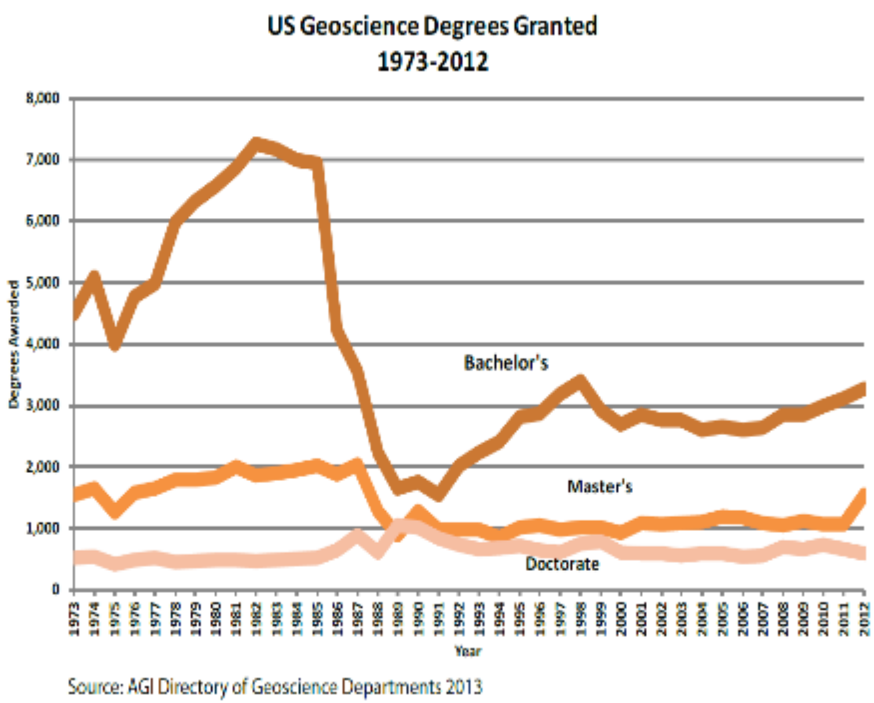
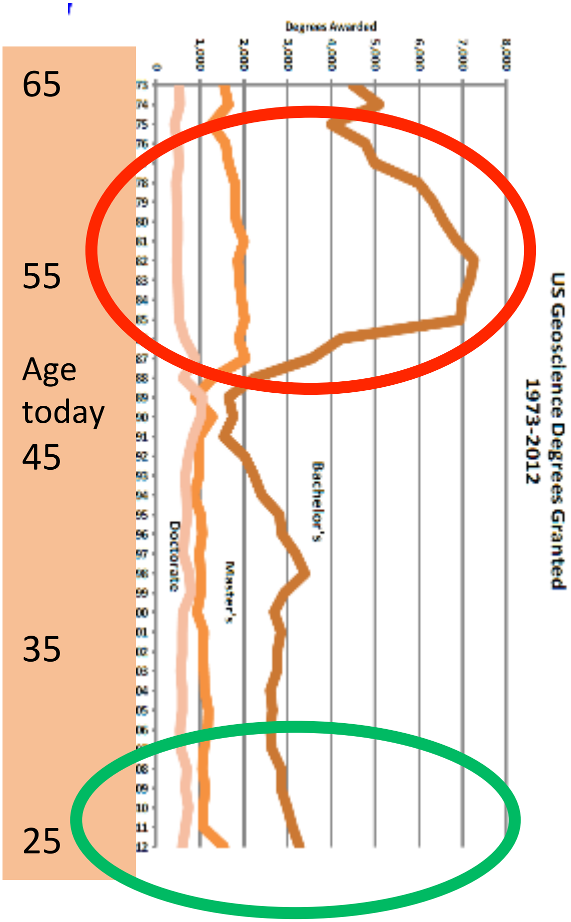
Just one more coffee, then we'll start

Geoscience graduations by year & graduates' current age

(Stewart, 2014, TLE)





Multicomponent seismic sensing: What else can it tell us?

Robert R. Stewart
Allied Geophysical Lab
University of Houston

June 3, 2014

Geophysical Society of Houston/IRIS
Active uses of passive seismic data

Multicomponent (3C and 4C) seismic is a superset of the conventional (1C) seismic method … Or multicomponent seismic contains all traditional seismic and much more!

Thus, there are many new challenges with beckoning rewards …

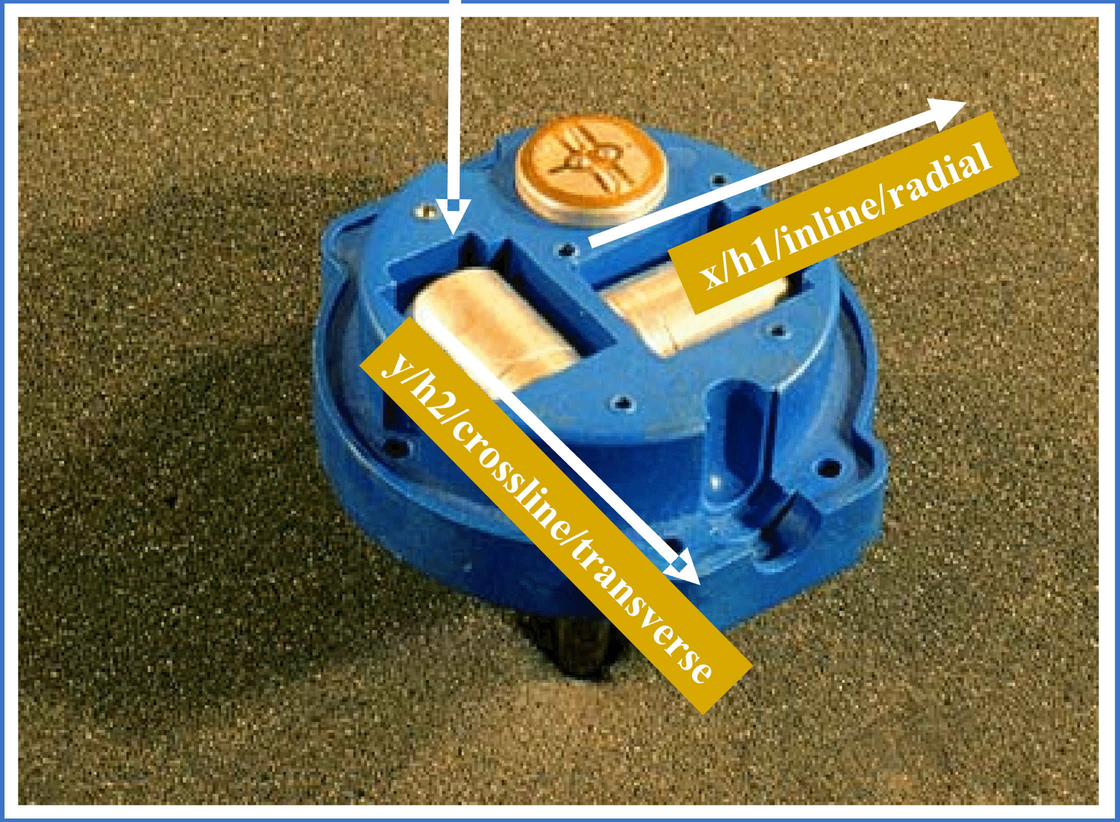
What can 3- or 4-component seismic recordings provide us?

- The complete seismic wavefield (P, S_i, R, L, …)
  - Fully capture P, multiples & multimodes
- Enhanced noise characterization & removal
- Better images & estimations of lithology, density, porosity, fractures
- Improved source location & type > Reservoir volumes
- Full wavefield inversion (doing elastic modeling anyway …)

3-C geophones (coil/analogue, MEMS/digital)

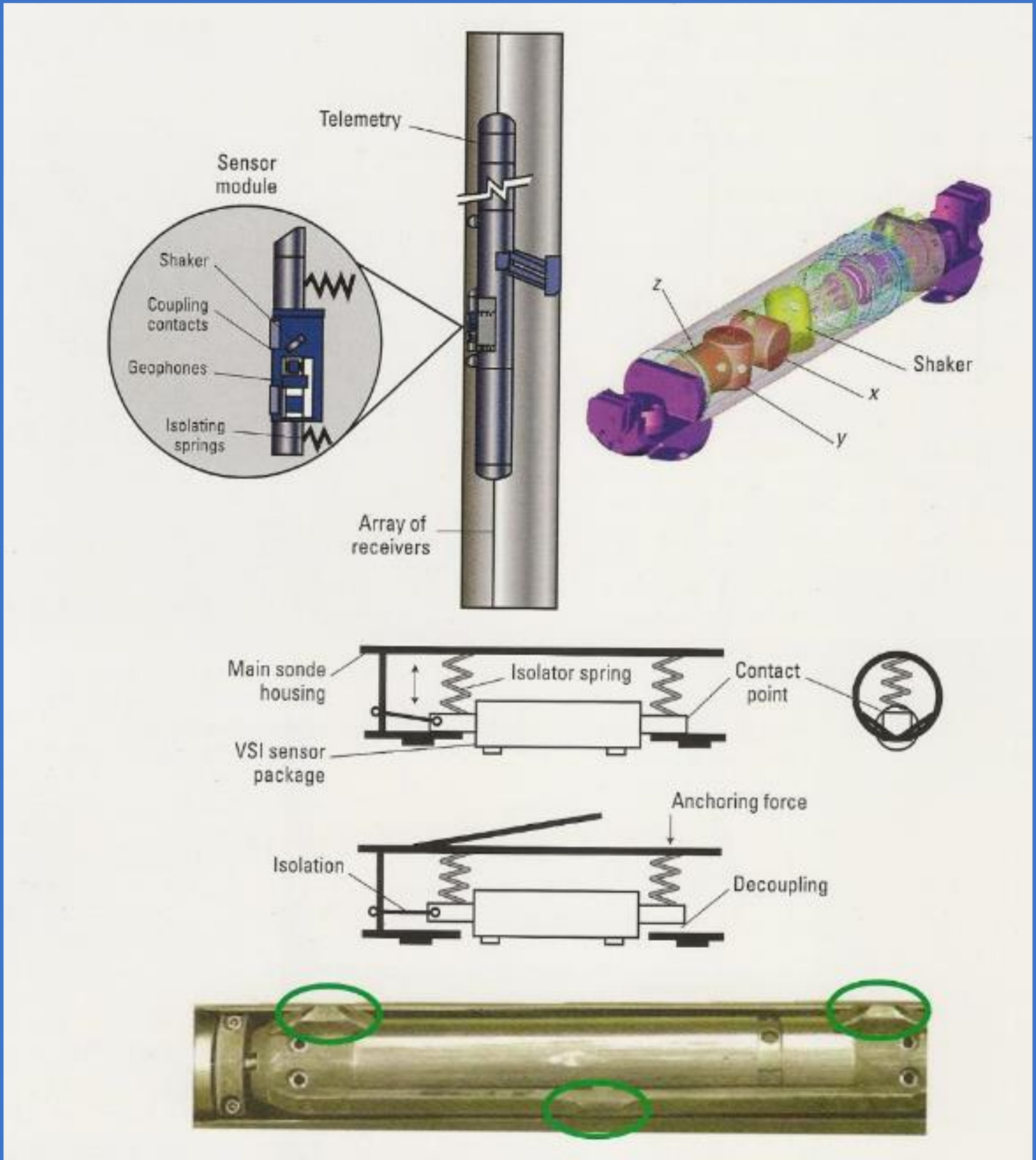
INOVA's VectorSeis ML-21 3C sensor

Sercel's DSU3 428 system

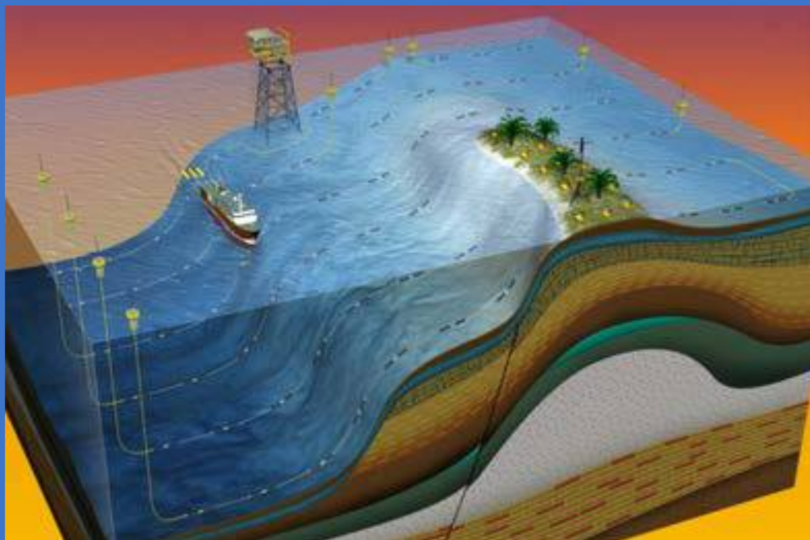


Sensor package

(VSI - Schlumberger, 2010)



