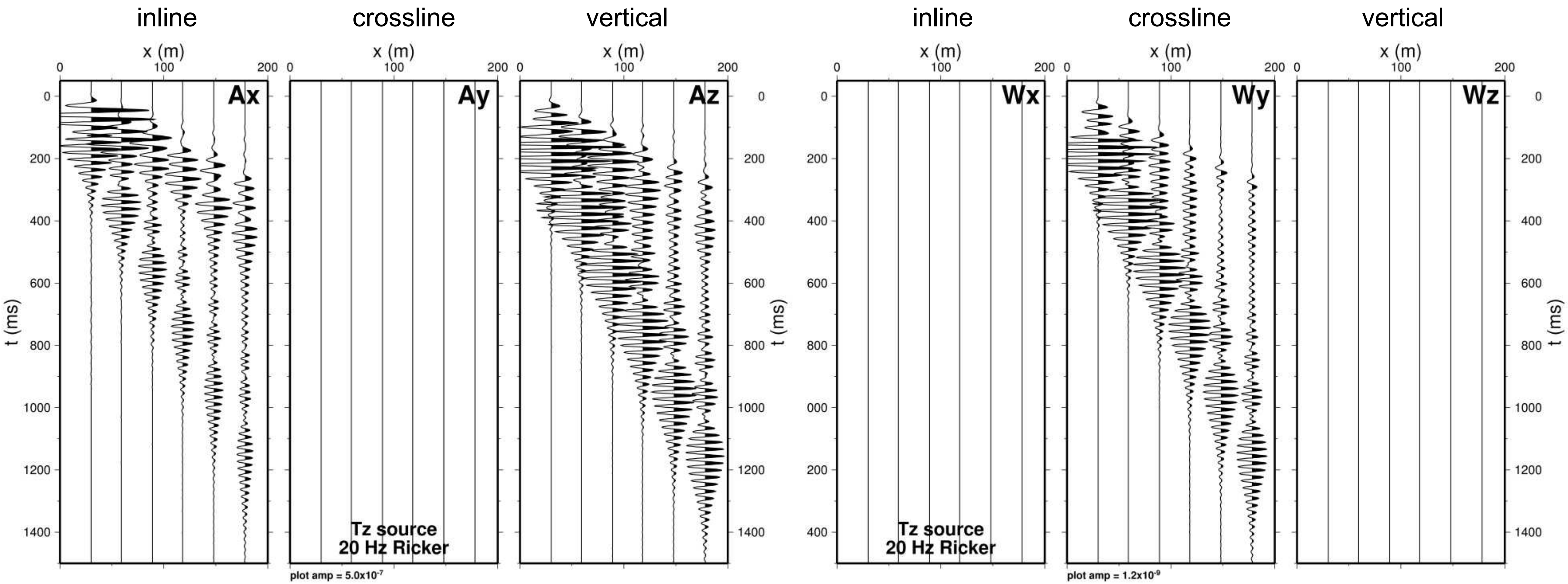
"T-Rex" three-component Vibroseis truck at Yucca Mountain, Nevada site



Source spectral content

Red: sweep active
Black: sweep inactive

Synthetic Data Example: Vertical (Tz) Traction Source; 20 Hz Ricker Wavelet

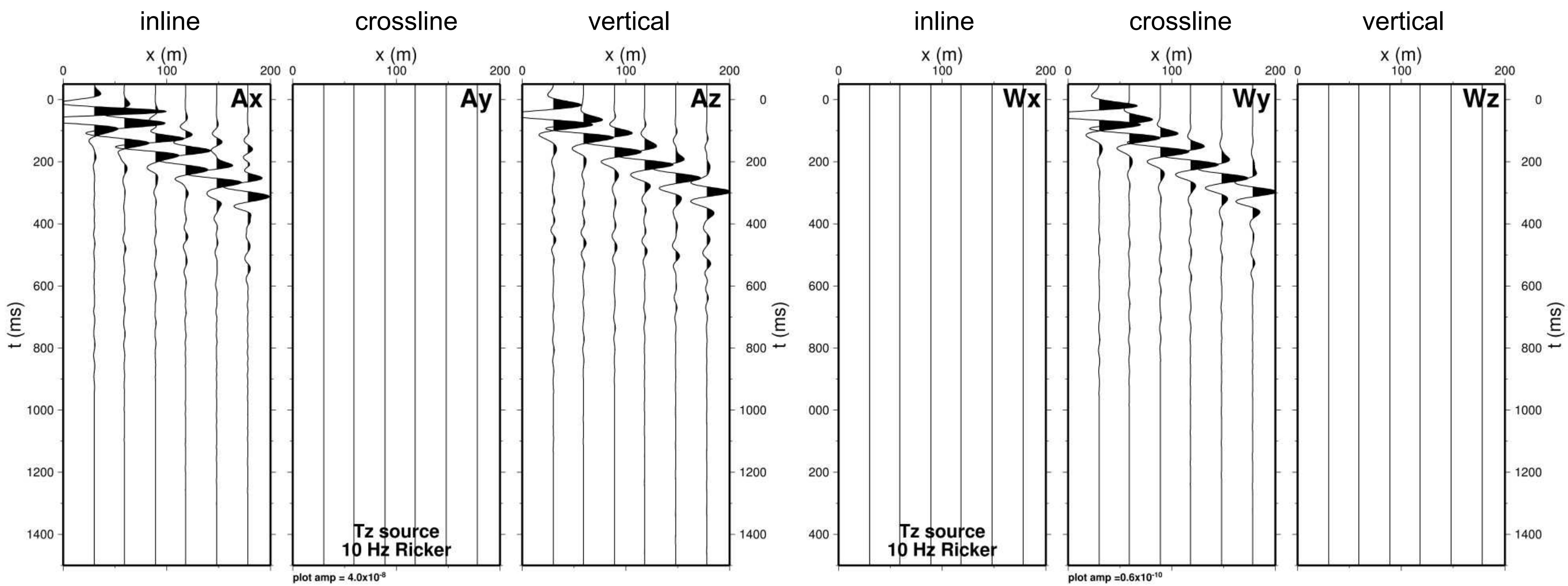


3C acceleration

3C rotation rate

Note strongly dispersed surface wave train. Also, acceleration and rotation (rate) are *orthogonal* vectors.

