The Reunification of Seismology and Geophysics

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Exploration geophysics – a brief history

Spectraseis

J.C. Karcher patents the reflection seismic method, focused
the exploration geophysicist for the next century
Beno Guttenberg becomes a professor of seismology

Gas research institute, Teledyne Geotech, & Sandia National Labs develop equipment
and techniques for microseismic monitoring to illuminate hydraulic fracturing

1920	1930	1940	1950	1960	1970	1980	1990	2000	2010	2013
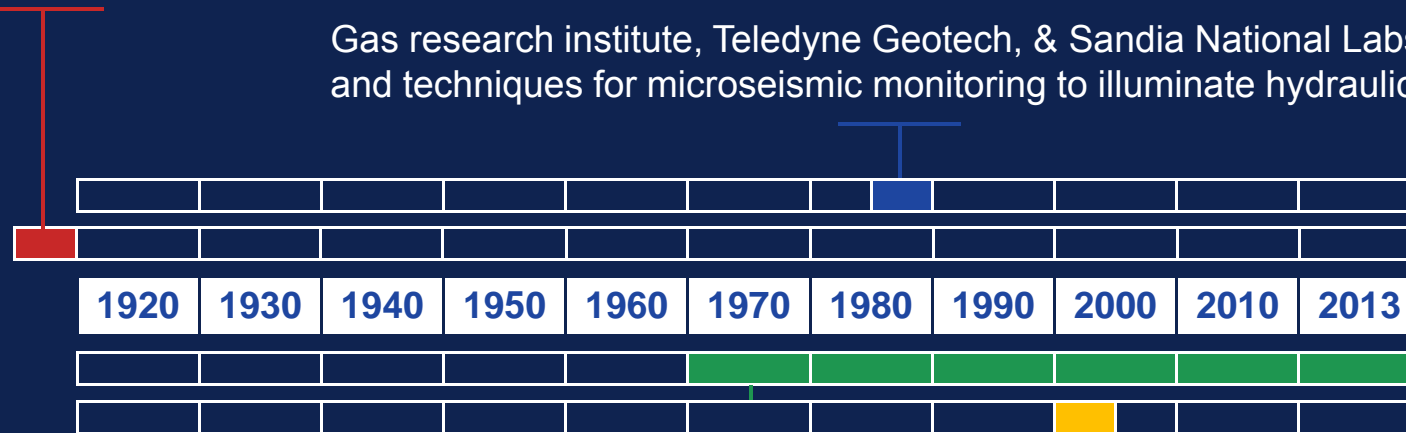
Rapid advances in computational capabilities allow processing
of ever-larger data volumes with more complete physics

Exploration geophysics begins (re) learning earthquake
seismology to commercialize microseismic monitoring

**Today, we have the opportunity to capitalize on the strengths of 100 yrs of development
in both communities**

Strength comparison

Seismology	Geophysics
Better sensors	More sensors
Better physics	More compute horsepower
Bigger events	Smaller domain

To extract the full potential from these measurements, we must capture the best of both knowledge bases.

Seismologists use cheap computers (grad. students) to do very thorough analysis on small numbers of traces.

Geophysicists use cheap computers (clusters) to do good-enough approximations on very large numbers of traces.

The merger of these fields is an historic opportunity to do exciting and valuable work
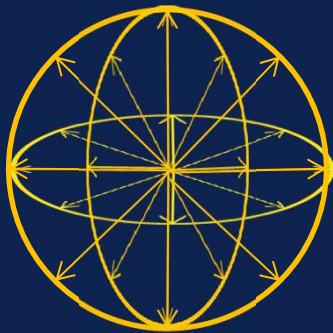
Agenda

Sensor selection

Survey design

Processing algorithms and computer requirements
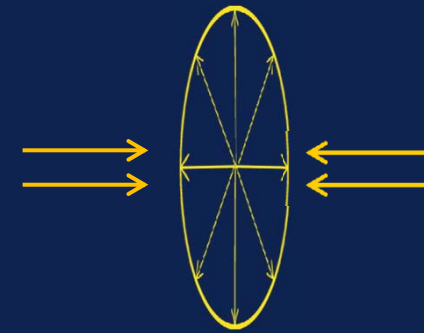
Conclusions

