SAND2012-10119C

THETA-DATA: Introduction to rotational seismology and its potential uses

David Aldridge
Sandia National Laboratories,
Albuquerque

Mirko van der Baan
Unuiversity of Alberta,
Edmonton

Robert Brune
Consultant/Geokinetics

James Gaiser
Geokinetics

Everhard Muyzert
Schlumberger,
Cambridge

Rotational Seismic:
measure & analyze rotational motion at geophones,
in addition to linear motion.

Potential applications:
spatial sampling, micro-seismic, elastic wave, . . .

Acknowledgements

- Geokinetics
- Sandia National Laboratories
- Schlumberger Cambridge Research

- Applied Technology Associates
- Eentec
- MetTech / MetSensing

Discussions with many others . . .

Synopsis – Theta-Data Rotational Seismic

- What is it and where did it come from?
- Sensors - How do we measure it?
- What does Theta-Data look like?

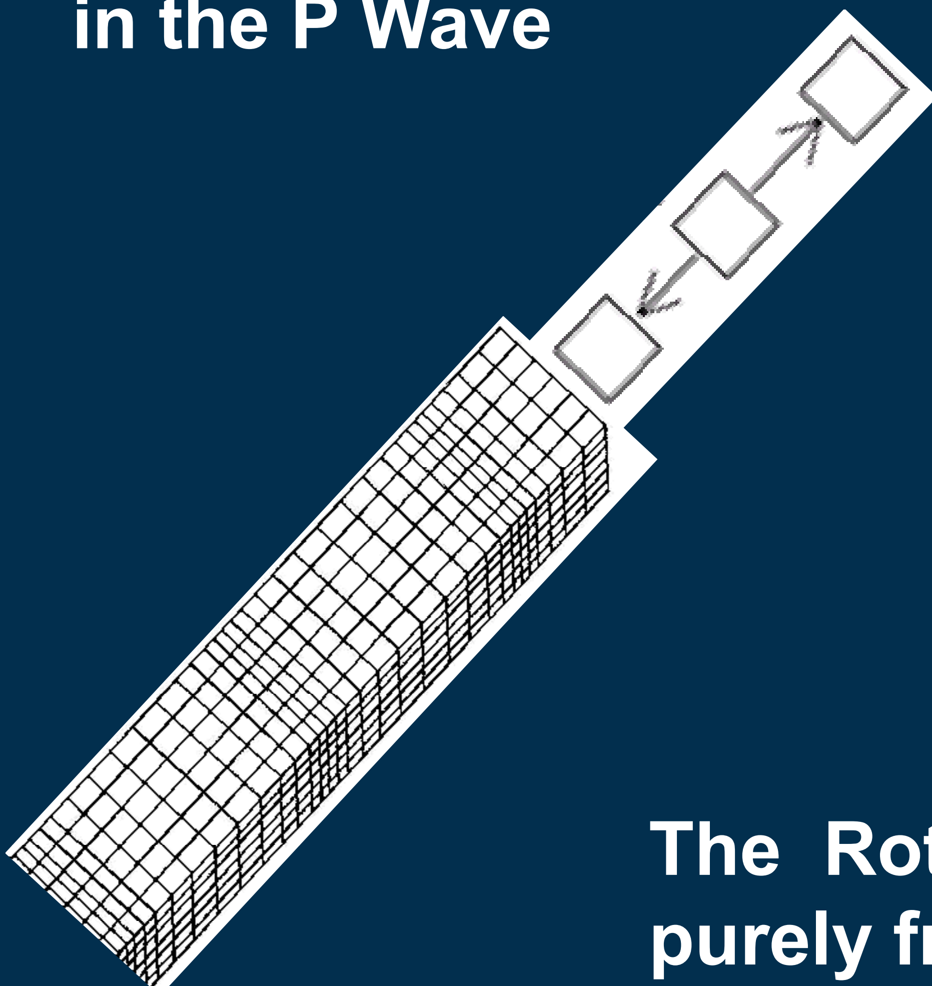
- What are possible Applications?
  - Spatial sampling enhancement
  - Shear Wave selectivity – microseismic
  - ‘other’ uses

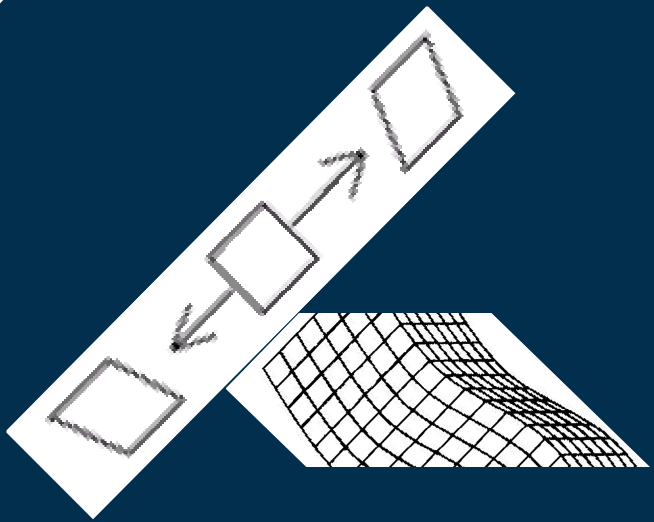
- Status and ‘Road Ahead’

Rotational Seismic – Shear Selectivity

There is NO ROTATION in the P Wave

There IS ROTATION in the S wave





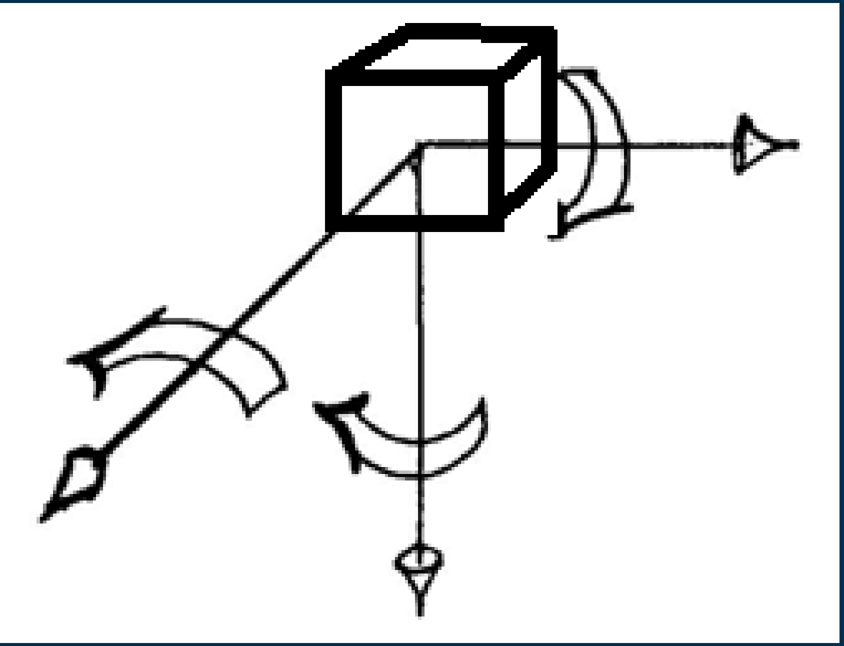
The Rotation Signal is purely from the S wave

3-Theta Data – What is it?

Measure Rotation
around 3 axes - 3θ

θ-x
θ-y
θ-z

Vector Curl
of displacement



Record 3-θ Rotation in
addition to 3-C or 4-C

"Theta Data"
is comprised of
"Curl Traces"

Six Degrees-Of-Freedom (6-DOF) Seismic

Classical Mechanics:

Need Roll, Pitch, Yaw, as well as x, y, z

To Fully Specify Motion

for a finite body ("elemental cube")

Y rotation =

Z gradient of X linear

- X gradient of Z linear

$$\underline{\theta} = \begin{bmatrix} \theta_x \\ \theta_y \\ \theta_z \end{bmatrix} \equiv \frac{1}{2} \nabla \times \underline{u}$$

$$\theta_y = \frac{1}{2}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right)$$

Origins – Where Did Rotational Seismic 'Come From'?

- **Earthquake Seismology:**
  - **William H. K. Lee (USGS) & others**
  - **Int'l Working Group on Rotational Seismology (IWGRS)**
  - **BSSA (May, 2009)**

- **Sensor technology development - *decades*:**
  - **Defense (US and USSR)**
  - **inertial guidance, etc.**

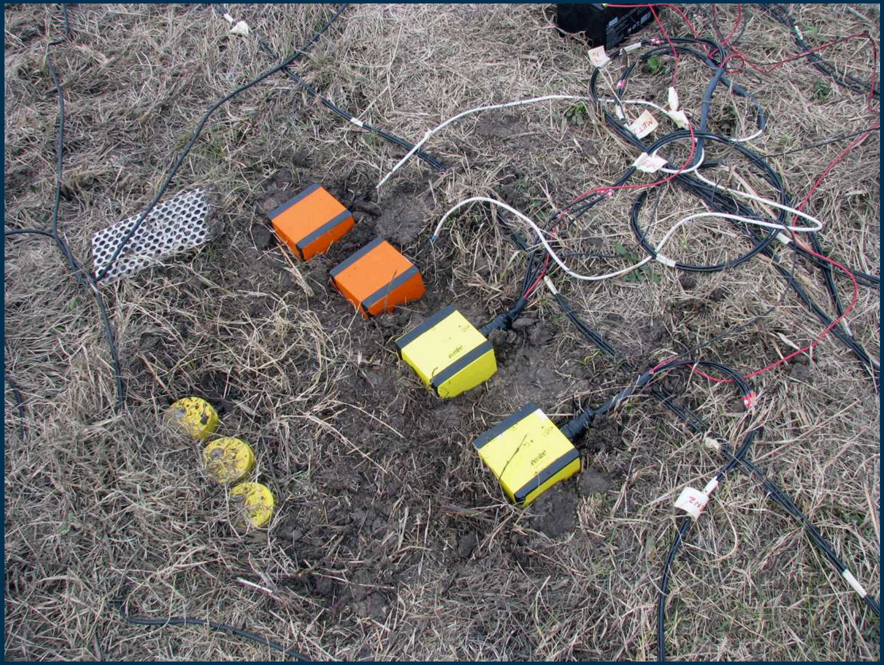
Synopsis – Theta-Data Rotational Seismic

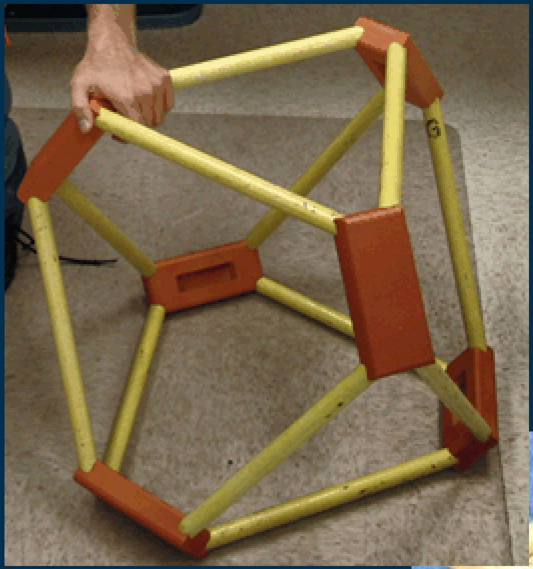
- **What is it and where did it come from?**
- **Sensors - How do we measure it?**
- **What does Theta-Data look like?**

