Quantitative 3D+4D Seismic

imaging, inversion and monitoring inside the earth

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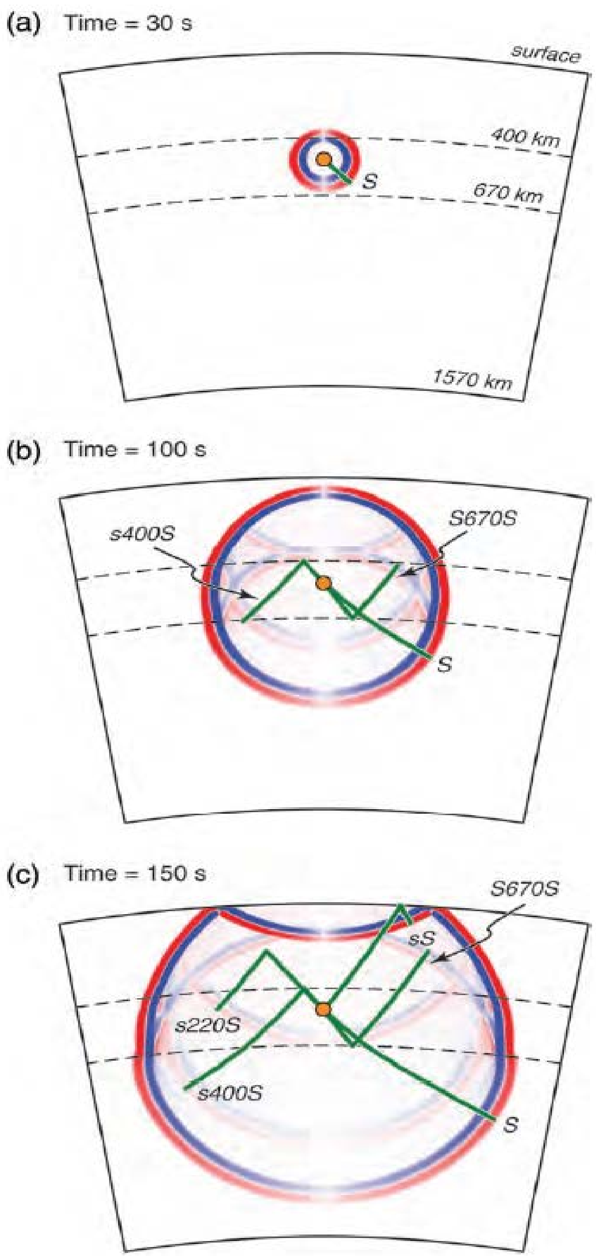
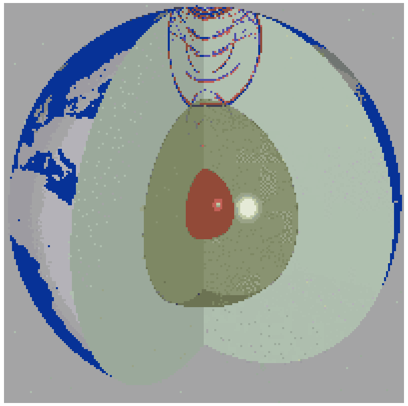
Introduction

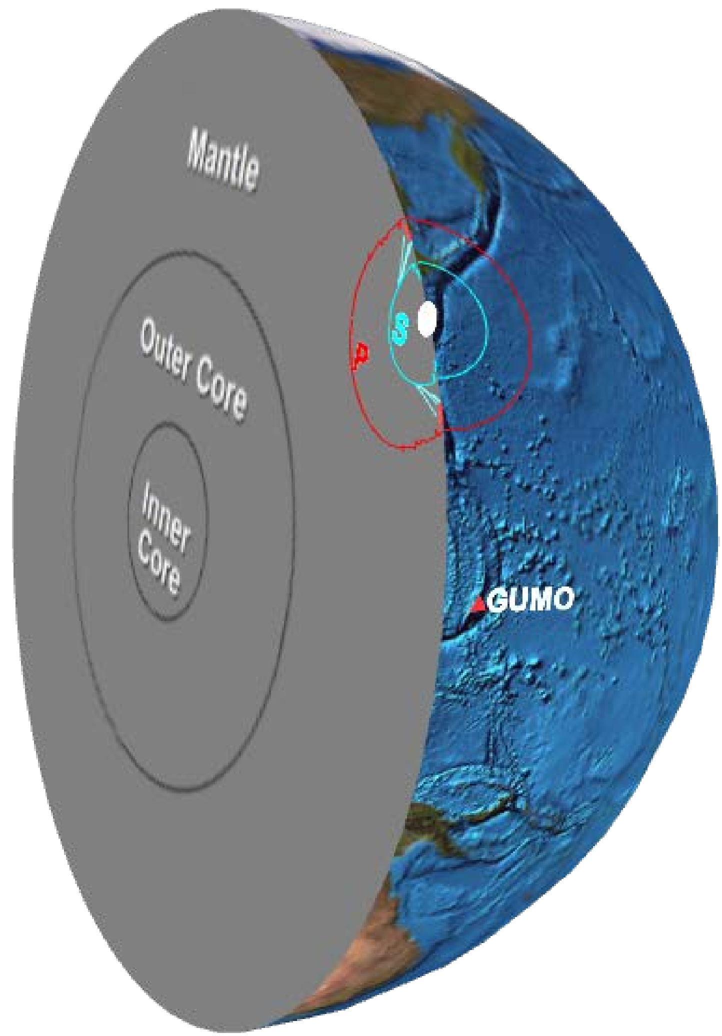
Seismology…





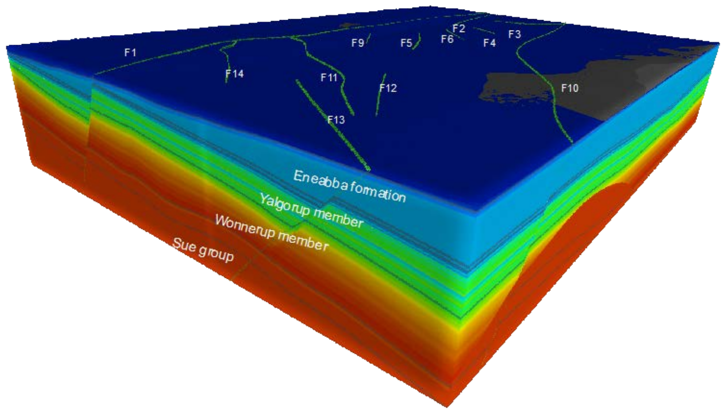
Thorne et al., SRL 2013

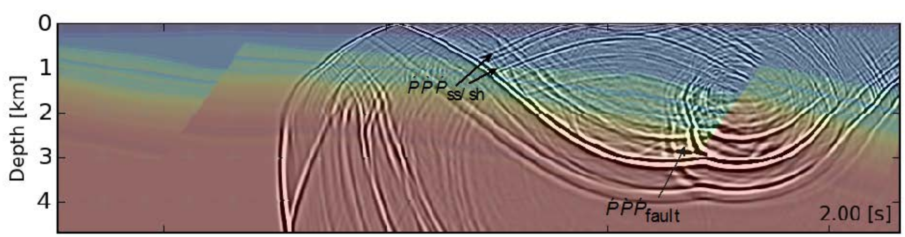
2011 Tohoku earthquake

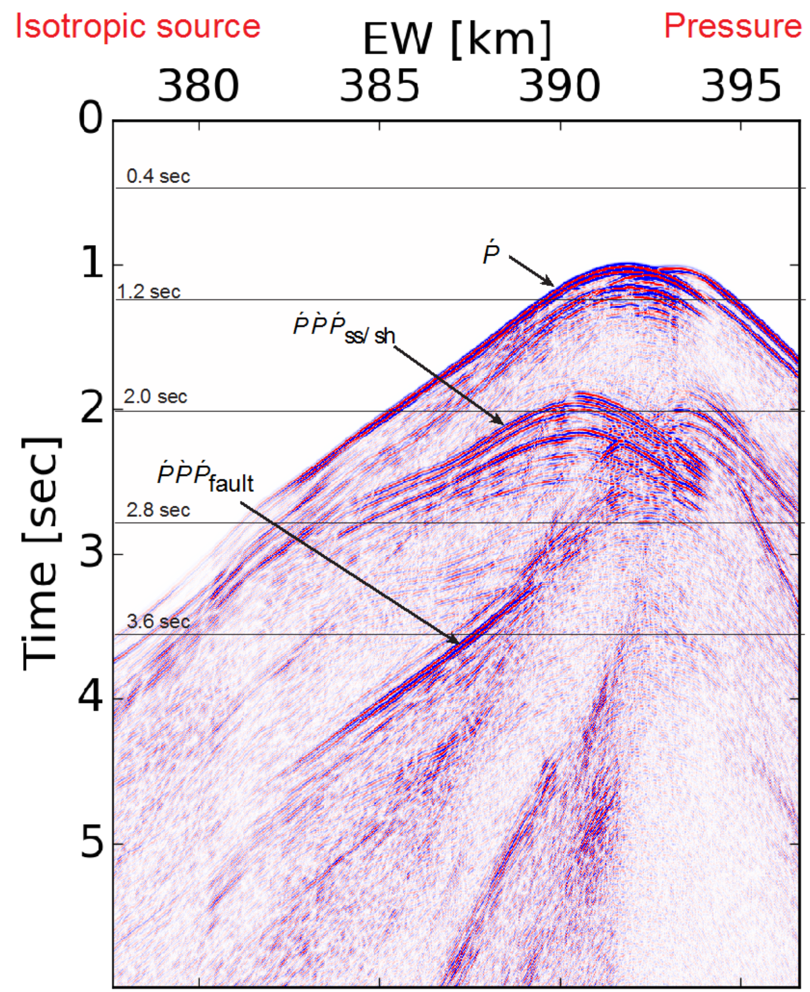


http://www.iris.edu/hq/inclass/software

3D Elastic wavefield modeling…







Lumley et al., ANLEC 2016

- **Large-scale 3D elastic modelling**
  - >5.2 billion grid points
  - Highly optimized parallel computation