Fracture mechanisms
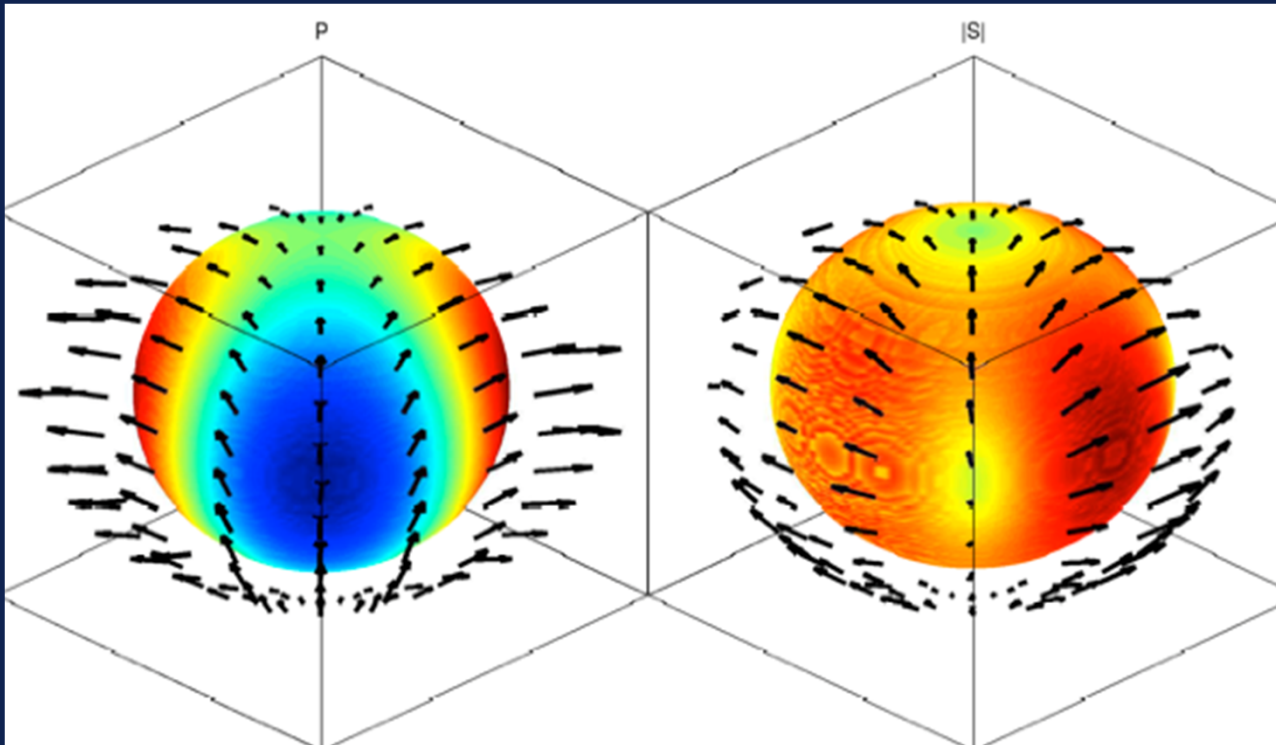
Isotropic
(explosion)

Double Couple
(DC)

Compensated Linear
Vector Dipole
(CLVD)

P-waves only

P- and S-waves

P- and S-waves

All fractures can be decomposed into these three mechanisms

DC radiation and particle motion

Particle motion of P waves is compressional and in the same direction direction to the traveling wavefront.

Particle motion of S waves is transverse and in the perpendicular direction to the traveling wavefront.

S pattern is |S| here, not preserving sign.
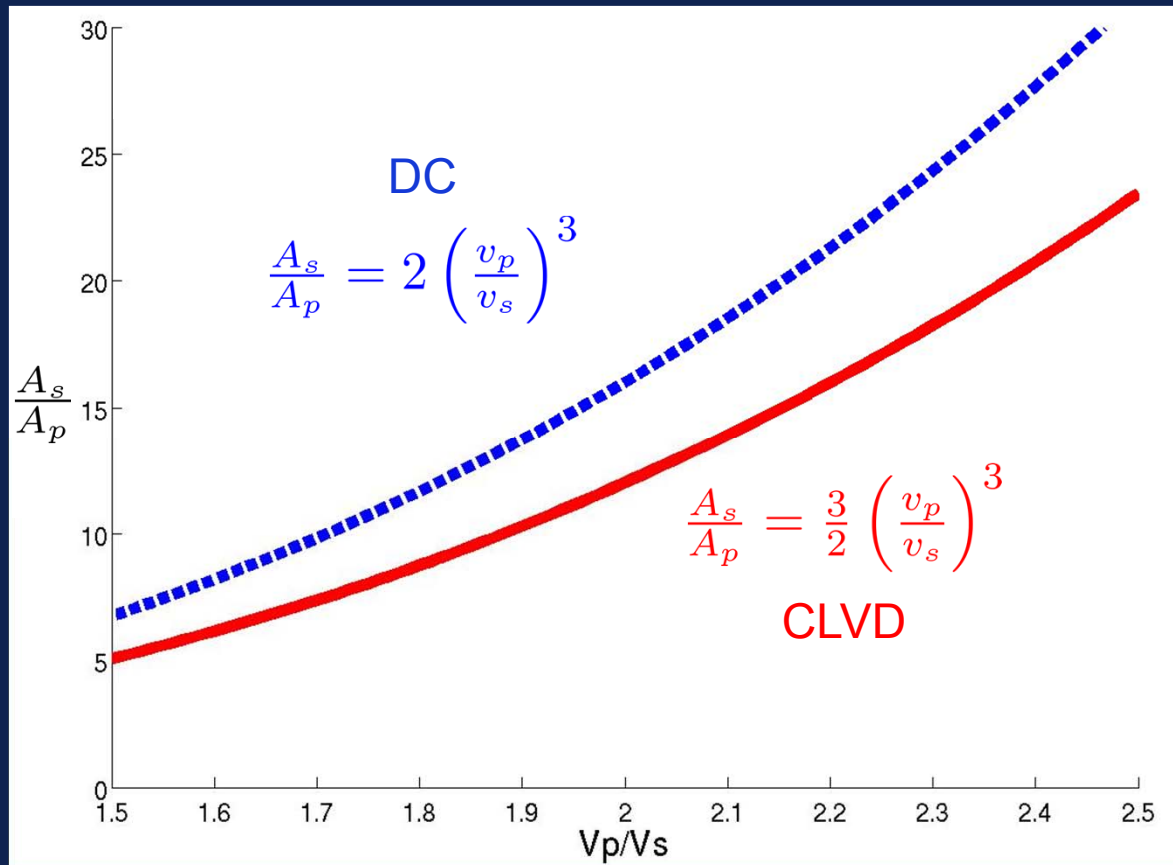
P energy is maximum where S is zero.