- **What are possible Applications?**
  - **Spatial sampling enhancement**
  - **Shear Wave selectivity – microseismic**
  - **‘other’ uses**

- **Status and ‘Road Ahead’**

Rotational Sensors



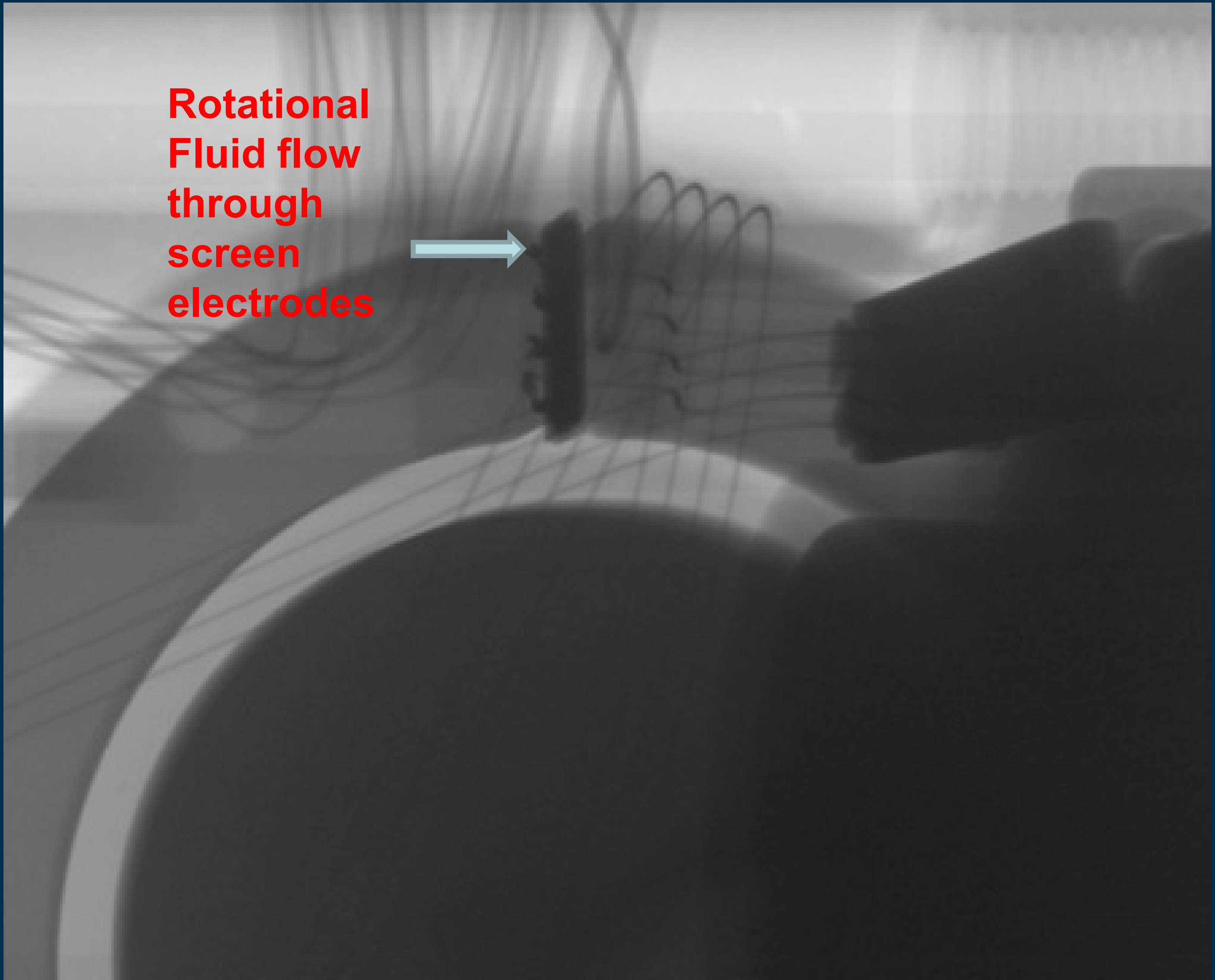


Typically flat spectral response for angular velocity.

Electrokinetic Sensors

- Simple Concept:
  - Ionic fluid in container is an inertial mass.
  - The ionic fluid flows through screen electrodes when there is motion.
  - Electrical current due to ionic fluid flow is a measure of velocity (linear or angular).
- Fluid in cylinder for linear motion
- Fluid in toroidal ‘donut’ for rotational motion
- Electrokinetic Sensor characteristics:
  - Low noise (order of 0.1 micro-radians sec)
  - Low frequencies possible

Electrokinetic Rotational Sensor



Synopsis – Theta-Data Rotational Seismic

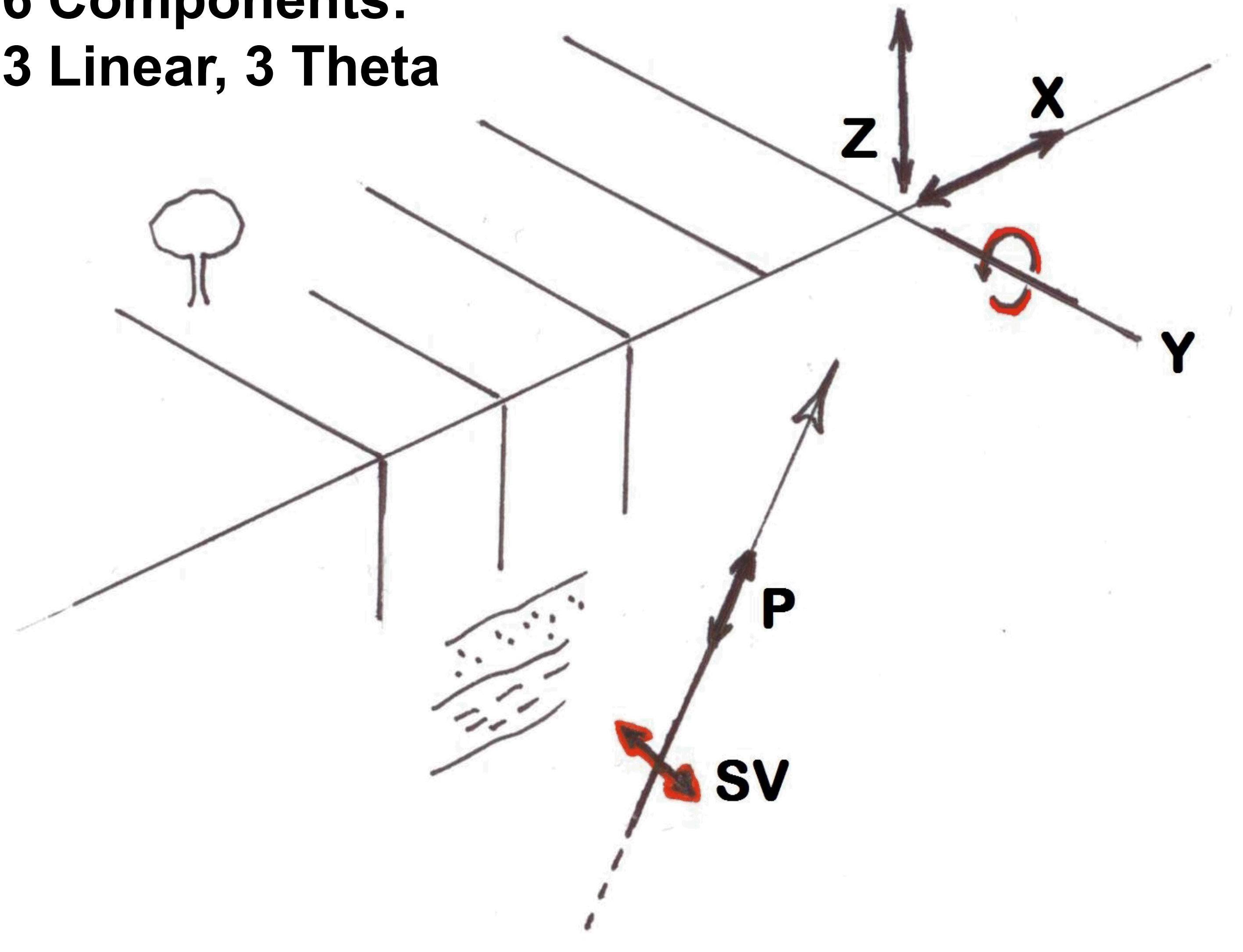
- What is it and where did it come from?
- Sensors - How do we measure it?
- What does Theta-Data look like?

- What are possible Applications?
  - Spatial sampling enhancement
  - Shear Wave selectivity – microseismic
  - ‘other’ uses

- Status and ‘Road Ahead’