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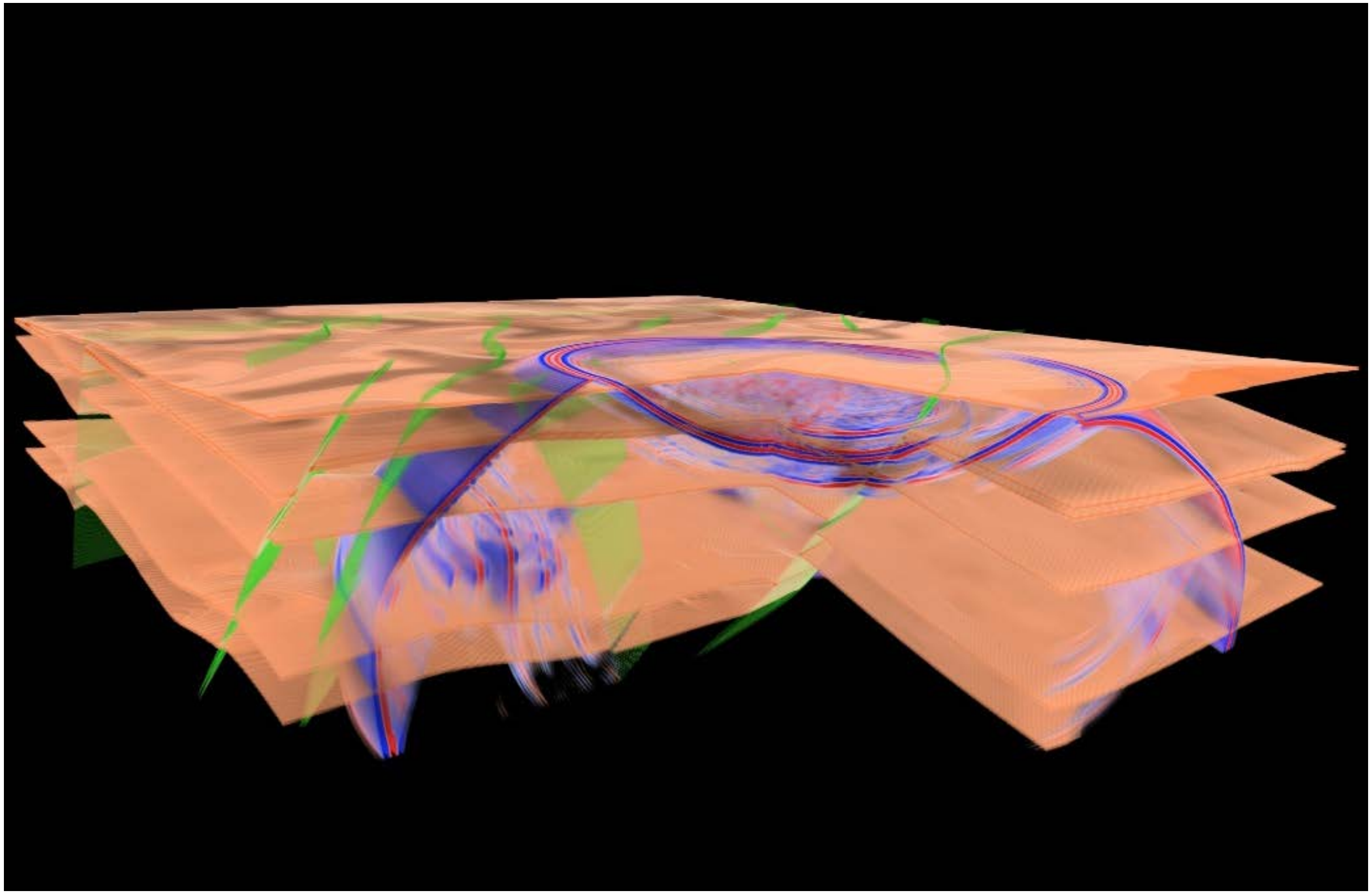
3D Elastic wavefield modeling...