Ocean-bottom cables



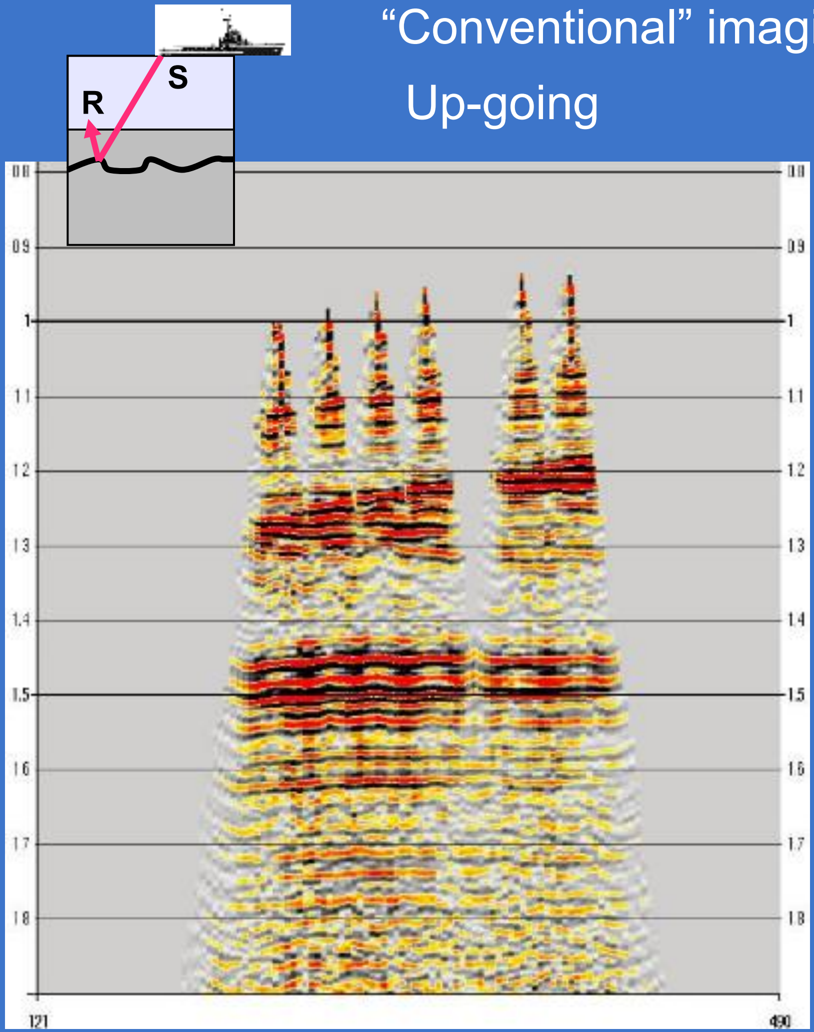
ION Vectorseis Ocean II

Sercel's SeaRay cable

Using other wavetypes: Mirror imaging with multiples

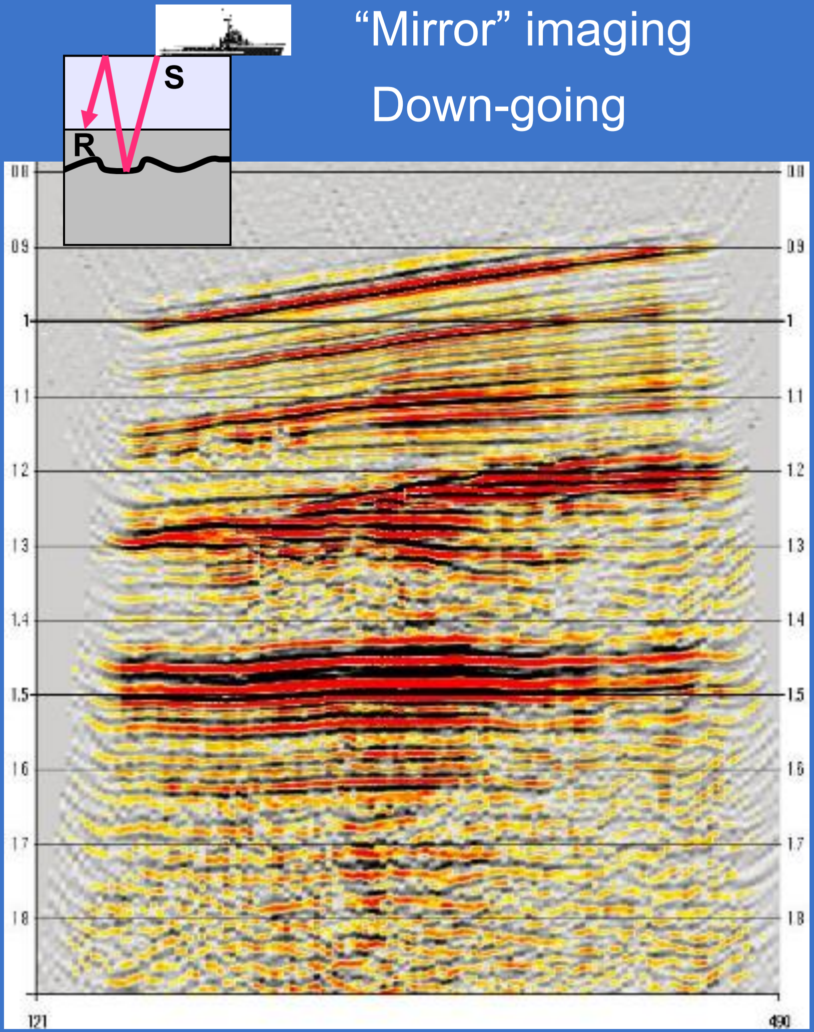
“Conventional” imaging

Up-going

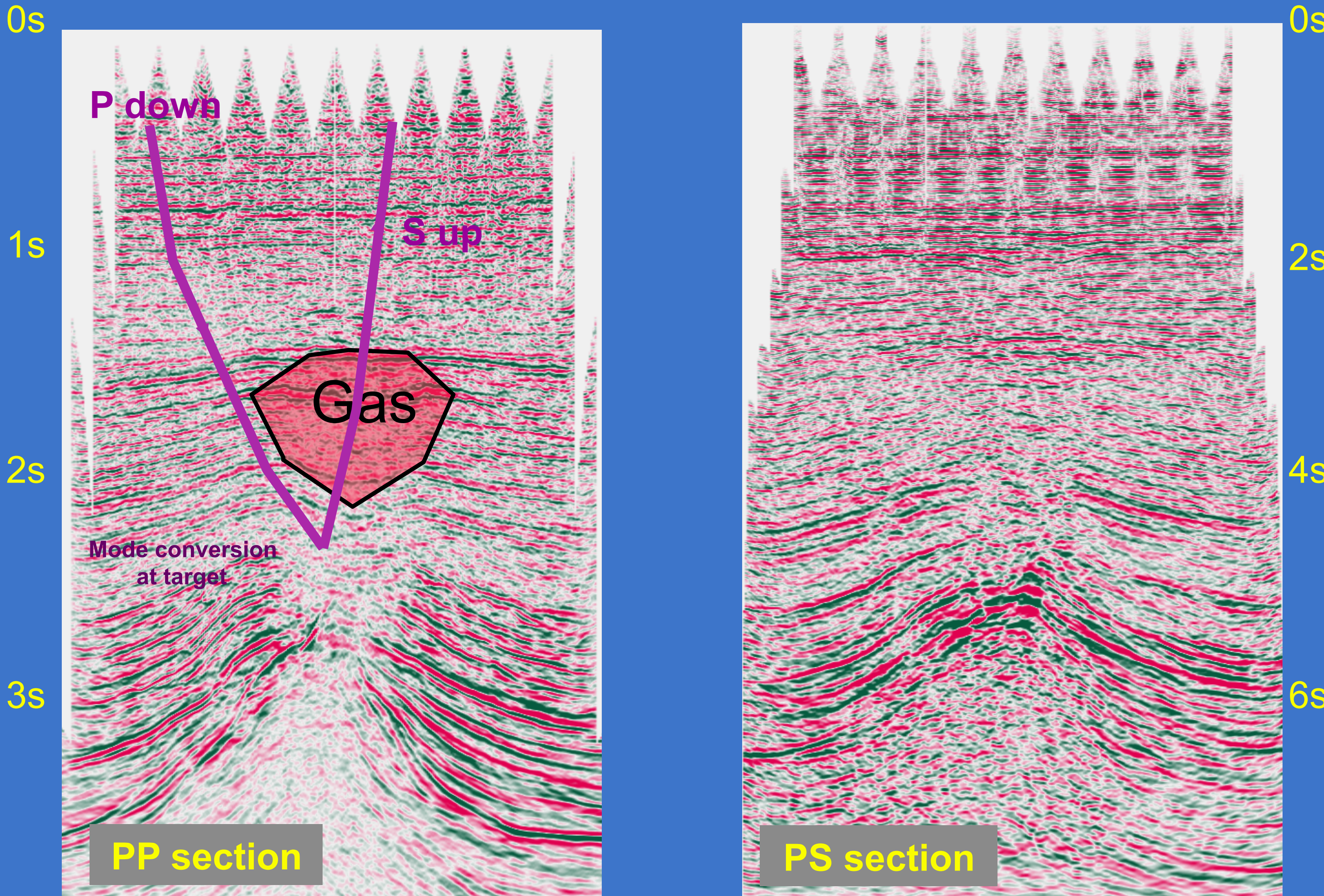


“Mirror” imaging

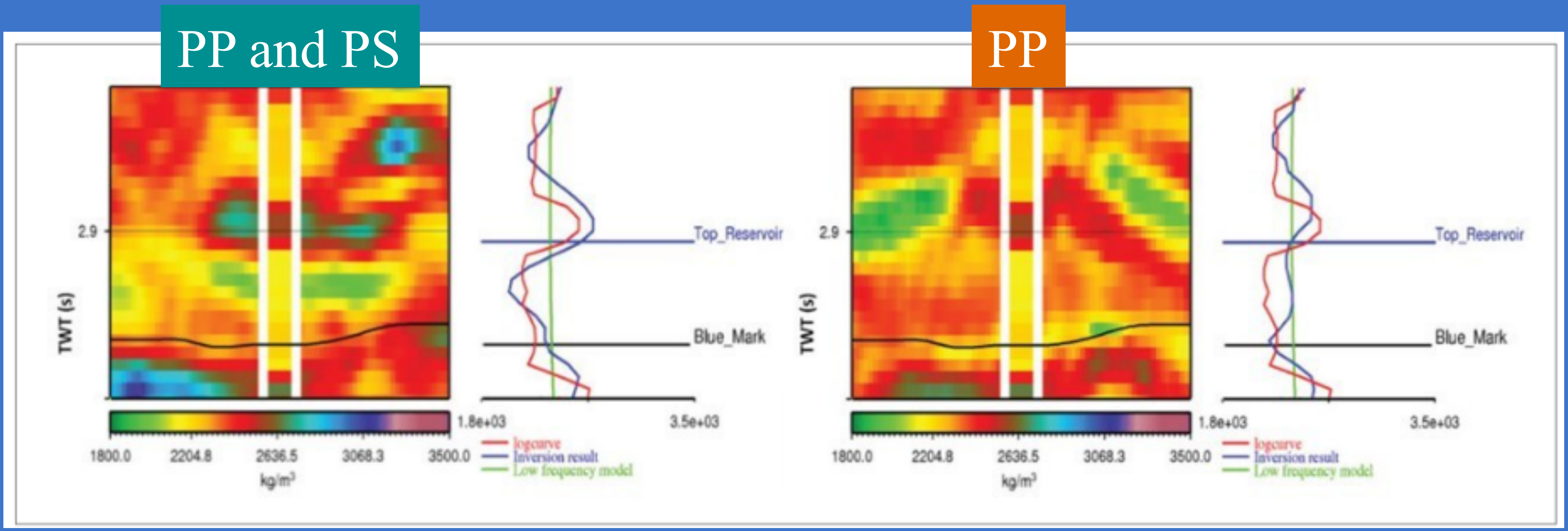
Down-going



4C seismic imaging (PP and PS): Lomond Field, N. Sea (Gaiser & WesternGeco)

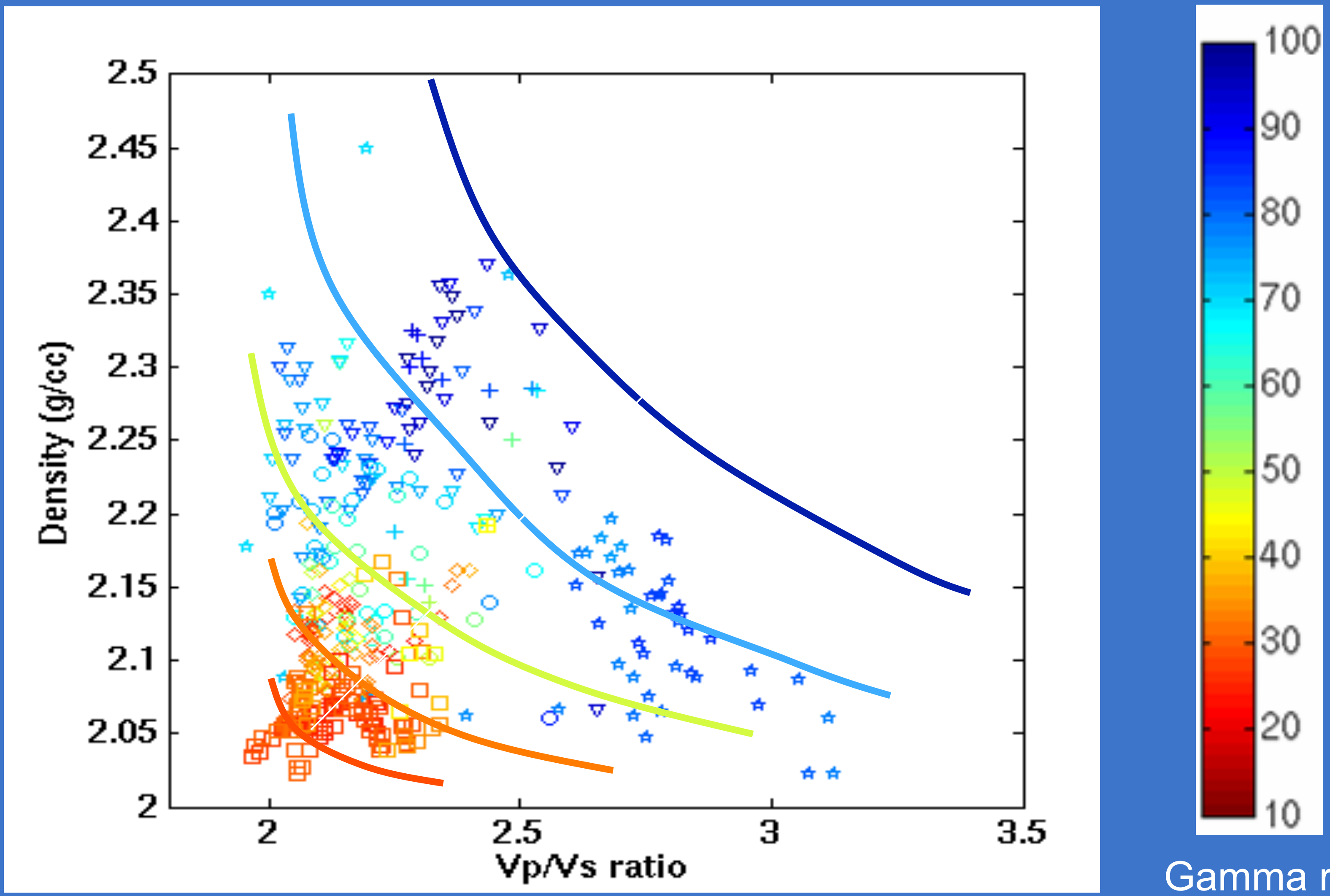


Leiceaga et al. (2010) – Improved density estimation via inversion of PP and PS data in a clastic section, Albacora field, offshore Brazil



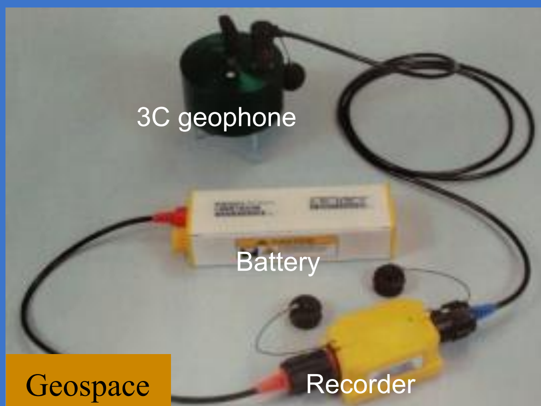
Vp/Vs vs density

Meadow Creek oil sands (Xu, 2007)



Two key sensing advancements!

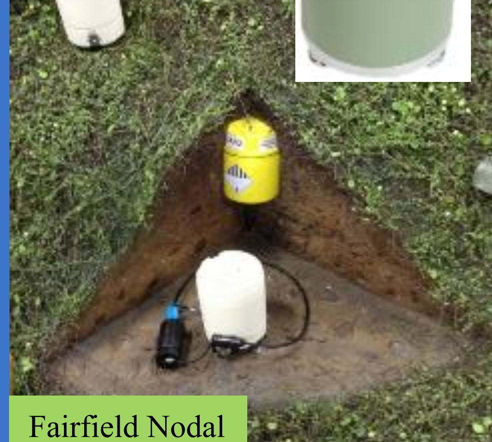
- Nodes (autonomous)



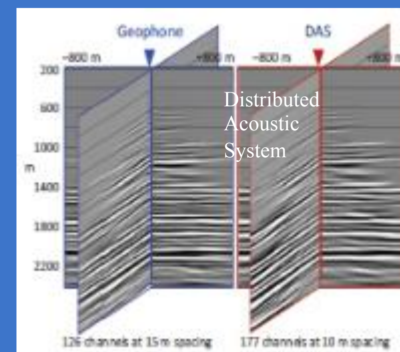
- 1 to 4C
- GPS
- No or little cabling

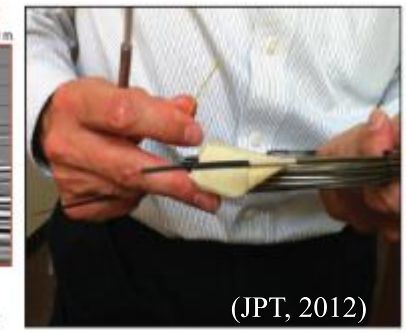
~ Month recording

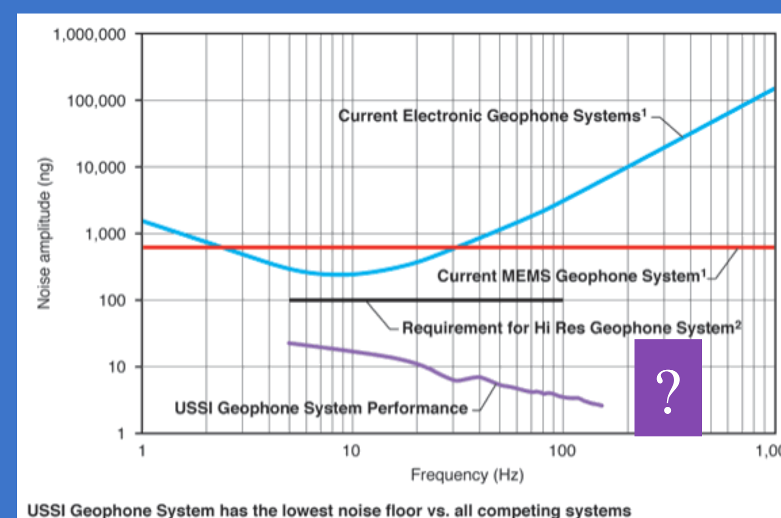
~ Wireless download



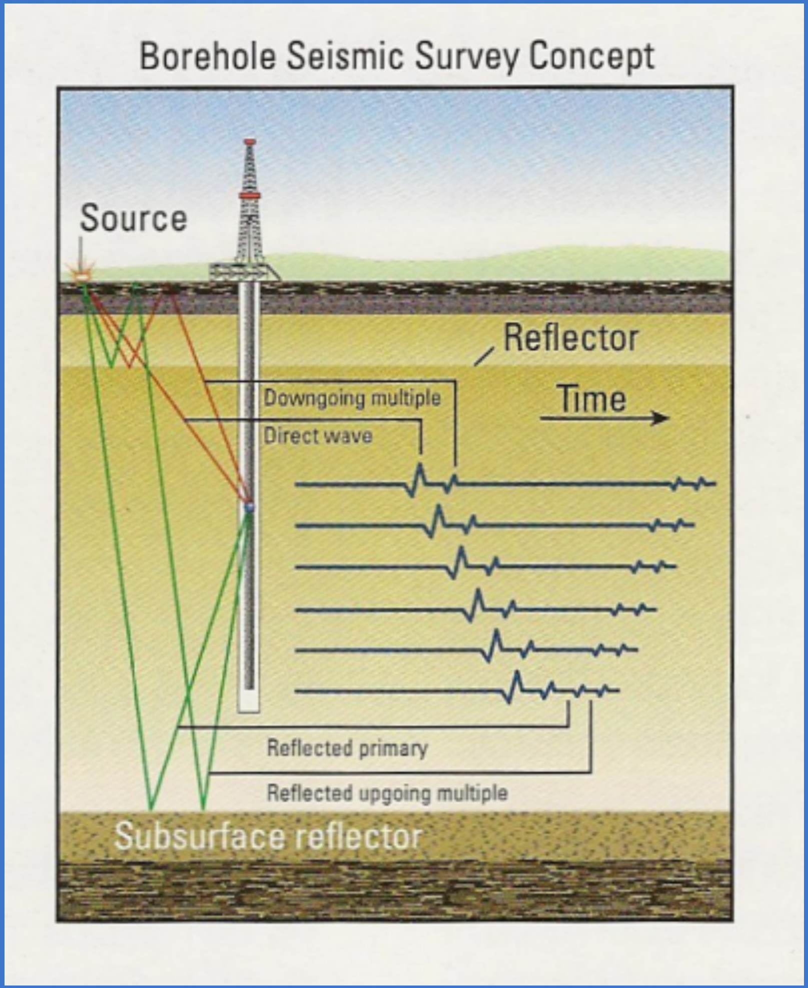
- Fibre-optics (axial)