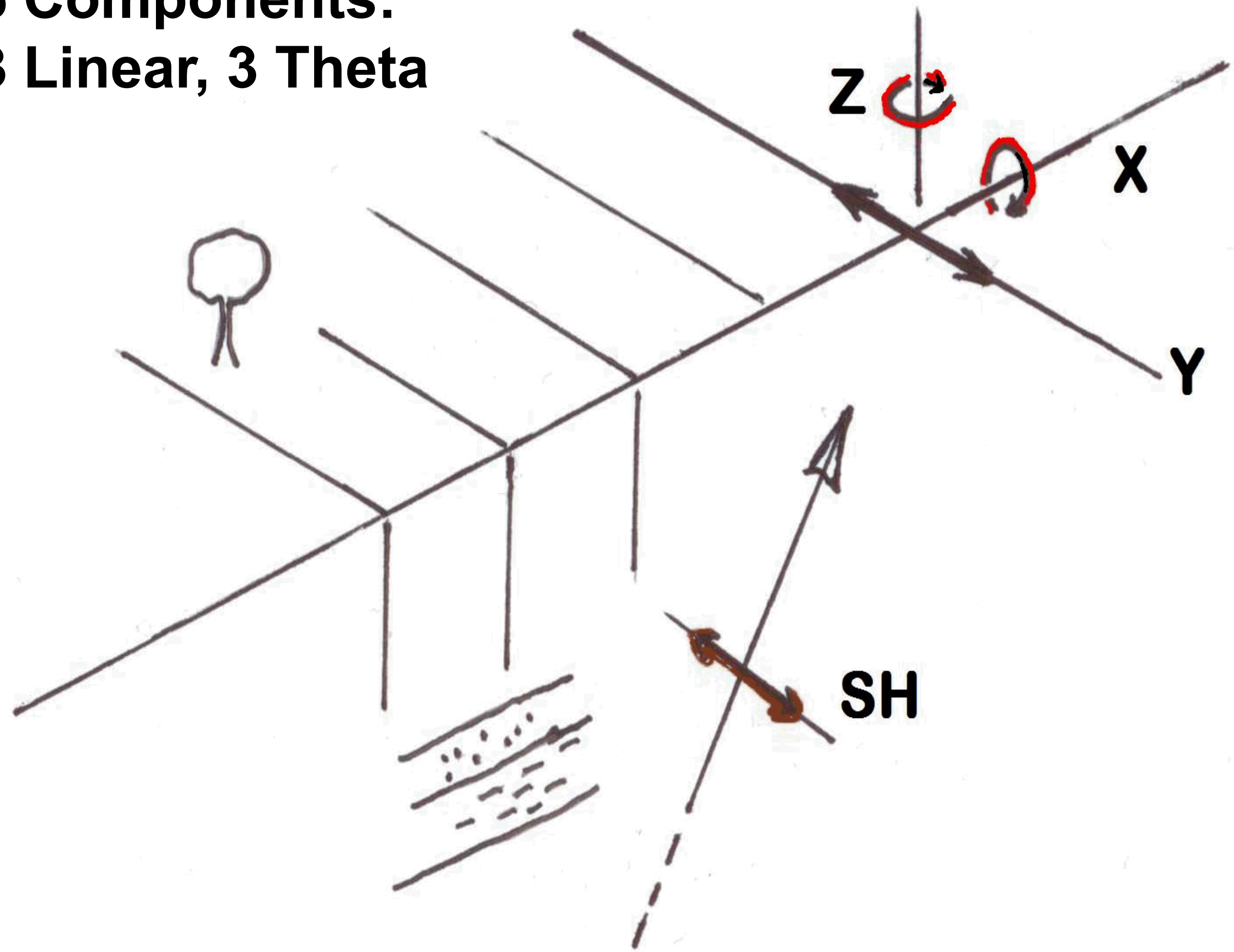
Transverse Rotational – TR Mode

6 Components:
3 Linear, 3 Theta

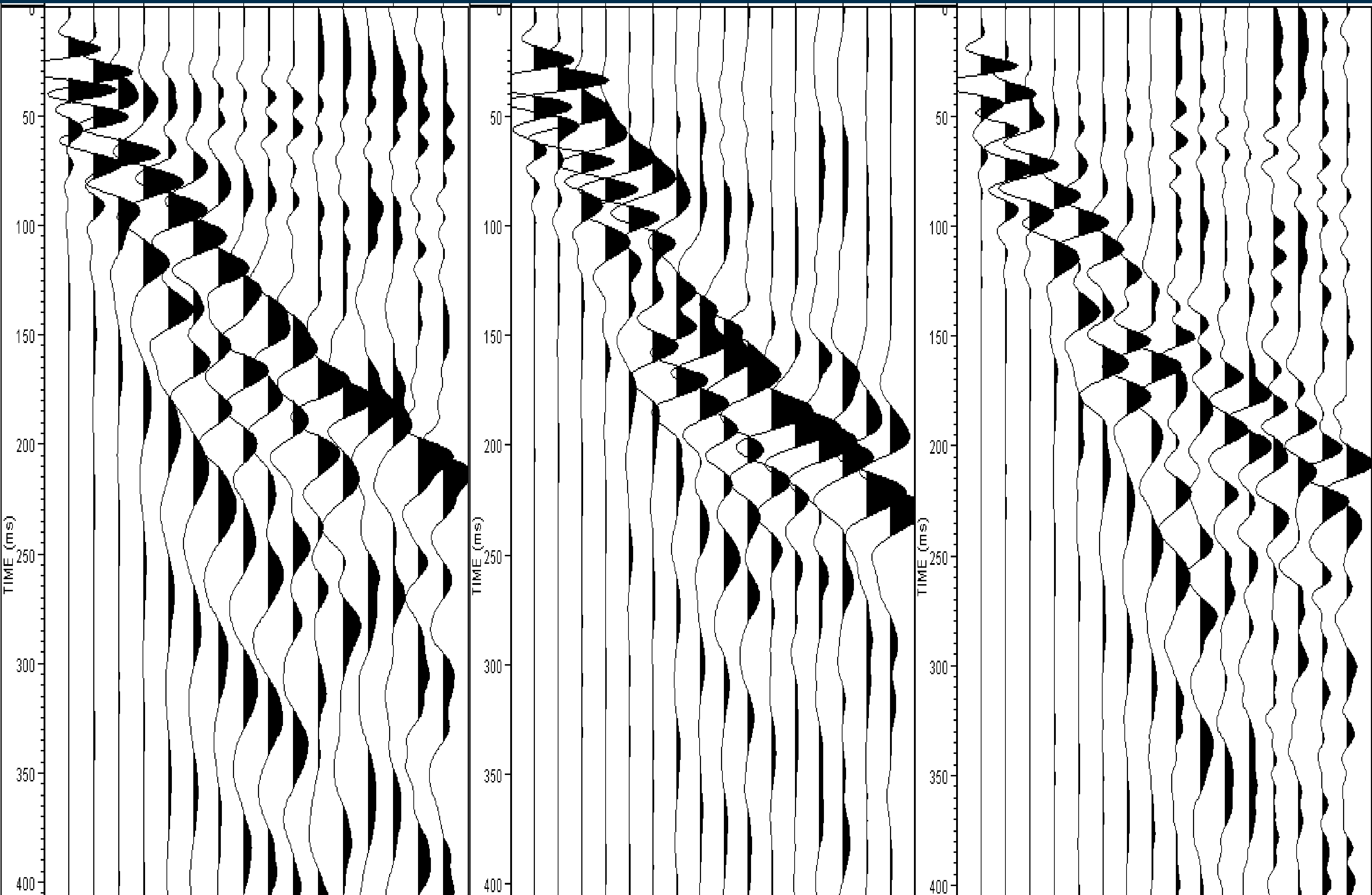


Transverse Linear – TL Mode

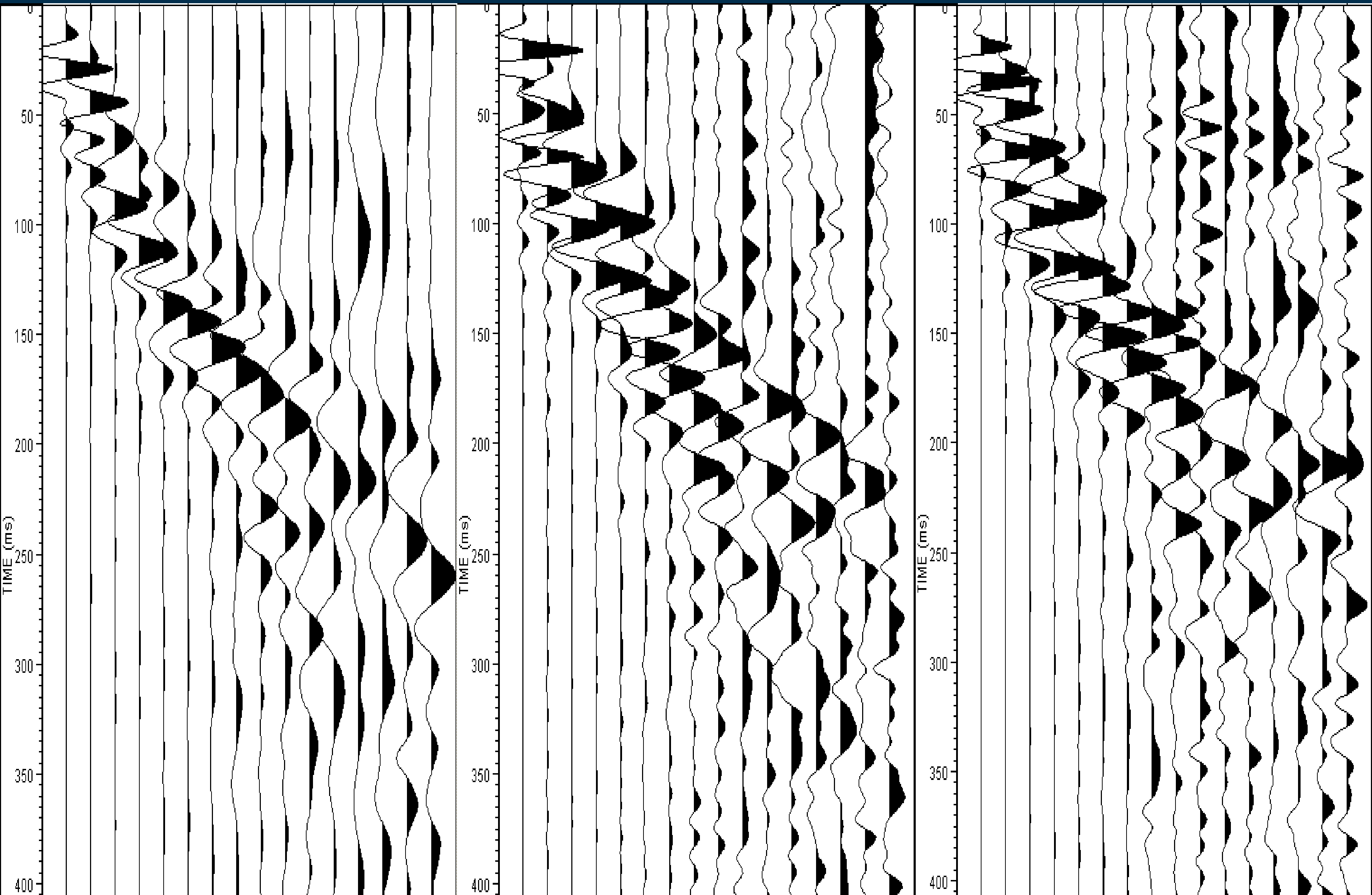
6 Components:
3 Linear, 3 Theta



PSV - 3C-Vert., 3C-Radial, 3θ-Trans.



SH - 3C-Trans., 3θ-Vert., 3θ-Radial



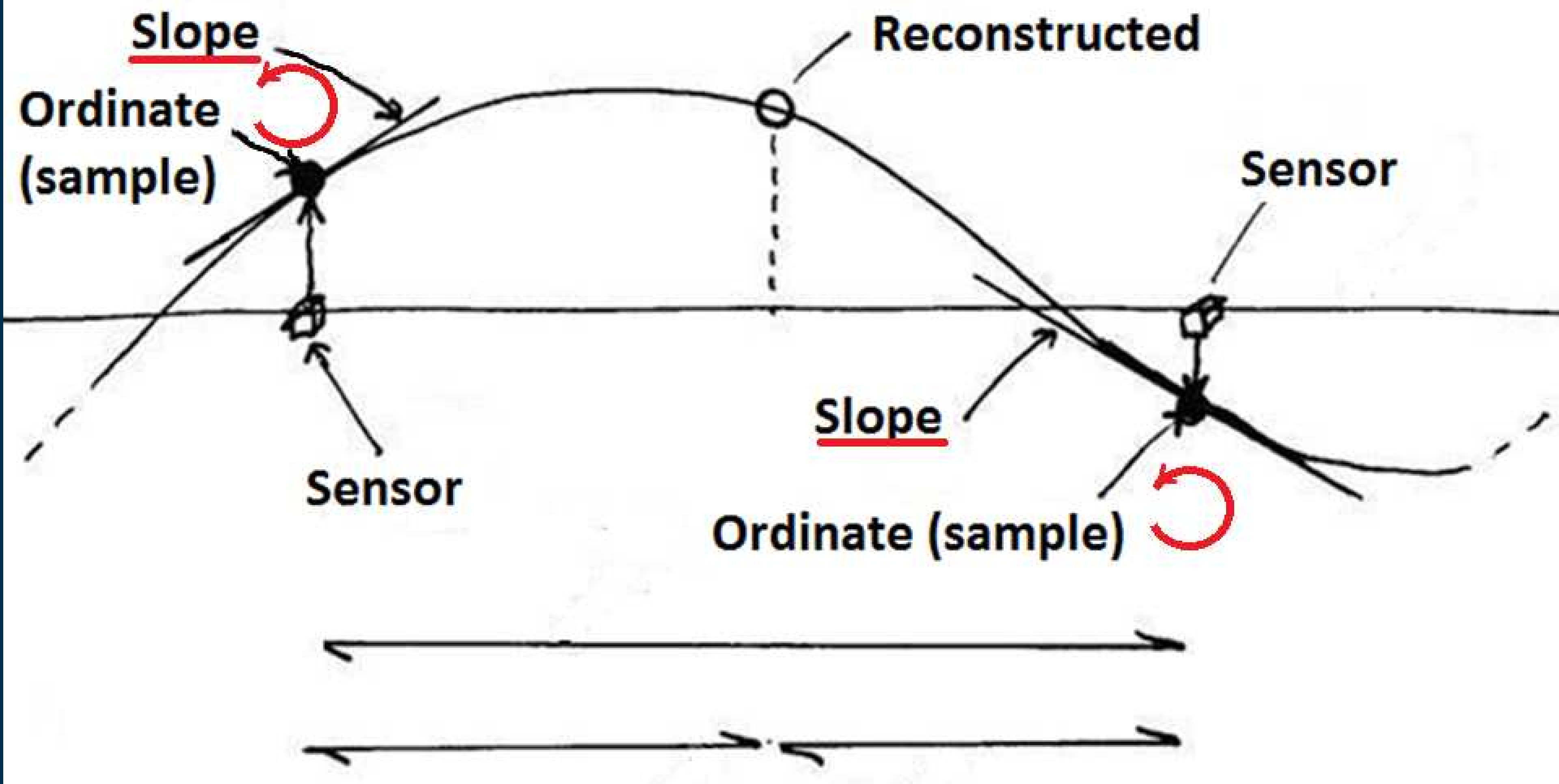
Synopsis – Theta-Data Rotational Seismic

- What is it and where did it come from?
- Sensors - How do we measure it?
- What does Theta-Data look like?