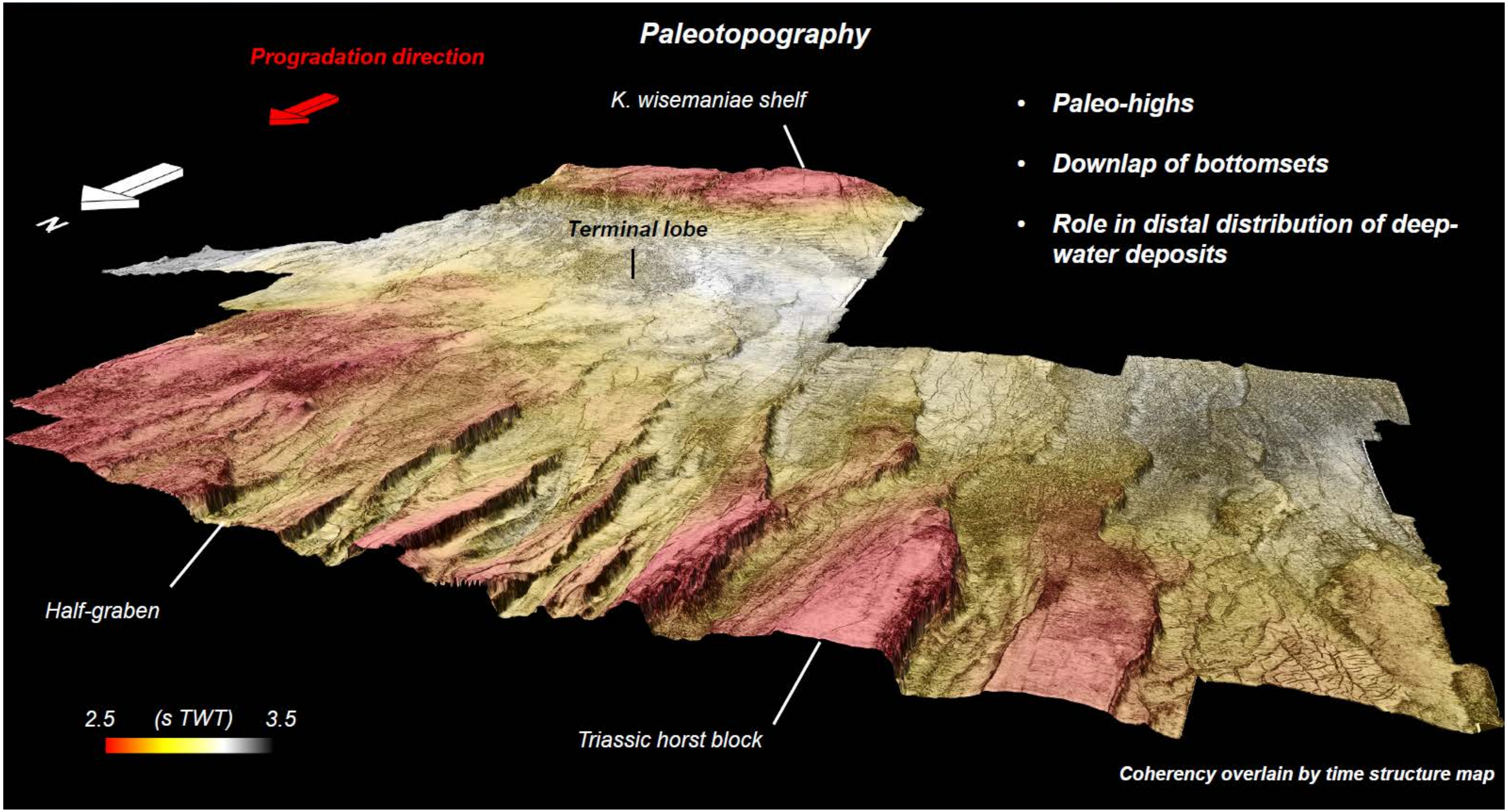


Miyoshi et al., 2016

Imaging… objects + patterns

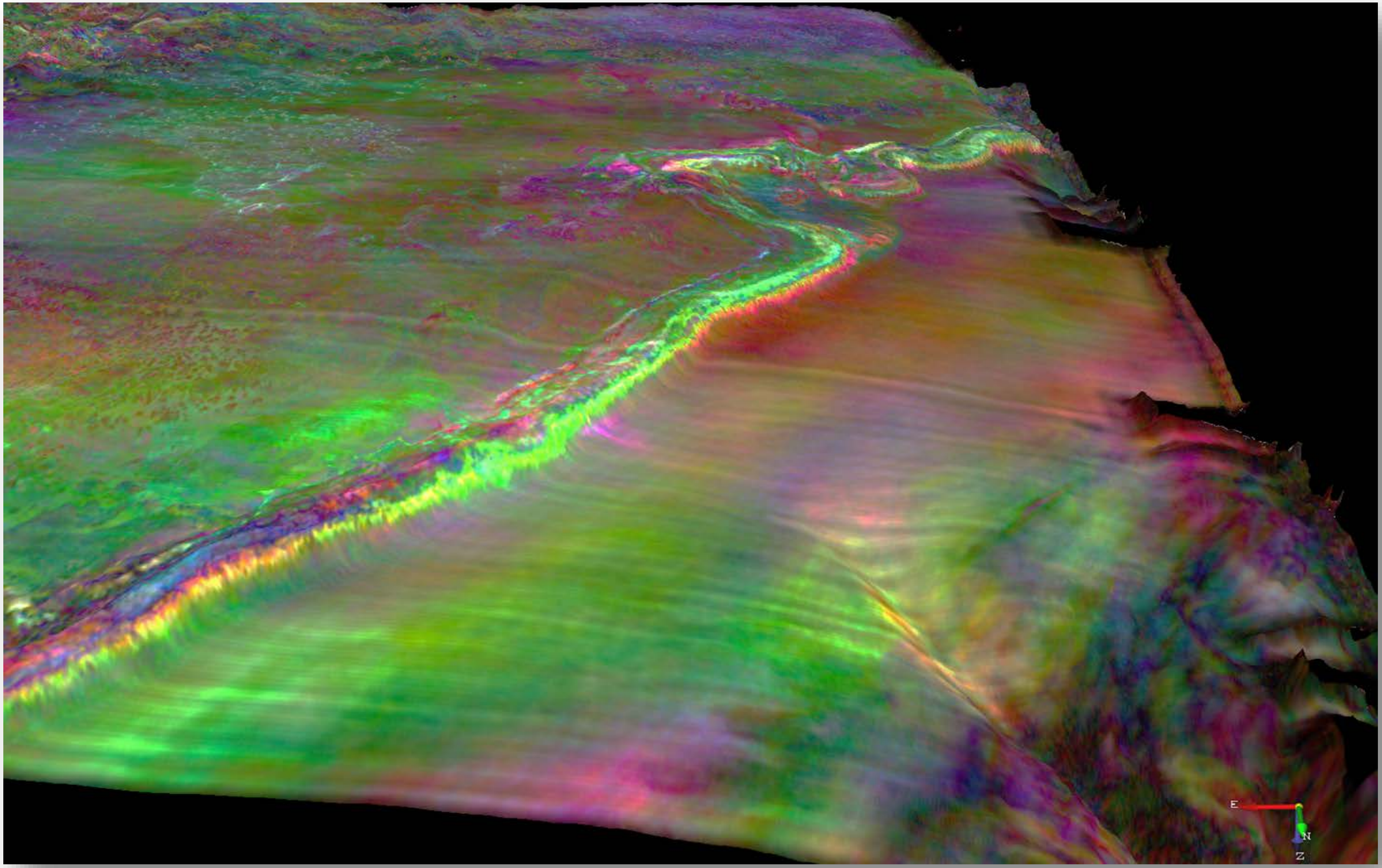
source, energy, sensors

3D Seismic imaging…



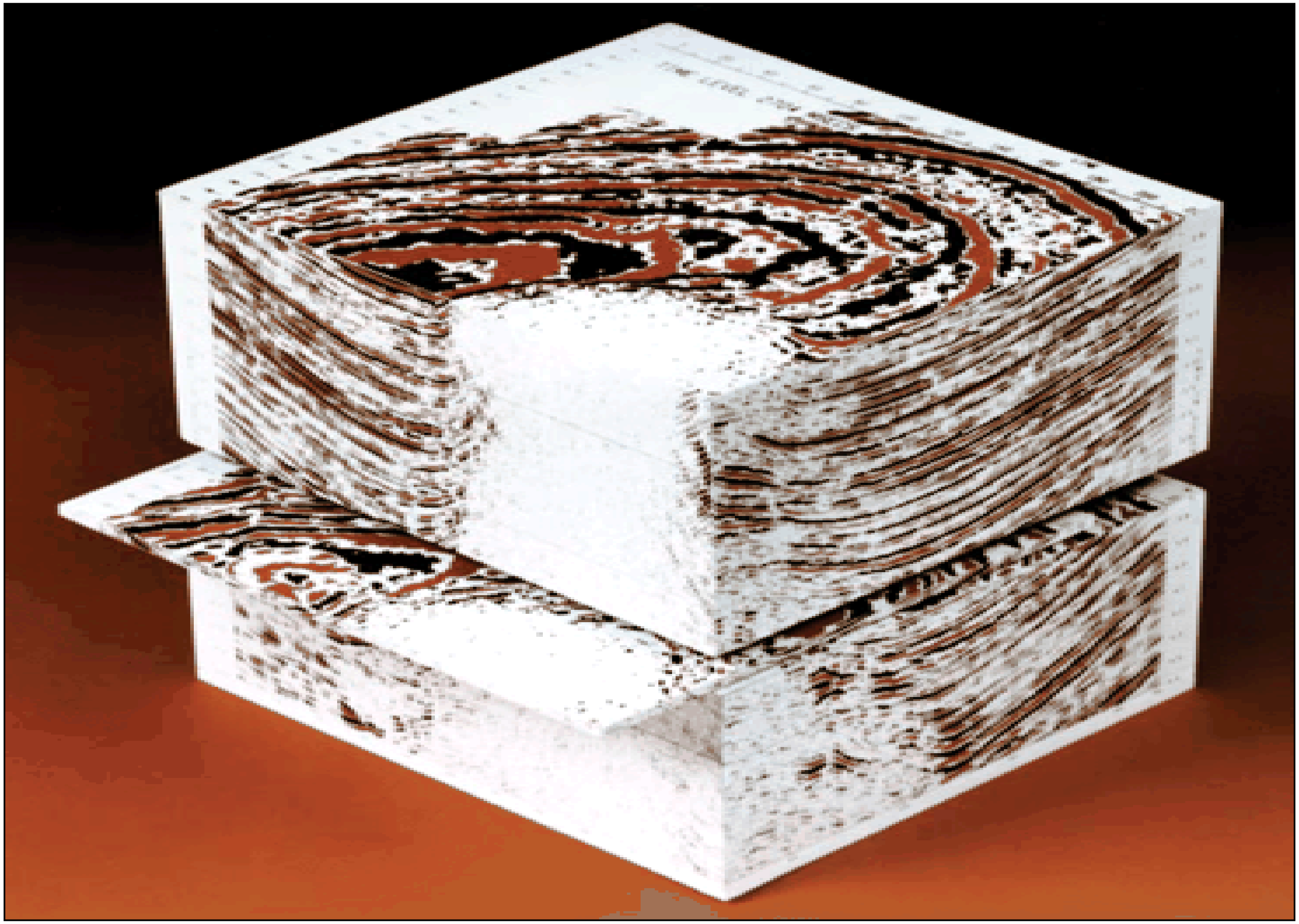
Paumard et al., 2015

3D Seismic imaging…



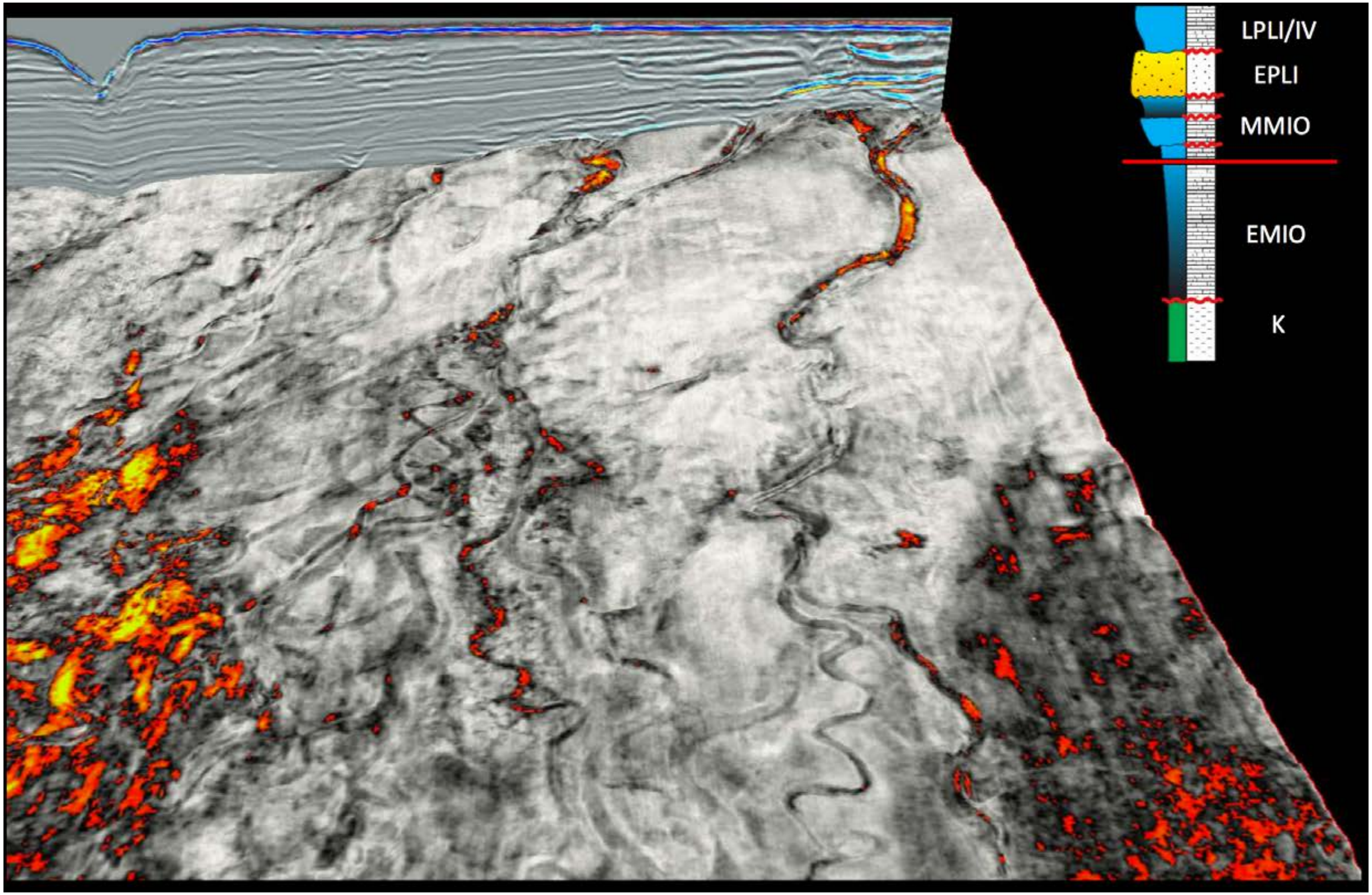