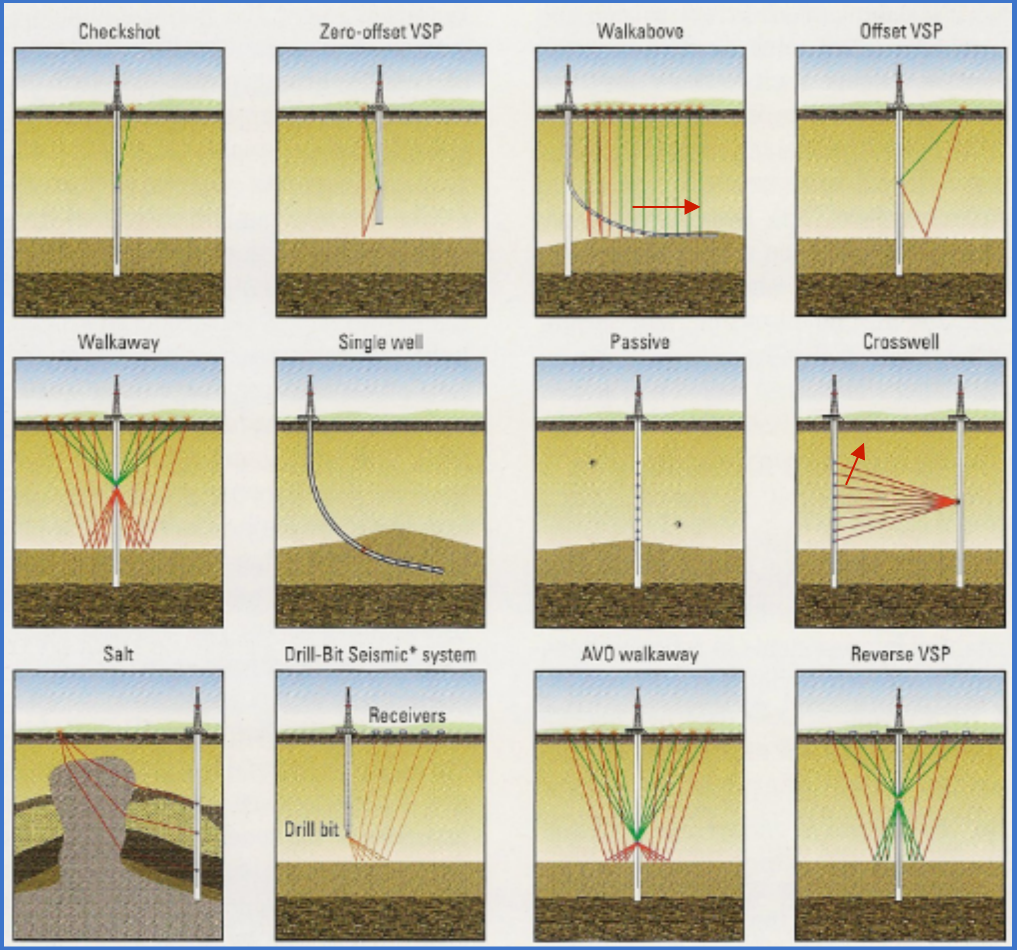


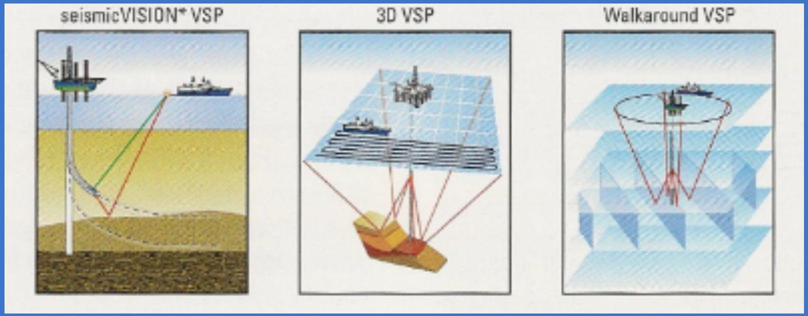




DAS sensitivity: Borehole seismic survey geometries & terminology







(Schlumberger, 2011)

Experiment No: 1

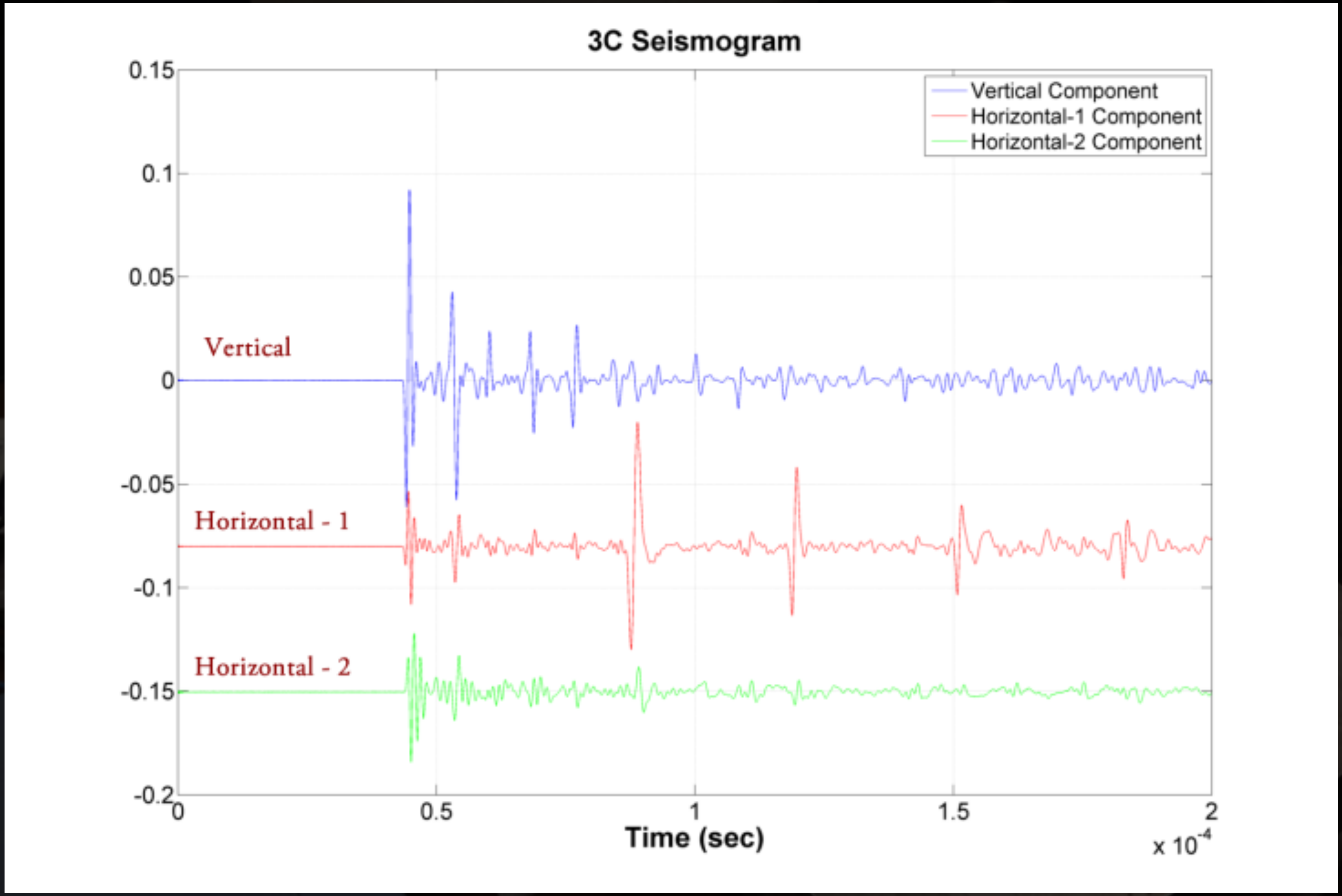
Plexiglas and Aluminum

- 2-layers (Plexiglas and Aluminum)
- 21 receivers: 17 surface, 4 well side
- Source placed underneath the block

Experiment No: 2

Real Rock: Sandstone

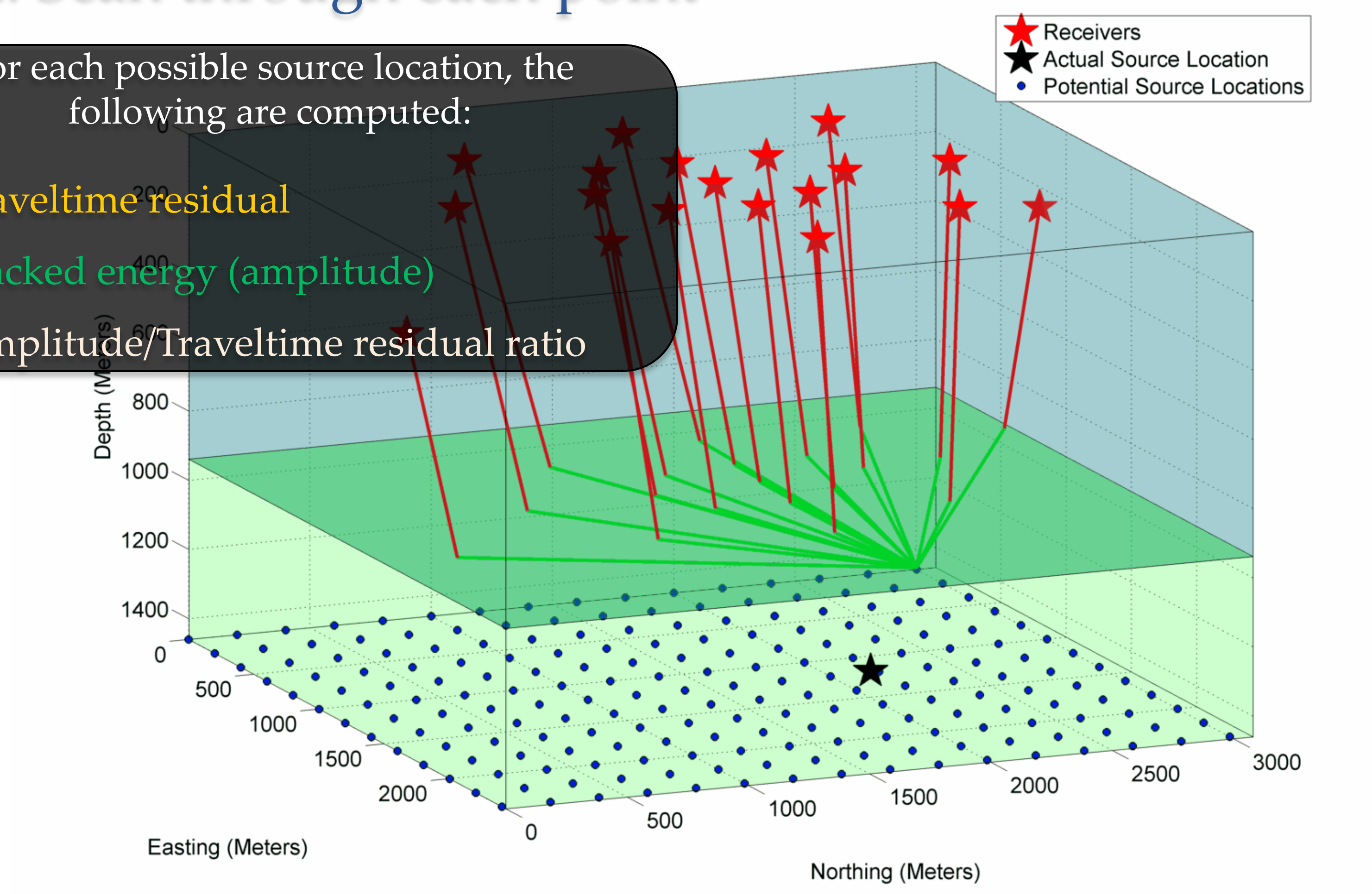
- 1-layer sandstone real rock
- 62 receivers: 54 surface, 8 well-side
- Source placed underneath the rock


3C Seismogram
Vertical Component
Horizontal-1 Component
Horizontal-2 Component
Vertical
Horizontal - 1
Horizontal - 2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
0.5
1
1.5
2
Time (sec)
x 10^-4

Step 2: Scan through each point

For each possible source location, the following are computed:

- Traveltime residual
- Stacked energy (amplitude)
- Amplitude/Traveltime residual ratio



Experimental Results

Approach	Relative Error (%)
P-wave & All Receivers	0.80
P-wave & Only Surface	1.15

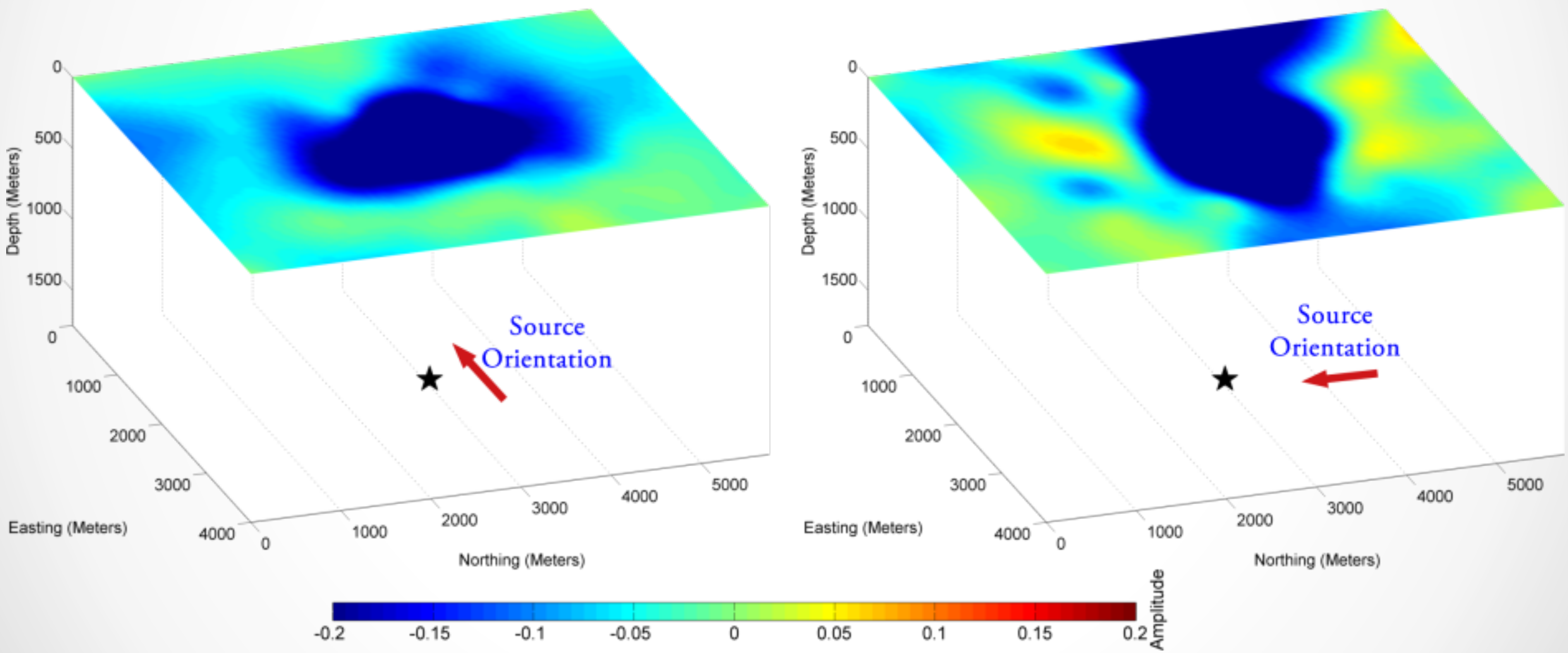
Approach	Relative Error (%)
S-wave & All Receivers	0.83
S-wave & Only Surface	0.94

Approach	Relative Error (%)
P and S-waves & All Receivers	0.58
P and S-waves & Only Surface	0.75