- What are possible Applications?
  - Spatial sampling enhancement
  - Shear Wave selectivity – microseismic
  - ‘other’ uses

- Status and ‘Road Ahead’

Ordinate and Slope Sampling *DOUBLE the Effective Spatial Nyquist*



For Z linear component:
Rotational yields the Spatial Slopes

At **Free Surface**, or **Water Bottom**, have zero traction/stress component, and thus zero strain component:

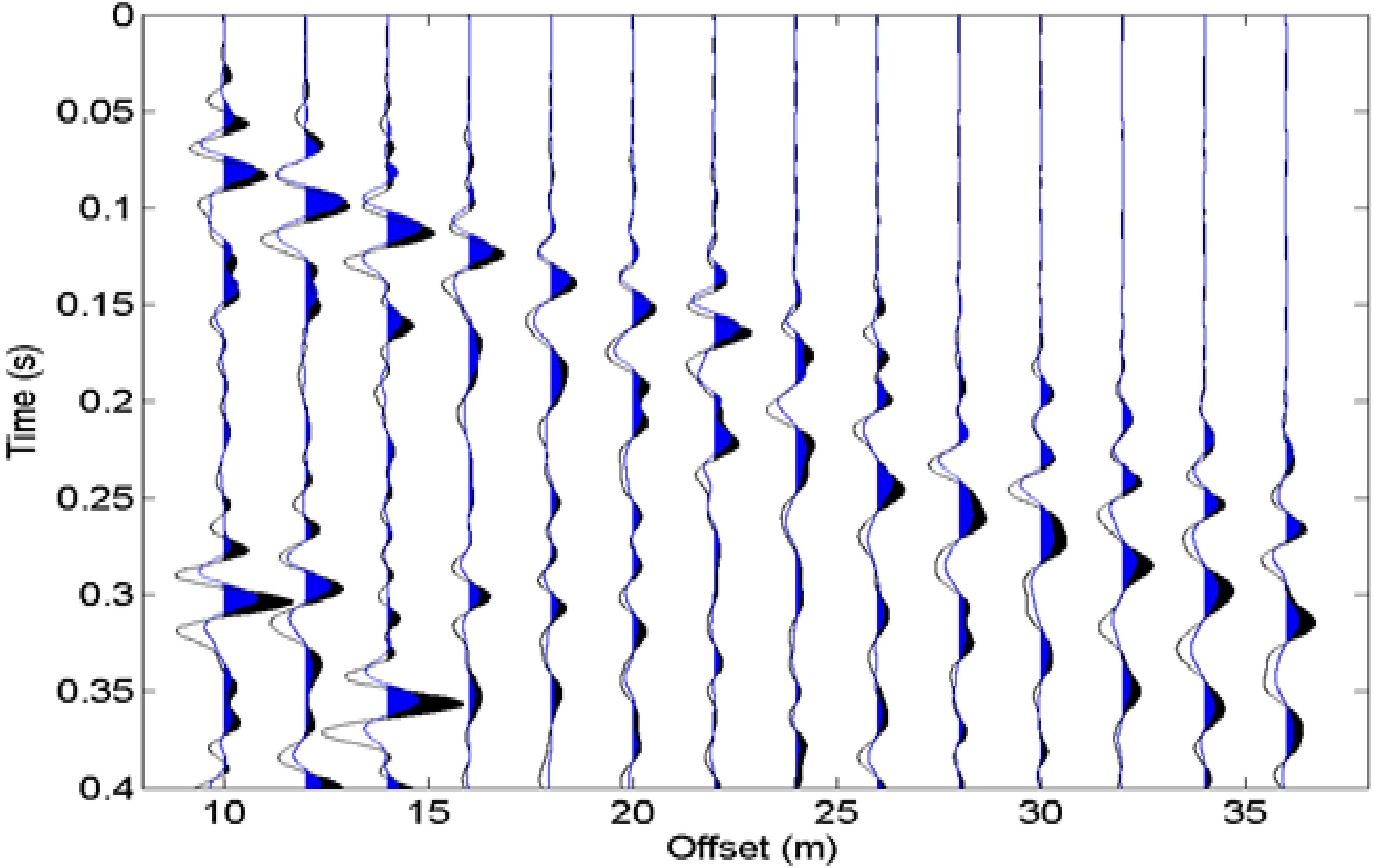
$$e_{yz} = \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) = 0$$

Thus we have the **y spatial gradient** of the vertical linear component of displacement, w, given by the **x component of rotational** Theta Data:

$$\theta_x = \frac{\partial w}{\partial y}$$

Rotational Spatial Sampling – Horizontal Gradients of Linear Z

Everhard Muyzert, Schlumberger, EAGE, 2012



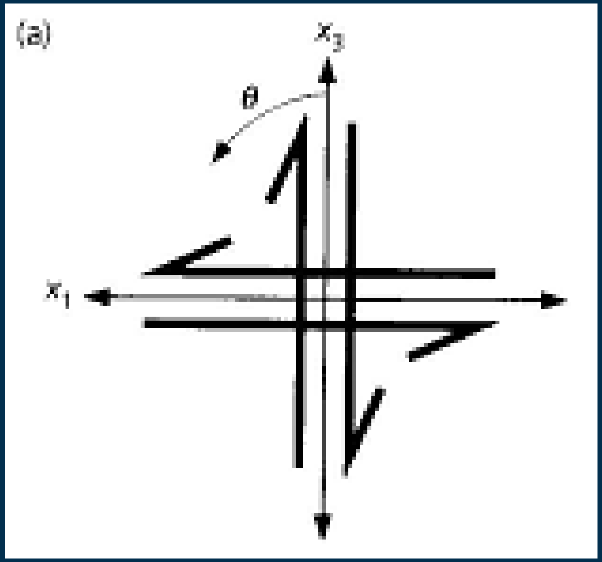
Synopsis – Theta-Data Rotational Seismic

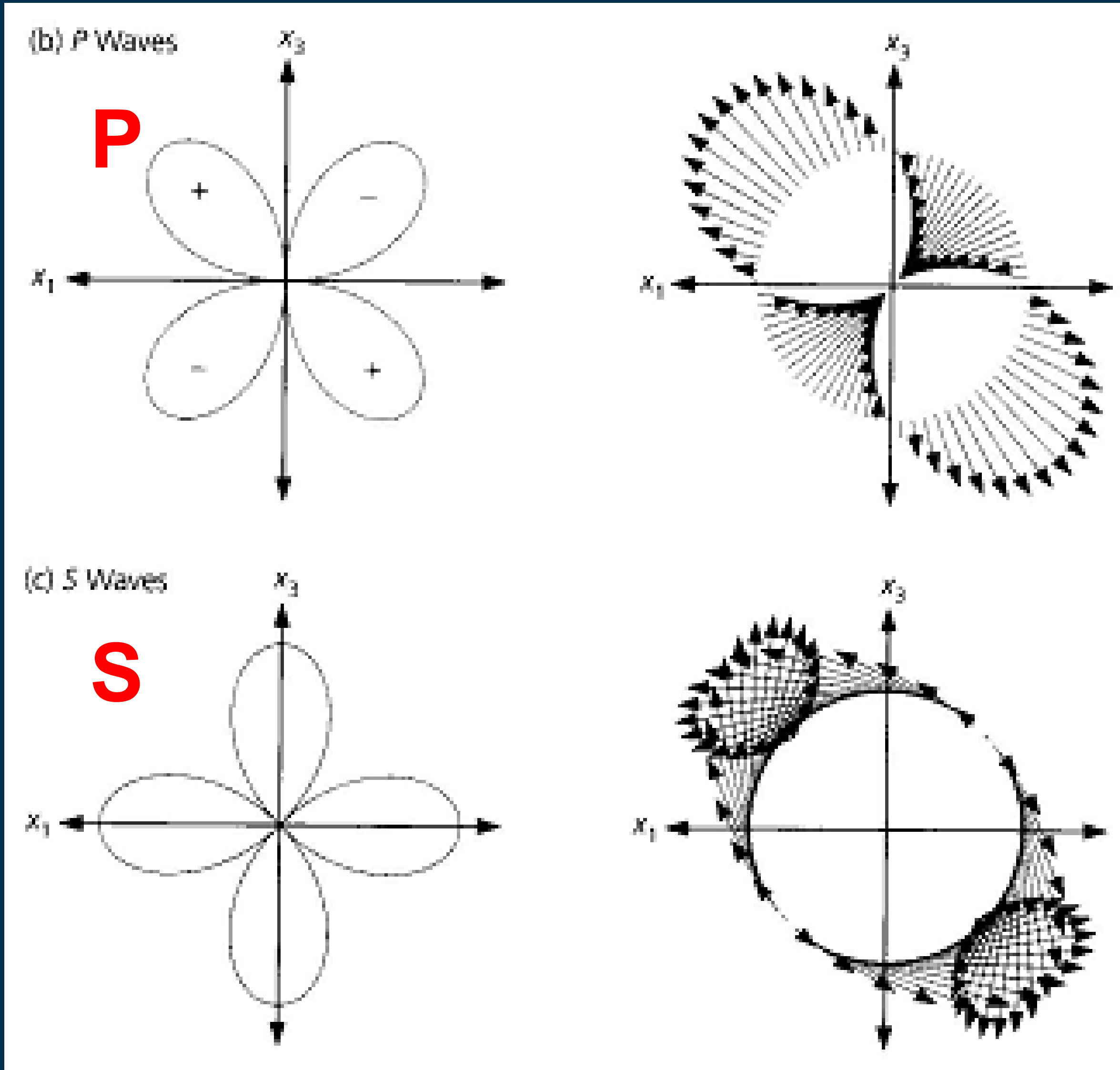
- What is it and where did it come from?
- Sensors - How do we measure it?
- What does Theta-Data look like?