Bourget et al., 2014

3D Seismic imaging…



Dragoset, TLE 2005

3D Seismic imaging…



Bourget et al., 2014

Inversion… physical properties

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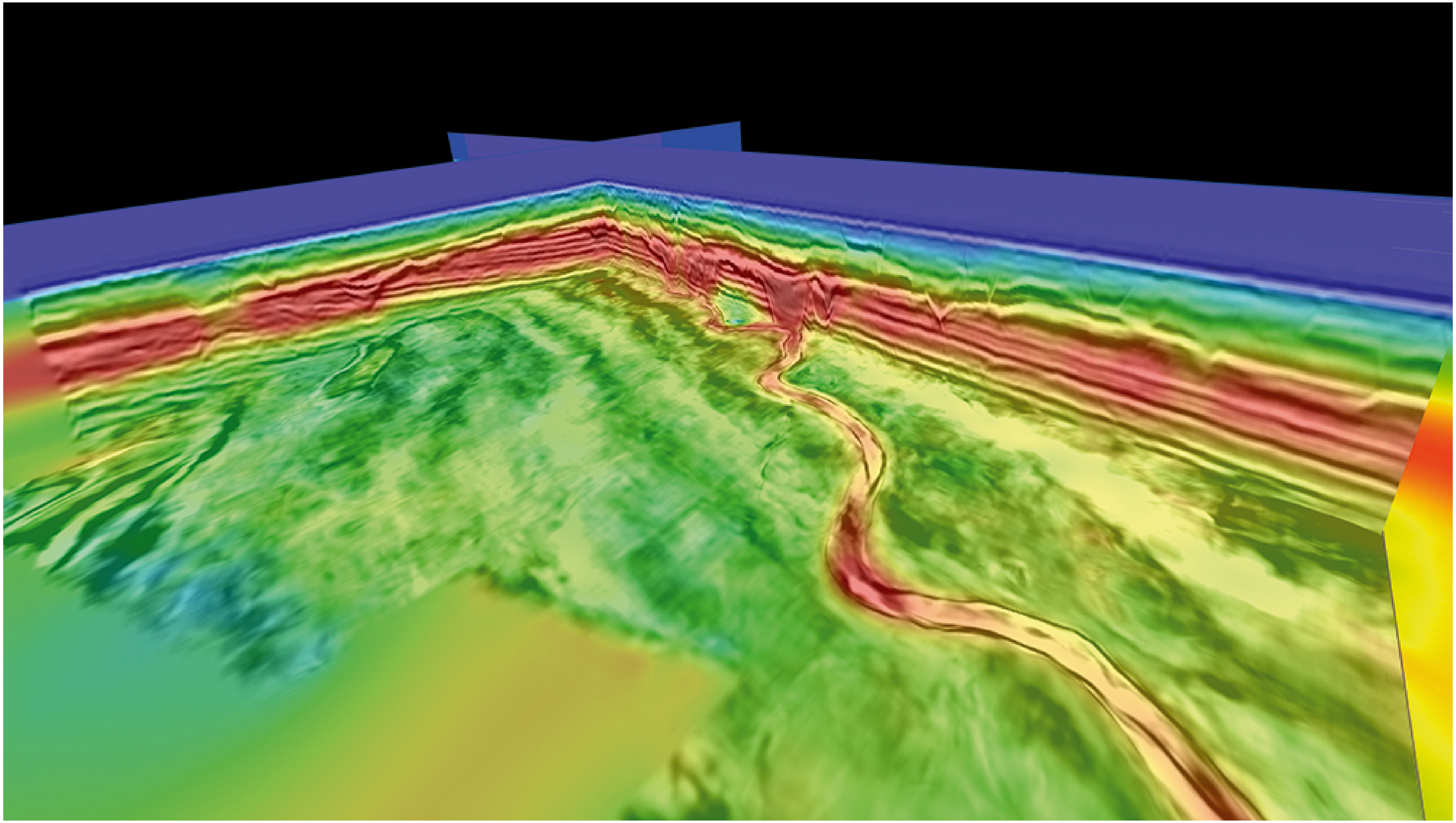
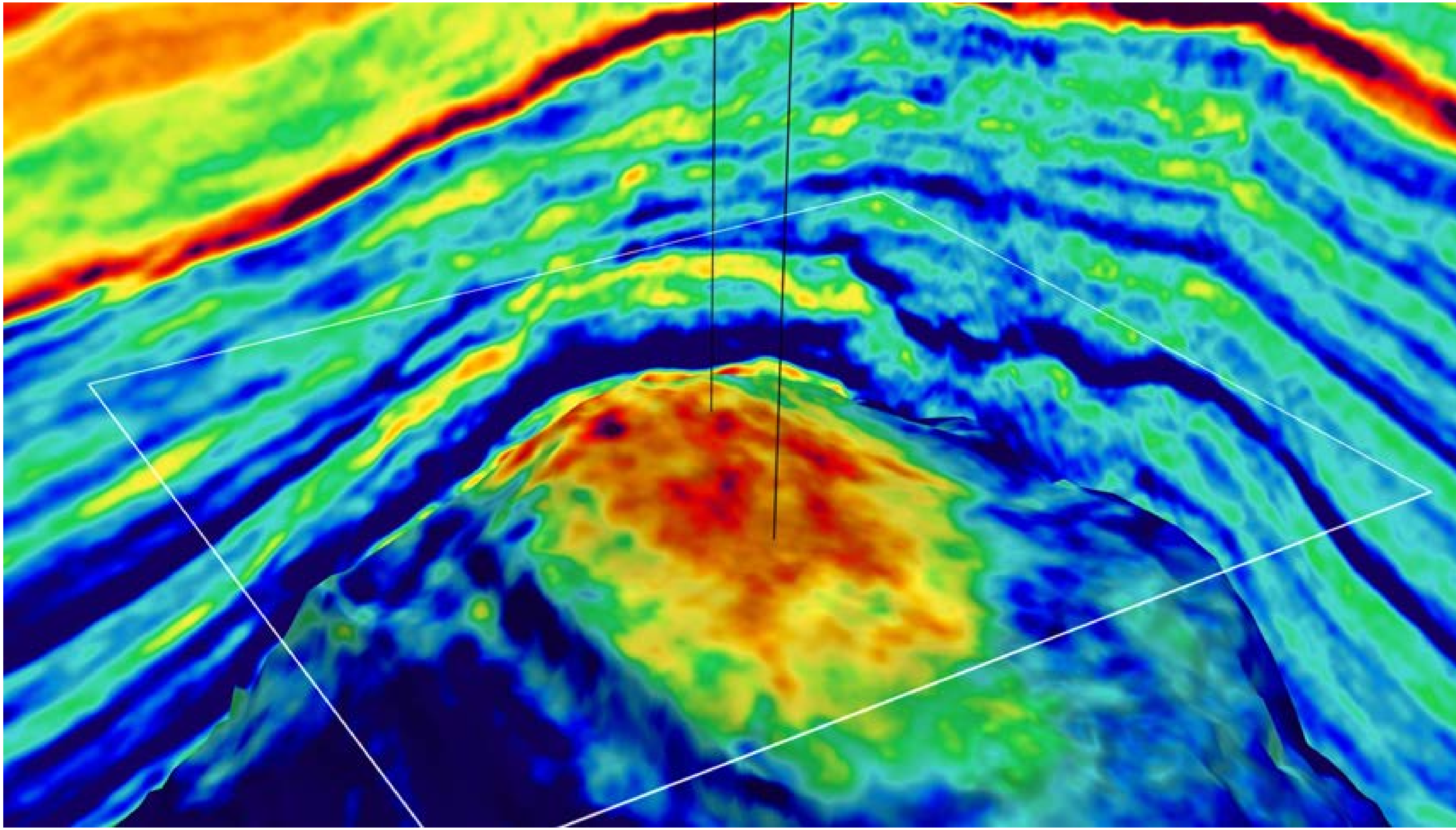
Full waveform inversion