Synthetic Data Example:
Vertical (Tz) Traction Source; 10 Hz Ricker Wavelet

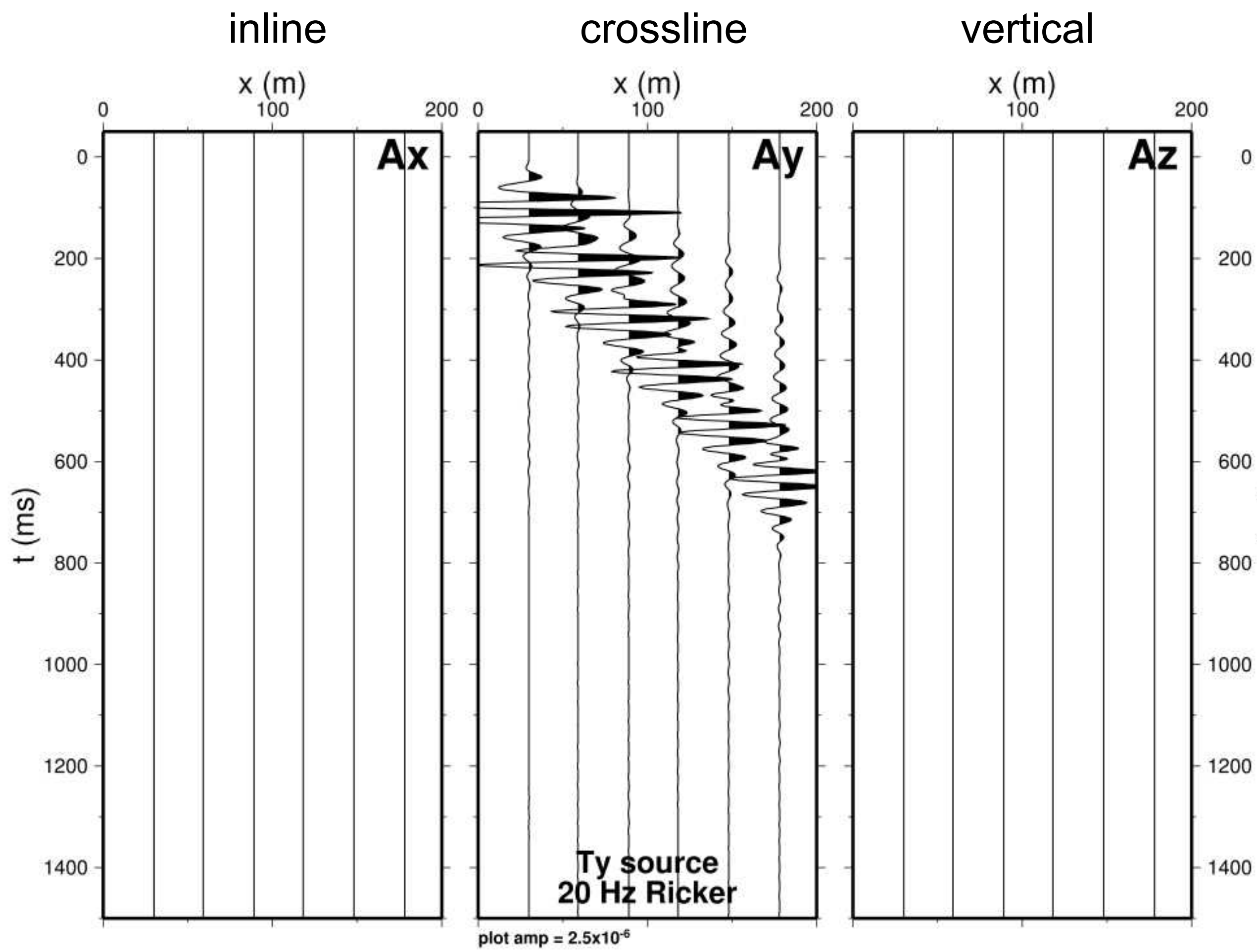


3C acceleration

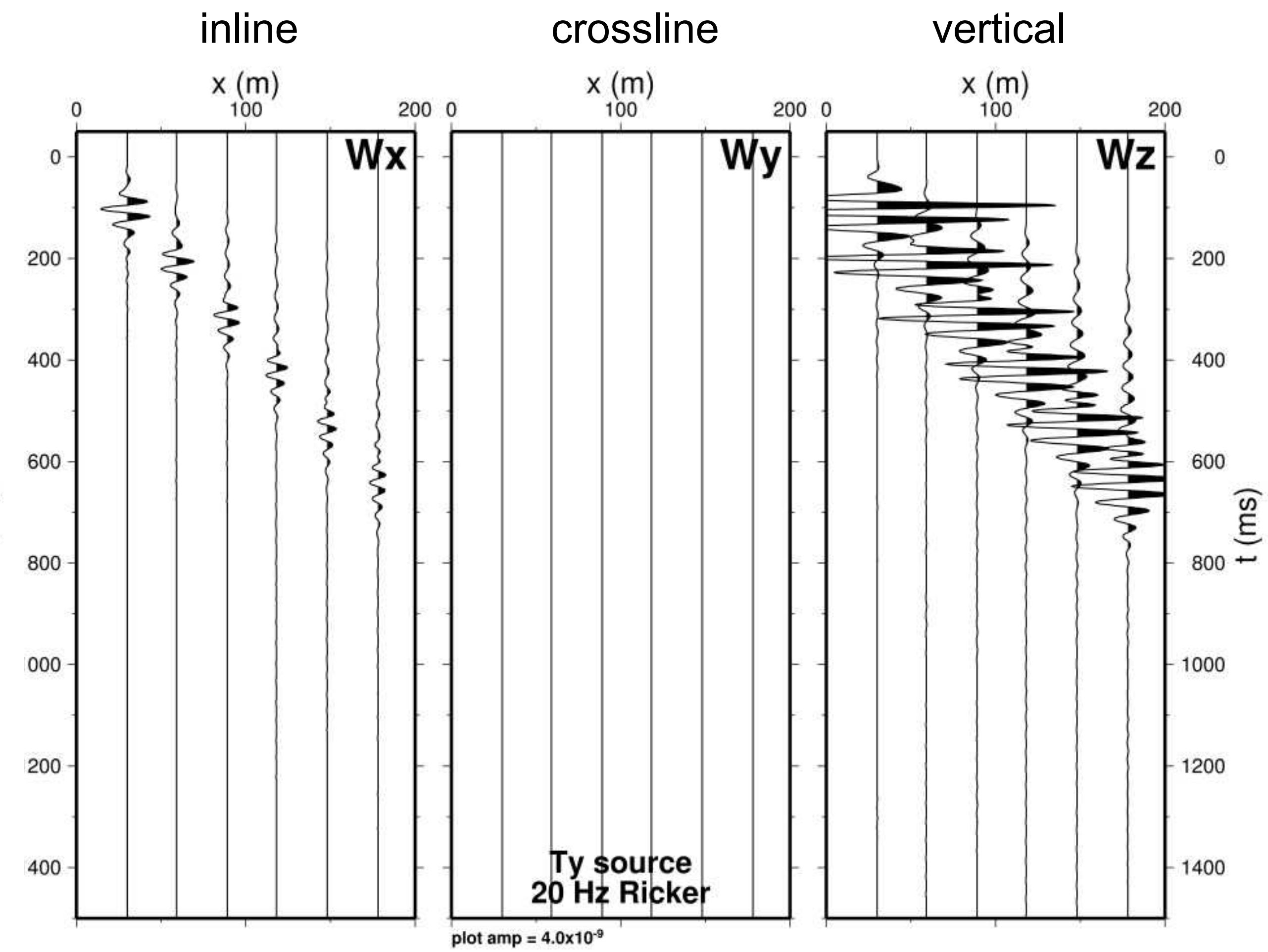
3C rotation rate

Note direct, surface, and reflected waves. Also, acceleration and rotation (rate) are *orthogonal* vectors.

Synthetic Data Example: Crossline (Ty) Traction Source; 20 Hz Ricker Wavelet



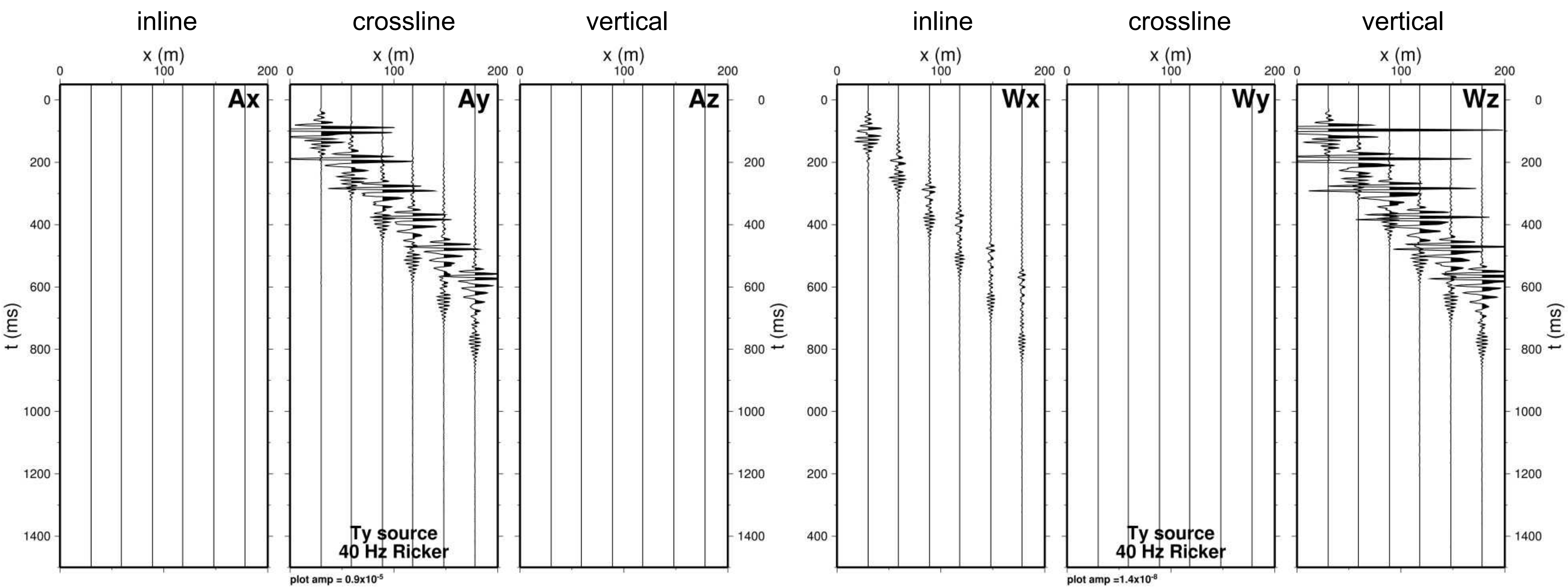
3C acceleration



3C rotation rate

Note surface wave train with less dispersion. Acceleration and rotation rate are again orthogonal.

Synthetic Data Example: Crossline (Ty) Traction Source; 40 Hz Ricker Wavelet



3C acceleration **3C rotation rate**

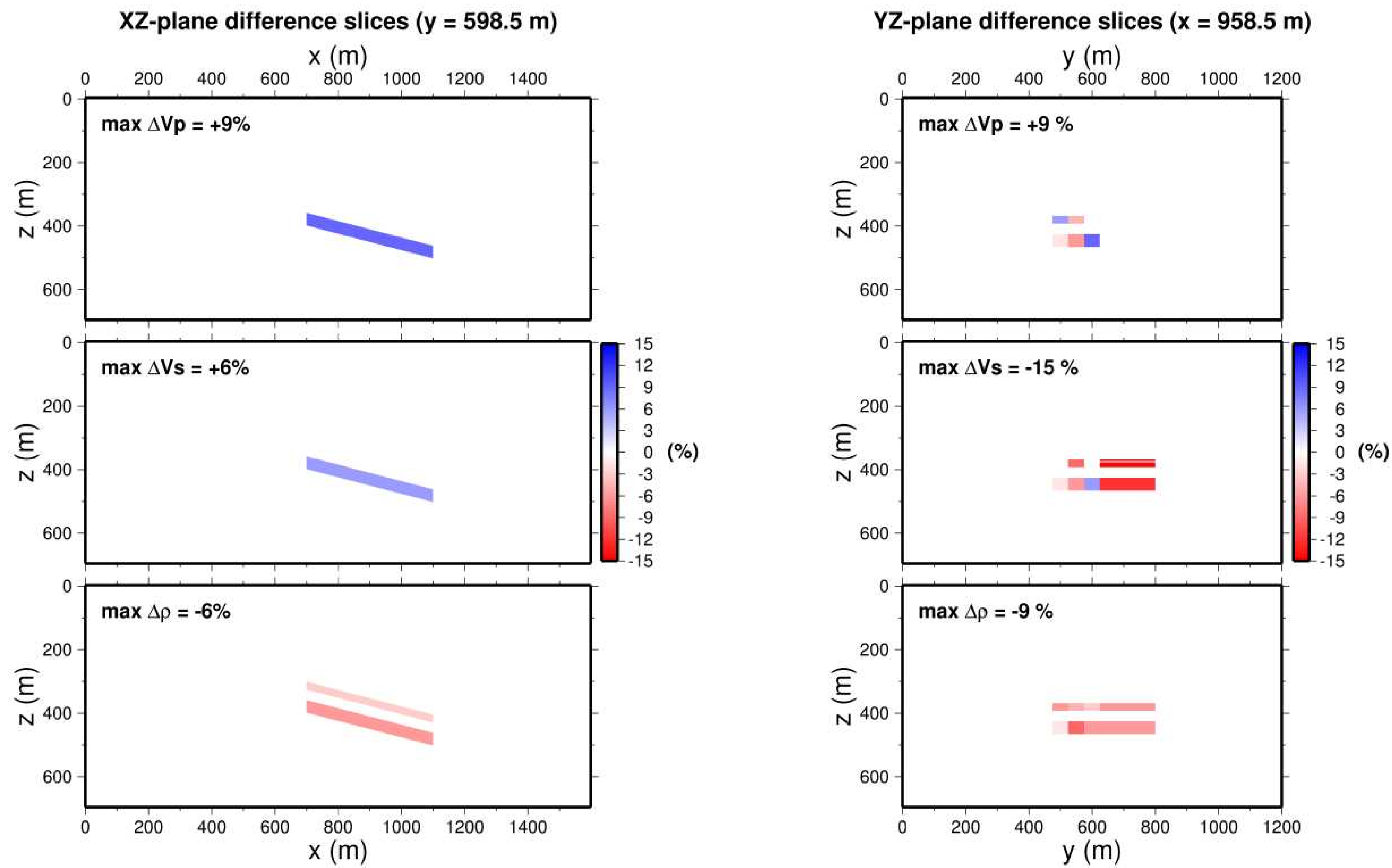
Note surface wave train with less dispersion. Acceleration and rotation rate are again orthogonal.