- What are possible Applications?
  - Spatial sampling enhancement
  - Shear Wave selectivity – microseismic
  - ‘other’ uses

- Status and ‘Road Ahead’

Frac'ing / Micro-Seismic – Double Couple





P and S body waves

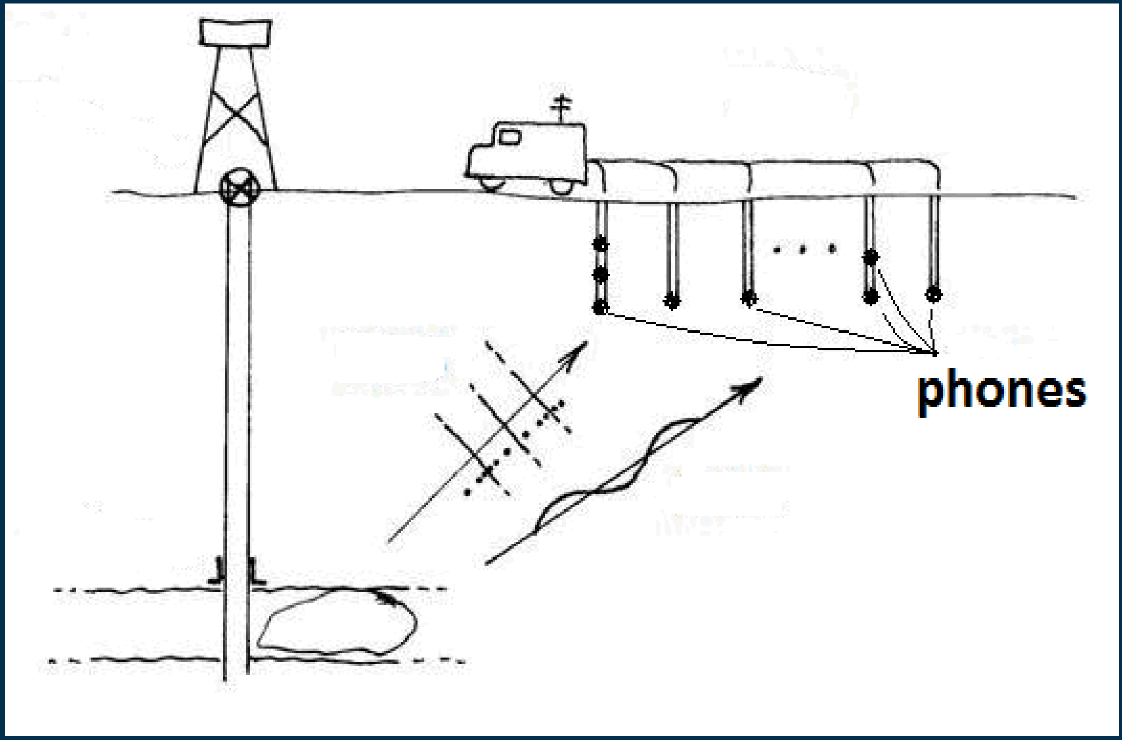
Motion Amplitude
And
Motion Direction

S is STRONGER

Micro-Seismic / Double Couple – Shear Detection

Rotational phones below the free surface, away from strong interfaces, and the associated P & S conversions.

Shear Selectivity of Theta Data possibly may enhance extraction of shear body wave data



Induced Seismicity: Frac Rotational Monitoring ?

From earthquake seismology:

"Observations . . . showed that the amplitudes of rotations can be one to two orders of magnitude greater than expected from the classical elasticity theory"

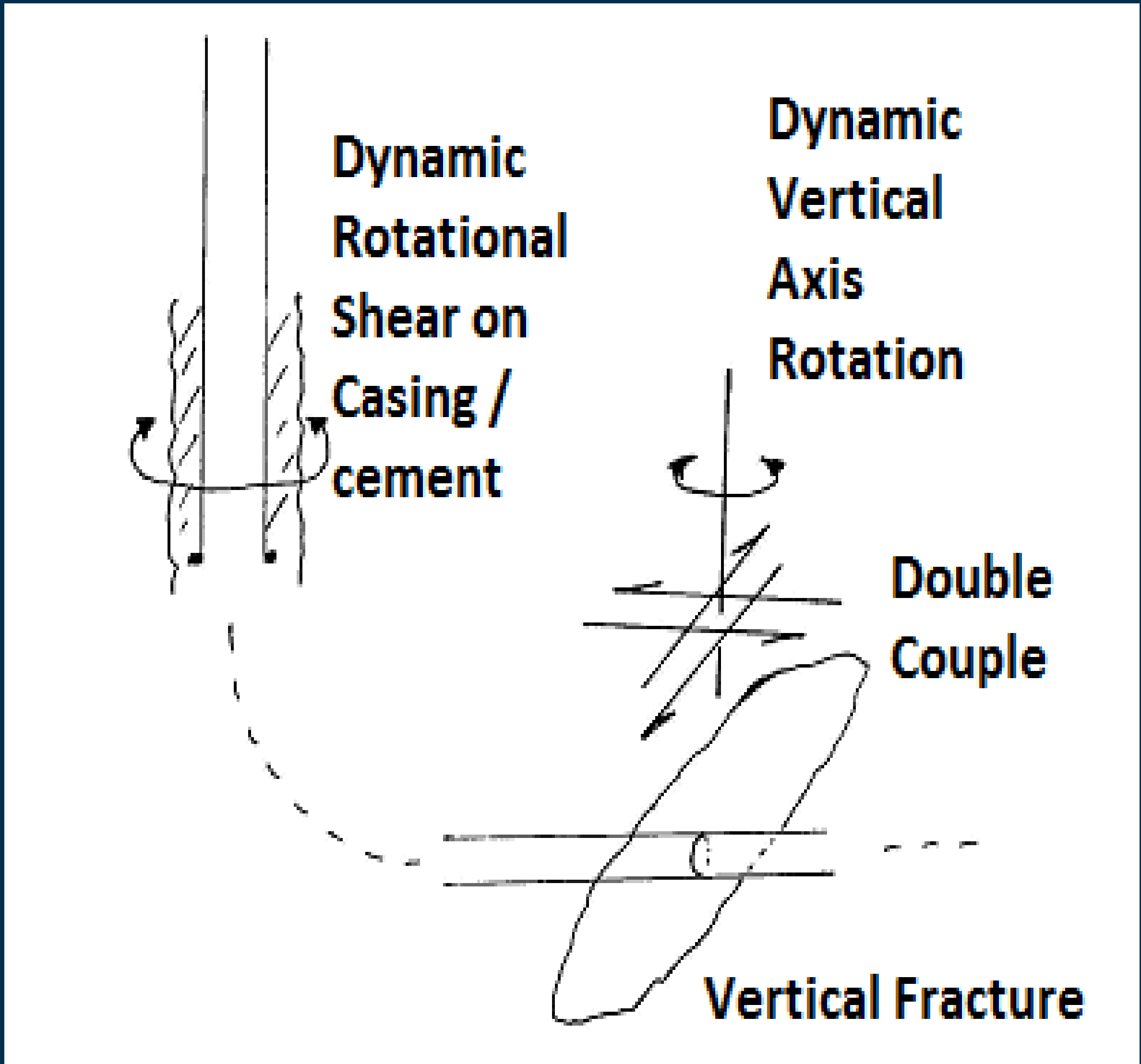
*Lee, Igel, & Trifunac, **2009**, "Recent Advances in Rotational Seismology", Seis. Res. Ltrs., vol. 80,no. 3, May/June*

Frac Rotational Monitoring ?

Vertical axis dynamic rotation.

Release pre-existing tectonic stress.

Shear bond strength of cement-casing is comparatively weak.



Synopsis – Theta-Data Rotational Seismic

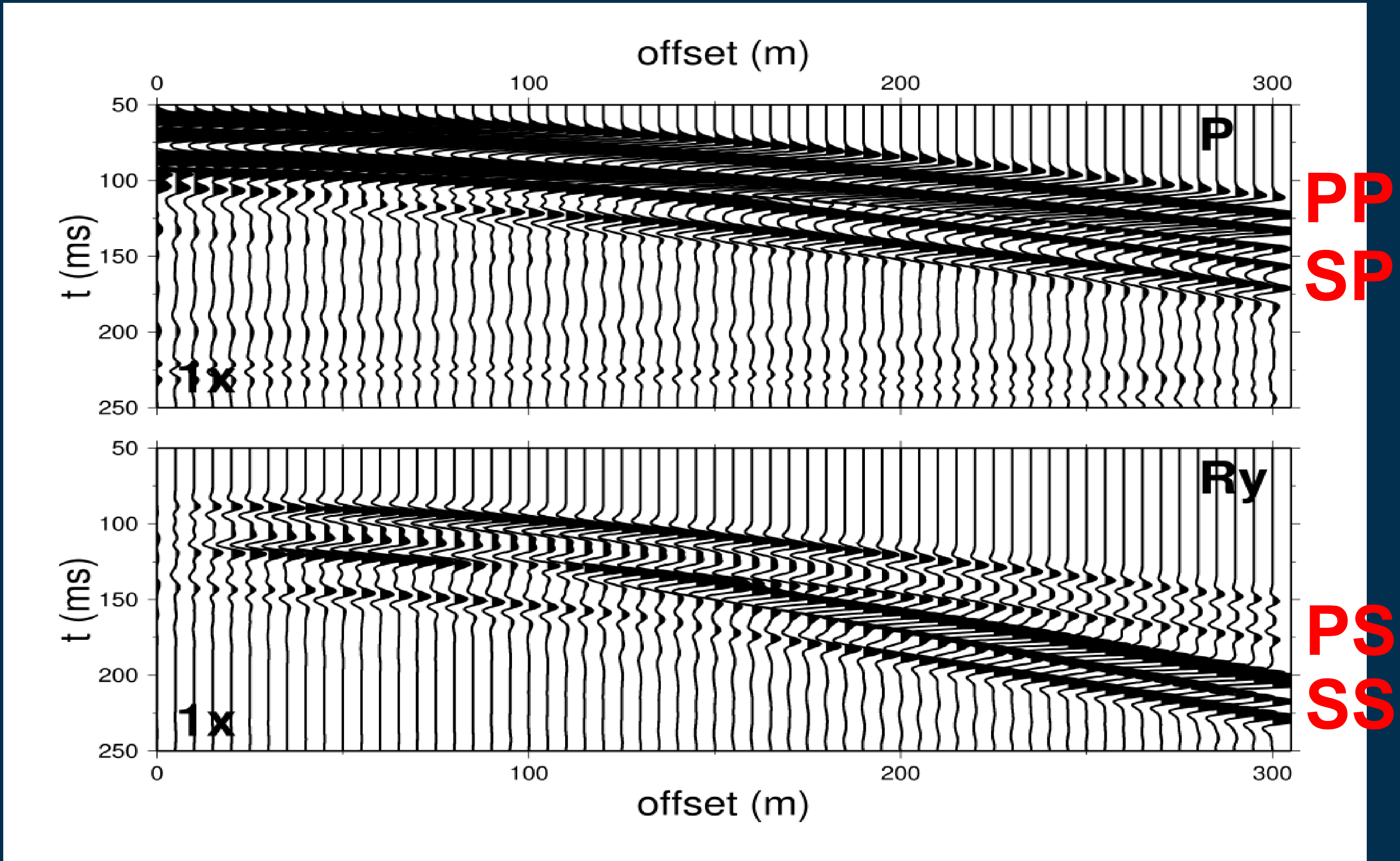
- **What is it and where did it come from?**
- **Sensors - How do we measure it?**
- **What does Theta-Data look like?**

- **What are possible Applications?**
  - **Spatial sampling enhancement**
  - **Shear Wave selectivity – microseismic**
  - **‘*other*’ uses – AVO; Point Array to determine propagation velocity; C-Wave; tilt correction; frac density; ground roll(?)**