The P and S radiation patterns are the same but rotated 45 degrees

CLVD radiation

P

S
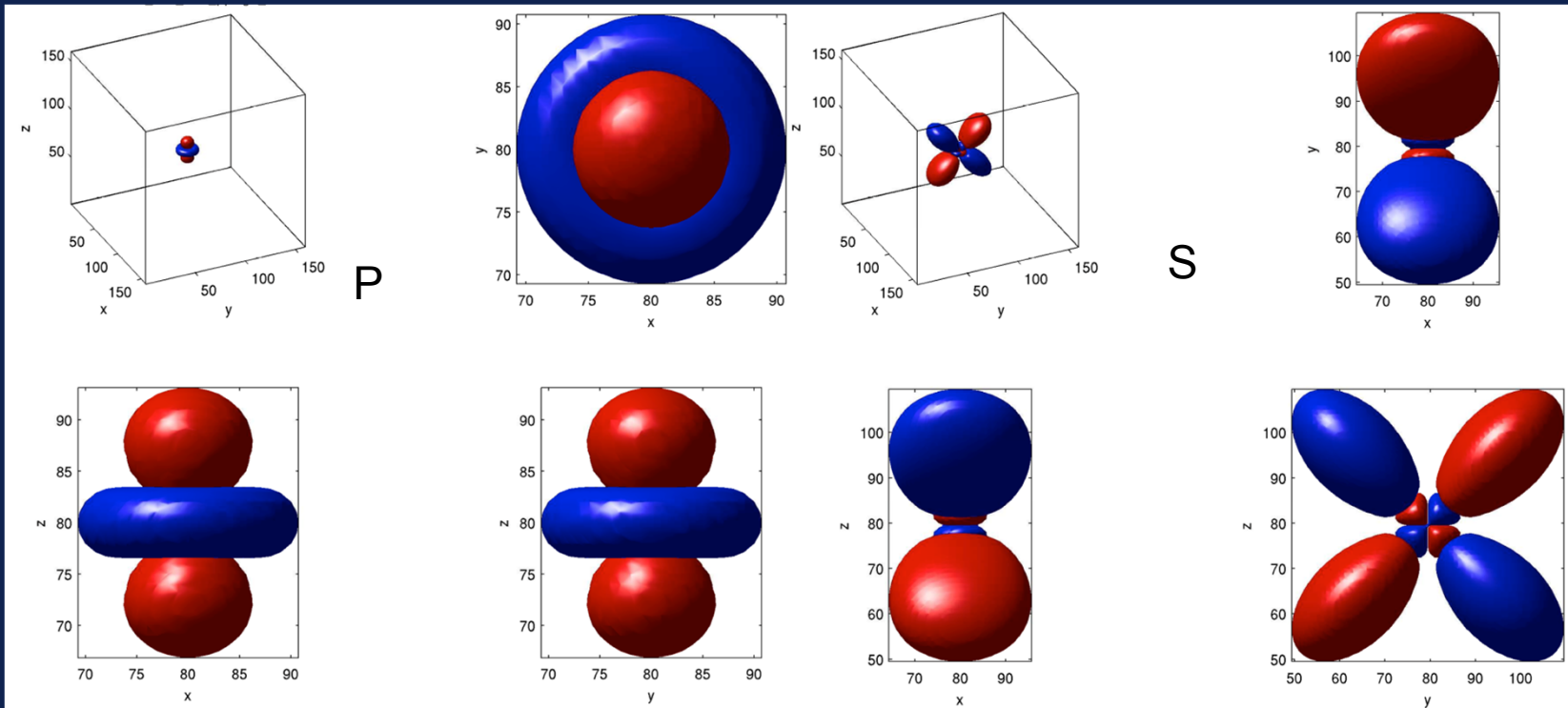
Radiation patterns are always the same, but rotate with the fault plane

Amplitude ratio (S/P)

$$\frac{A_s}{A_p} = 2\left(\frac{v_p}{v_s}\right)^3$$

DC

$$\frac{A_s}{A_p} = \frac{3}{2}\left(\frac{v_p}{v_s}\right)^3$$

CLVD

Average amplitude over the unit sphere is a function of Vp/Vs ratio

**Theory predicts that S-wave energy dominates**

Microseismic wave field is not high frequency

We have no control over the source- but the physics are well understood

- Attenuation/distance effects high frequencies most

- High frequency phones systematically underestimate magnitude
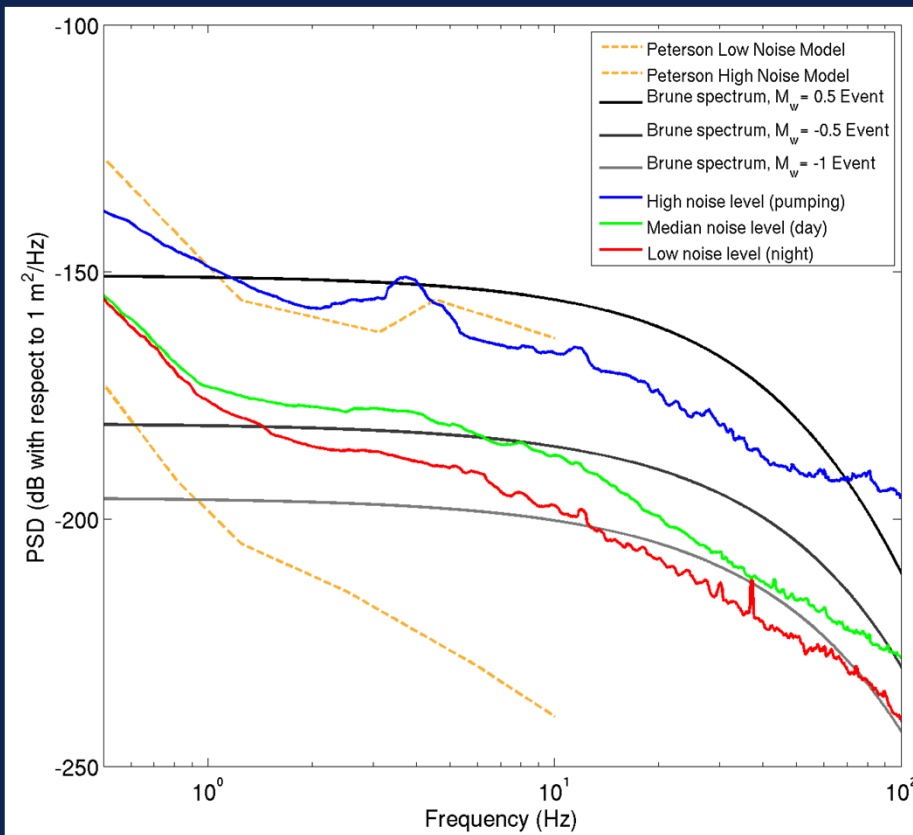
- b-values reported for stimulation may be biased