Time Lapse Seismology Modeling Example

Images of Vp, Vs, and ρ for a 3D earth model containing shallow subsurface randomly-distributed heterogeneities are deleted from this PowerPoint presentation.

However, *differences* in medium parameters associated with a subsurface fluid-injection event are displayed on subsequent slide. This is a “time-lapse” seismic modeling experiment.

Time Lapse Seismology Modeling Example: Medium Property Differences



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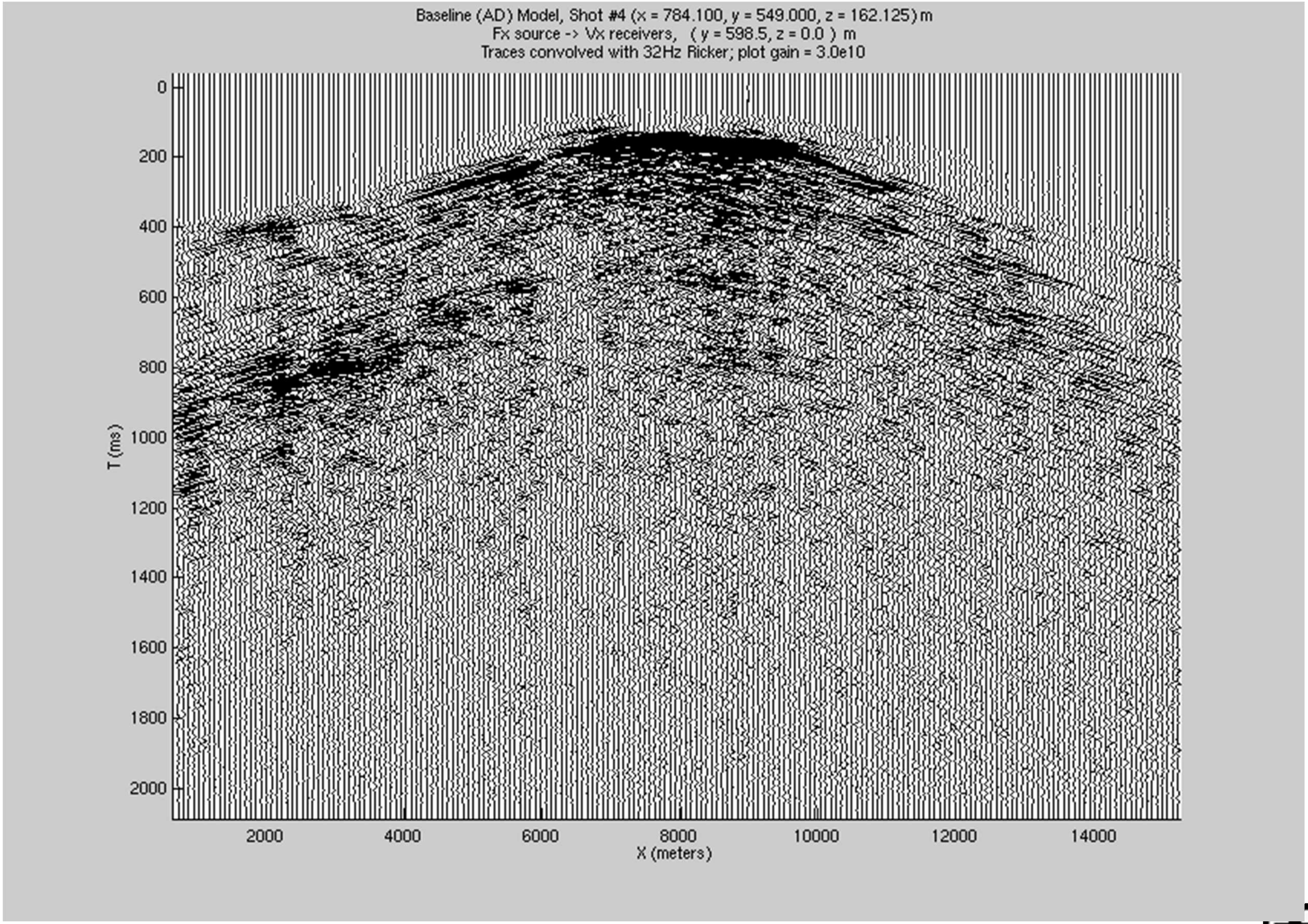
Synthetic Seismic Reflection Data: Baseline Model, Buried Fx source / Surface Vx receivers



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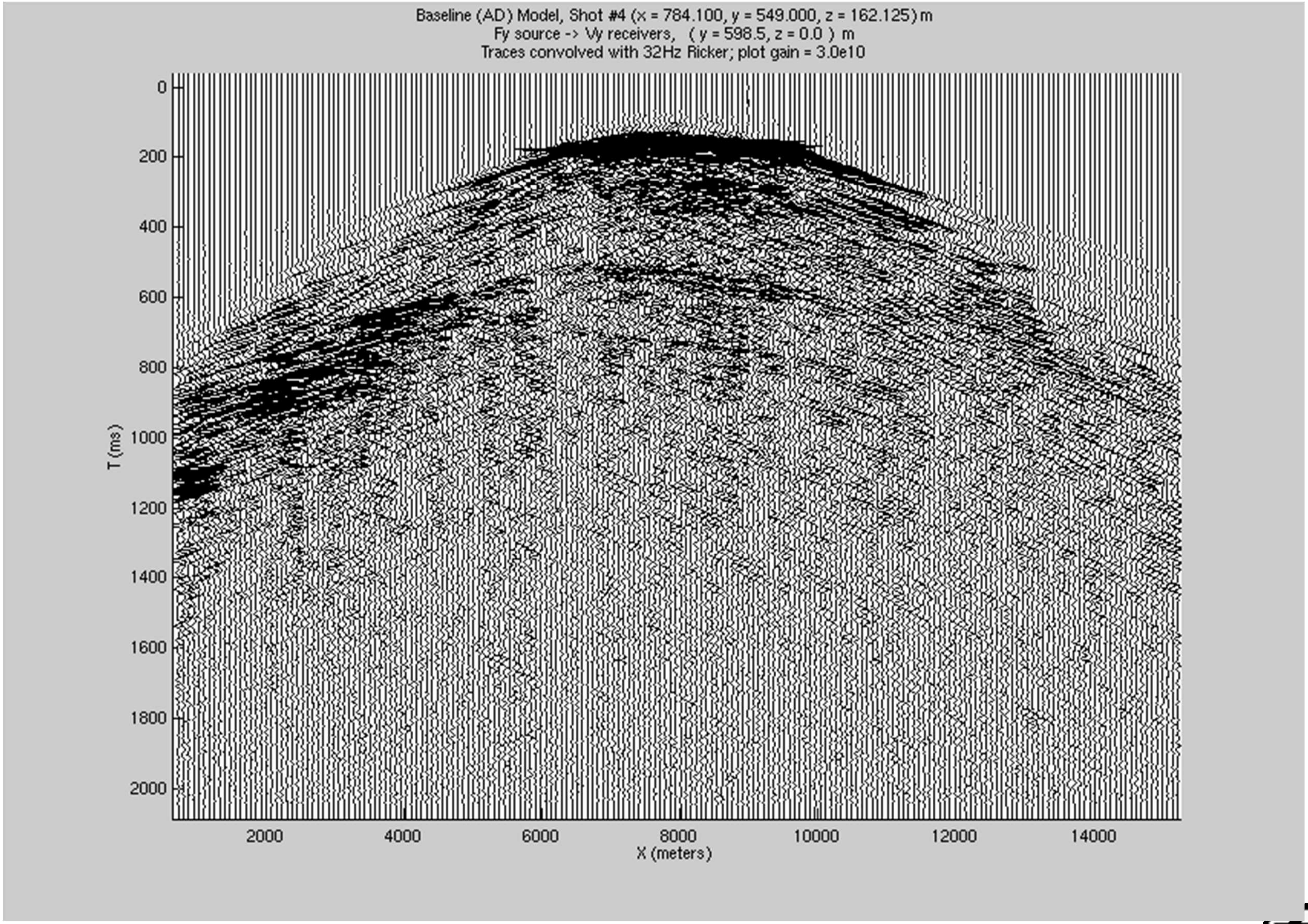
Synthetic Seismic Reflection Data: Baseline Model, Buried Fy source / Surface Vy receivers



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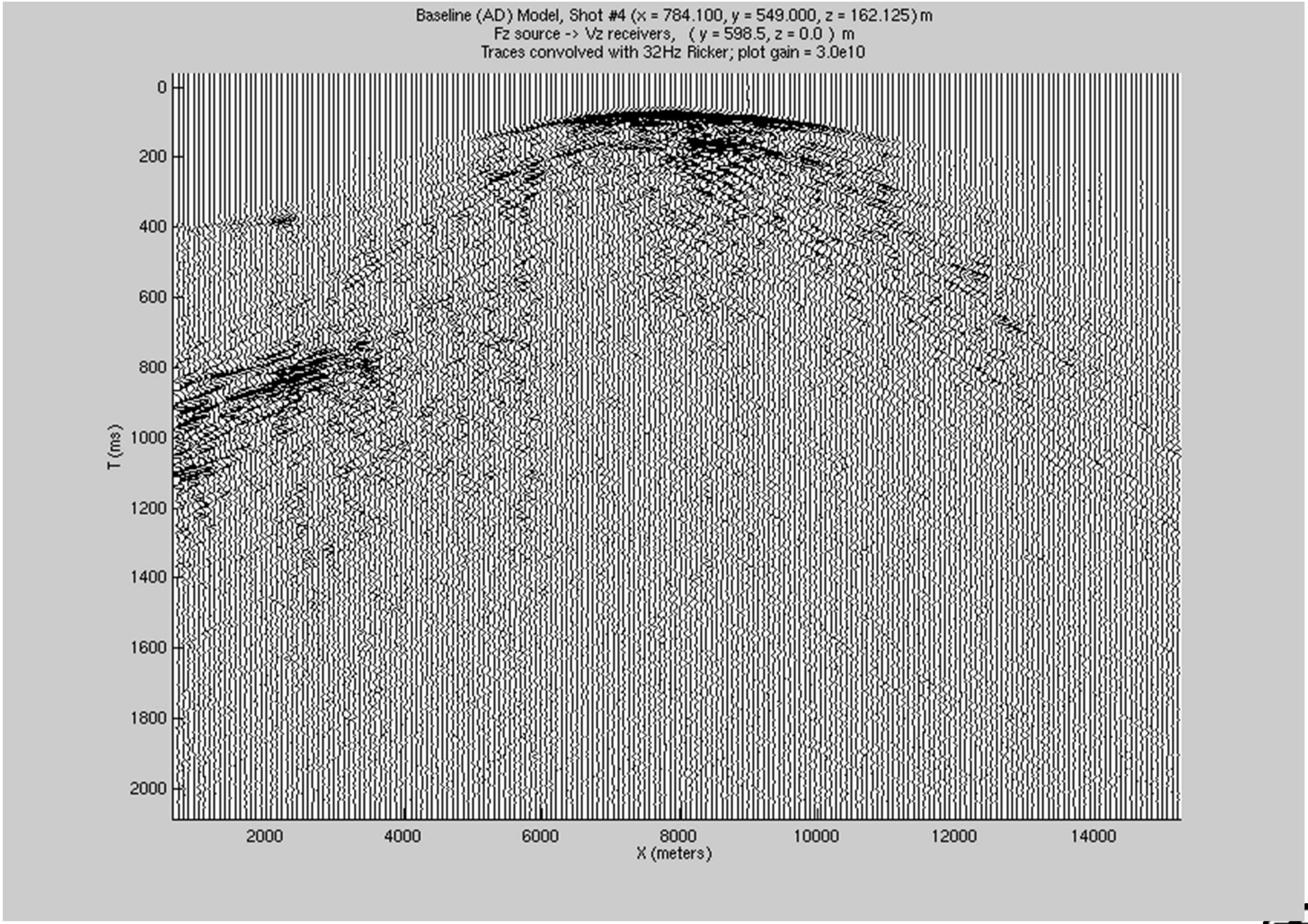
Synthetic Seismic Reflection Data: Baseline Model, Buried Fz source / Surface Vz receivers