- **Status and ‘Road Ahead’**

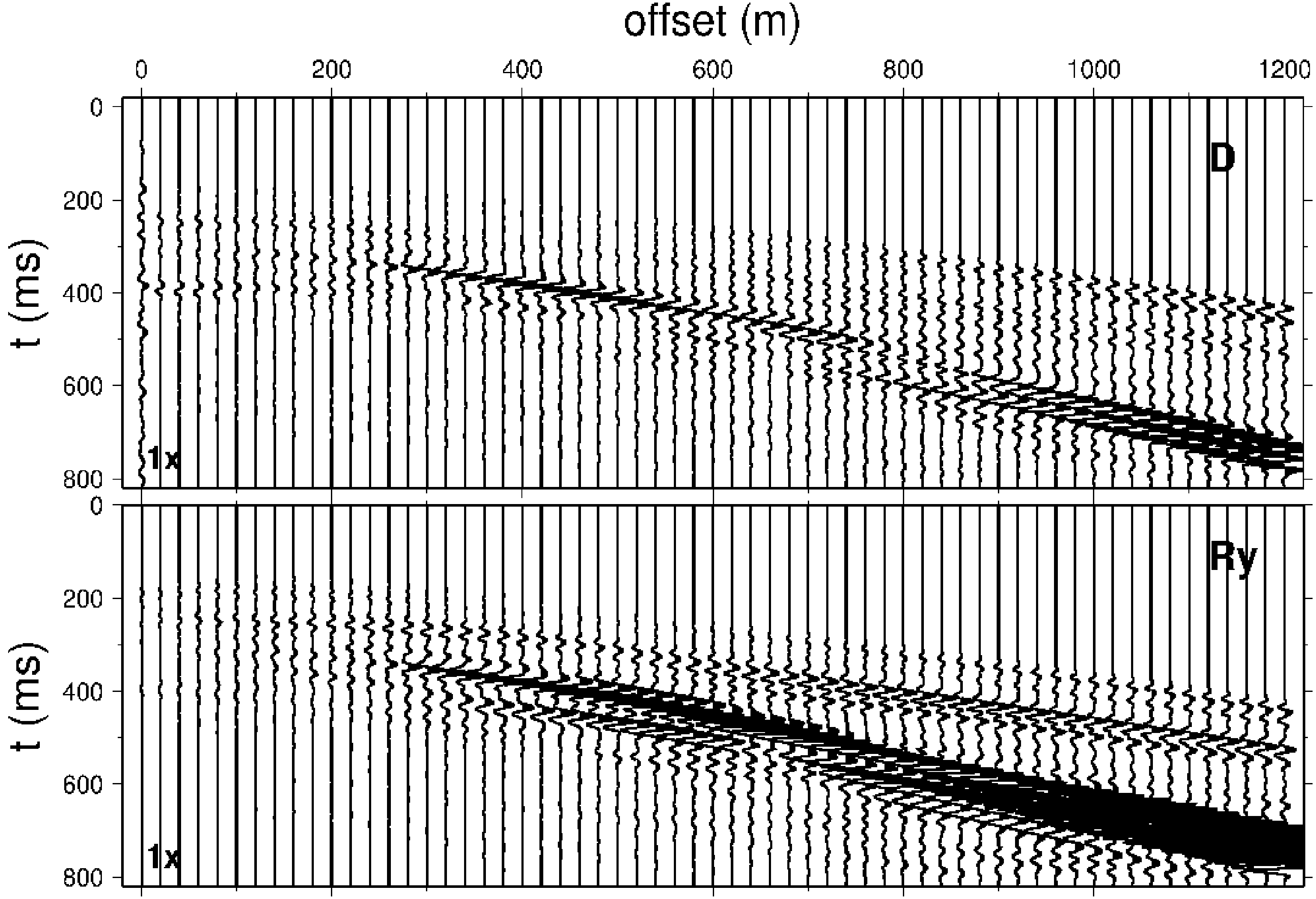
Pressure (P wave only) + TR-Theta (S wave only)
AVO for gas sandstone
No Free Surface, buried phones

David Aldridge, et al., Sandia National Laboratories, 2007-2009



Pressure (P wave only) + TR-Theta (S wave only)
Free Surface, AVO for brine saturated sandstone

David Aldridge, et. al., Sandia National Lab, 2007-2009



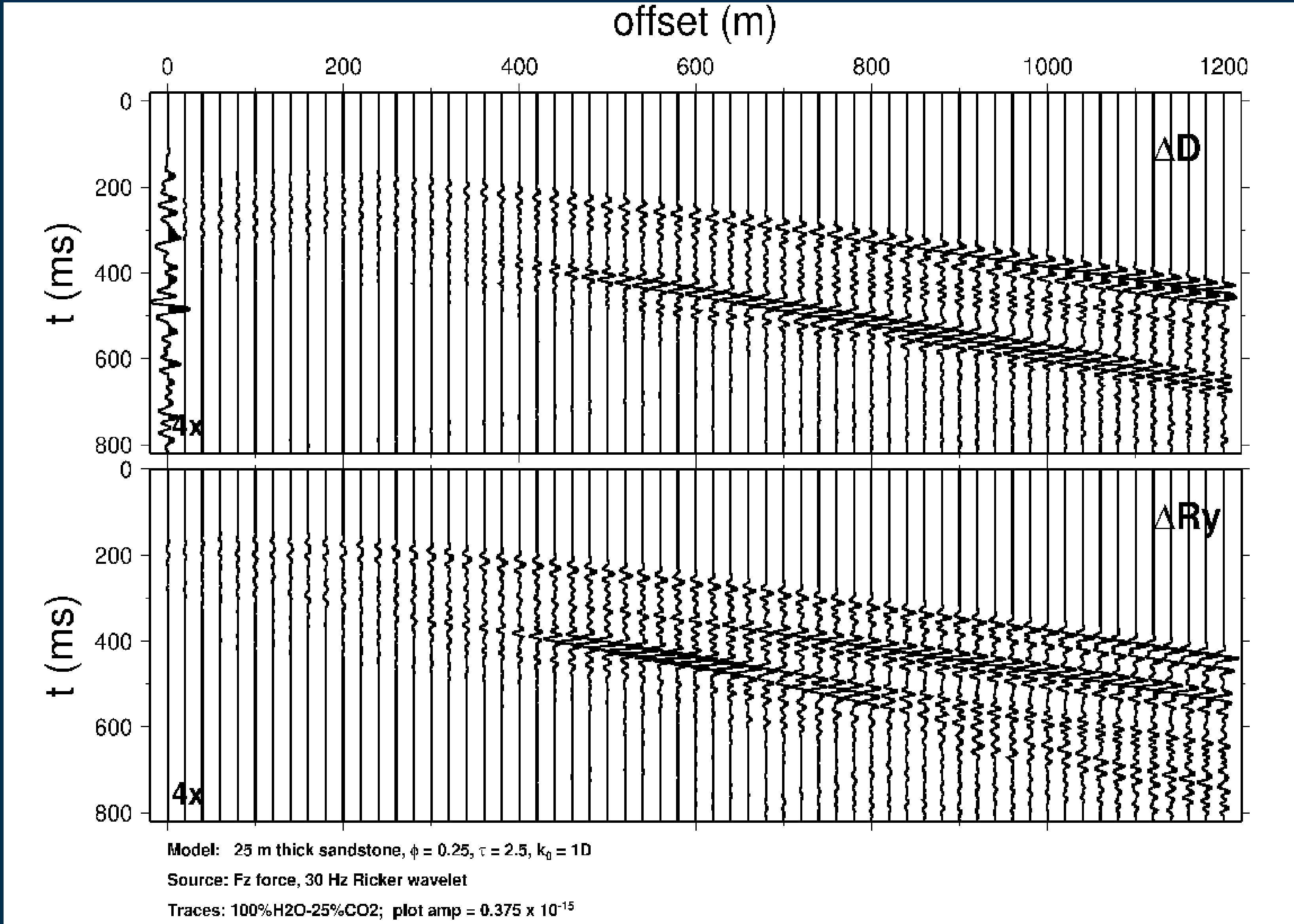
Model: 25 m thick sandstone, $\phi = 0.25$, $\tau = 2.5$, $k_0 = 1D$

Source: Fz force, 30 Hz Ricker wavelet

Traces: 100%H2O; plot amp = 1.5×10^{-15}

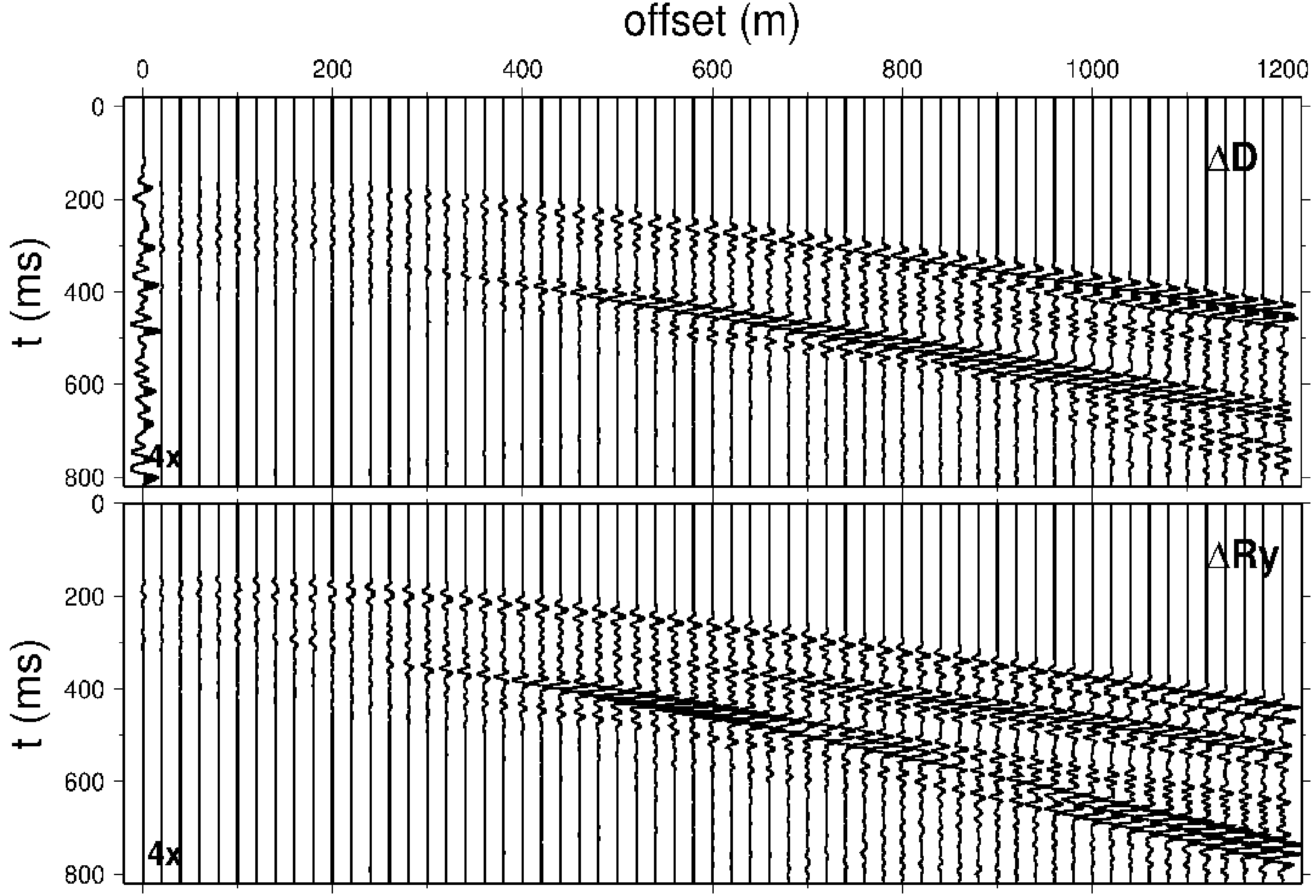
Pressure (P wave only) + TR-Theta (S wave only)
Delta AVO for 25% CO2 saturated sandstone