Angular roll-off change is corner frequency

12 dB/oct

Round roll-off due to attenuation
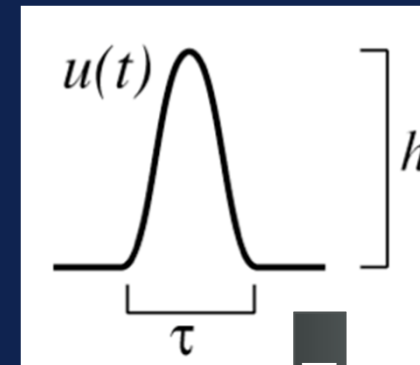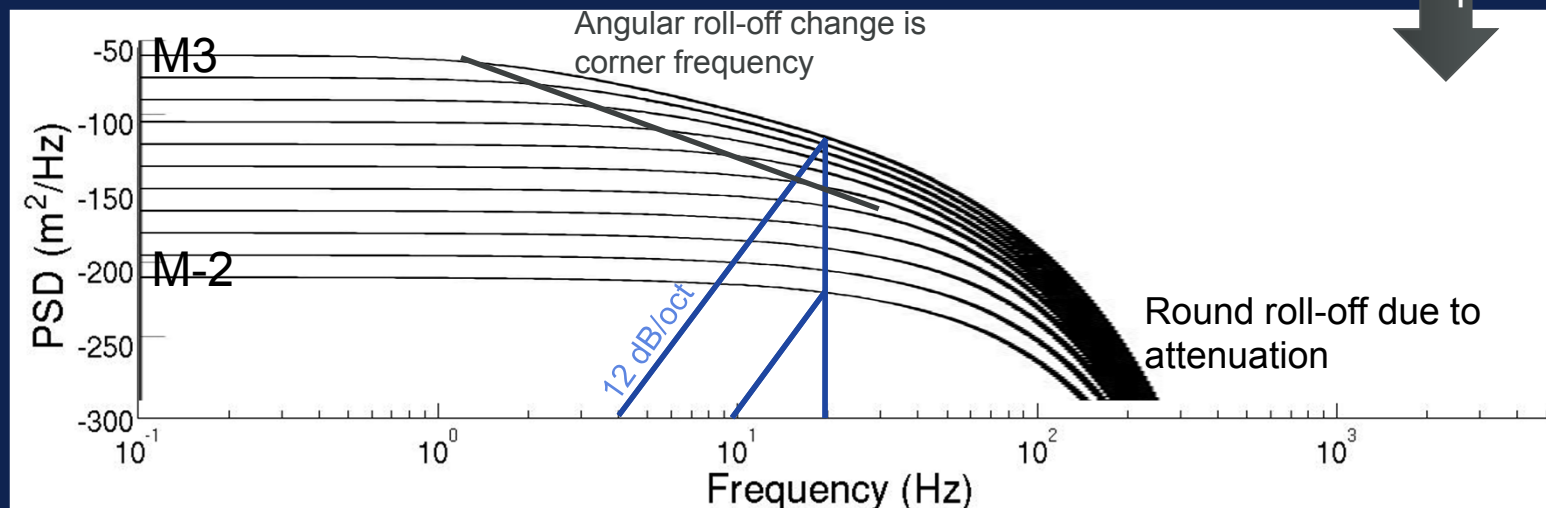
Industry database over last decade using high frequency phones may be saturated

Detection thresholds

Spectraseis

With only 7 petrophysical and field parameters we can compare field noise measurements to predicted and measured event spectra.

Finite displacement models have been validated as description of micro- & macro-seisms

Lessons from seismology

- − Geomechanics of fractures dictates failure mechanisms limited to slip and opening events.

- − Rock physics allows us to predict typical amplitude levels as a function of magnitude and distance.

- − These seismic wave fields are dominated by low frequencies and shear arrivals.