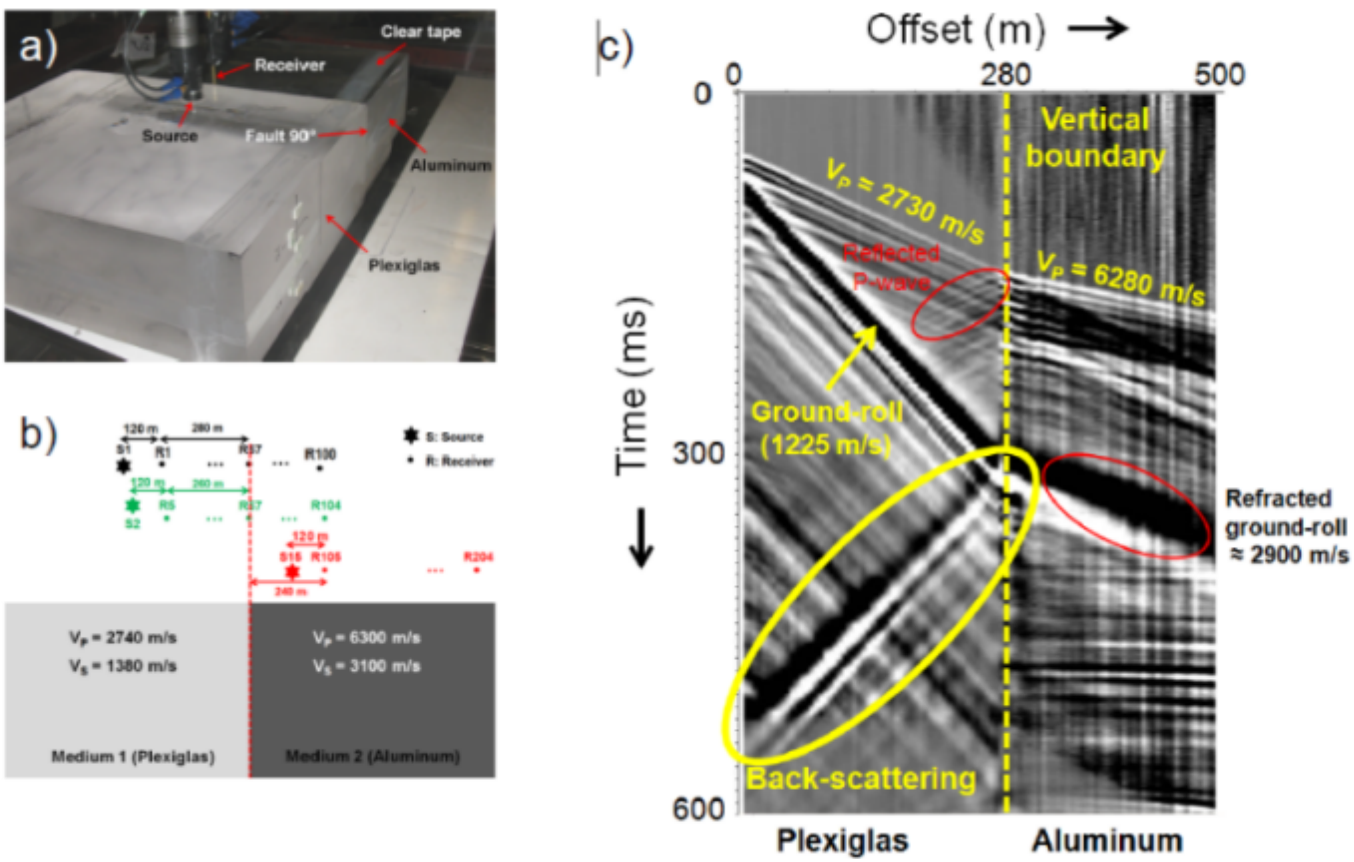
S-Wave Radiation Pattern Contour Map

Test 1: Source parallel to y-Axis

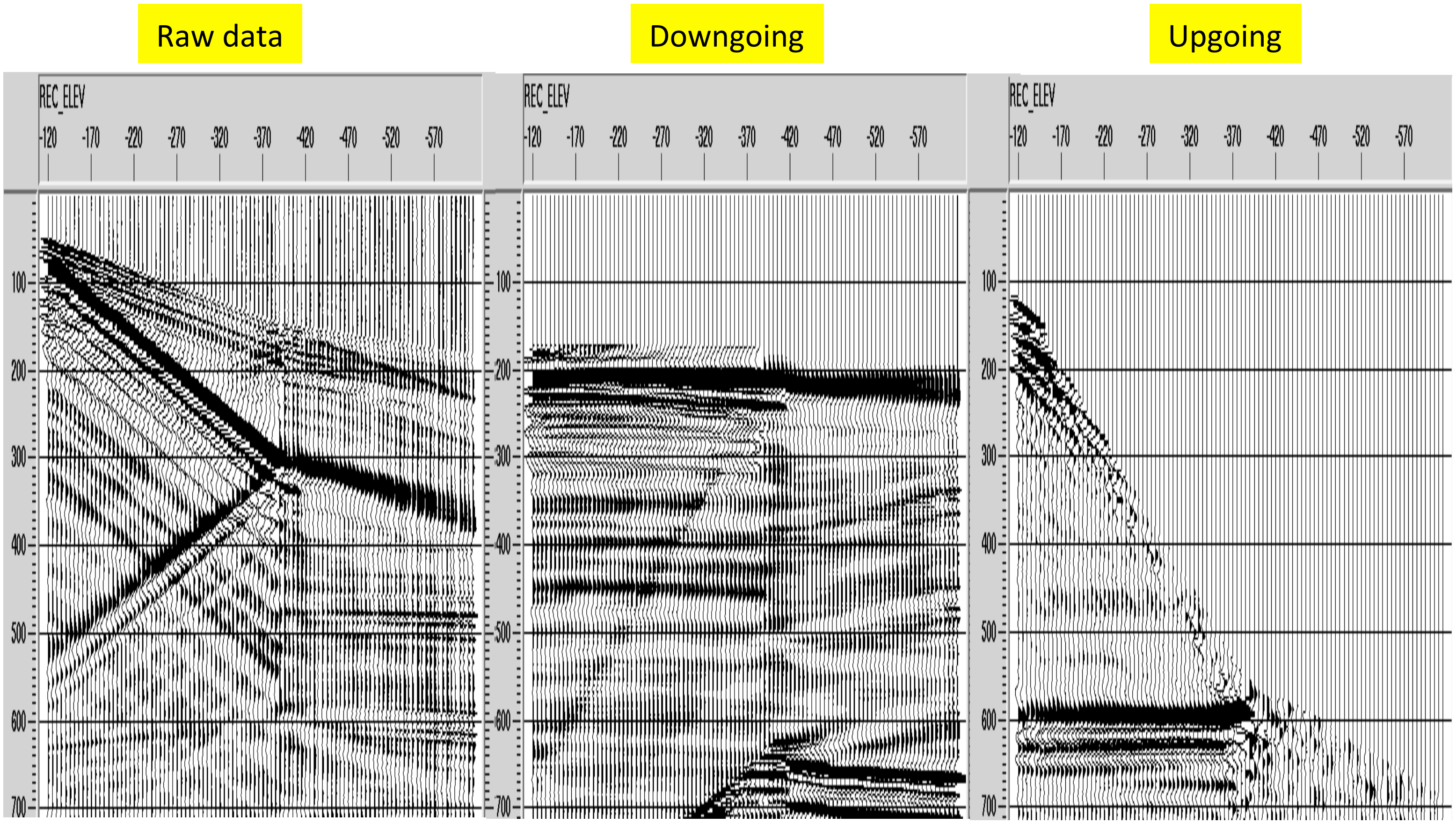
Test 2: Source parallel to x-Axis



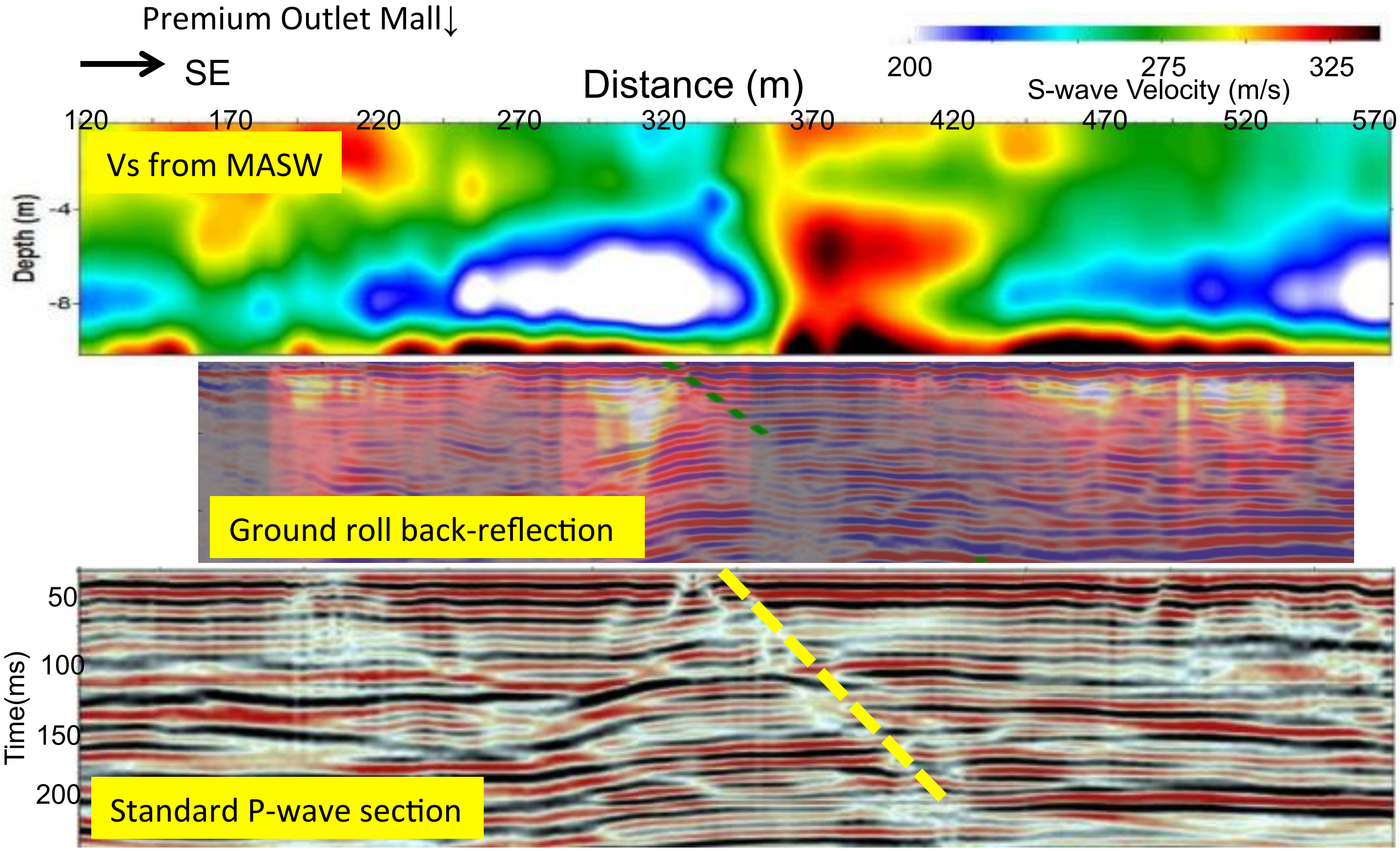
Using elastic waves:
Understanding & processing ground roll reflections



Processing ground roll as a VSP



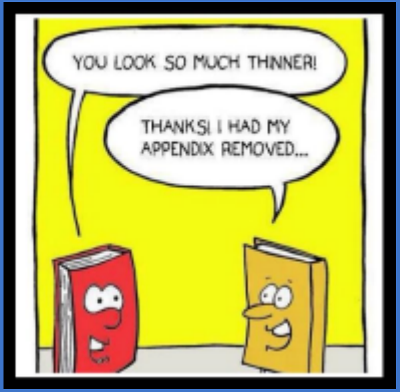
Hockley Fault: S-wave Velocities



Roy et al., 2013 Chang et al., 2013 Hyslop & Stewart, 2014

Summary

- Multicomponent seismic method includes all conventional seismic
- Improved imaging and lithology with 3C/4C
- Nodes and DAS provide great promise for elastic waves
- Including 3C/4C analysis can assist passive applications



Thank you for your interest…

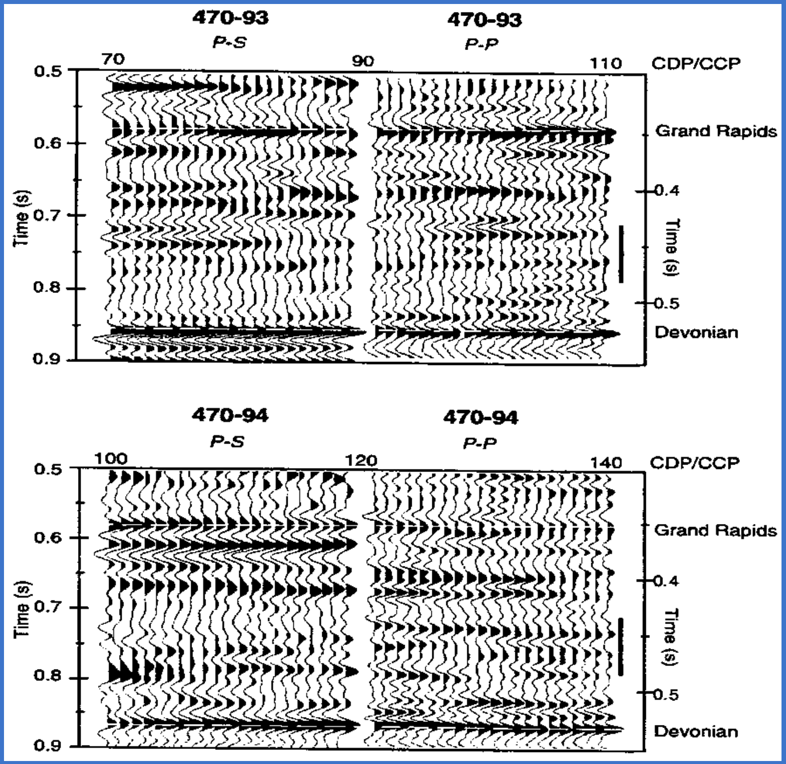
…the End

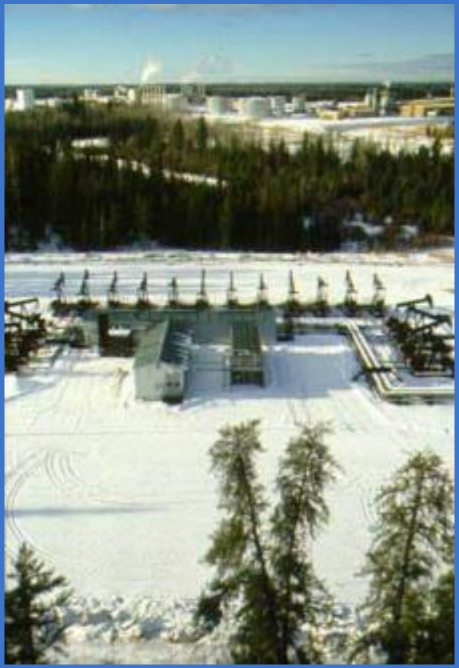
Much gratitude to AGL, CREWES, J. Gaiser, & P. Cary for their expertise and material!

Limitations, issues, & problems to solve

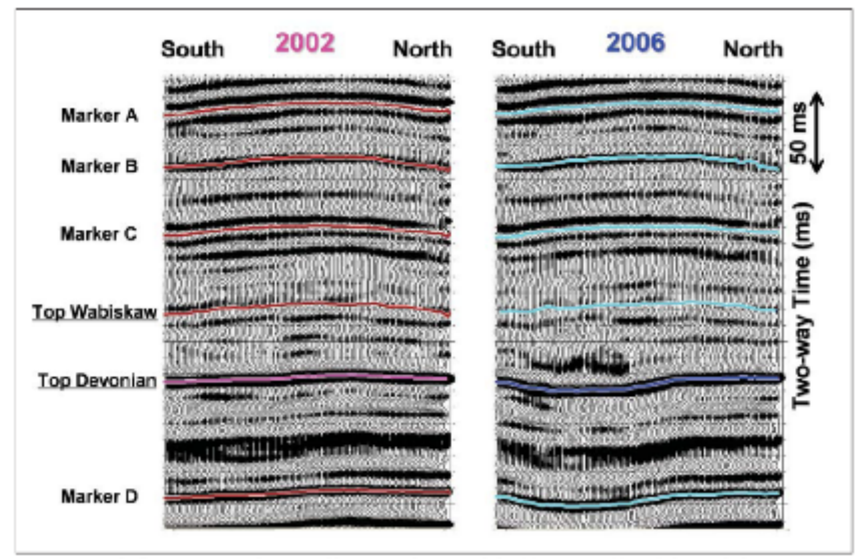
- Expense (newer & more equipment, more channels; longer & more detailed processing)
- Expertise (complex processing, more sophisticated interpretation)
- Technical matters (lower frequency content, more noise, anisotropic effects)

Cold Lake, Alberta time-lapse 3C-2D survey after heating
(Isaac, 1996)





Time-lapse P-wave seismic Fort McMurray oil sands (Kato et al., 2008, TLE)



Concept of 3D time-lapse PP & PS inversion

- **P-P time lapse data**

$$\begin{bmatrix} d_{PP02} \\ d_{PP06} \end{bmatrix} = \begin{bmatrix} A_{\alpha 1} & A_{\beta 1} & A_{\rho 1} & 0 & 0 & 0 \\ A_{\alpha 2} & A_{\beta 2} & A_{\rho 2} & A_{\alpha 2} & A_{\beta 2} & A_{\rho 2} \end{bmatrix} \begin{bmatrix} L_\alpha \\ L_\beta \\ L_\rho \\ \Delta L_\alpha \\ \Delta L_\beta \\ \Delta L_\rho \end{bmatrix}$$

$$R_{PP} = A_\alpha(\theta)L_\alpha + A_\beta(\theta)L_\beta + A_\rho(\theta)L_\rho$$
$$R_{PS} = B_\beta(\theta)L_\beta + B_\rho(\theta)L_\rho$$

- **When P-S data is available**

$$\begin{bmatrix} d_{PP02} \\ d_{PP06} \\ d_{PS06} \end{bmatrix} = \begin{bmatrix} A_{\alpha 1} & A_{\beta 1} & A_{\rho 1} & 0 & 0 & 0 \\ A_{\alpha 2} & A_{\beta 2} & A_{\rho 2} & A_{\alpha 2} & A_{\beta 2} & A_{\rho 2} \\ 0 & B_{\beta 2} & B_{\rho 2} & 0 & B_{\beta 2} & B_{\rho 2} \end{bmatrix} \begin{bmatrix} L_\alpha \\ L_\beta \\ L_\rho \\ \Delta L_\alpha \\ \Delta L_\beta \\ \Delta L_\rho \end{bmatrix}$$