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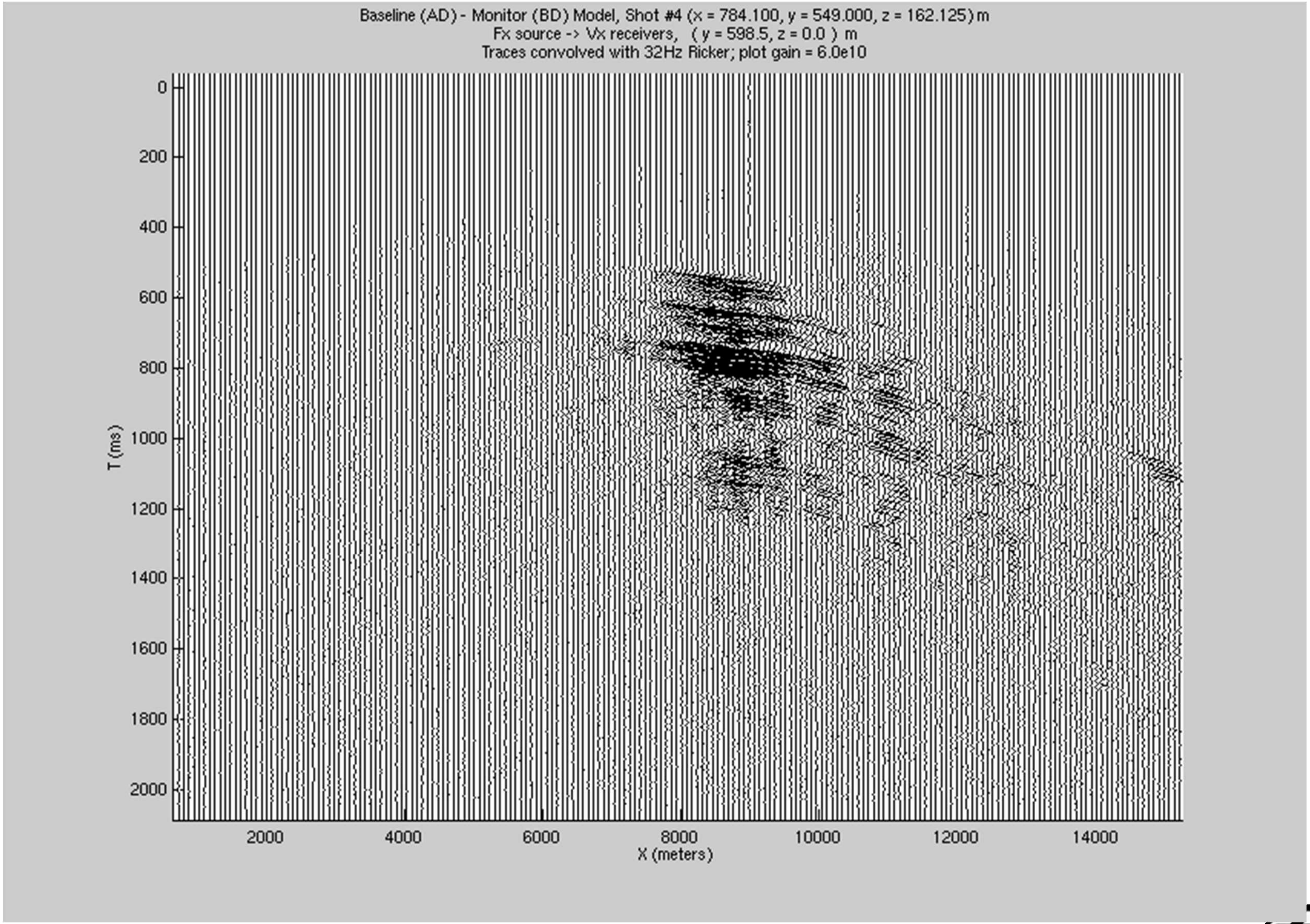
Difference Data: Baseline *minus* Monitor
Buried Fx source / Surface Vx receivers



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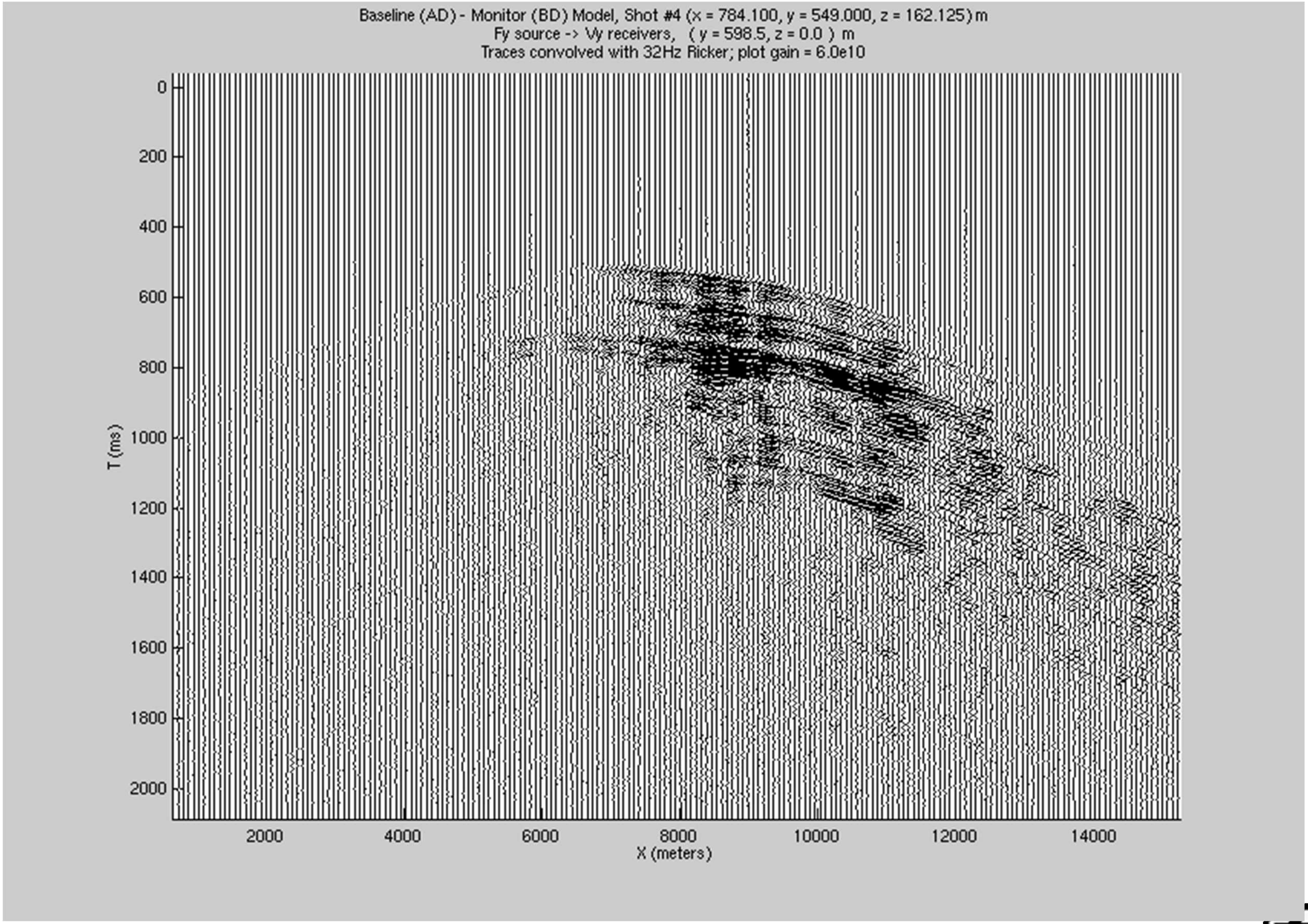
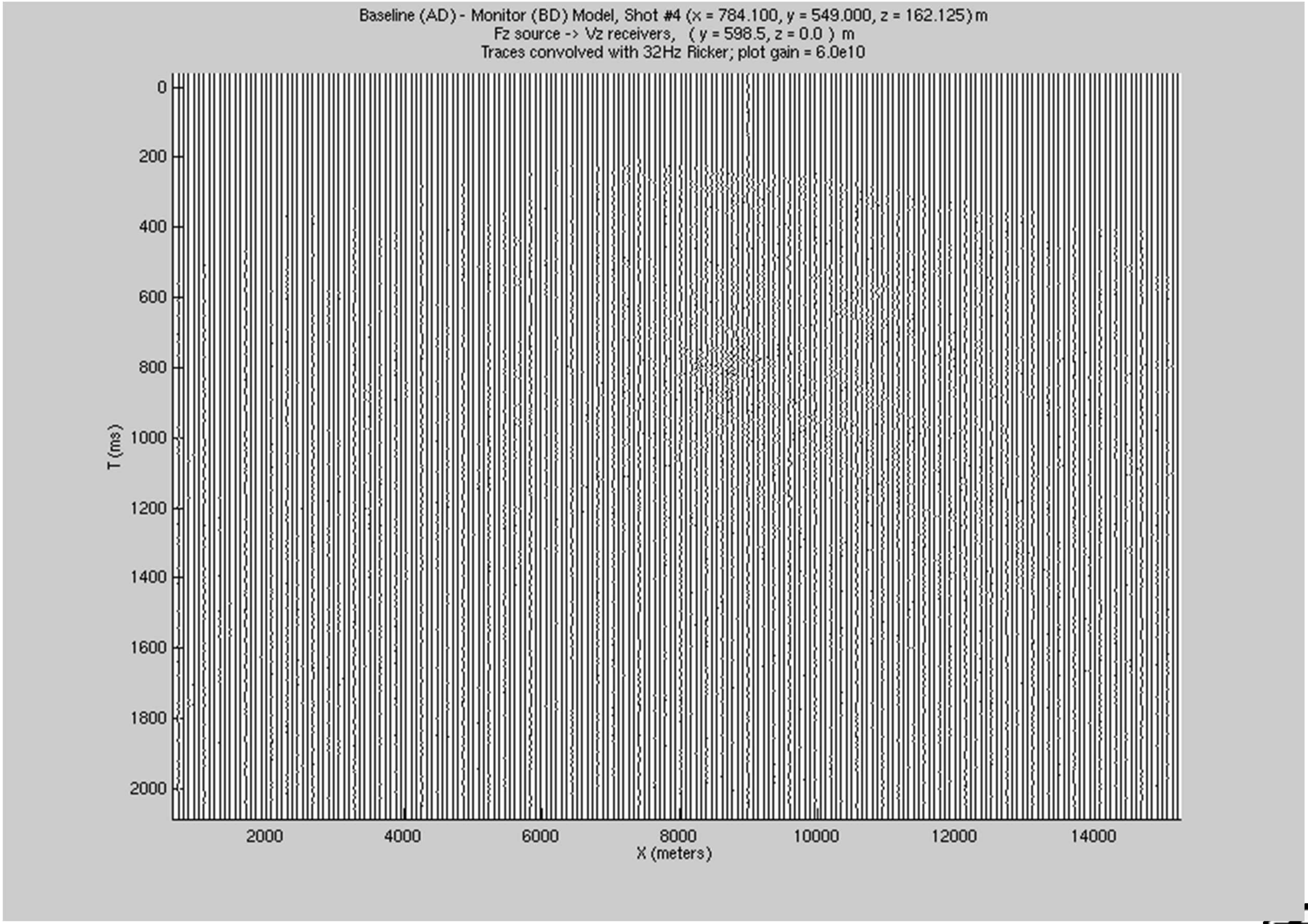
Difference Data: Baseline *minus* Monitor
Buried Fy source / Surface Vy receivers