- − Broadband sensors required for complete detection and accurate characterization.
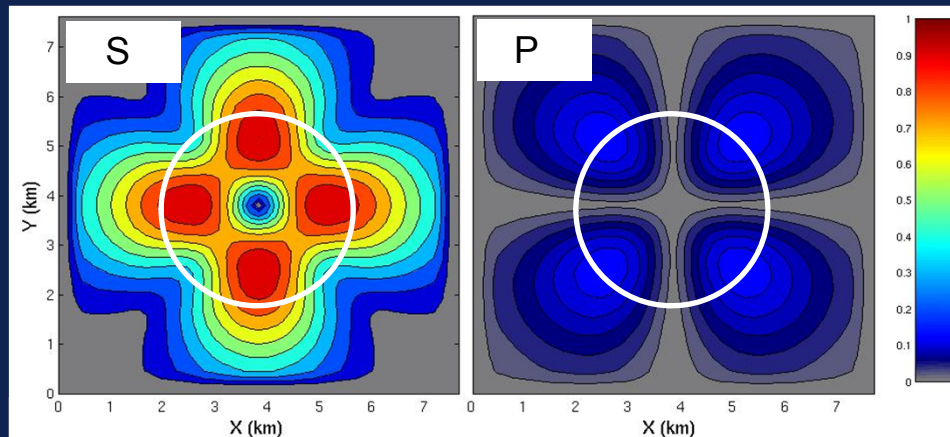
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Elastic modeling for survey design

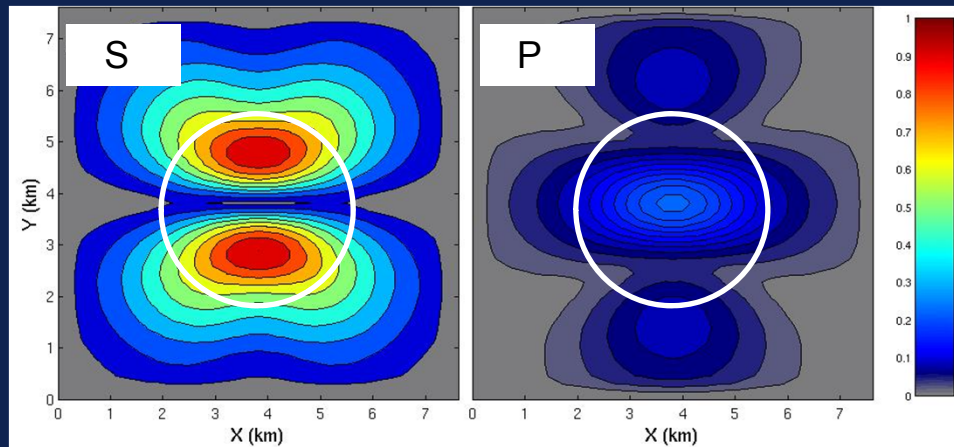Normalized RMS amplitude for all components

DC source

$$\begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Maximum amplitude within circle with radius
equal target depth

**Simple modeling of likely failures and locations define optimal aperture and sampling
requirements to fulfill the survey objectives**

Elastic modeling for survey design

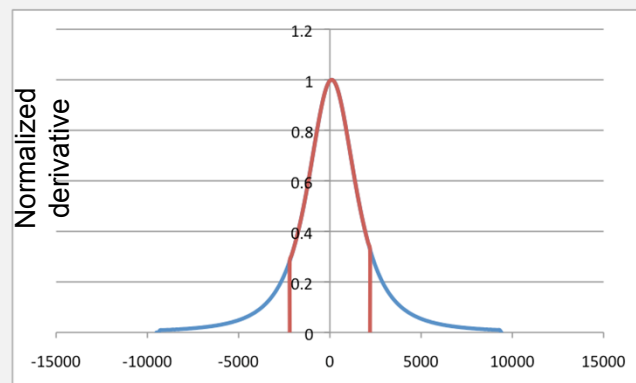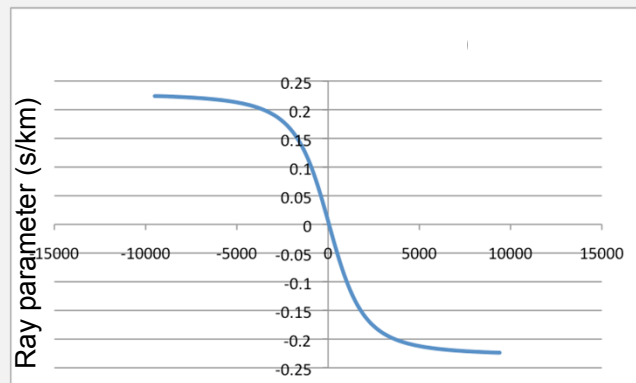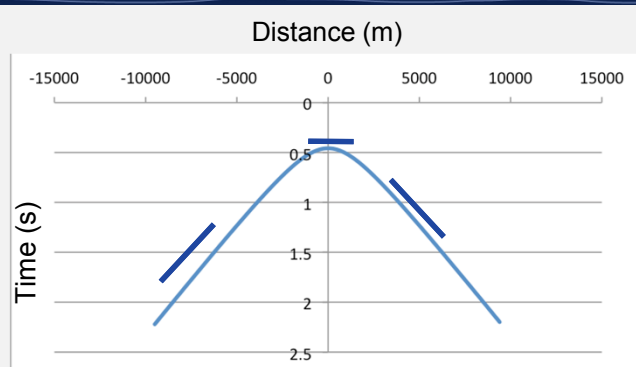Normalized RMS amplitude for all components

CLVD source

$$\begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Maximum amplitude within circle with radius equal target depth

Maximum amplitude at the surface slightly less than target depth away from epicenter

Sampling on a plane or line

Not sampling all the components of the arrival surface leads to systematic location errors.

The derivative of the hyperbola shows all the ray parameters sampled to far offsets.