Observation Data

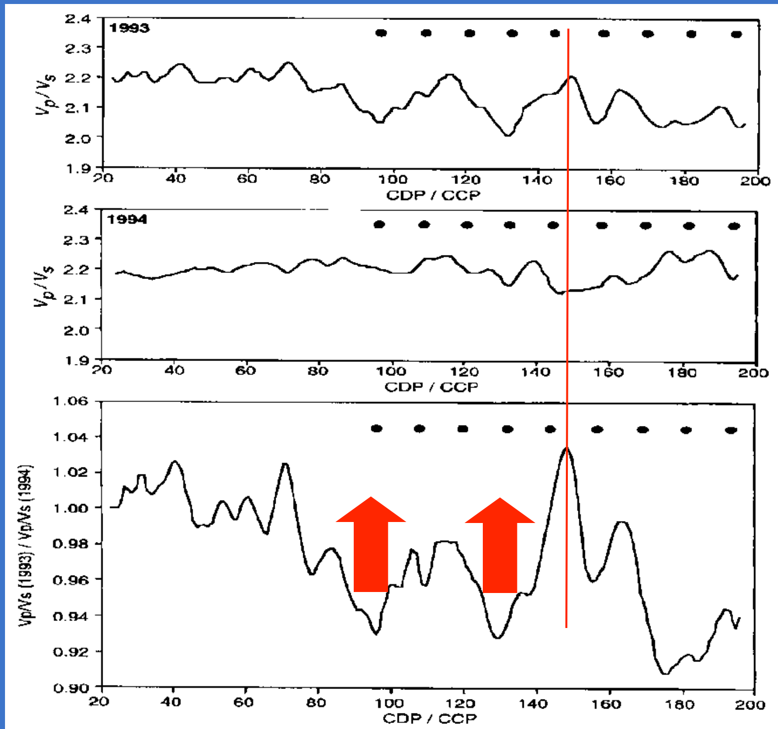
Forward Modeling Operator

Model Parameters

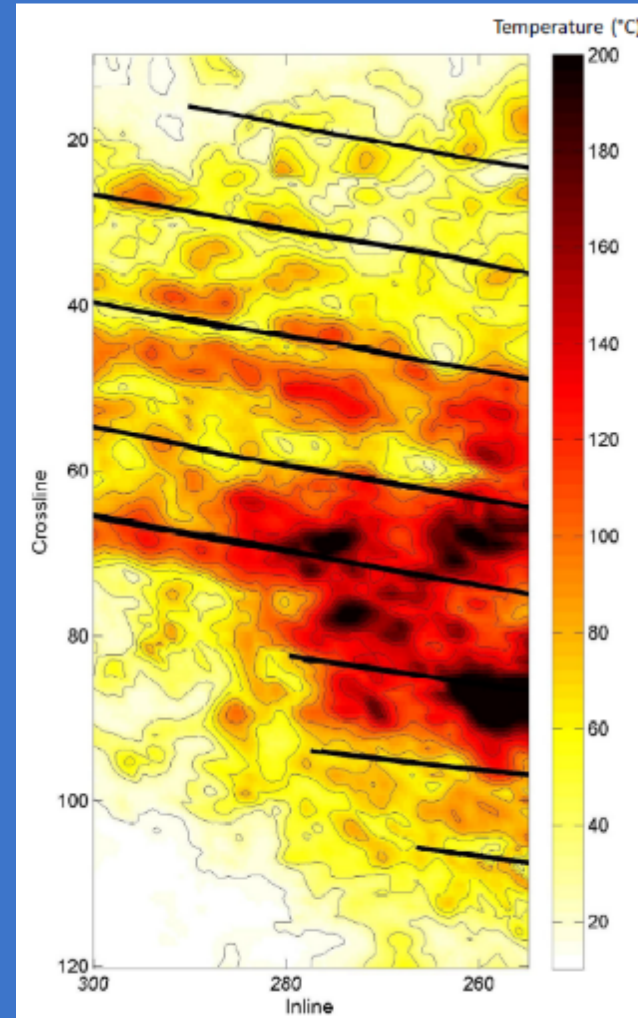
Linear system

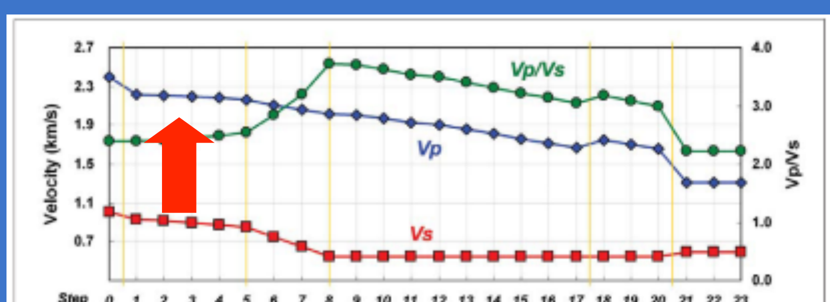
d = Gm

This process is repeated at each time step for angle-dependent amplitude data



Time-lapse 3C-2D results: Cold Lake, AB (Isaacs,1996)



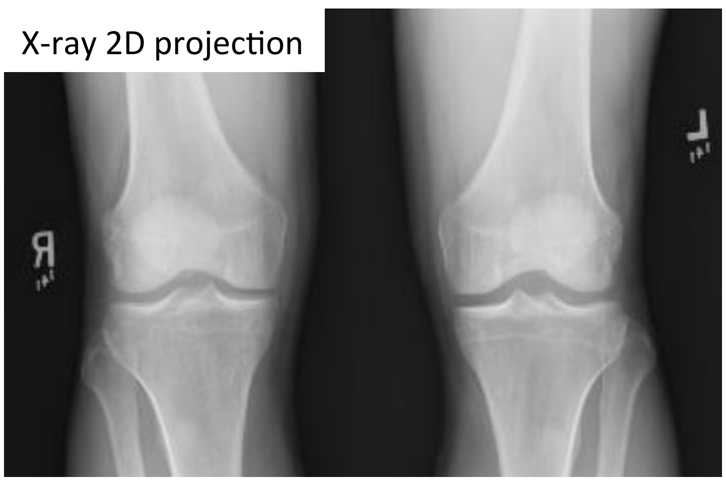


Step	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Pp (psi)	300	300	400	500	600	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700
T (°C)	10	10	10	10	10	10	15	20	25	30	50	70	80	100	120	140	160	180	200	220	240	260	280	300
Sw (%)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	80	80	80	80	80	80

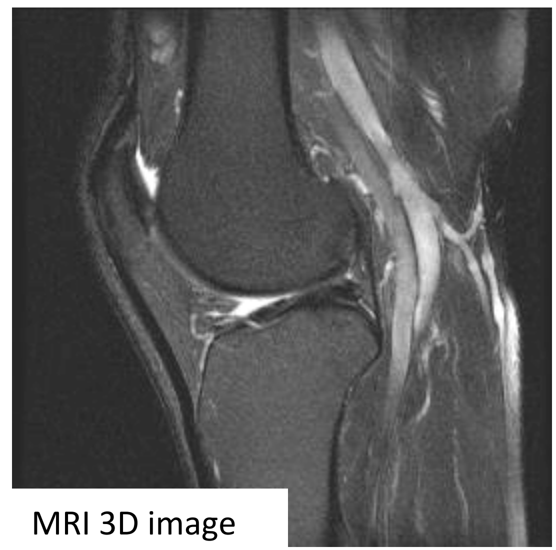
Lab & field (3C-4D inversion) results – Fort McMurray oil sands
(Kato et al., 2008; Kato & Stewart, 2011)

The Role of More Complete Imaging

Would you have knee surgery without multicomponent medical imaging?

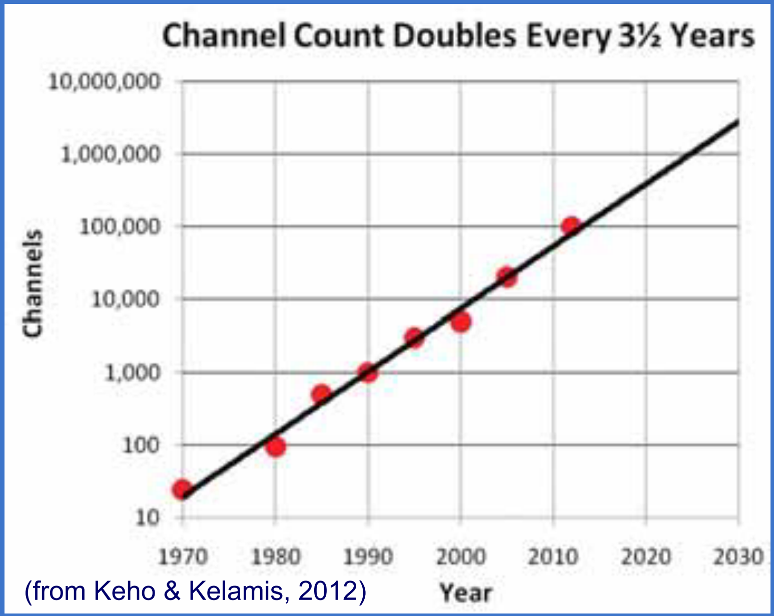


X-ray 2D projection

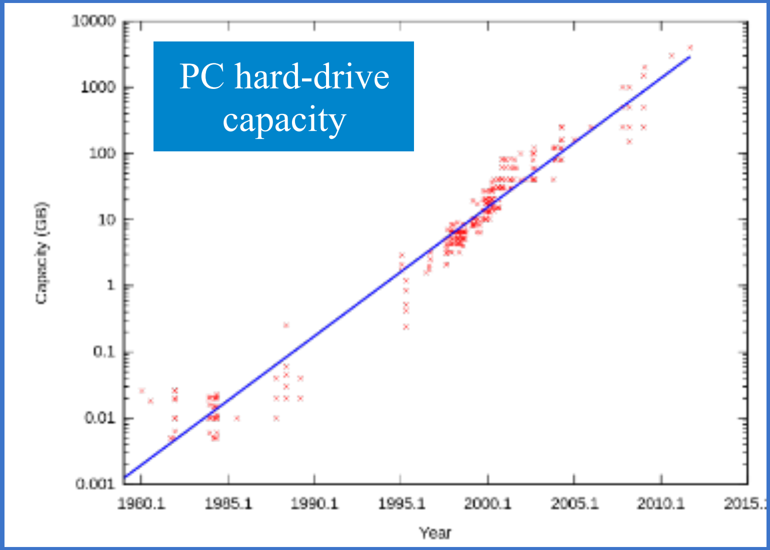


MRI 3D image

Advances in acquisition & processing



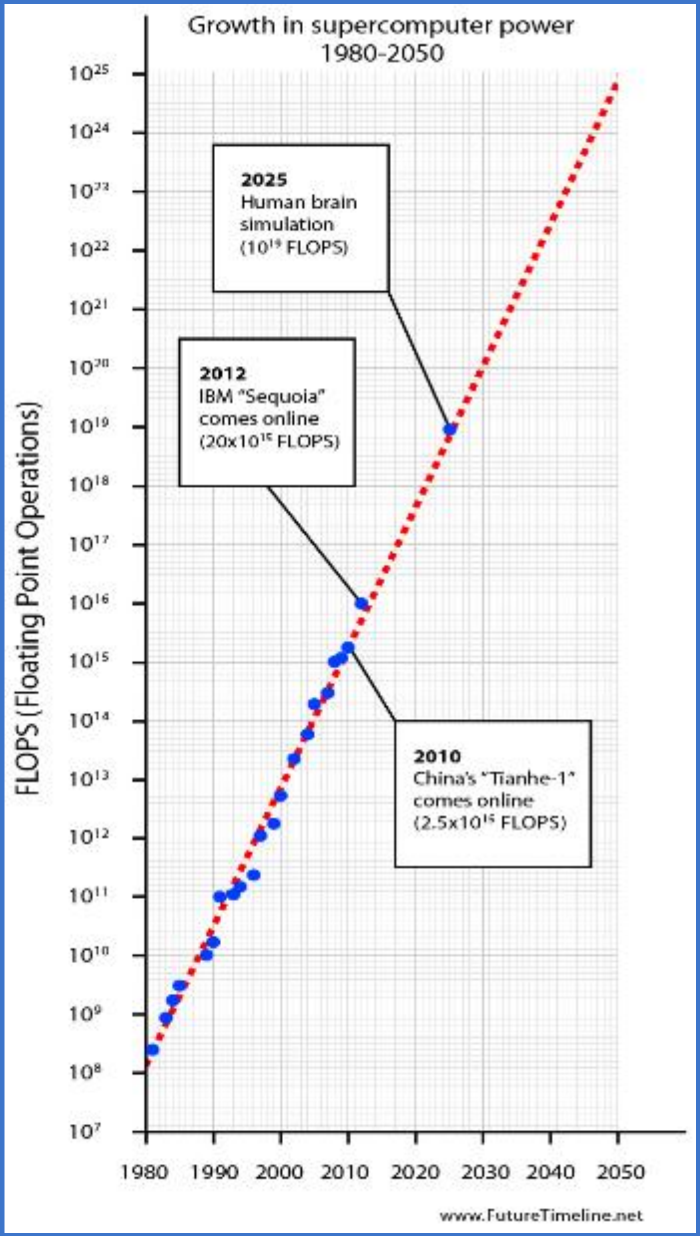
(from Keho & Kelamis, 2012)



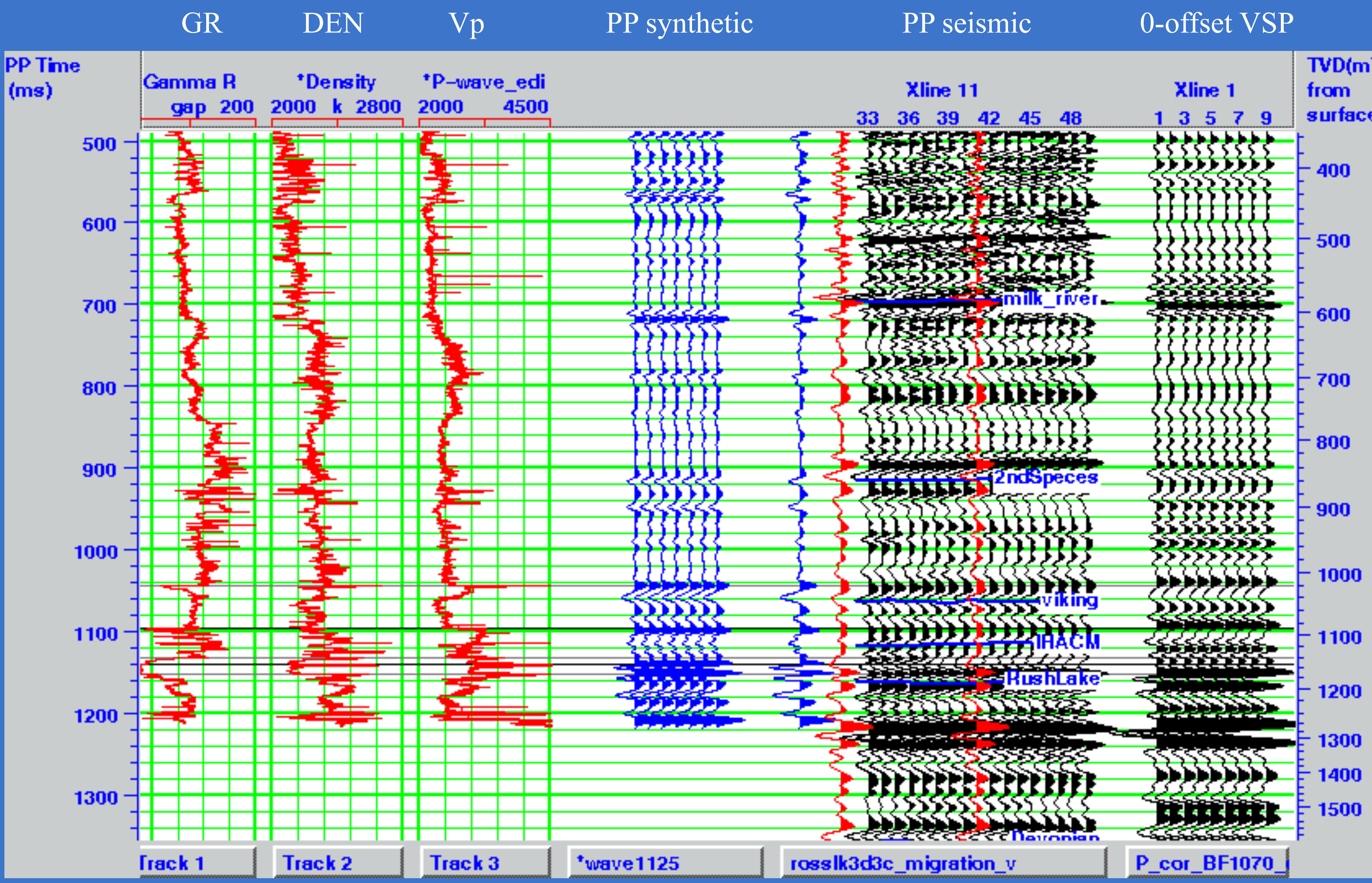
Huge opportunities to solve problems!

New types of acquisition & algorithms required.

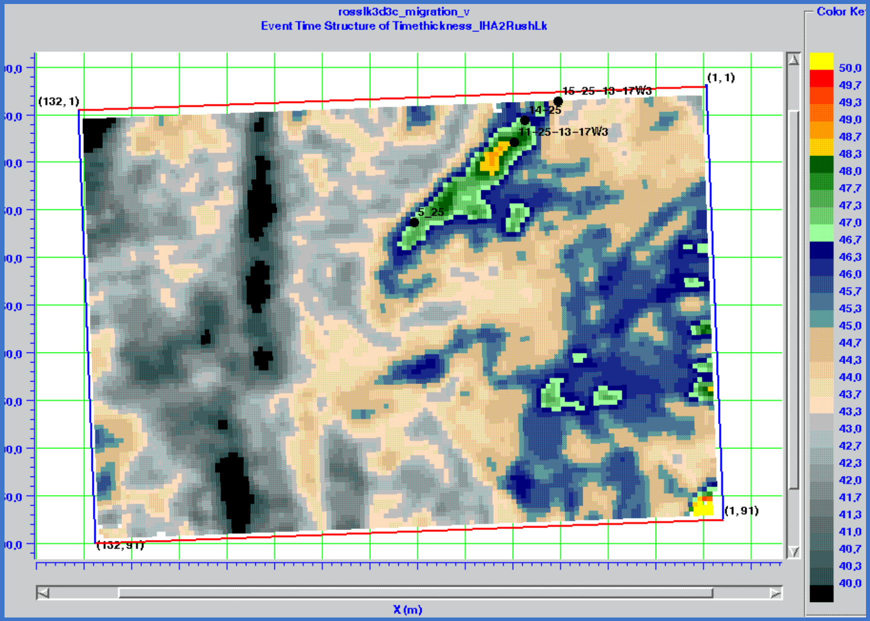
R&D costs can increase. Advanced expertise often required.