Difference Data: Baseline *minus* Monitor
Buried Fz source / Surface Vz receivers



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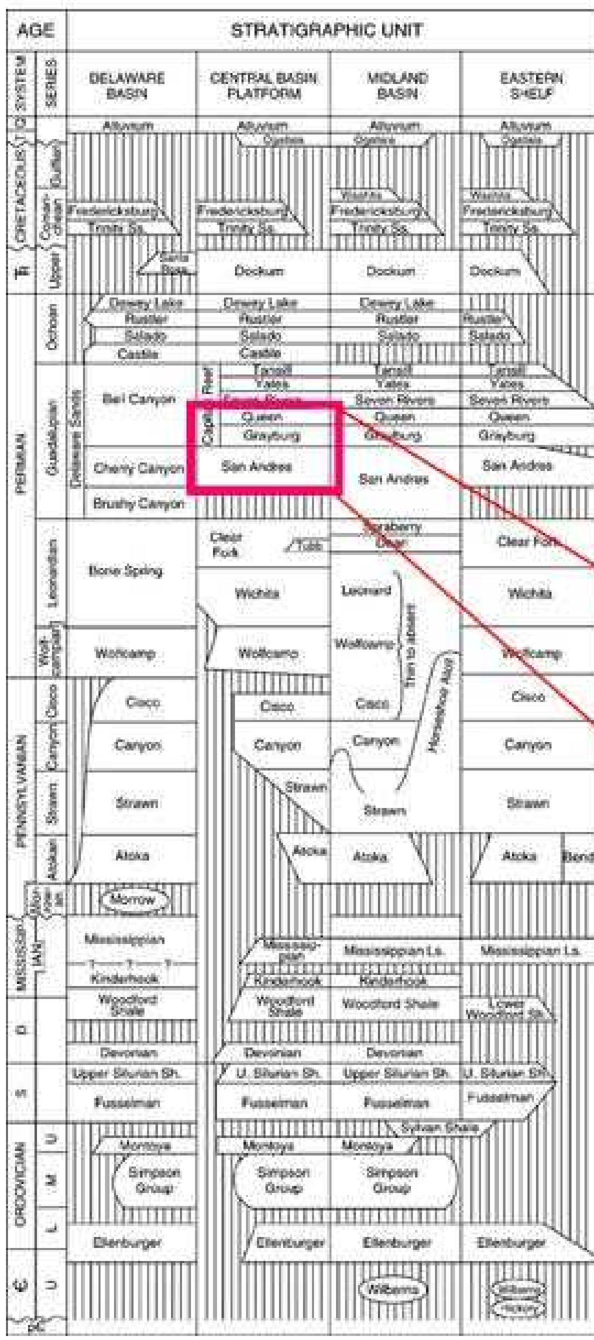
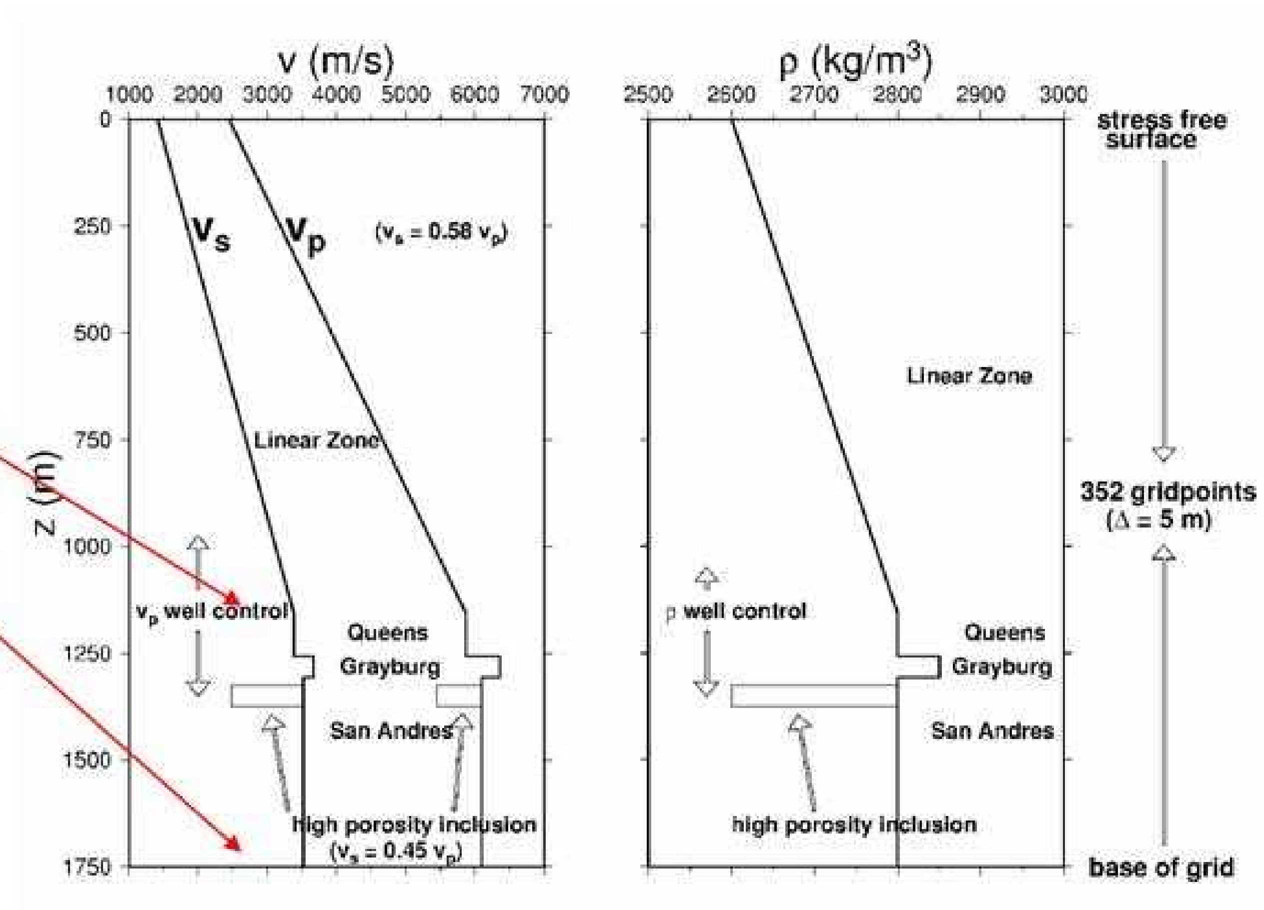
Synthetic Seismic Modeling Example: High Porosity Inclusions in a Central Basin Platform Stratigraphic Sequence



Synthetic seismic velocity and mass density logs



High-porosity anomaly modeled as low-impedance ellipsoidal inclusion within San Andres dolomite.