David Aldridge, et. al., Sandia National Lab, 2007-2009



Pressure (P wave only) + TR-Theta (S wave only) *Delta AVO for 50% CO_2 saturated sandstone*

David Aldridge, et. al., Sandia National Lab, 2007-2009



Model: 25 m thick sandstone, $\phi = 0.25$, $\tau = 2.5$, $k_0 = 1D$

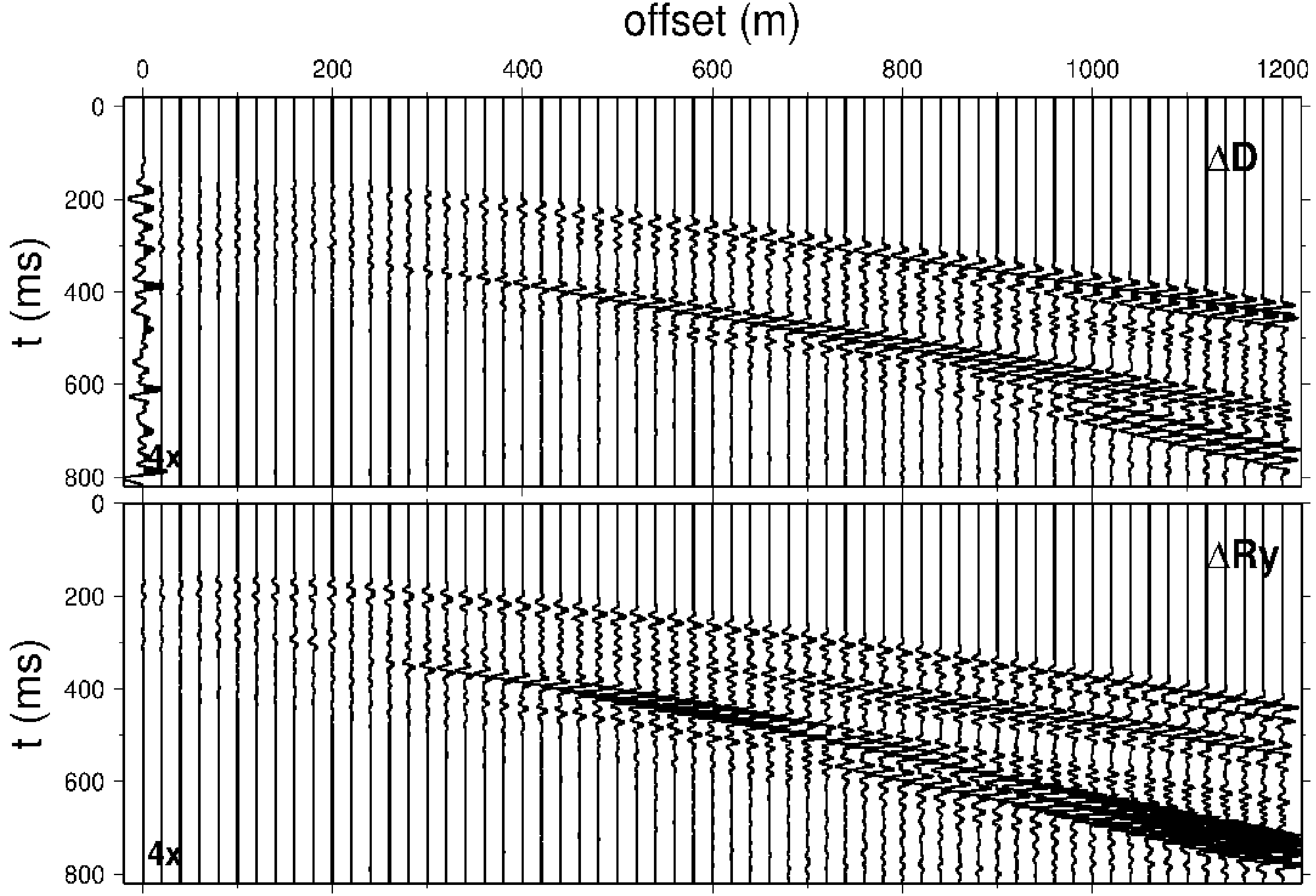
Source: Fz force, 30 Hz Ricker wavelet

Traces: 100%H2O-50%CO2; plot amp = 0.375×10^{-15}

Pressure (P wave only) + TR-Theta (S wave only)

Delta AVO for 75% CO_2 saturated sandstone

David Aldridge, et. al., Sandia National Lab, 2007-2009



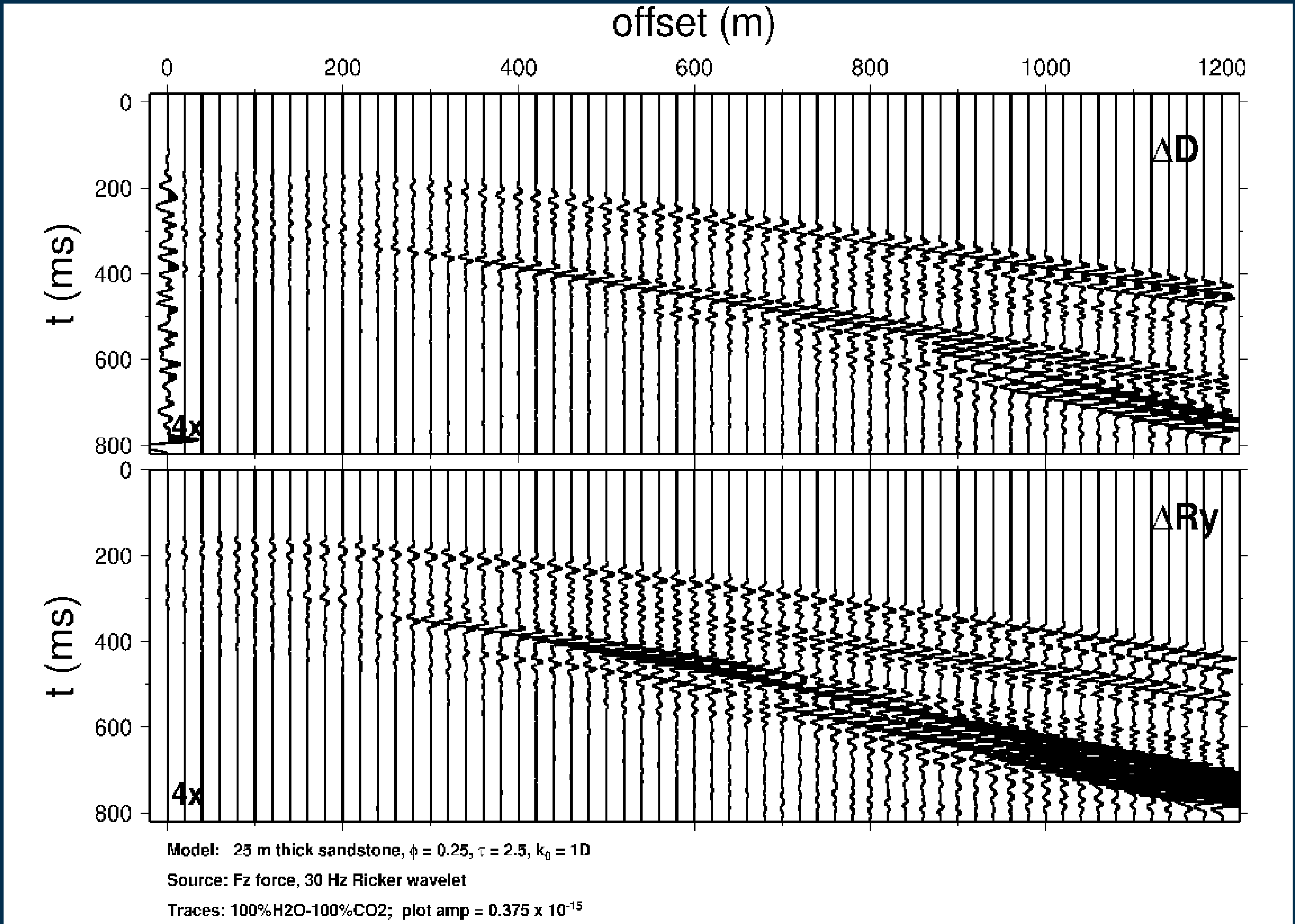
Model: 25 m thick sandstone, $\phi = 0.25$, $\tau = 2.5$, $k_0 = 1D$

Source: Fz force, 30 Hz Ricker wavelet

Traces: 100%H2O-75%CO2; plot amp = 0.375×10^{-15}

Pressure (P wave only) + TR-Theta (S wave only)
Delta AVO for 100% CO_2 saturated sandstone

David Aldridge, et. al., Sandia National Lab, 2007-2009



Igel / Aldridge Point Array

At a single 3-C / 3-Θ sensor:

$$\text{S VELOCITY} = \frac{\text{transverse linear acceleration}}{\text{orthogonal transverse rotational velocity}}$$

Potential use for shear statics:

get shear velocity around each 6-C phone.

From 3-C *and* 3-Θ data can determine direction AND velocity of shear wave propagation.

Shear Waves / C-Waves

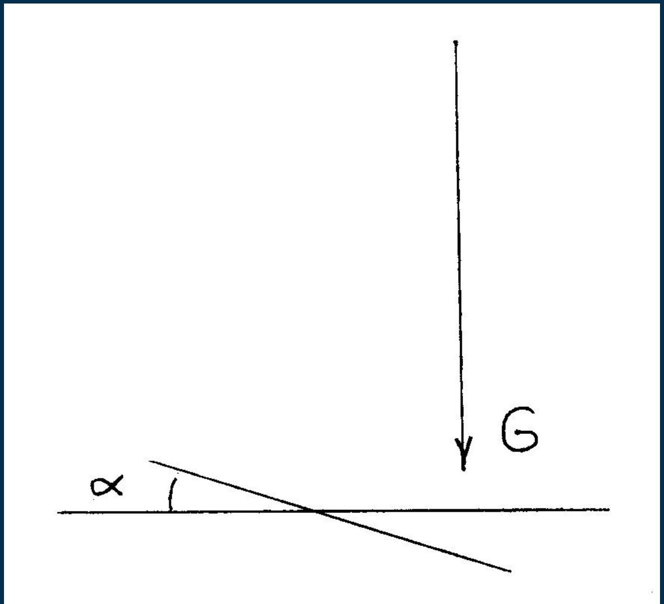
- **Great effort in the 1980's pursuing shear sources, *but* always with 3-C linear phones that didn't differentiate P from S.**
- **Now we can use Rotational Phones to get pure shear 3-ϴ data as a 3-component vector.**
- **Related concept: use Pressure Gradients to get pure compressional 3-∇ P data as a 3-component vector.**

- **Processing issues:**

  3 components with mode purity (gain, decon).

  Direction and propagation velocity.

Tilt Correction of Linear using Rotation



If a Horizontal Linear Phone tilts by angle α, then it picks up error:

Gravity * sin(α)

Micro- or milli-radians of tilt give a potentially significant error compared to weak seismic reflections (C-waves).