The derivative of the ray parameters shows information content. By doubling the aperture for this project, we only sampled < 20% more ray parameters.
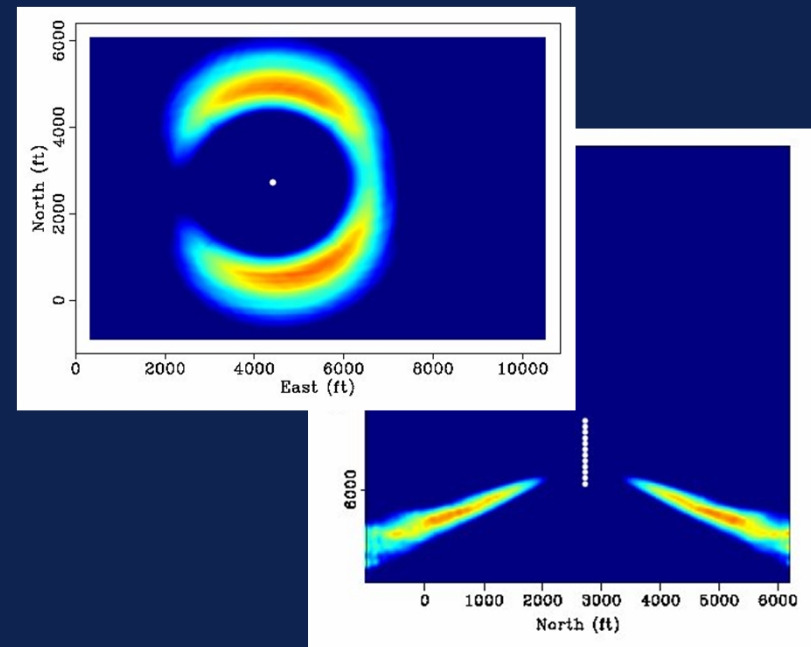
Little value of extra sensors near hyperbola asymptote

All arrays have an aliased response

A regular staggered grid has apparent triangular limb artifacts in its impulse response.
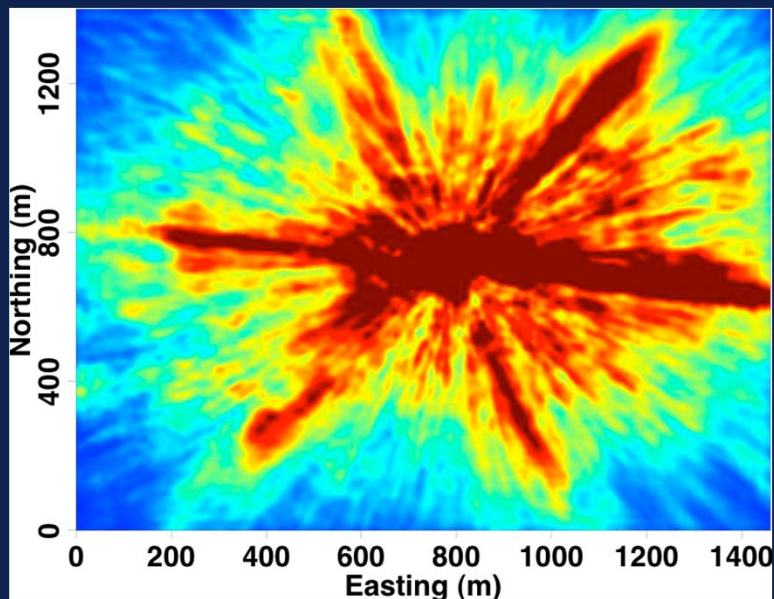
Linear borehole arrays have large azimuthal uncertainty because of the impulse response

All experiments are aliased to some degree, and this needs to be acknowledged in processing

Lessons

- Geometry controls information potential of a survey

- Forward modeling allows better survey design

- Appropriate aperture has kinematic and amplitude terms

- Lop-sided sampling of the hyperbola gives systematic error too close, and the direction pointing to the center of the array

- Constant station density in space maintains the same array response for all events

Survey design is our only variable under direct control

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Elastic waves

$$\rho\ddot{\mathbf{u}} - (\lambda + 2\mu)\nabla\nabla \cdot \mathbf{u} + \mu\nabla \times \nabla \times \mathbf{u} = \mathbf{d}(\mathbf{x}, t)$$

Single modes and rays

$$d = vt$$

Simplified physics makes processing fast when assumptions are valid

Why simplify?

$$\frac{\partial Sx}{\partial t} = (\lambda + 2\mu)\frac{\partial Vx}{\partial x} + \lambda\frac{\partial Vy}{\partial y} + \lambda\frac{\partial Vz}{\partial z}$$

$$\frac{\partial Sy}{\partial t} = (\lambda + 2\mu)\frac{\partial Vy}{\partial y} + \lambda\frac{\partial Vx}{\partial x} + \lambda\frac{\partial Vz}{\partial z}$$

$$\frac{\partial Sz}{\partial t} = (\lambda + 2\mu)\partial Vz\partial z + \lambda\frac{\partial Vy}{\partial y} + \lambda\frac{\partial Vx}{\partial x}$$

$$\frac{\partial Sxy}{\partial t} = \mu\left(\frac{\partial Vx}{\partial y} + \frac{\partial Vy}{\partial x}\right)$$

$$\frac{\partial Sxz}{\partial t} = \mu\left(\frac{\partial Vx}{\partial z} + \frac{\partial Vz}{\partial x}\right)$$

$$\frac{\partial Syz}{\partial t} = \mu\left(\frac{\partial Vz}{\partial y} + \frac{\partial Vy}{\partial z}\right)$$