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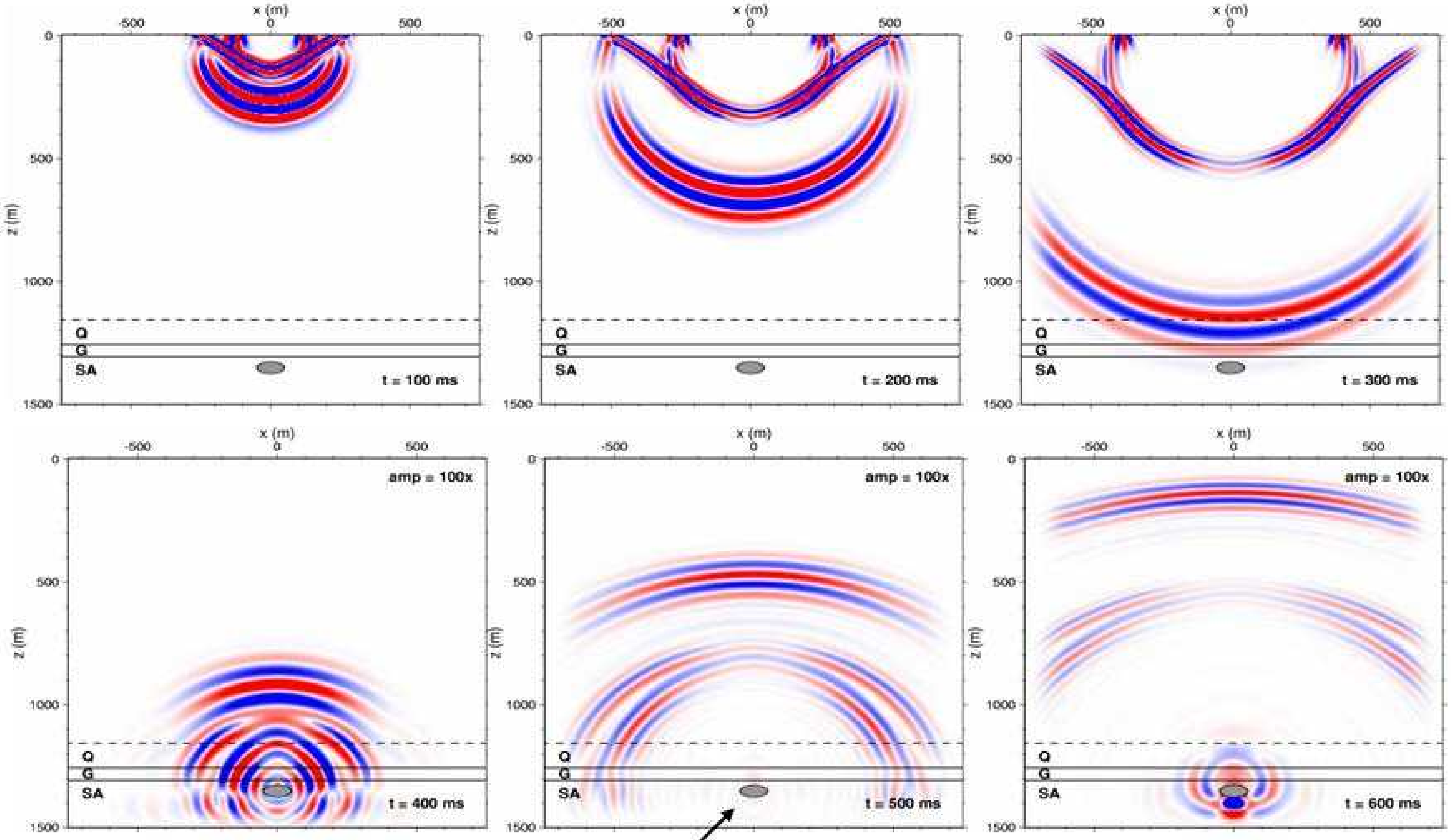
Seismic Scattering From an Ellipsoidal Porosity Inclusion



Ellipsoidal porosity inclusion

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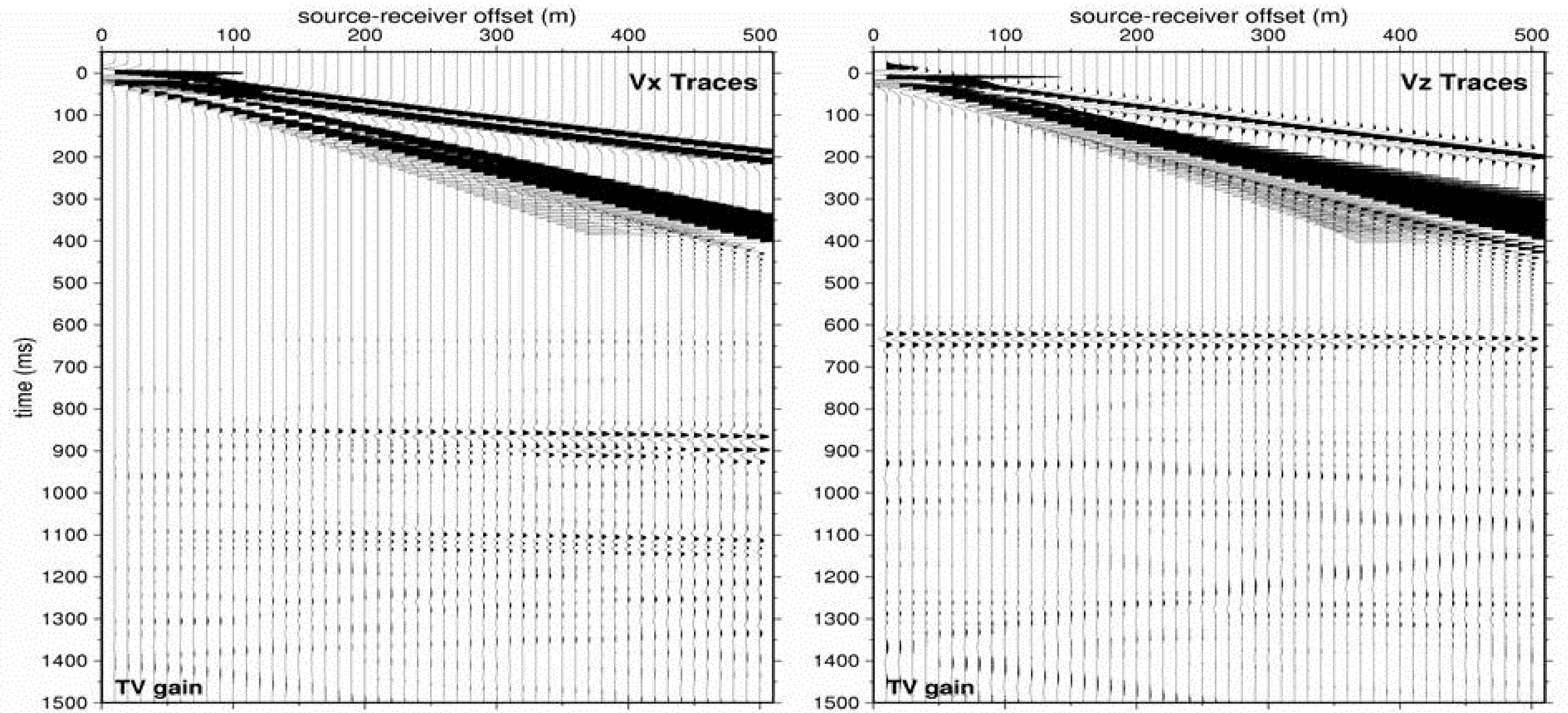
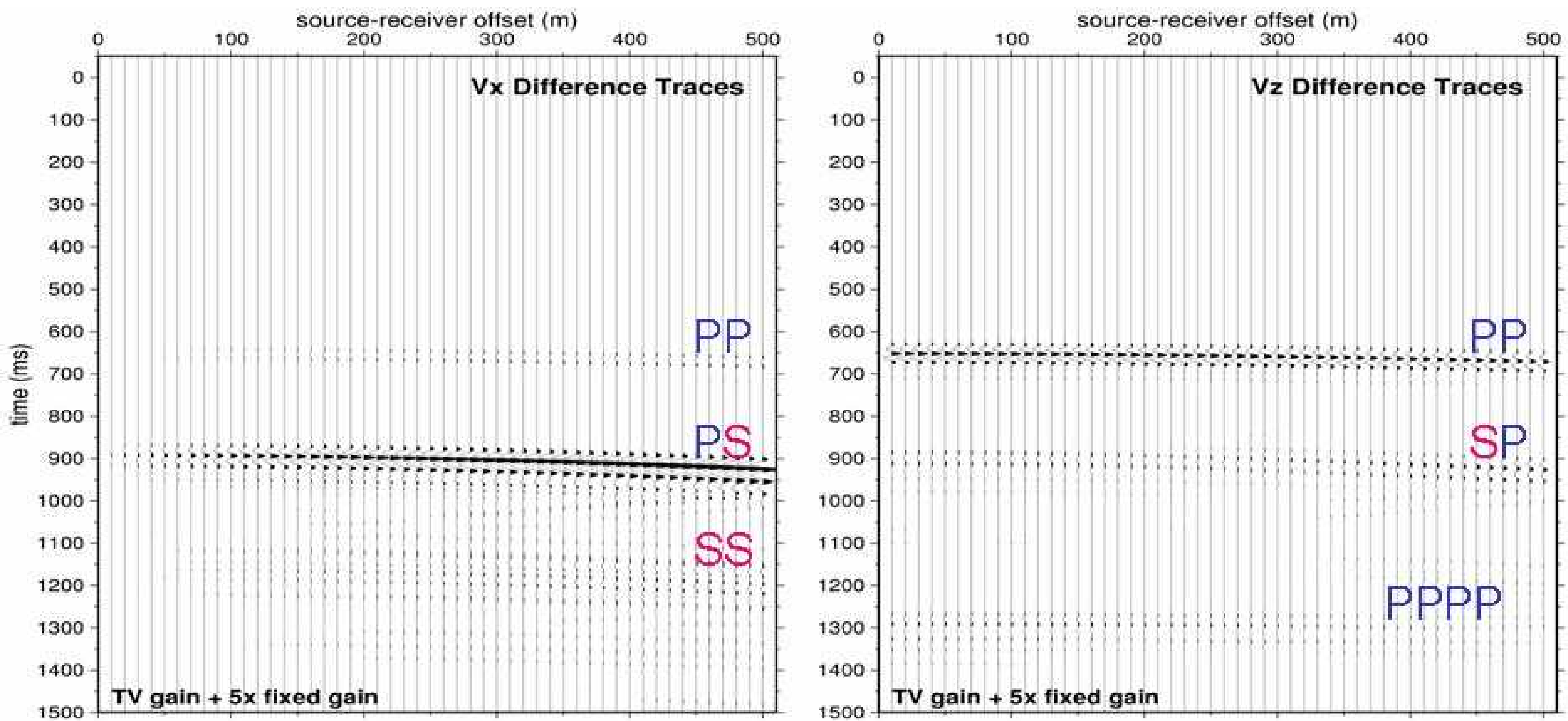
Two-Component Particle Velocity Data Recorded by Surface Geophones (shallow explosion source; 30 Hz Ricker wavelet)



Horizontal component of surface motion

Vertical component of surface motion

Two-Component *Difference* Velocity Traces Reveal Events Scattered by Porosity Inclusion



Horizontal component of surface motion

Vertical component of surface motion

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2D Traveltime Tomography Investigations of the Brine Pocket Issue

1) Conduct synthetic 2D traveltime tomography experiments, with seismic energy sources and receivers emplaced within boreholes, on surface, and within the WIPP facility.