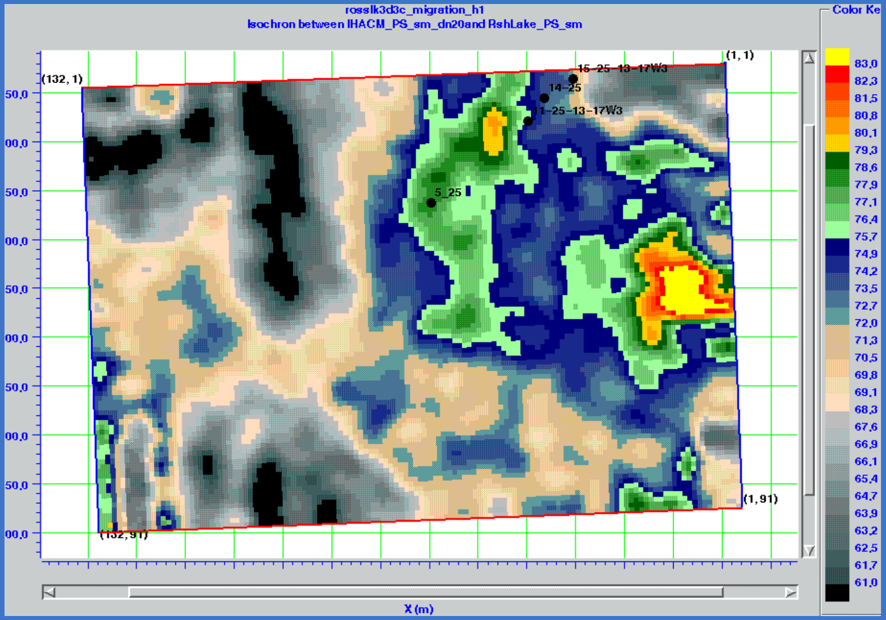
PP seismic, 0-offset VSP and synthetic seismogram at well 11-25



PP time thickness RushLake-IHACM

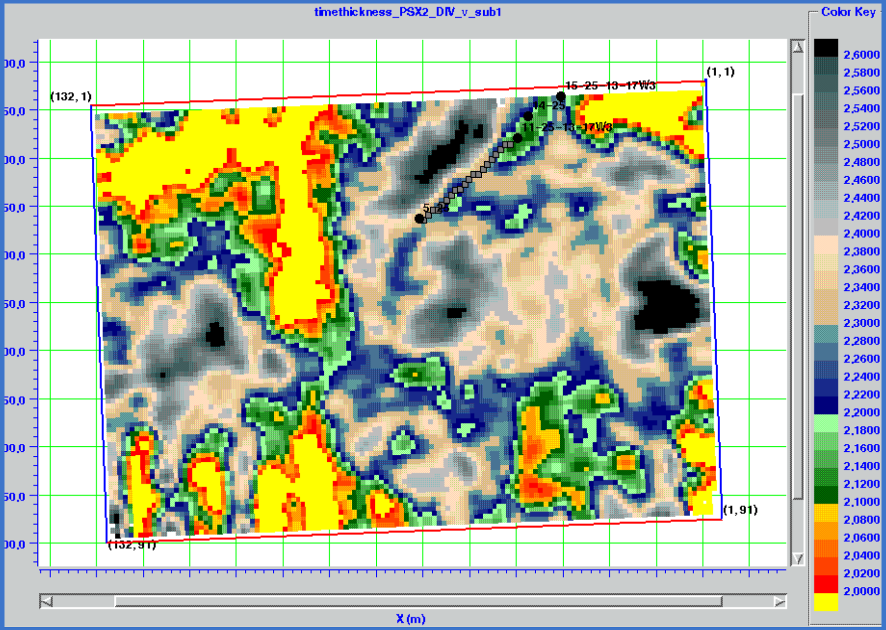


PS time thickness RushLake-IHACM

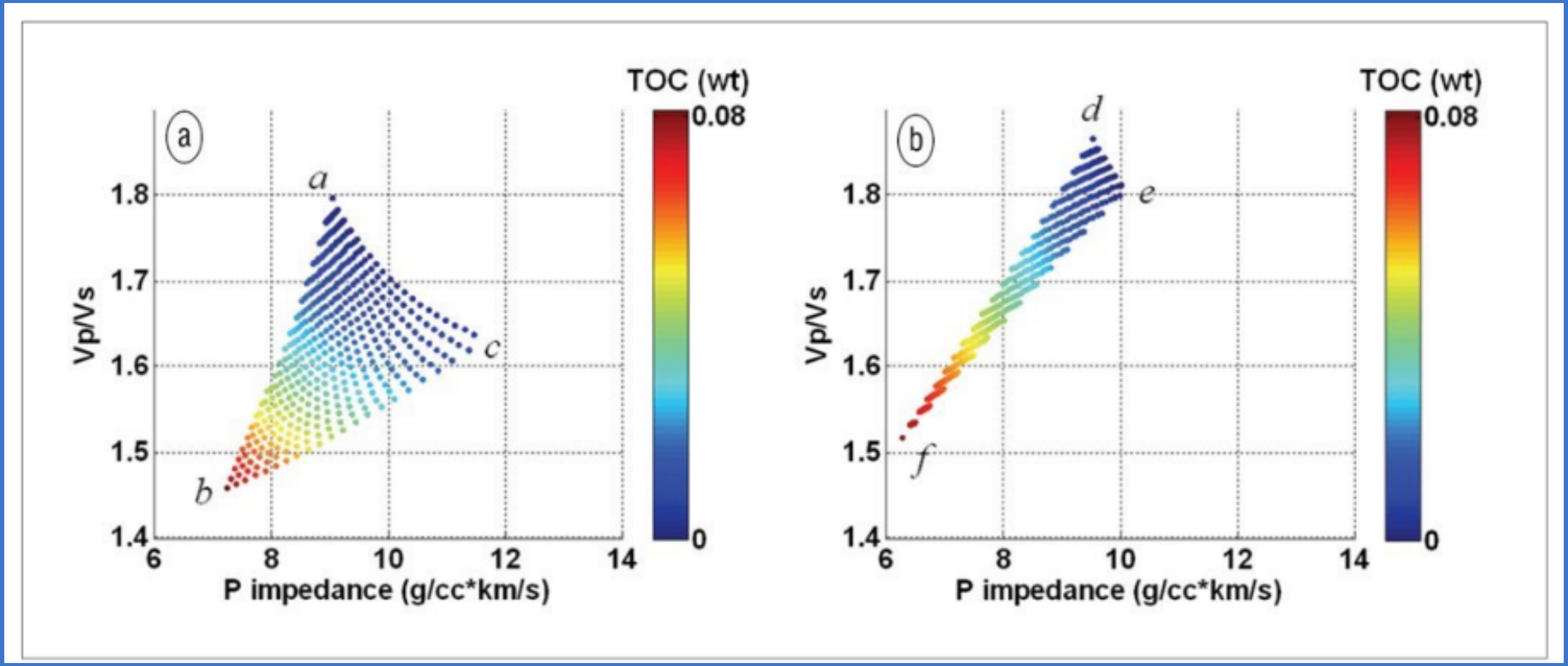


Map of average Vp/Vs between RushLake and IHACM

$$Vp/Vs = \frac{2*\Delta Tps}{\Delta Tpp} - 1$$



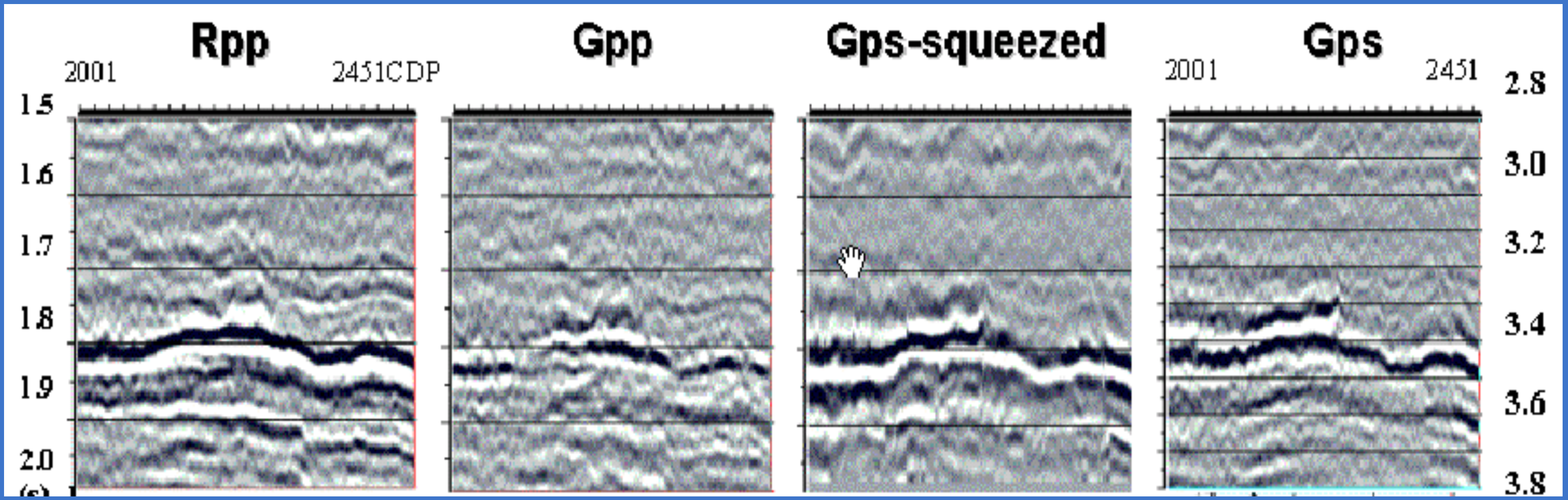
Elastic property modeling of gas shales (Zhu et al., 2010)



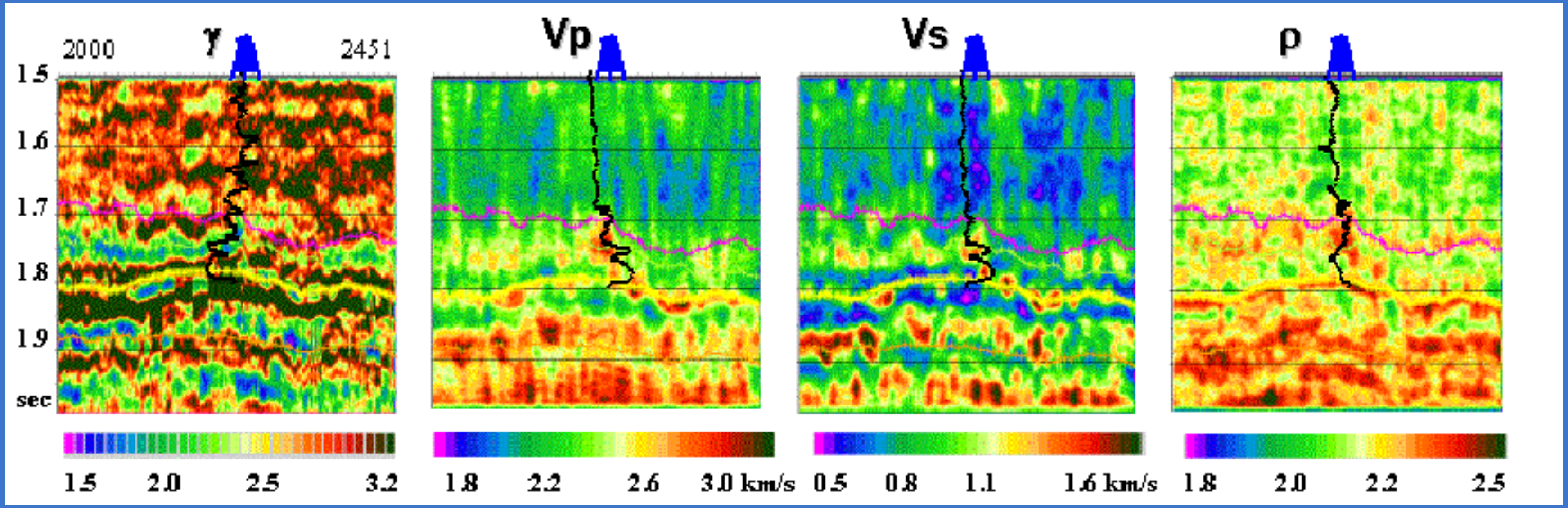
- Quartz-dominated
- Calcite-dominated

PP-PS Joint AVO Inversion

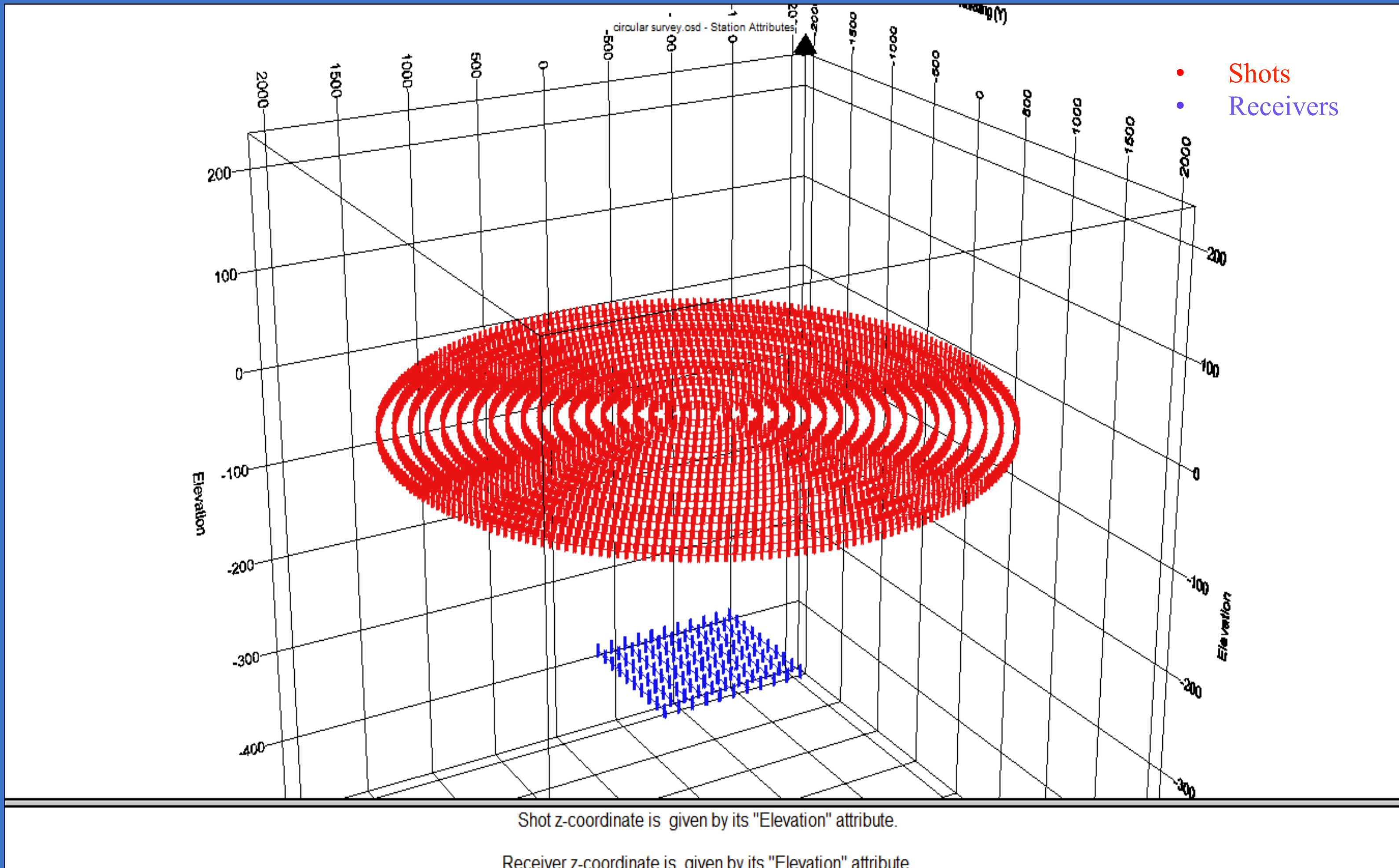
AVO Attributes



Inversion Results



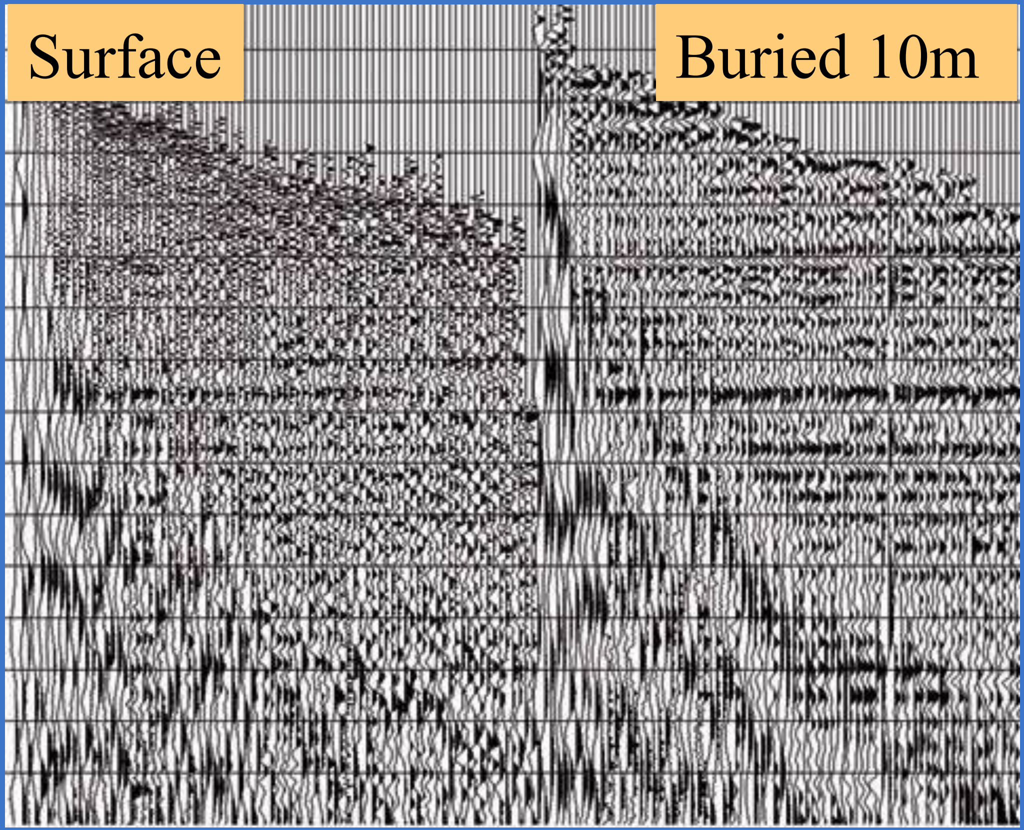
Dariu et al., 2003



3D view of shot and receiver locations

Receivers are deployed at 250 m deep from sea surface. Depth of target is 2000 m.
Maximum radius of shot rings is 2000 m.
Minimum radius of shot rings is 100 m.