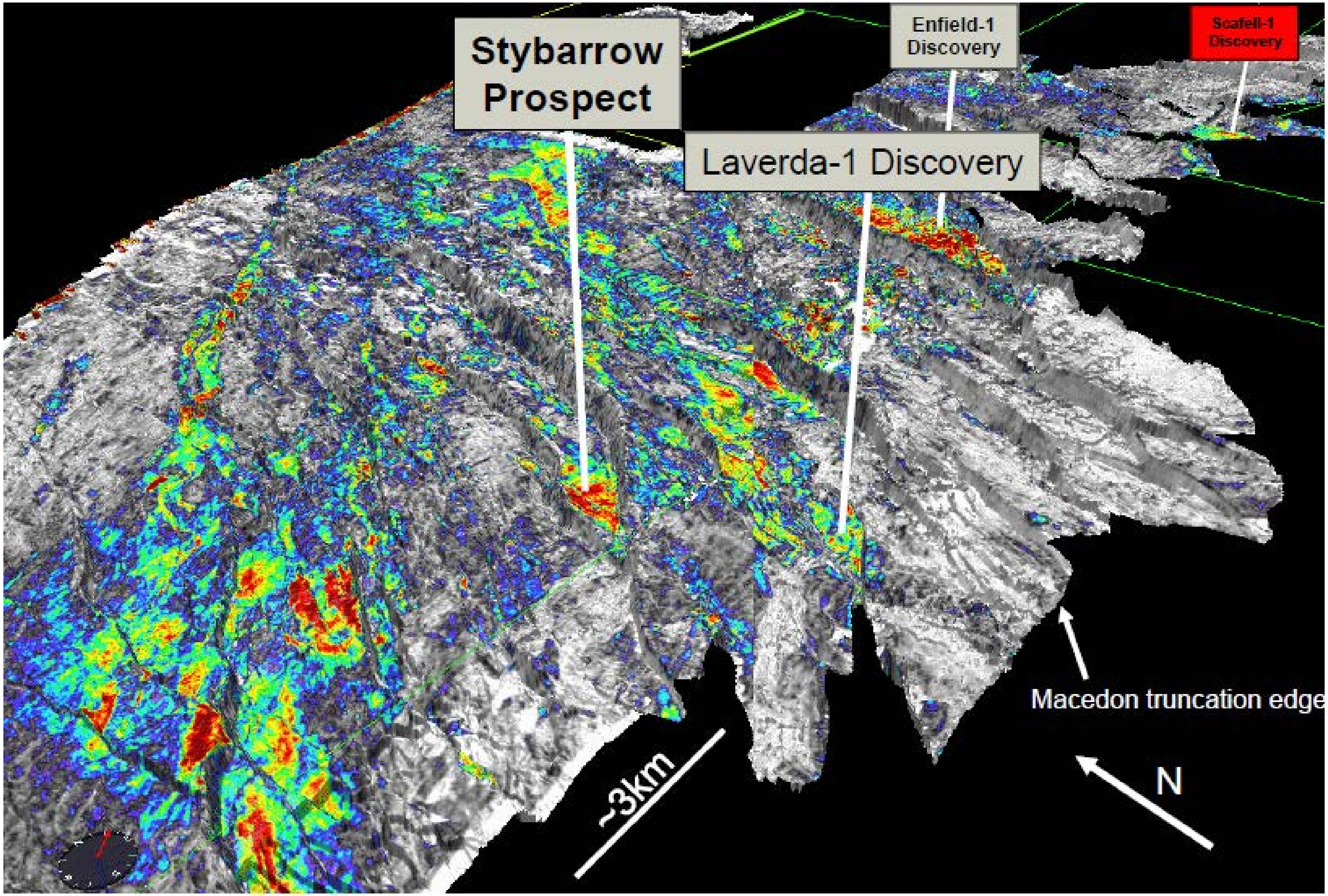
PGS

Full waveform inversion



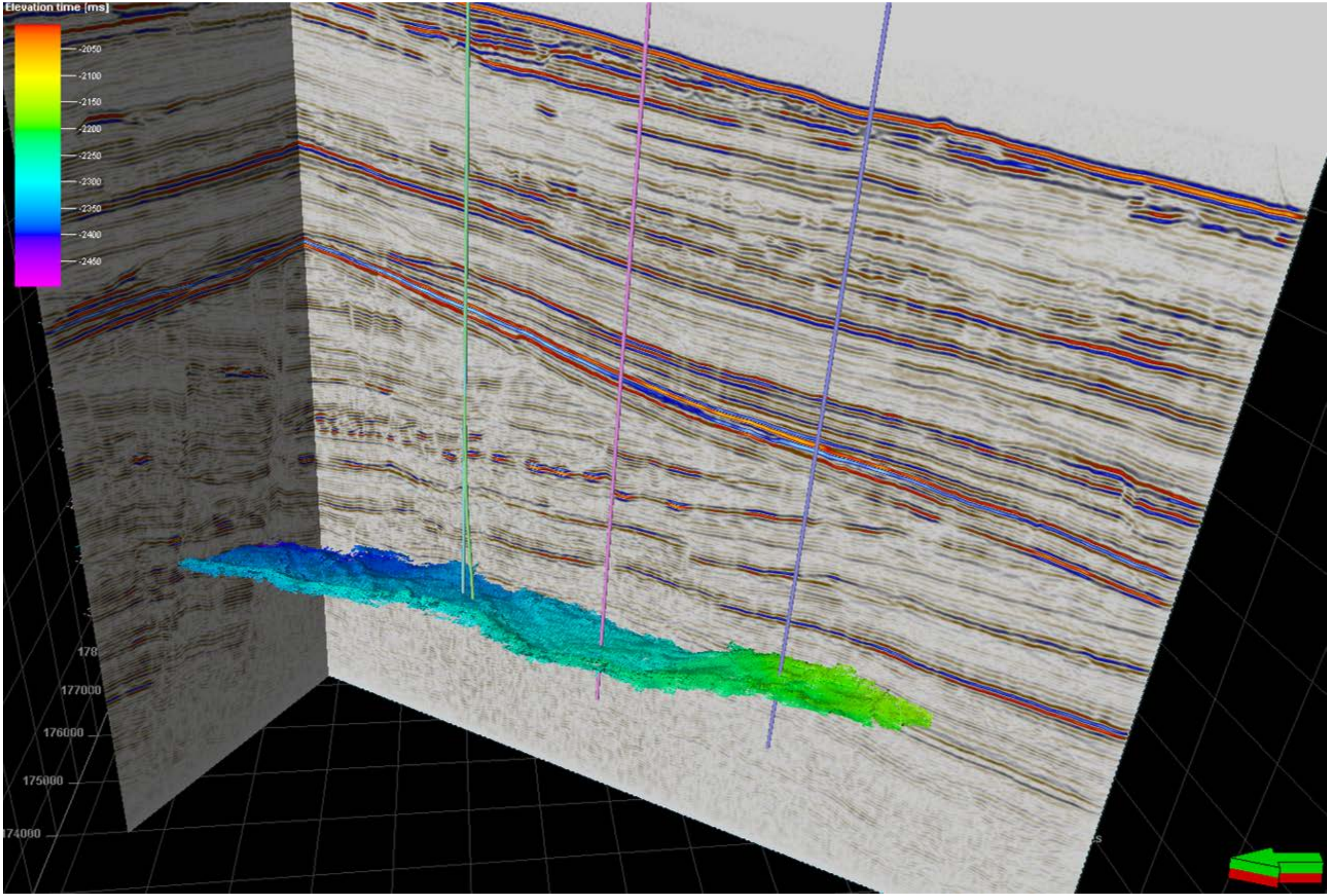
PGS

3D Exploration Seismology



Hill et al., 2009

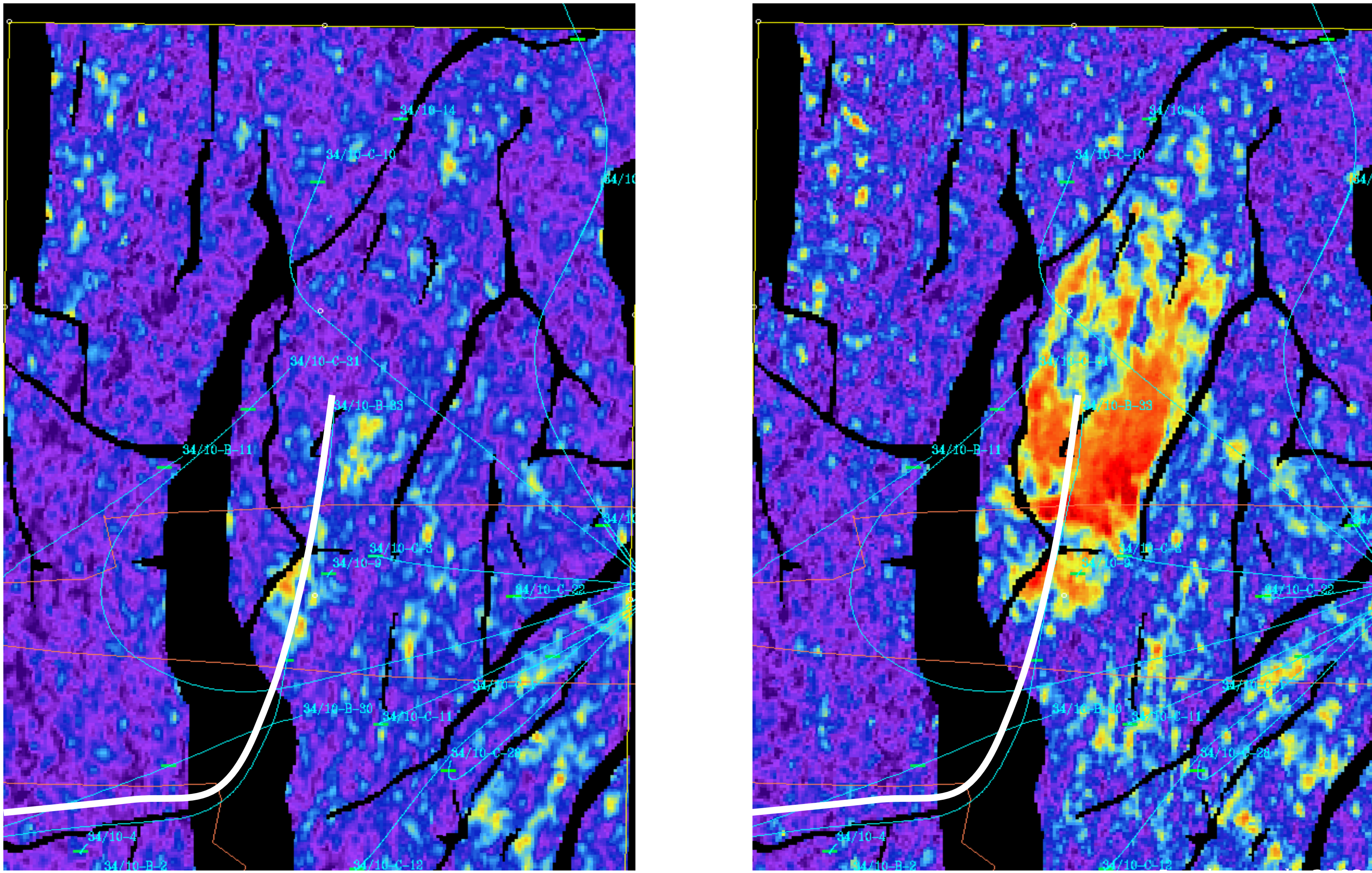
3D+4D Seismic Reservoir Analysis



Lumley et al., 2012

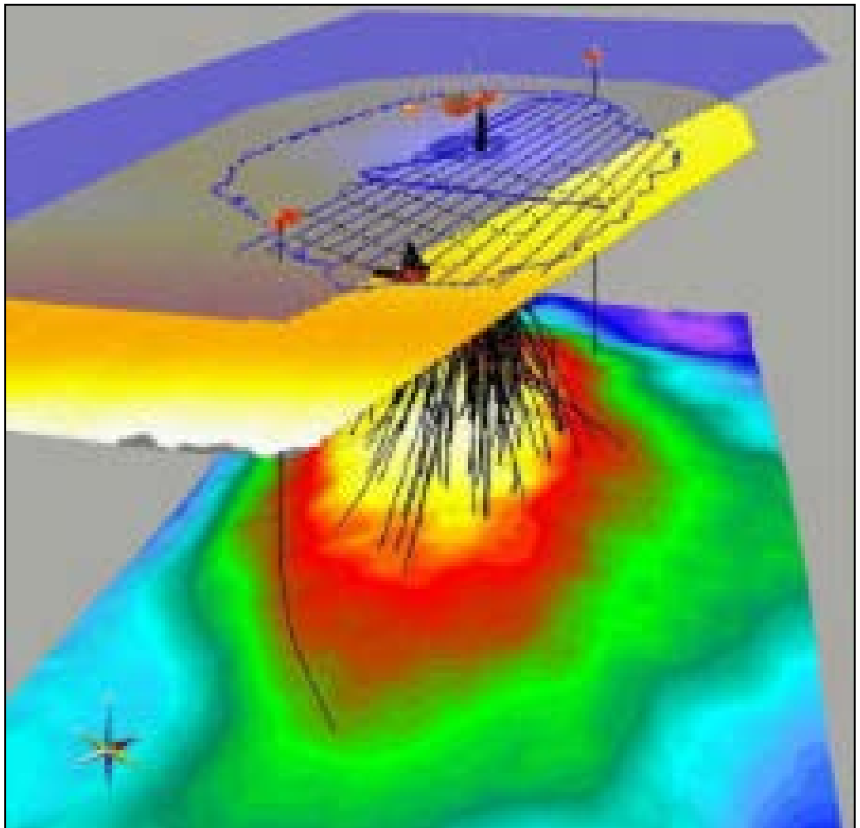
Time-lapse 4D Seismic Monitoring

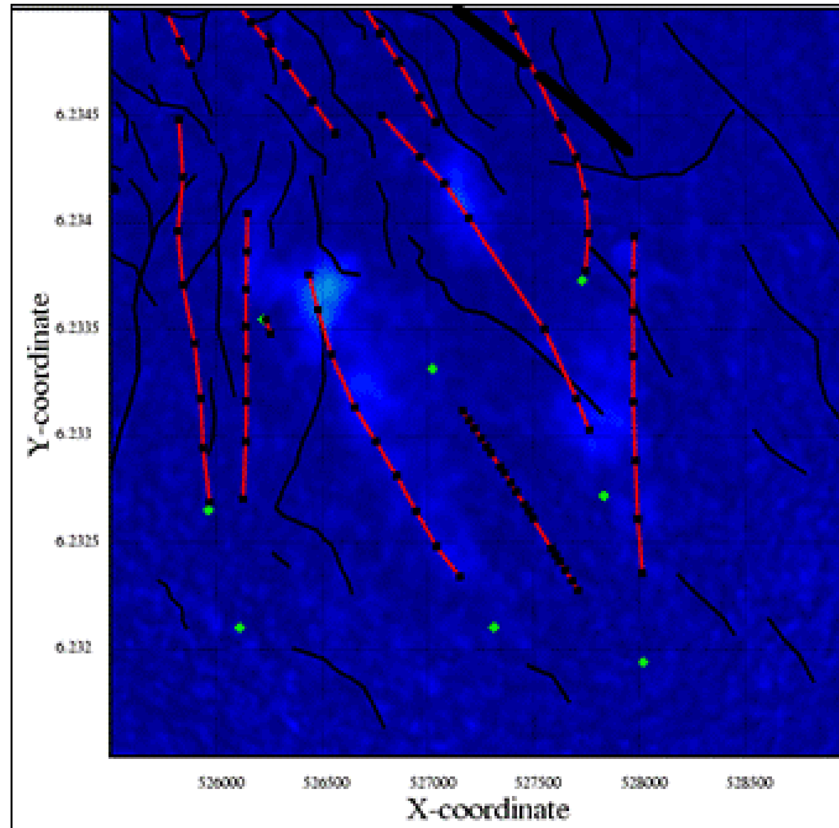
Before After



Lumley et al., FB 2003

Valhall permanent seafloor array





Barkved et al., 2004

courtesy BP

Elastic Wave Equation

Elastic wave equation

http://blog.gaborit-d.com/les-icones-gif-3d-moran-goldstein/

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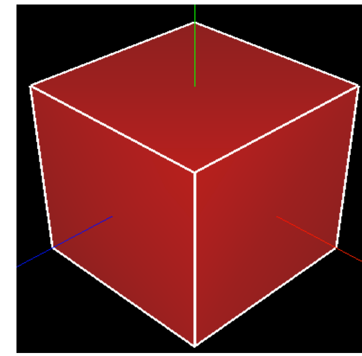
UT DALLAS

Newton's 2nd Law

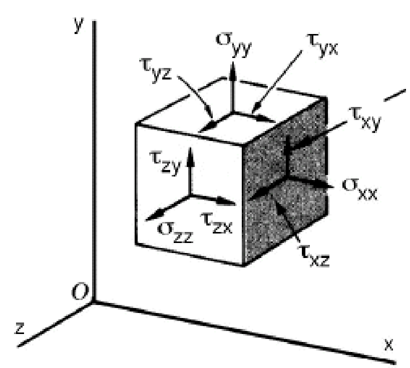
$$F_{total} = F_{volume} + F_{surface} = ma$$