Consider a worse case:
weak C-wave data on horizontal phone at same time as strong ground roll in uncorrelated vibroseis data

Possibly(?) Map Frac Density

Some precedent: Lg Scattering measurements in earthquake seismology & use of vertical rotation

Perhaps we can use rotation measurements to map scattering / fracture density:

- **Use time, offset windows to target shales in Resource Plays. Compare Polarization modes.**
- **Azimuthal Anisotropy of 6-C (3-C and 3-Θ):**
    - **Amplitude Anisotropy**
    - **Velocity Anisotropy**
    - **Shear splitting**

Ground Roll – Rayleigh Waves

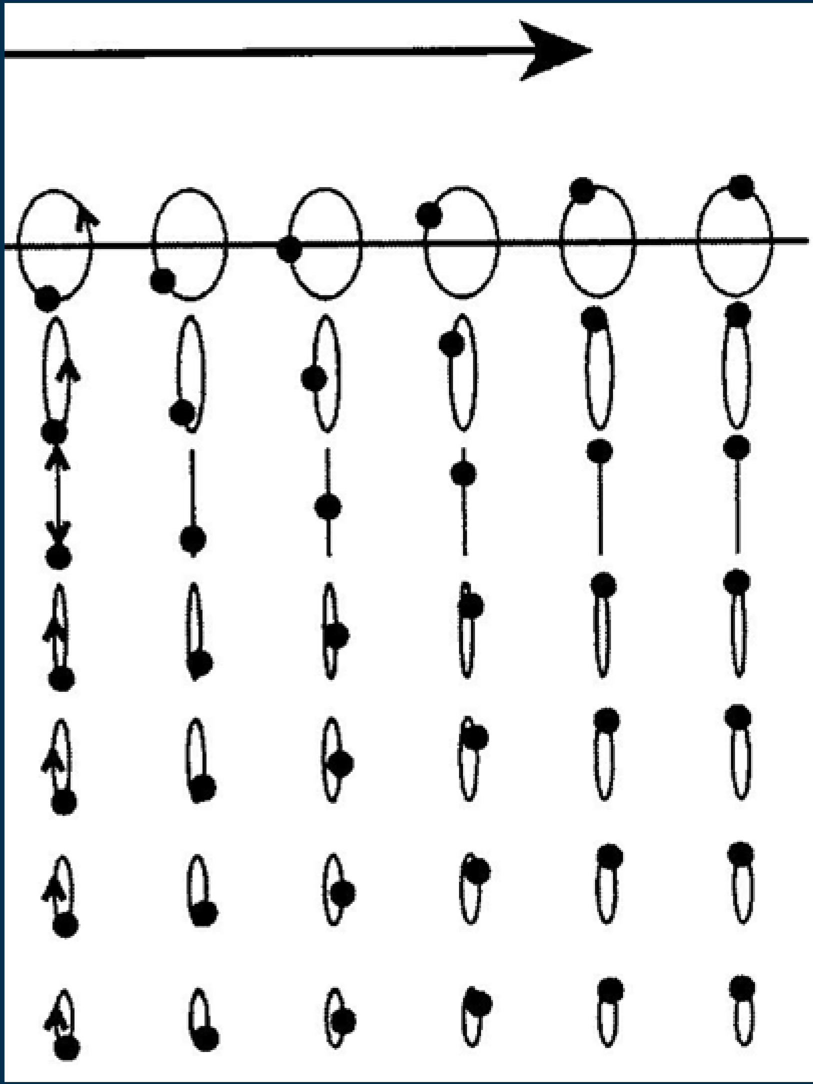
Classic Rayleigh Retrograde Elliptical motion:

only for Poisson Solid (0.25)

For Poisson Ratio above 0.265, have 3 modes of polarization.

Hodograph of point is not actually ‘true’ rotation.

Rayleigh wave / Rotational Seismic: not simple.



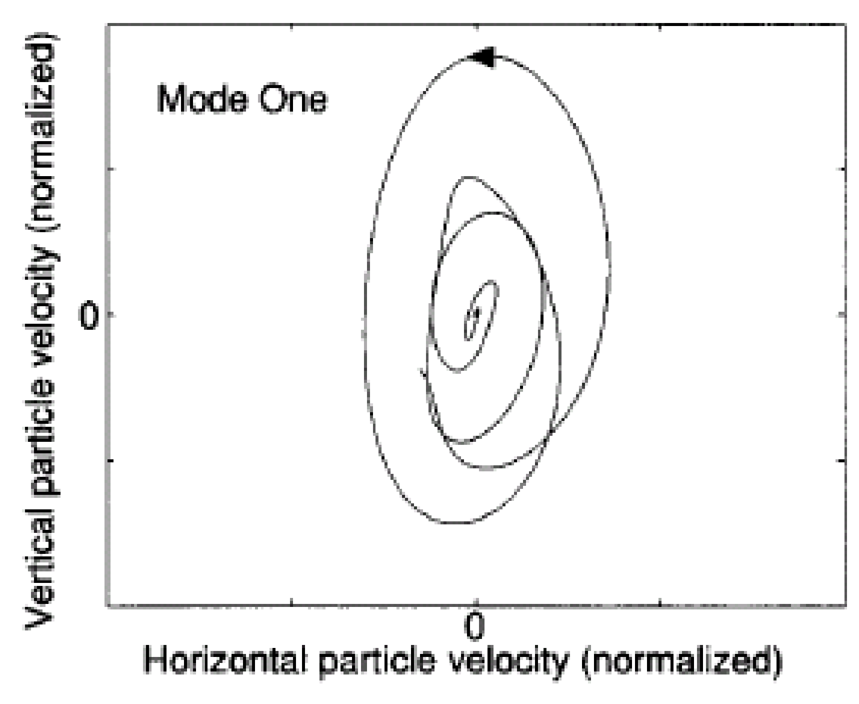
Rayleigh Modes: Hodographs

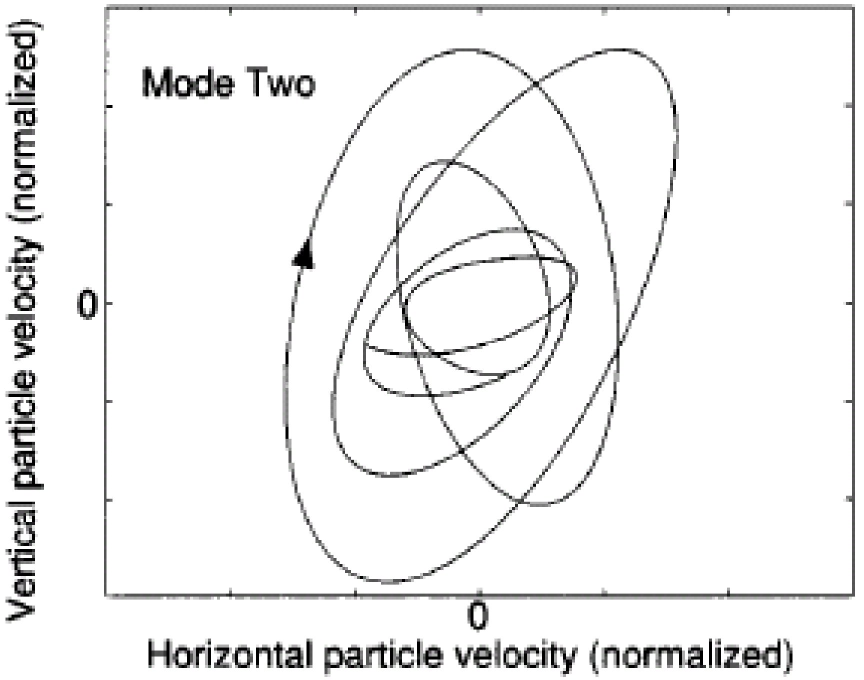
High Poisson Ratio Near Surface

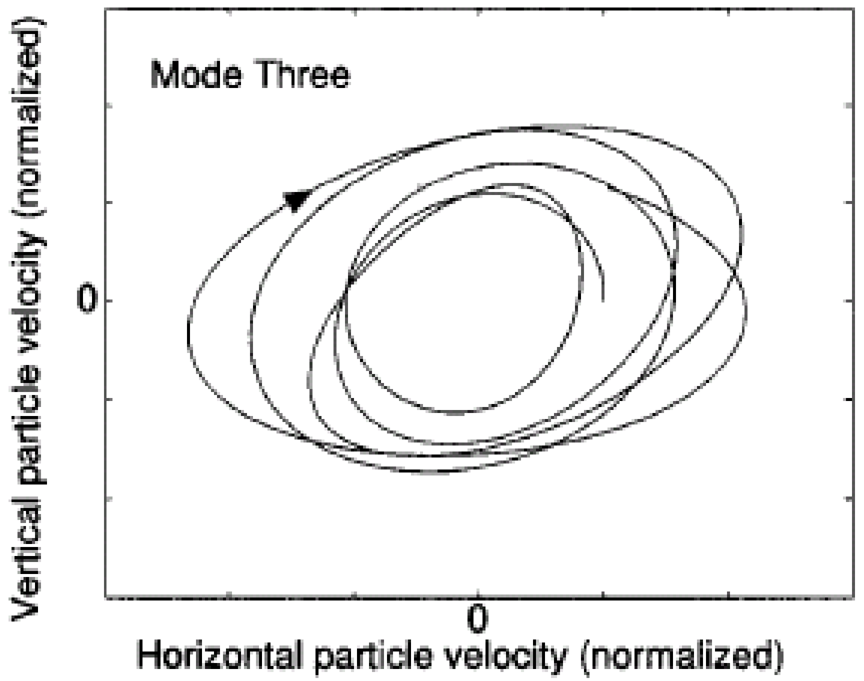
Mode 1 – Retrograde

Modes 2 & 3 – Prograde

Smith, et. al., JASA 1998







Synopsis – Theta-Data Rotational Seismic

- **What is it and where did it come from?**
- **Sensors - How do we measure it?**
- **What does Theta-Data look like?**

- **What are possible Applications?**
  - **Spatial sampling enhancement**
  - **Shear Wave selectivity – microseismic**
  - **‘*other*’ uses – AVO; Point Array to determine propagation velocity; tilt correction; frac density; ground roll(?)**

- **Status and ‘Road Ahead’**

Rotational Seismic – 'Status'

- **E&P Operating Companies**
  - **Activity in only very few (~1) Companies.**
  - **No testing to date**

- **Geophysical (Equipment/Contractor) Cos.**

  2 [3] contractors have done small scale tests

- **3 +/- Rotational Phone manufacturers**

- **Patent Status (8 companies)**
  - **Defensive**
  - **Perception that Rotational Seismic has potential to be a significant technology, *but . . . .***

Rotational Seismic – 'Failures'

- Failure in Market Research
  - Confuse technical enthusiasm vs. willingness for expenditures / investment
- Not Backward Compatible
- No incremental path / no retrofit
- Not Market Driven – no user requests
- Not Proven –
  - Wavefield Scale in multiple locations
  - Meaningful Geological Scale

Thank you for your attention !

- Rotational sensor prototypes
- Limited data - no geological scale data
- Many Applications possible:

Spatial Sampling

Shear Selectivity – micro-seismic & C- wave

"Other" – AVO, Point Array, Tilt correction, Frac density, Rayleigh wave(?), etc.

- Technically attractive for multiple purposes
- BUT, commercially 'challenged'

ROAD AHEAD ?

Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly-owned subsidiary of Lockheed Martin Corporation, for the US Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.