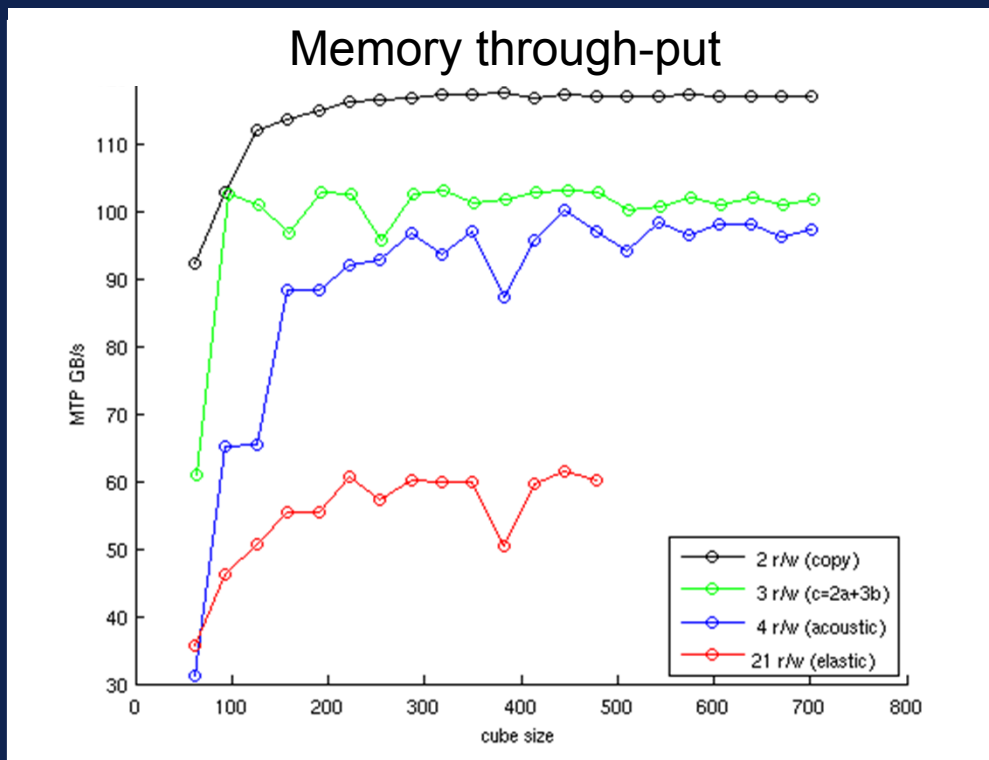$$\frac{\rho}{\partial Vx}\partial t = \frac{\partial Sx}{\partial x} + \frac{\partial Sxy}{\partial y} + \frac{\partial Sxz}{\partial z} - aVx$$

$$\frac{\rho}{\partial Vy}\partial t = \frac{\partial Sy}{\partial y} + \frac{\partial Sxy}{\partial x} + \frac{\partial Syz}{\partial z} - aVy$$

$$\frac{\rho}{\partial Vz}\partial t = \frac{\partial Sz}{\partial z} + \frac{\partial Sxz}{\partial x} + \frac{\partial Syz}{\partial y} - aVz$$

Elastic solution requires 165 flop's per location per time step and 13 wave fields in memory

GPU programming revolution

Memory through-put

Migration algorithms are 'memory bound' meaning few calculations performed at each point in a huge, independent domain.

Therefore, moving memory through the processor is the best test of optimal code.

GPU performance is very implementation dependent, but can be orders of magnitude faster than CPU codes.

In theory, runtime scaling should be 5.75x slower for elastic. Spectraseis is currently at 8.7x.

Spectraseis has implemented nearly optimal acoustic solvers. Elastic solvers are ½ as efficient.
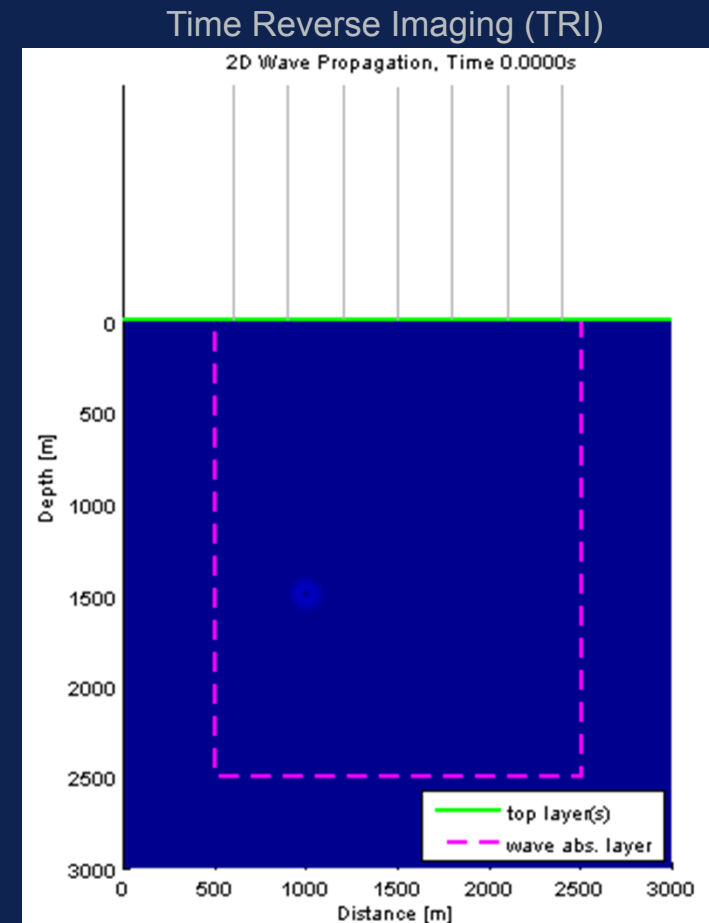
Wave-equation migration

Time-reverse imaging

Elastic wave equation propagation of time-reversed data.