Body force: $f_i = F_i/V$

Surface force (Traction): $T_i = F_i/A$

$$F_{total} = \int_v f_i + \int_s T_i = m\ddot{u}_i$$



Stress: $T_i = \sigma_{ij}\, n_j$; $\sigma_{ij} = T_i\, x_j$

$$F_{total} = \int_v f_i + \int_s \sigma_{ij}\, n_j = m\ddot{u}_i$$

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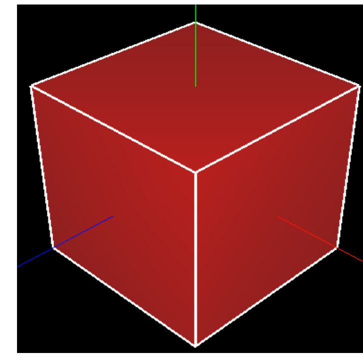
General elastic wave equation

$$F_{total} = \int_V f_i + \int_S \sigma_{ij} n_j = m\ddot{u}_i$$



Gauss Divergence Theorem

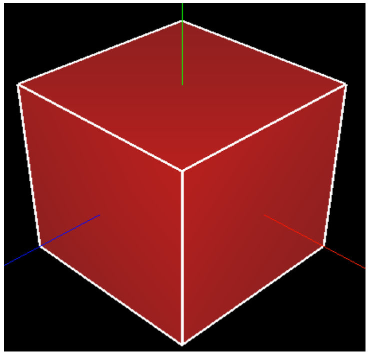
$$\int_S F \cdot n = \int_V \nabla \cdot F$$

$$F_{total} = \int_V f_i + \int_V \partial_j \sigma_{ij} = \int_V \rho \ddot{u}_i$$

$$\rho \ddot{u}_i - \partial_j \sigma_{ij} = f_i$$ Elastic Wegn #1

$$\rho \partial_t v_i - \partial_j \sigma_{ij} = f_i$$ "velocity-stress FD/FEM method"

Linear Stress and Strain



Strain: $e_{k\ell} = \frac{1}{2}(\partial_k u_\ell + \partial_\ell u_k)$

Normal: $k = \ell$ Shear: $k \neq \ell$

Generalized Hooke's Law (linear stress-strain)

$\sigma_{ij} = c_{ijk\ell}\, e_{k\ell}$ $c_{ijk\ell}$: elastic stiffness tensor

$$\rho \ddot{u}_i - \partial_j c_{ijk\ell}\, e_{k\ell} = f_i$$ **Elastic Weqn #2**

Elastic Stiffness Tensor c_{ijkl}

- 81 coefficients in general, but due to symmetry etc.
  - Reduces to **21** independent coefficients

- c_{ijkl} can be written in compact 6x6 Voigt notation as c_{ij}

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} C_{1111} & C_{1122} & C_{1133} & C_{1123} & C_{1113} & C_{1112} \\ & C_{2222} & C_{2233} & C_{2223} & C_{2213} & C_{2212} \\ & & C_{3333} & C_{3323} & C_{3313} & C_{3312} \\ & & & C_{2323} & C_{2313} & C_{2312} \\ & symm & & & C_{1313} & C_{1312} \\ & & & & & C_{1212} \end{bmatrix} \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ 2\epsilon_{23} \\ 2\epsilon_{13} \\ 2\epsilon_{12} \end{bmatrix}$$

www.web.mit.edu

Voigt Elastic Stiffness Tensor c_{ij}

- c_{ijkl} can be written in compact 6x6 Voigt notation as c_{ij}

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} C_{1111} & C_{1122} & C_{1133} & C_{1123} & C_{1113} & C_{1112} \\ & C_{2222} & C_{2233} & C_{2223} & C_{2213} & C_{2212} \\ & & C_{3333} & C_{3323} & C_{3313} & C_{3312} \\ & & & C_{2323} & C_{2313} & C_{2312} \\ & symm & & & C_{1313} & C_{1312} \\ & & & & & C_{1212} \end{bmatrix} \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ 2\epsilon_{23} \\ 2\epsilon_{13} \\ 2\epsilon_{12} \end{bmatrix}$$

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ & & C_{33} & C_{34} & C_{35} & C_{36} \\ & & & C_{44} & C_{45} & C_{46} \\ & symm & & & C_{55} & C_{56} \\ & & & & & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix}$$

www.web.mit.edu

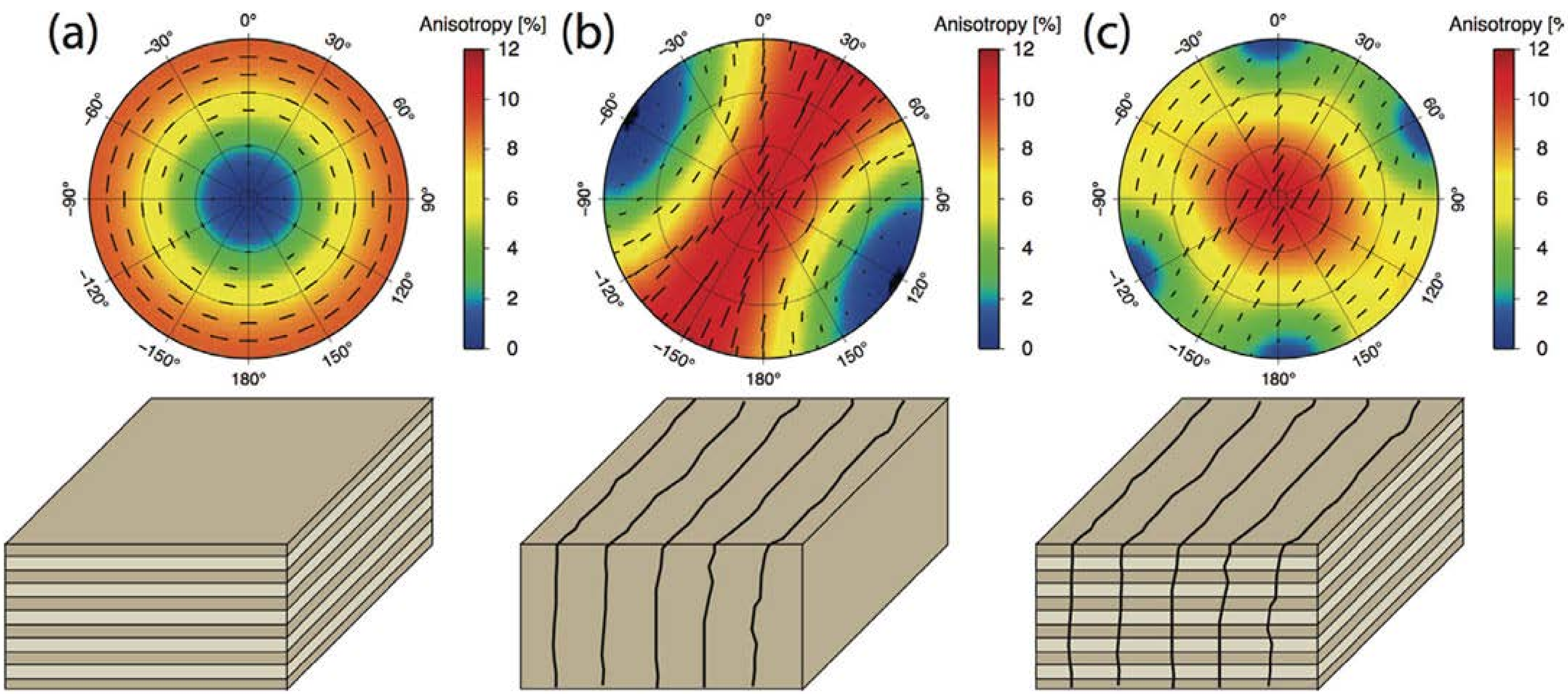
Elastic Stiffness Tensor c_{ijkl}

- Isotropic
  - 2 independent coefficients… λ and μ… "*Lamé parameters*"

$$\{c_{ij}\} = \begin{pmatrix} \lambda+2\mu & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda+2\mu & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & \lambda+2\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & 2\mu & 0 & 0 \\ 0 & 0 & 0 & 0 & 2\mu & 0 \\ 0 & 0 & 0 & 0 & 0 & 2\mu \end{pmatrix}.$$

Seismic Anisotropy

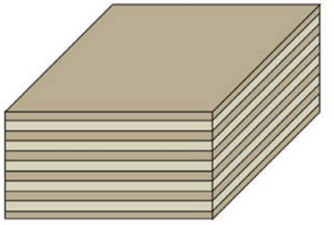
VTI HTI Ortho



after Kendall et al., CSEGR 2014

Elastic Stiffness Tensor c_{ijkl}

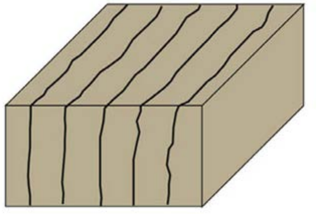
- VTI (polar) anisotropy
  - 5 independent coefficients **$*C_{12} = C_{11} - 2C_{66}$**



$$C_{\mathrm{VTI}} = \begin{bmatrix} c_{11} & c_{12}^{*} & c_{13} & 0 & 0 & 0 \\ c_{12}^{*} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix}$$

Elastic Stiffness Tensor c_{ijkl}

- HTI (azimuthal) anisotropy
  - 5 independent coefficients



$$\mathbf{c}^{(HTI)} = \begin{bmatrix} c_{11} & c_{13} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{33} & c_{33}-2c_{44} & 0 & 0 & 0 \\ c_{13} & c_{33}-2c_{44} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{55} \end{bmatrix}$$

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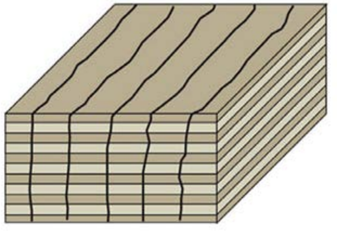
Elastic Stiffness Tensor c_{ijkl}

- Orthorhombic anisotropy
  - 9 independent coefficients



$$\mathbf{C} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}.$$

Elastic Stiffness Tensor c_{ijkl}

- Monoclinic anisotropy
  - 13 independent coefficients

$$
\mathbf{C}' = \begin{bmatrix} c'_{11} & c'_{12} & c'_{13} & 0 & 0 & c'_{16} \\ c'_{12} & c'_{22} & c'_{23} & 0 & 0 & c'_{26} \\ c'_{13} & c'_{23} & c'_{33} & 0 & 0 & c'_{36} \\ 0 & 0 & 0 & c'_{44} & c'_{45} & 0 \\ 0 & 0 & 0 & c'_{45} & c'_{55} & 0 \\ c'_{16} & c'_{26} & c'_{36} & 0 & 0 & c'_{66} \end{bmatrix}
$$

Isotropic elastic wave equation

$$\rho \ddot{u}_i - \partial_j c_{ijkl} e_{kl} = f_i$$ Weqn#2

$$\rho \underline{\ddot{u}} - \nabla \cdot \underline{c} : (\nabla \underline{u} + \nabla \underline{u}^T)/2 = \underline{f}$$

substitute $\underline{c}_{iso}$; assume ~homogeneous: $\partial\lambda, \partial\mu \sim 0$

$$\rho \underline{\ddot{u}} = \underline{f} + \rho Vp^2 \nabla(\nabla \cdot \underline{u}) - \rho Vs^2 \nabla \times (\nabla \times \underline{u})$$ #3