What could the future hold?

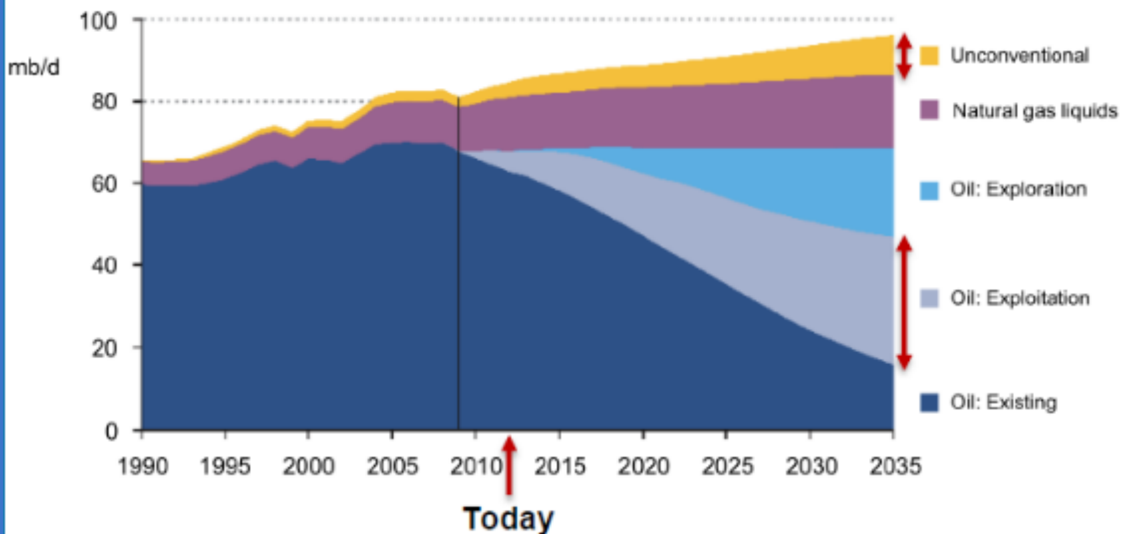


Comparison of surface and buried (10m) receivers (Criss, 2007): better data & permanent monitoring

"With a trillion sensors embedded in the environment – all connected by computing systems, software and services – it will be possible to hear the heartbeat of the Earth, impacting human interaction with the globe as profoundly as the Internet has revolutionized communication," said Peter Hartwell, senior researcher, HP Labs

Geophysics and the oil & gas industry

Geophysics for exploitation:
Requires new technology and workflows



"By the time I get an answer from a geophysicist, I've forgotten the question."

Dr. Nansen Saleri, formerly Head of Reservoir Management, Saudi Aramco

New paradigm* – *engineers as customers

- Turnaround in days not months
- Reservoir properties in depth, with quantitative measurements including uncertainties

New workflows

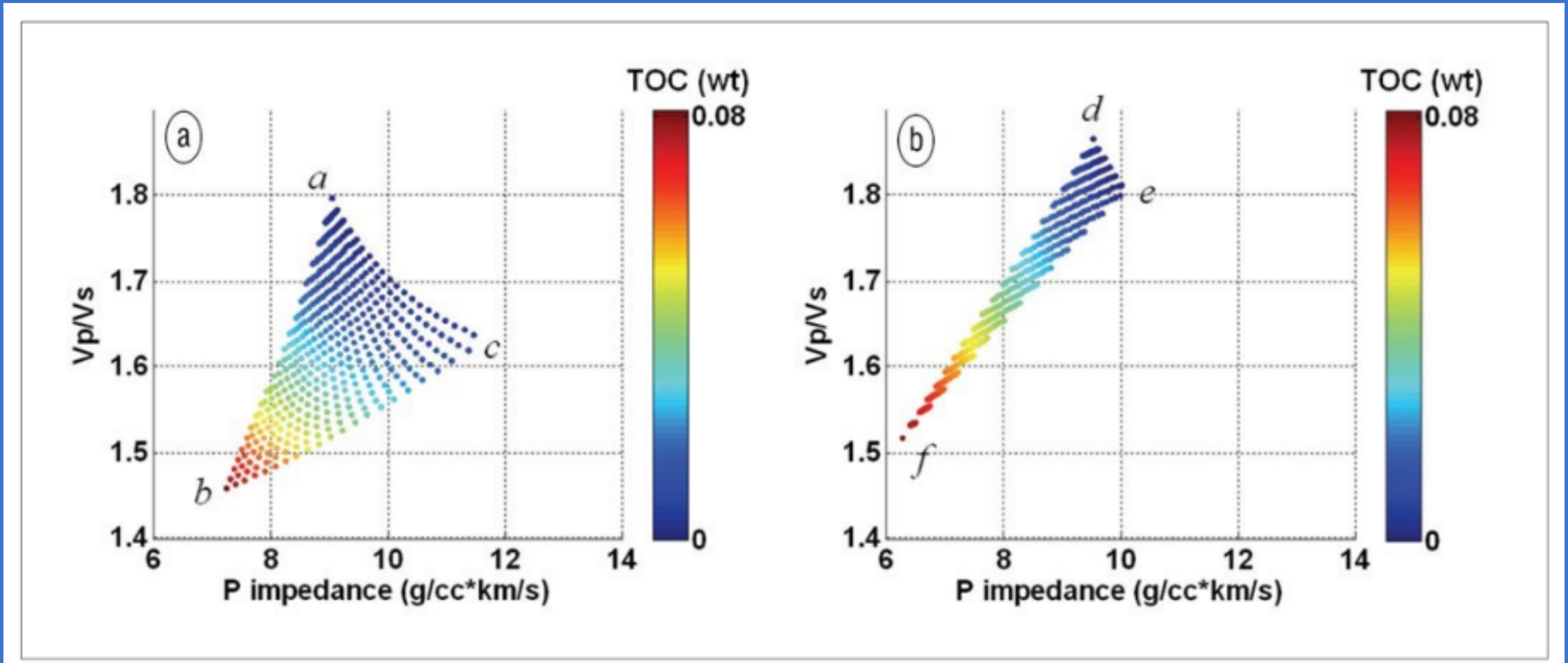
- Convergence of processing and interpretation, e.g. pre-stack
- Convergence of imaging and inversion
- Azimuthal seismic data

New technologies

- Complete integration of geophysical measurements (seismic, well, EM, gravity) and engineering and production data
- Translation of geophysical measurements to geological and geomechanical properties
- Quantifying uncertainty

R. Ackermann, RSI, talk at UH October, 2012

Elastic property modeling of gas shales (Zhu et al., 2010)



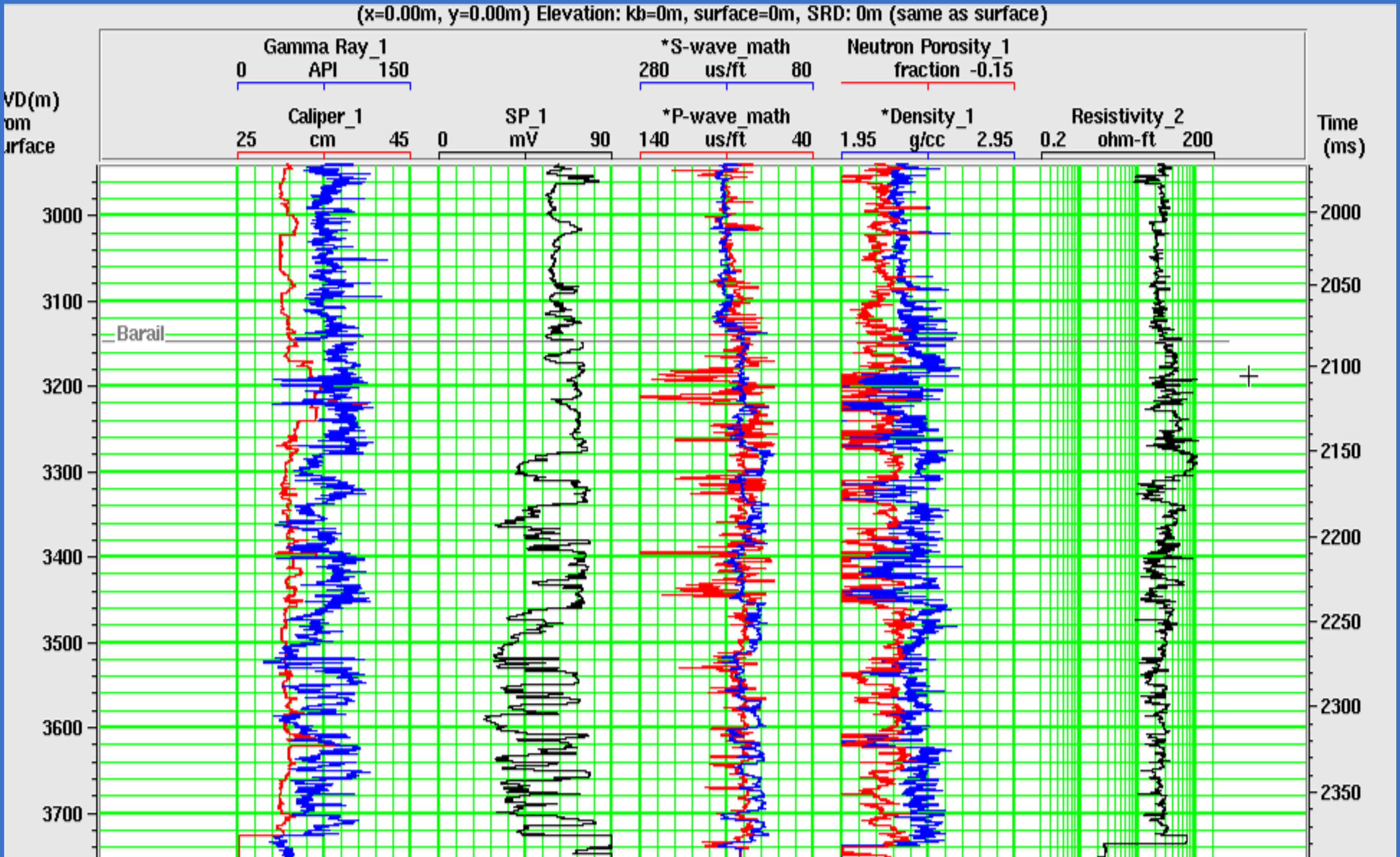
- Quartz-dominated
- Calcite-dominated

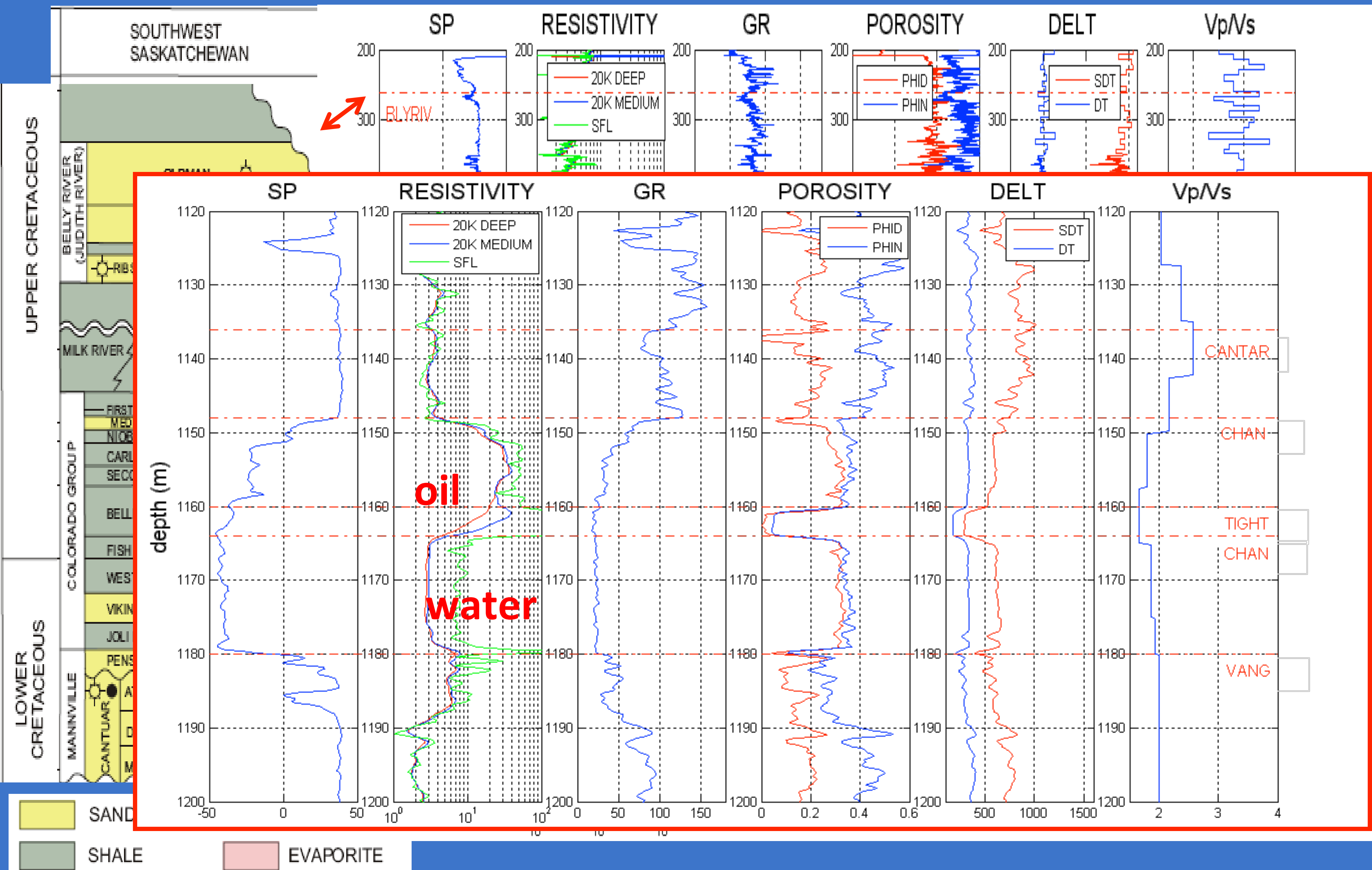
Summary

- Basic converted-wave (P-to-S) exploration method established
- Many advancements in field, processing, and interpretation methods and facility
- Still room for improvement in: acquisition quality & costs, processing sophistication, interpretive understanding & application
- A number of successful lithology examples (e.g., sand/shale) and imaging cases (gas, fractures, faults)
- Consider PS imaging for a more complete subsurface picture of rocks and resources!

Quickie quiz: Define the interval of greatest hydrocarbon interest:

Hints - GR; SP; P/S crossover; porosity; resistivity



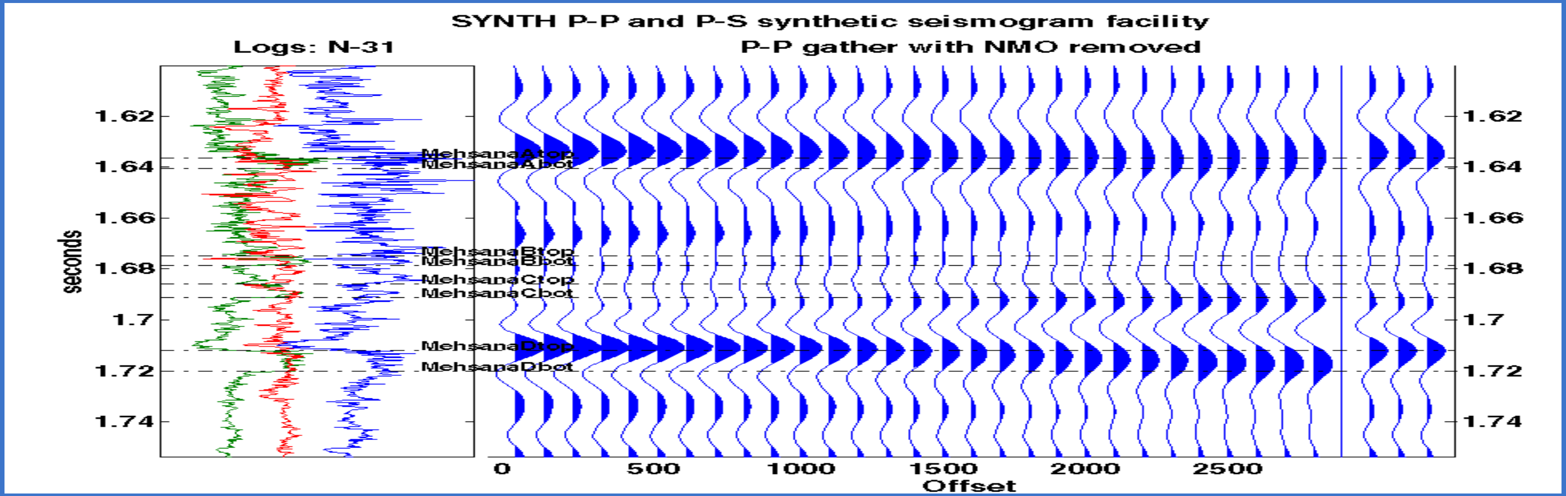


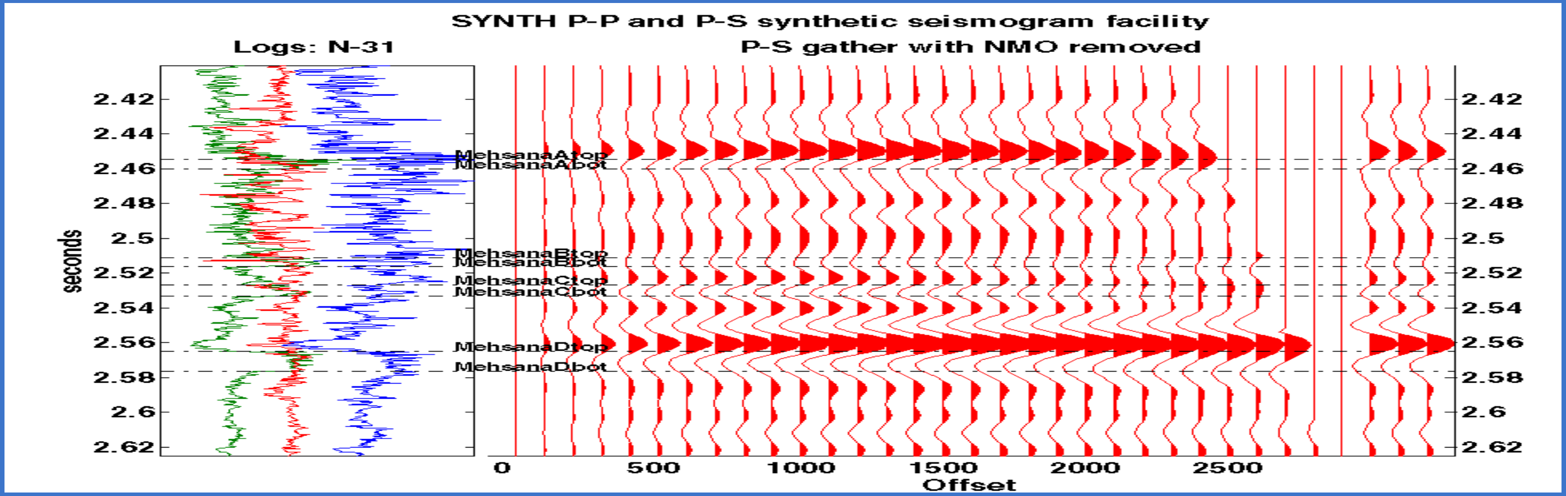
Regional table of formations and well log curves for the Well 11-25-13-17W3