2) Examine effect on recovered velocity model estimates of varying brine pod parameters (size, shape, orientation, contrast with background, edge definition, spatial distribution, etc.) as well as variations in in data acquisition geometry (VSP, Xwell, both) and noise conditions.

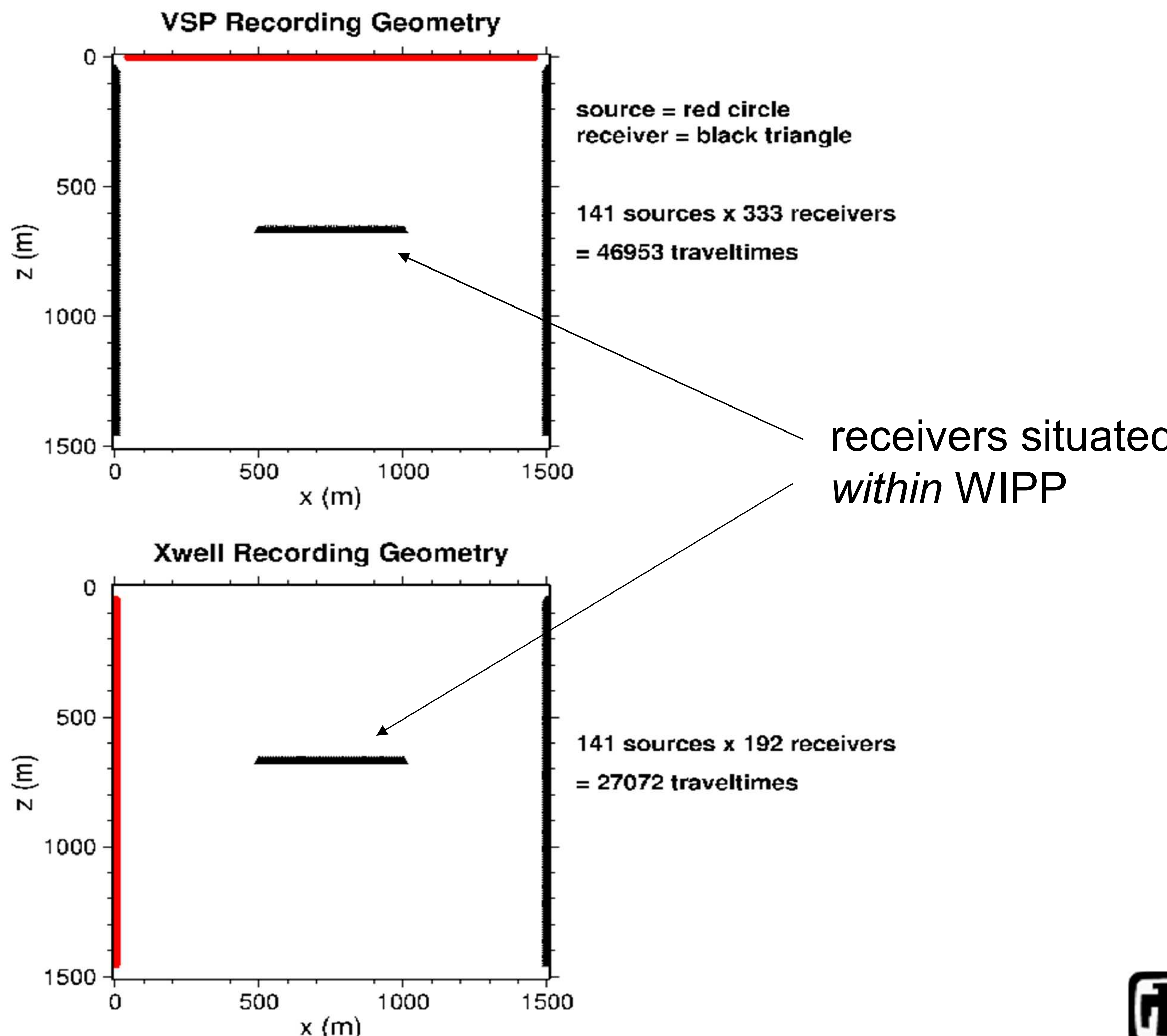
3) ***Goal:*** Understand conditions (earth model, brine pod parameters, and acquisition geometry) which lead to well-resolved images of a brine pod. Recognize implications for design of a field experiment.

4) ***Risks:*** Available wells at WIPP site for conducting a traveltime tomography experiment are too far apart. Hence, seismic signal level will be very low, and 2D wave propagation assumption will probably be invalid. Finally, traveltime tomography itself may not offer sufficient resolving power: may need to augment existing SNL tomographic inversion algorithm to handle amplitudes in addition to traveltimes.

Combined Vertical Seismic Profile (VSP) *and* Crosswell (Xwell) Data Acquisition Configuration

Large well spacing:

2D wave propagation assumption will begin to break down!



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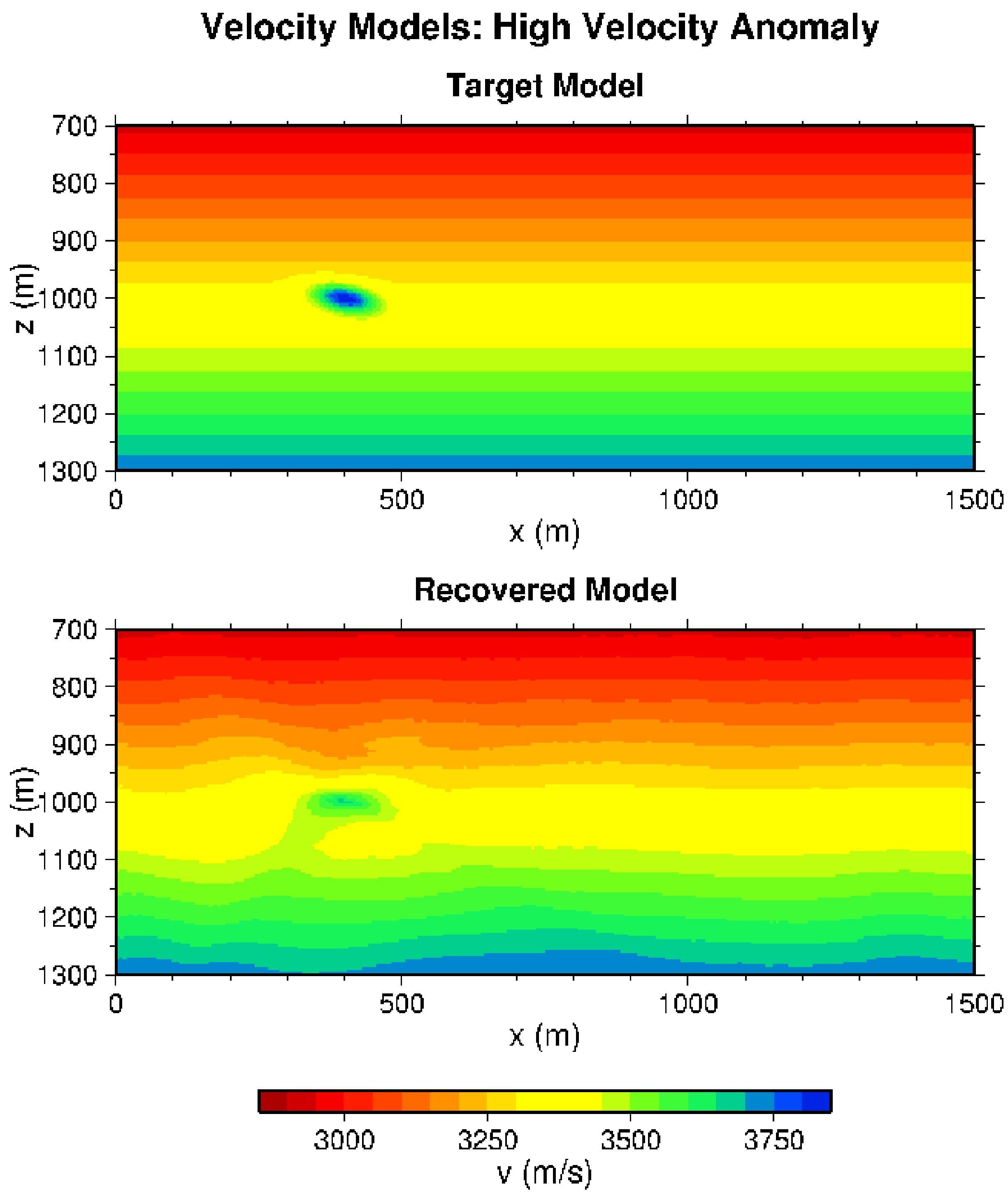
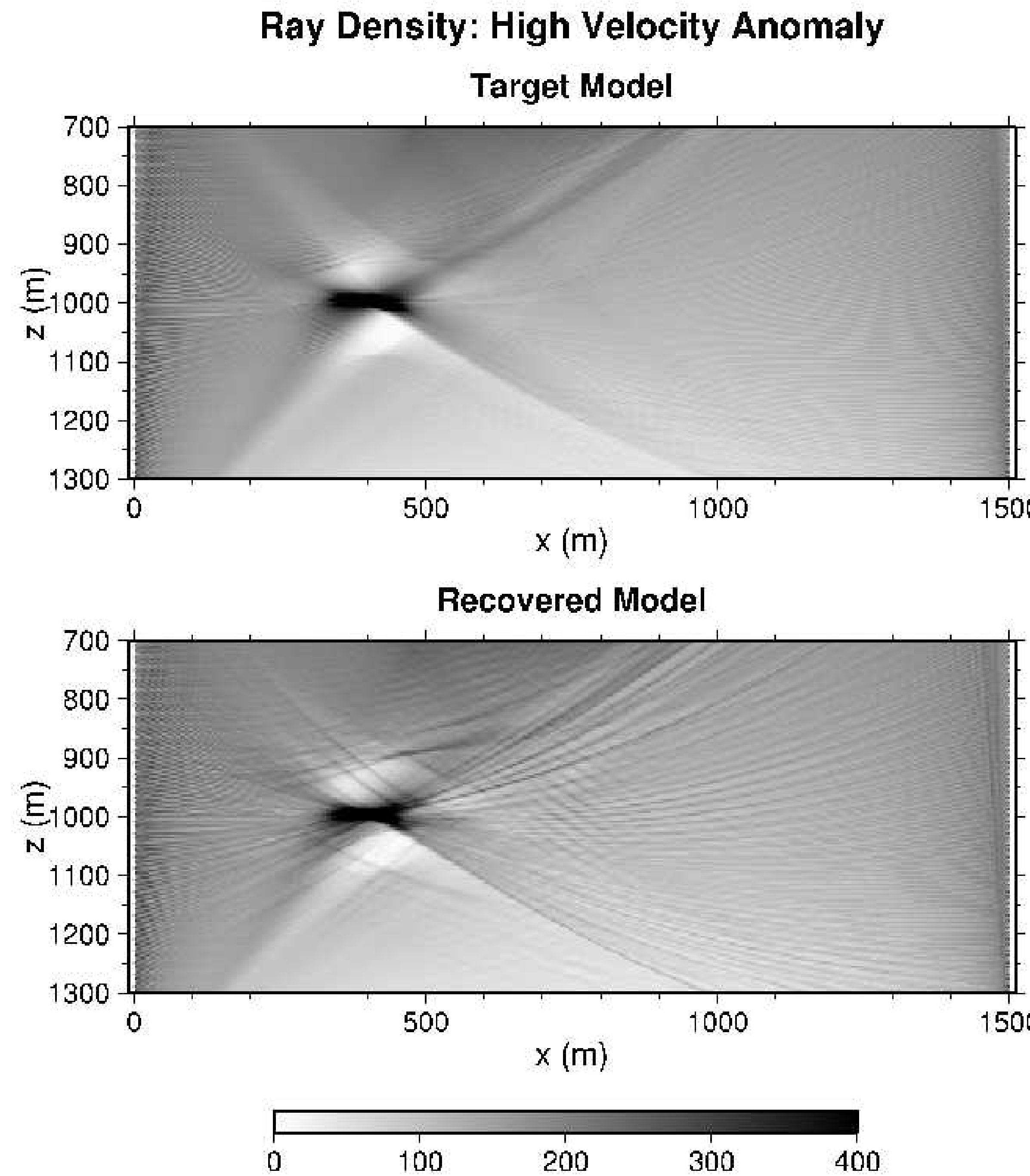
Synthetic Traveltime Tomography Results: Isolated High Velocity Anomaly