P-wave velocity: $Vp^2 = (\lambda + 2\mu)/\rho$

S-wave velocity: $Vs^2 = \mu / \rho$

P-wave scalar wave equation (iso)

$$\rho \ddot{\underline{u}} = \underline{f} + \rho Vp^2 \nabla(\nabla \cdot \underline{u}) - \rho Vs^2 \nabla \times (\nabla \times \underline{u}) \quad \#3$$

Take Divergence of Eqn #3… let $P = \nabla \cdot \underline{u}$

$$(\partial_{tt} - Vp^2 \nabla^2) P(\underline{x},t) = \delta_p(\underline{x},t) \qquad \text{Weqn \#4}$$

P-wave velocity: $Vp^2 = (\lambda + 2\mu)/ \rho$

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S-wave vector wave equation (iso)

$$\rho \underline{\ddot{u}} = \underline{f} + \rho Vp^2 \nabla(\nabla \cdot \underline{u}) - \rho Vs^2 \nabla \times (\nabla \times \underline{u}) \quad \#3$$

Take Curl of Eqn #3… let $\underline{Q} = \nabla \times \underline{u}$

$$(\partial_{tt} - Vs^2 \nabla^2) \underline{Q}(\underline{x},t) = \underline{\delta}_s(\underline{x},t) \qquad \text{Wegn \#5}$$

S-wave velocity: $Vs^2 = \mu / \rho$

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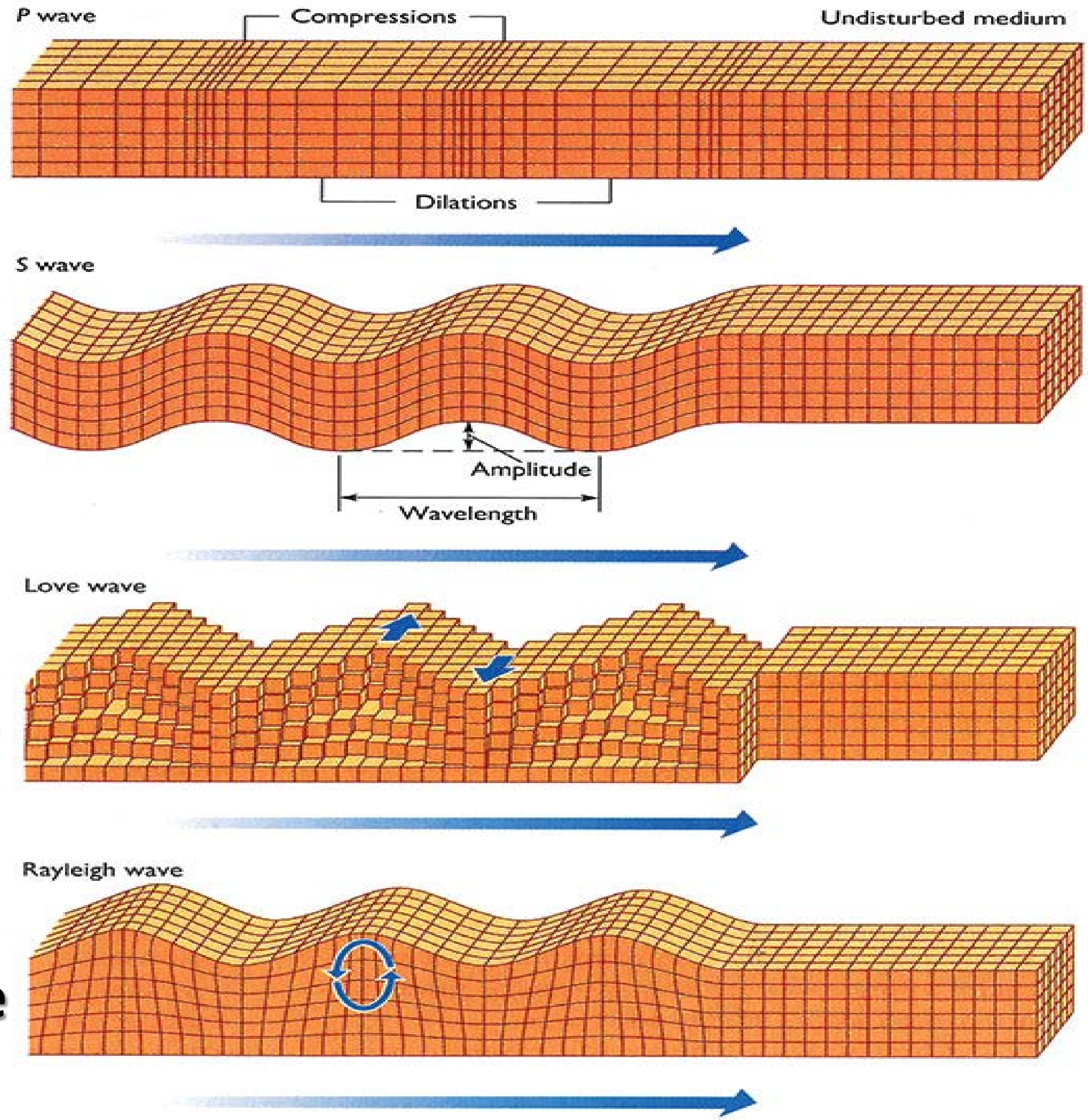

P wave

S wave

Love wave

Rayleigh wave

Sources, Sensors, Acquisition geometry

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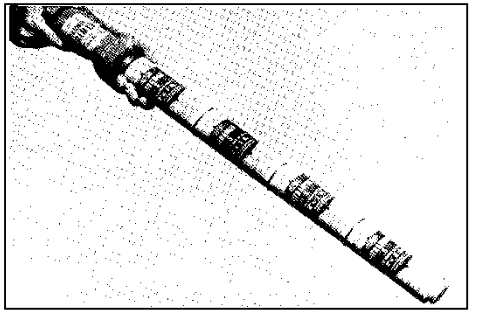
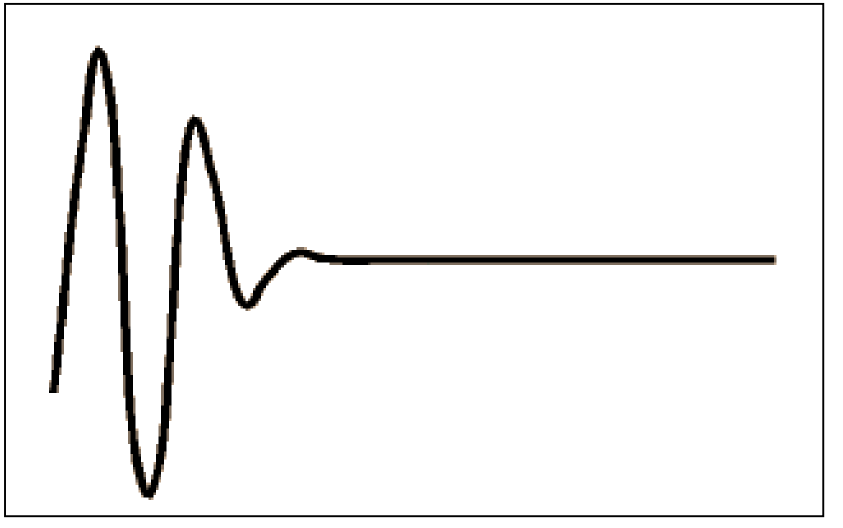
land sources - dynamite



“impulsive” signal



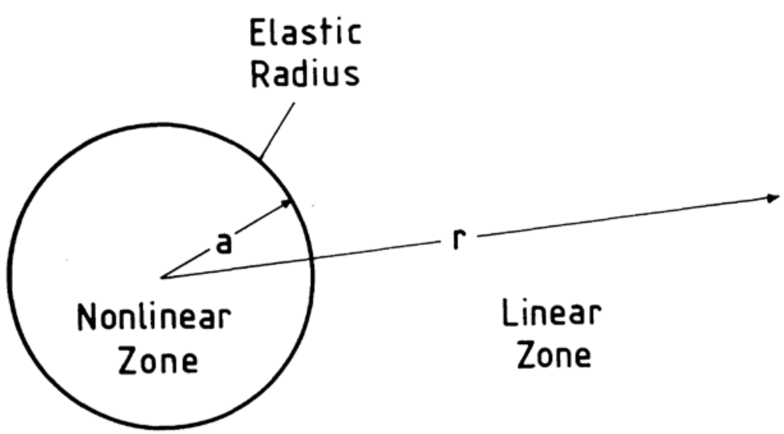
$s(t) = \sin(wt)\, e^{-at}$

land sources - dynamite

$$u(r,t) = \frac{1}{r^2}\,F\left(t - \frac{r}{v}\right) + \frac{1}{r\,v}\,F'\left(t - \frac{r}{v}\right); \quad t \geq r/v;\ r > a$$

near field
r <1 wavelength

far field
r >>1 wavelength



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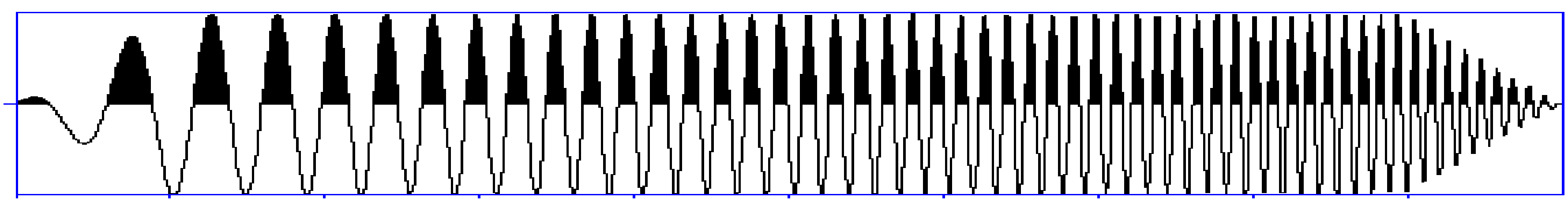
land sources - vibroseis

Conoco

$$s(t) = \sin(2\pi f_0 t + \pi k t^2)$$

f_0 = starting frequency
$k = (f_1 - f_0)/t_1$ = chirp rate

"chirp" signal



land source array

Geokinetics

marine sources - airgun

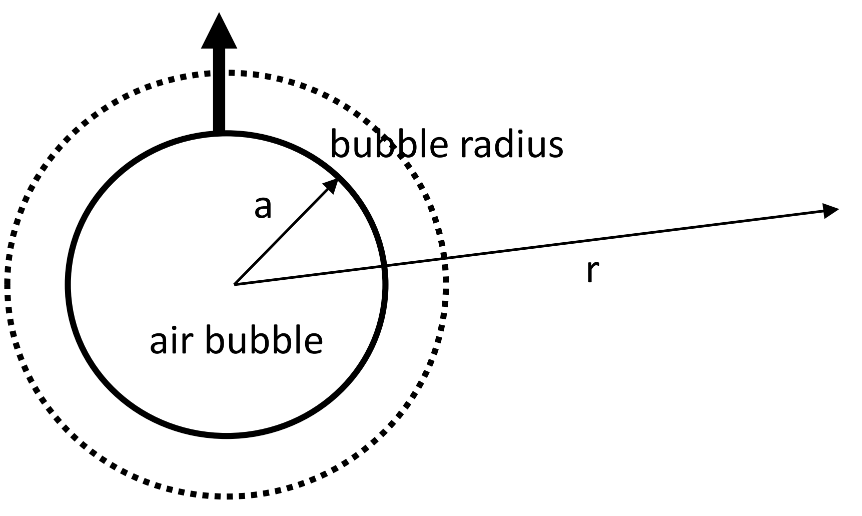
Bolt Technologies

marine sources - airgun

$$u(r,t) = \frac{1}{r^2}\, F\left(t - \frac{r}{v}\right) \;+\; \frac{1}{r\,v}\, F'\left(t - \frac{r}{v}\right)\;; \qquad t \geq r/v\;;\; r > a$$