- Artman et al., 2010 (Geo. Pros.)
- Witten and Artman, 2011 (Geophysics)
- Artman and Witten, 2011 (SEG

No picking. No rays.

- Make no assumptions about the source
- No pre-processing
- Properly account for multiples and radiation pattern
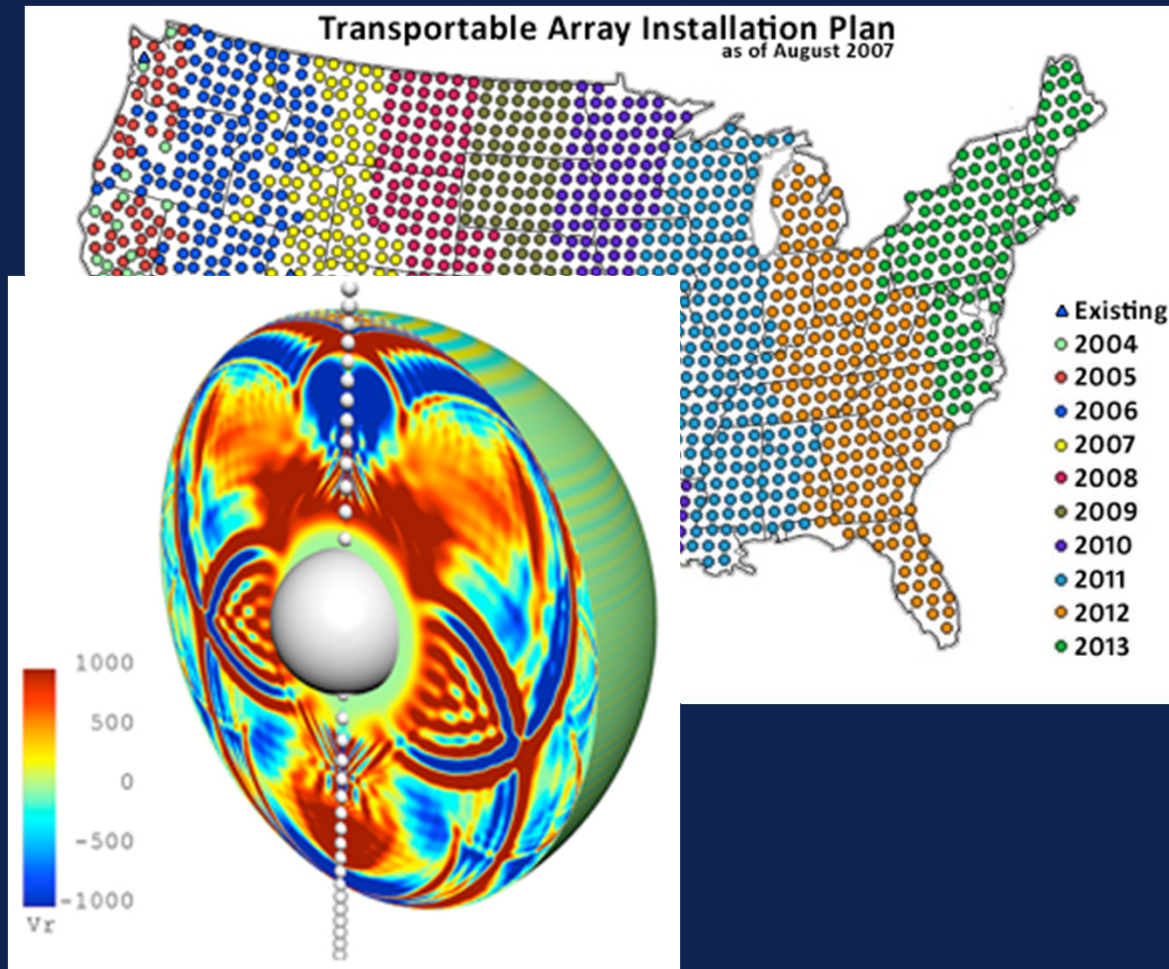- P & S waves focus at same location

Time Reverse Imaging (TRI)

Wave equation migration constructively focuses arrivals in the data

Lessons

- Faster computers are allowing continuous improvements in our ability to implement near-complete physics in our processing algorithms.

- More complete sampling of the wave field, by increasing the dimensionality of arrays, is increasing the information we can extract from measurements.

Survey design is our only variable under direct control

It goes the other way too

Transportable Array Installation Plan
as of August 2007

△ Existing
○ 2004
● 2005
● 2006
● 2007
● 2008
● 2009
● 2010
● 2011
● 2012
● 2013

The NSF has spent $287.5M on EarthScope in the last 5 years.

Prof. J. Tromp, Princeton Theoretical & Computational Seismology Group, awarded 100M core hours on Titan- the world's fastest supercomputer with 17.59 petaflops and over a quarter of a million NVIDIA K20x accelerator cores.

Sampling and compute power in seismology is increasing rapidly

Conclusions

- Microseismic monitoring is one of the few direct measures of what's (not) happening during a stimulation.

- The development of microseismic analysis, launched in the 80's, is still ongoing, but can capitalize on a rich history.

- The parameter space for these measurements is not large, so survey planning/modeling should not be avoided.

- We are no longer handicapped by fear of large data sets.

- We must use the right equipment and the best physics to maximize the potential for success.