Nandesan Detail of Sand Zone

VP/VS 1. 5 in 4 sands, 2 elsewhere

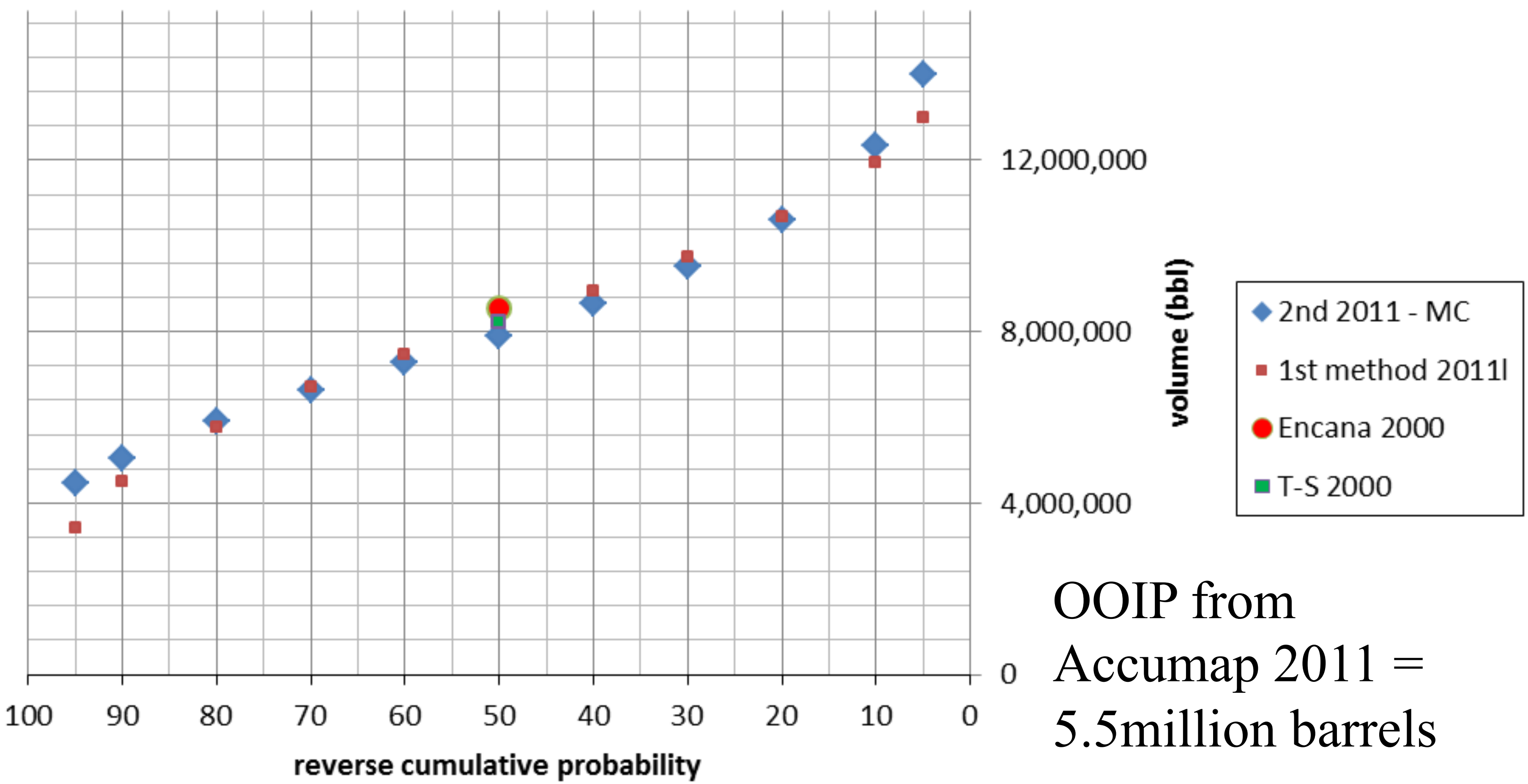
40 Hz. Ricker wavelet





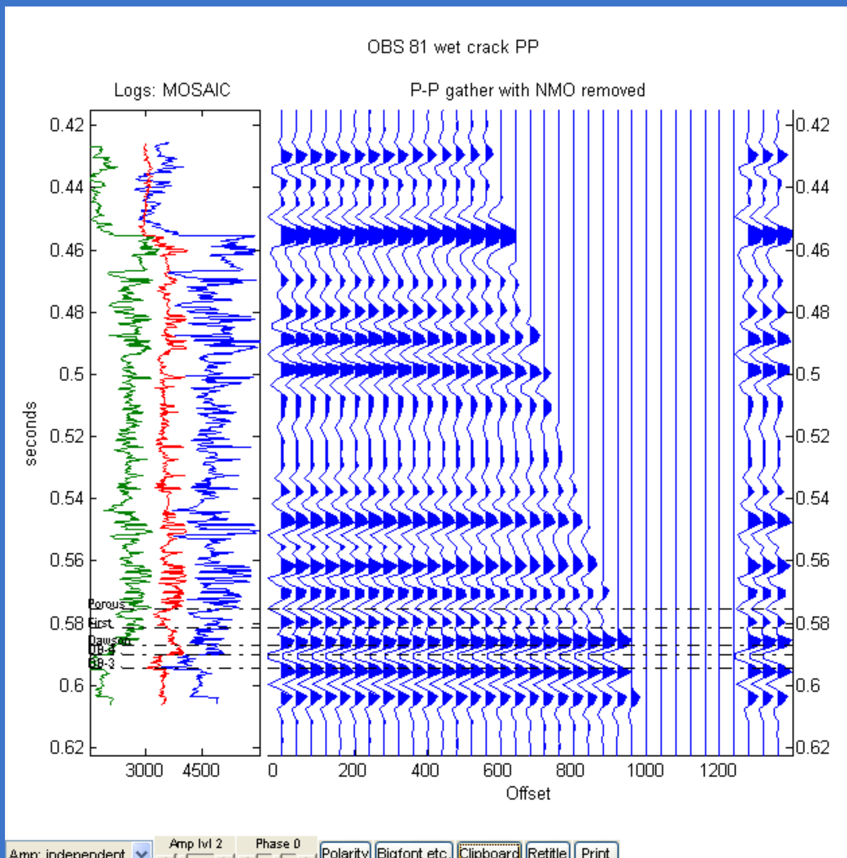
Summary of hydrocarbon volume results

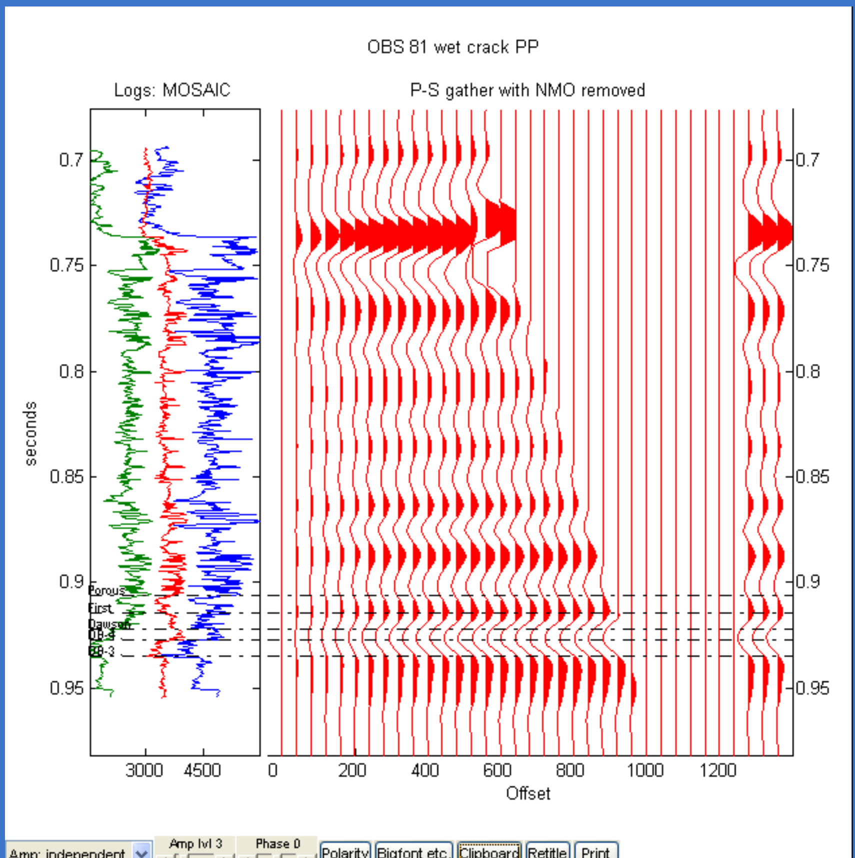
CDFs obtained from our calculations



OOIP from Accumap 2011 = 5.5million barrels

Well OBS 81 synthetic seismogram of cracked rock (2 sets of crack, 1% crack porosity)

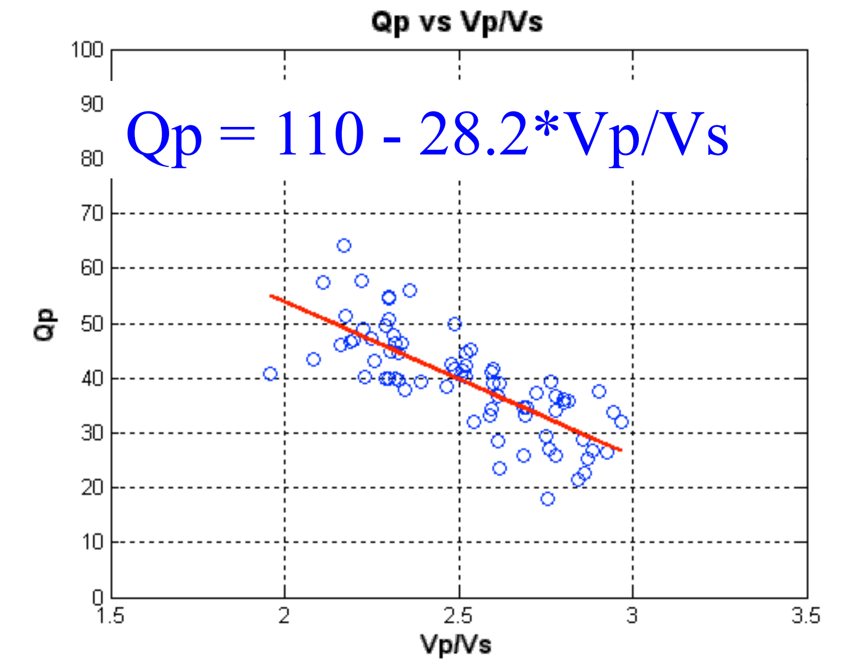




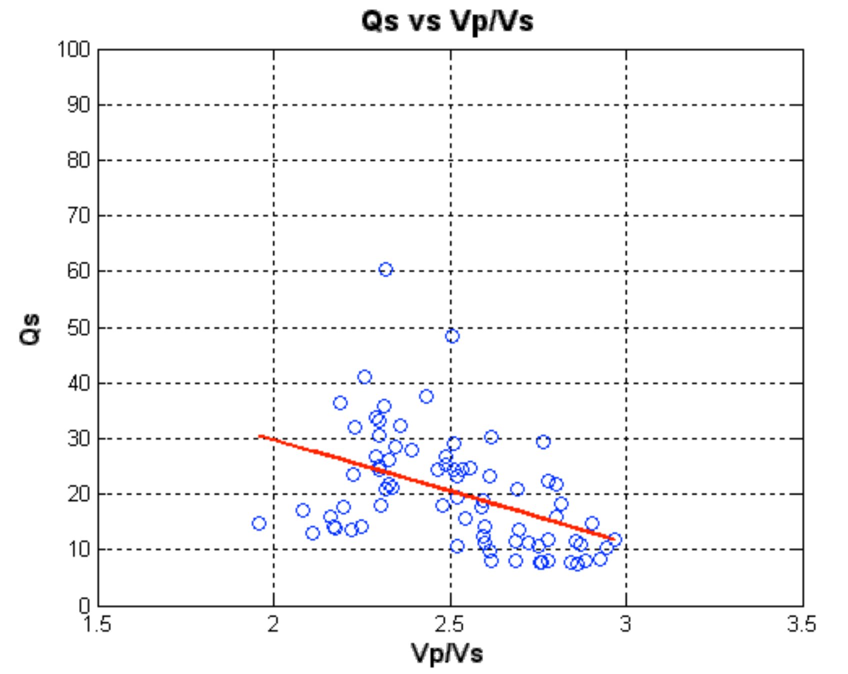
Water-saturated cracks

Q vs. Vp/Vs

Attenuation as a rock property, fluid indicator



Qp vs. Vp/Vs



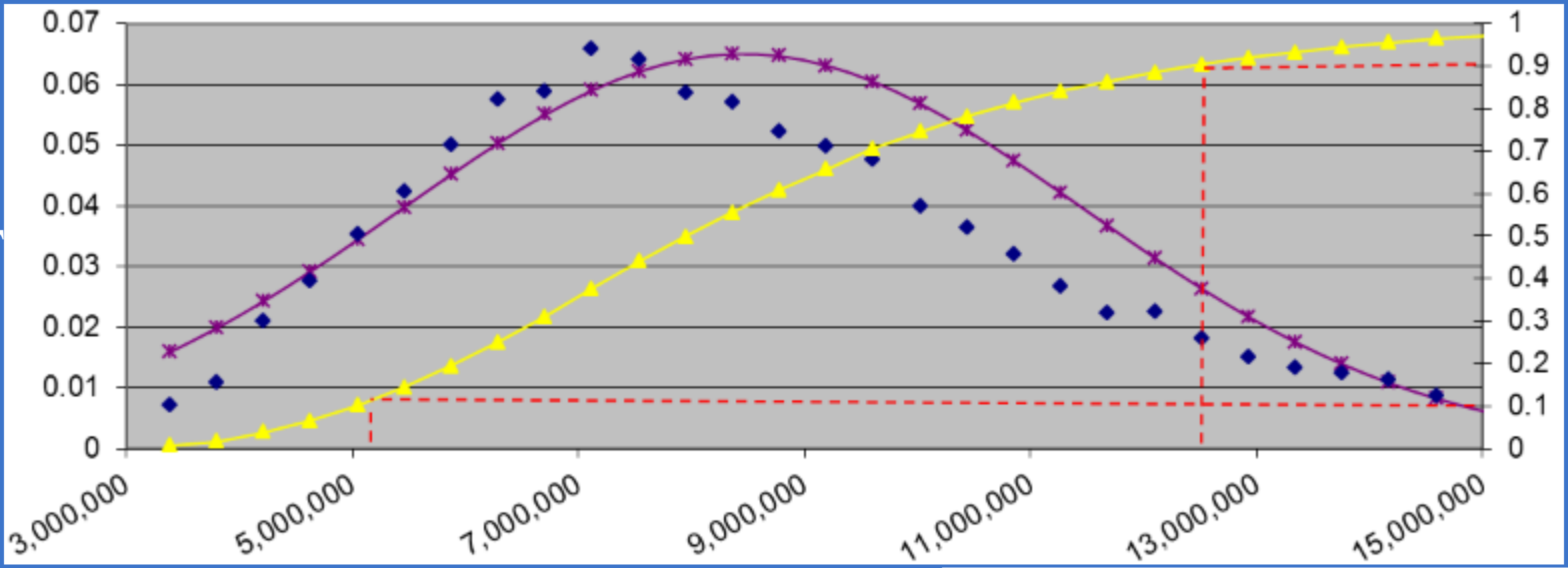
Qs vs. Vp/Vs

2nd Method of estimation of uncertainty in OV

Monte Carlo approach

- OV = thickness × %sand × ϕ × $(1 - S_{wi})$ × Area
- 10,000 simulations

PDF



CDF

bbl

P_{90} = 5,033,000 bbl

P_{10} = 12,494,000 bbl