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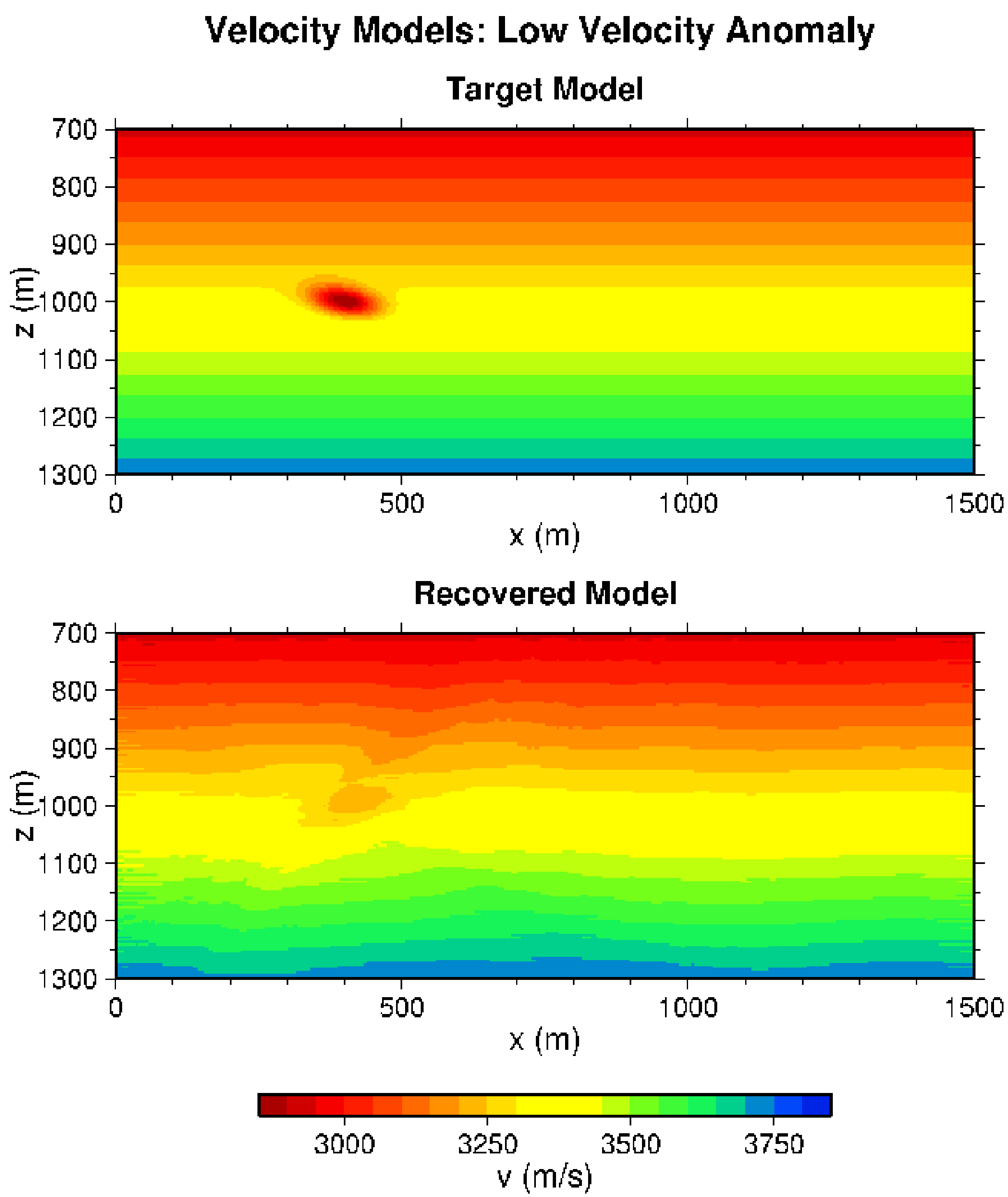
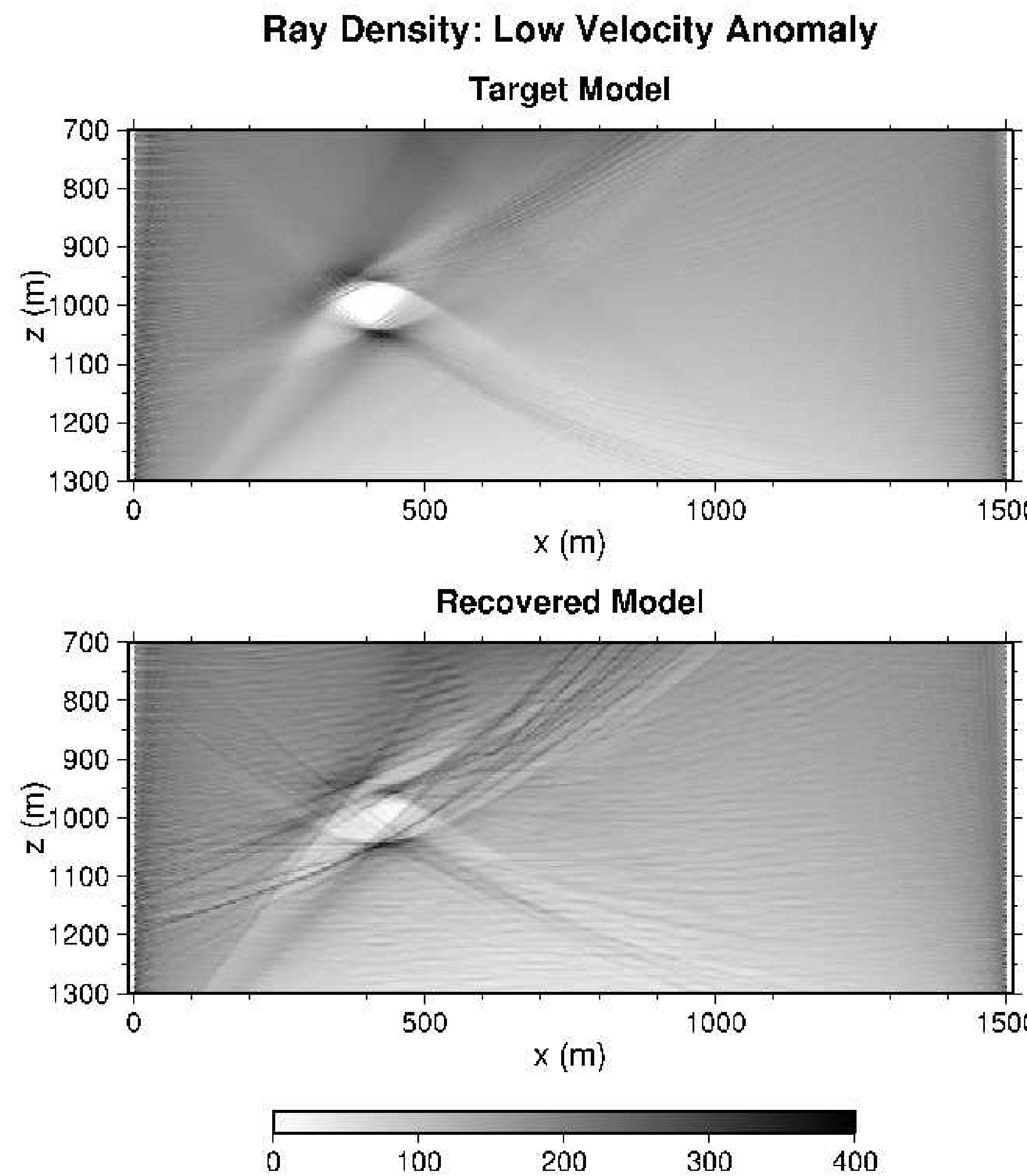
Synthetic Traveltime Tomography Results: Isolated Low Velocity Anomaly





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Some Traveltime Tomography Issues

The Earth:

1) Size and magnitude of a velocity anomaly needs to be "adequate".

2) Good initial estimate of background velocity model is desirable (already exists for WIPP?).

3) 2D wave propagation assumption (i.e., all raypaths connecting source/receiver pairs are confined to a plane) may not be realistic, esp. for strong 3D heterogeneity and large well spacing.

Data Acquisition:

1) For good raypath coverage, recording geometry should "surround" target of interest.

2) Access to boreholes for emplacement of seismic energy sources and receivers is problematical (and expensive!).

Data Processing:

1) Picking of first-arrival times on a large trace dataset is time-consuming. Emergent arrivals on noisy traces are difficult to recognize and pick.

Data Inversion

1) Accurate amplitude recovery of a velocity anomaly is problematical.

2) 2D tomographic inversions with SNL Geophysics Department algorithm PRONTO can be conducted in a few *minutes* of run time on a workstation computational platform → many scenarios can be investigated in relative short time.