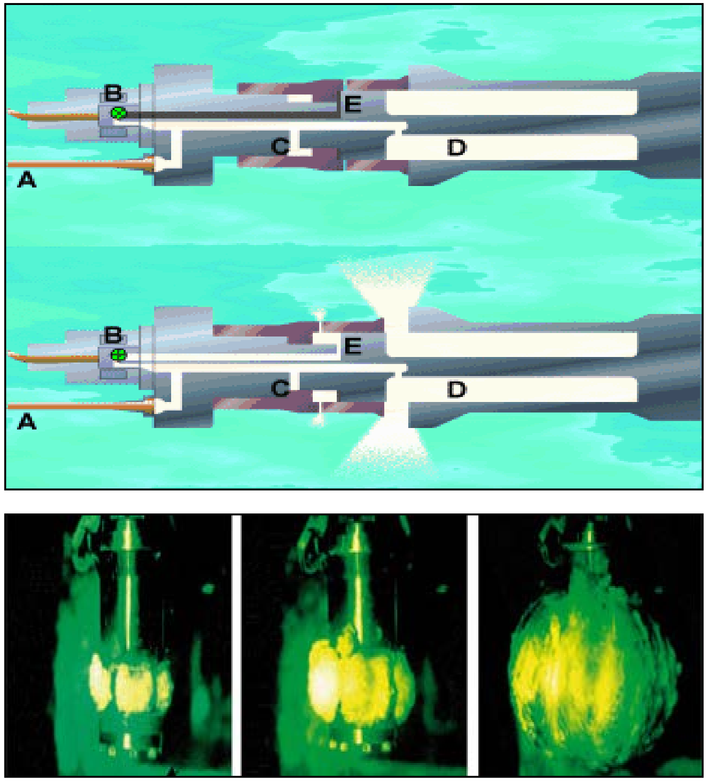
near field
r <1 wavelength

far field
r >>1 wavelength



marine sources - airgun

"impulsive" signal



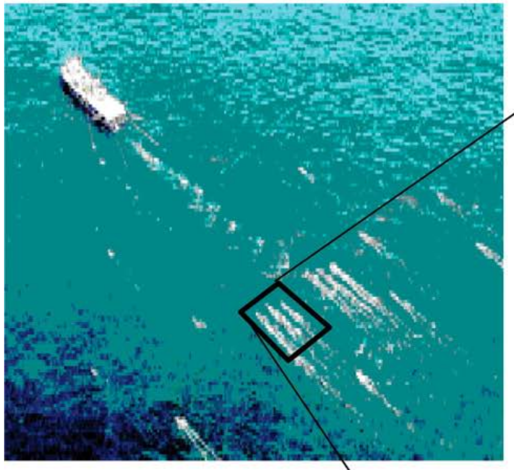
GeoExpro

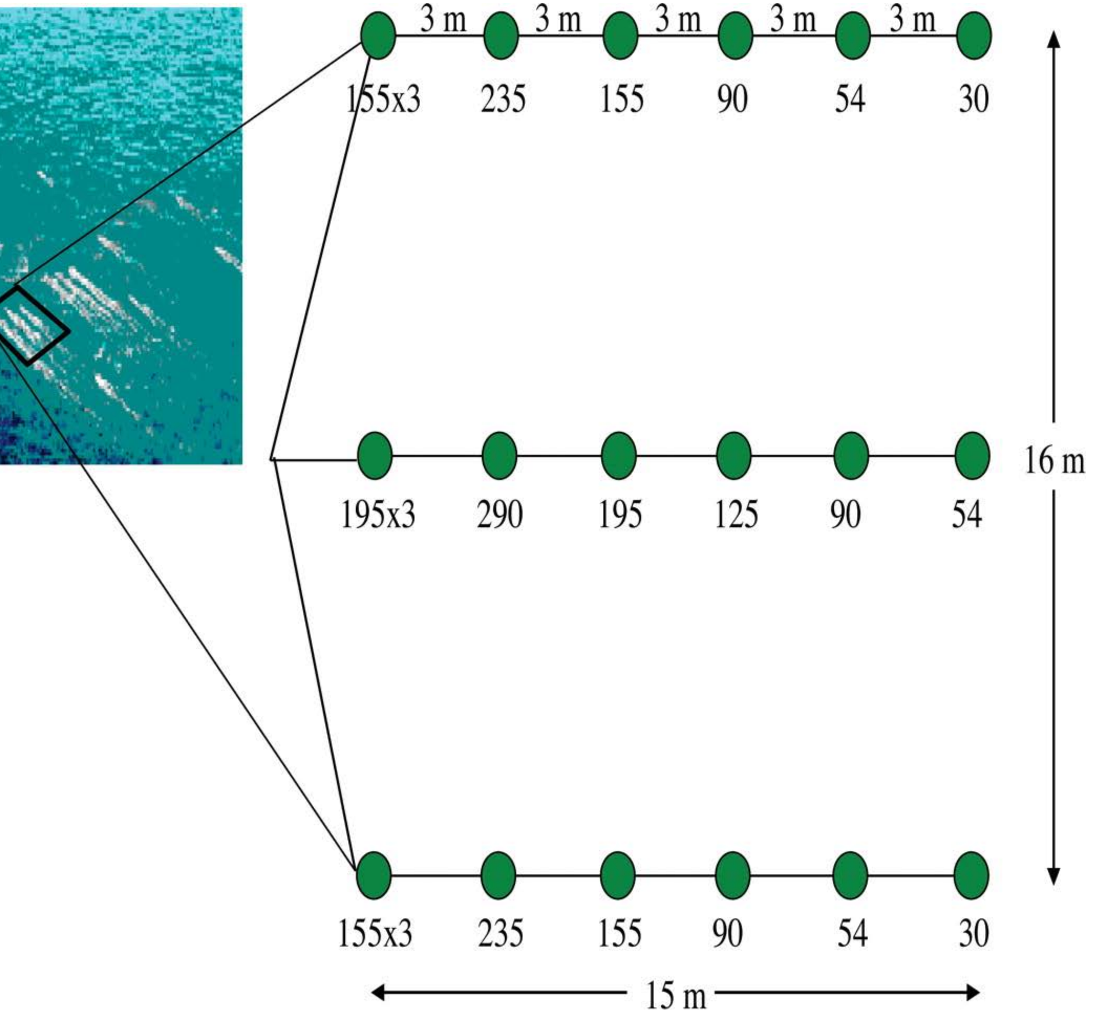
air gun array

marine airgun array

fugro

marine airgun array





dragoset, TLE, 2000

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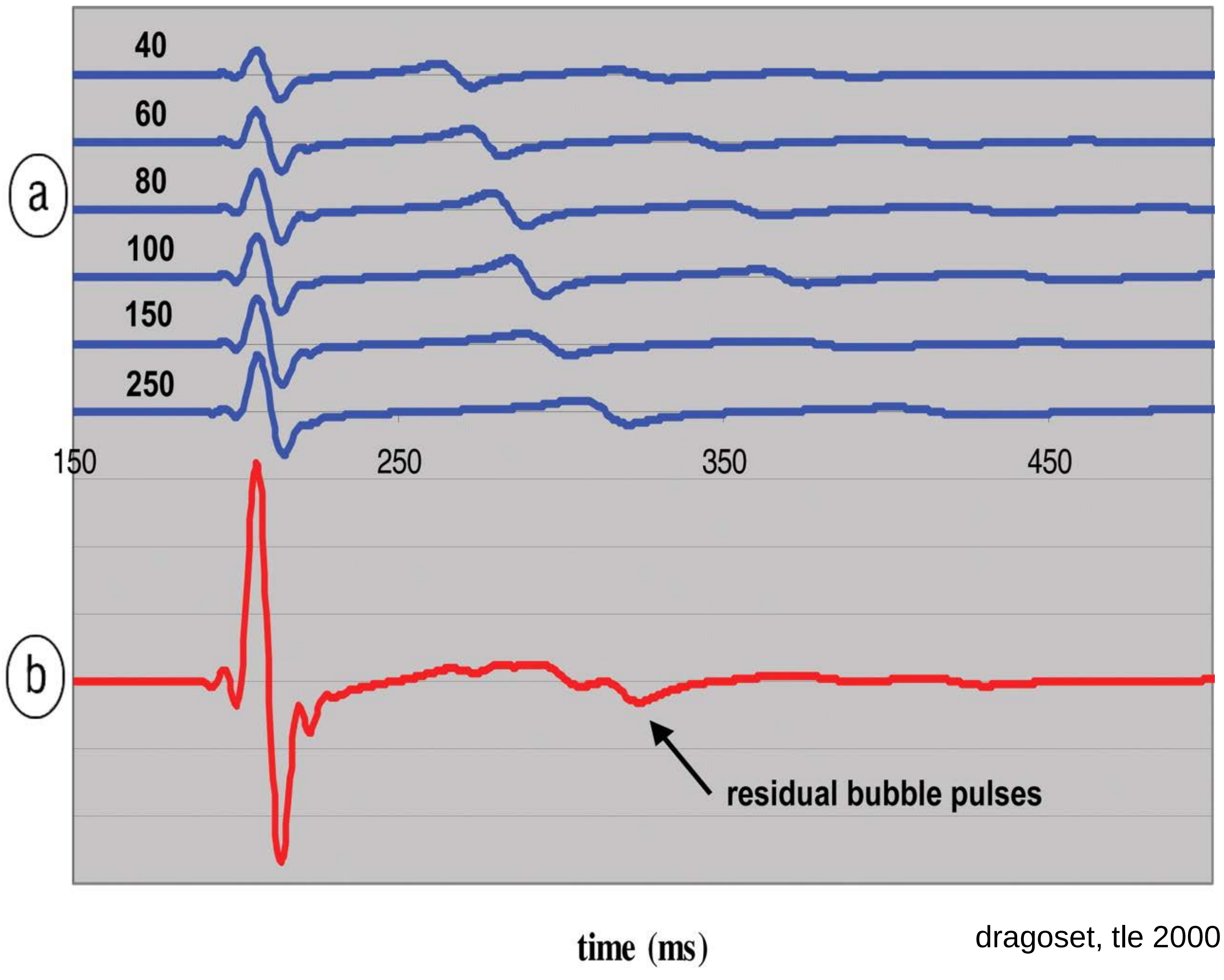
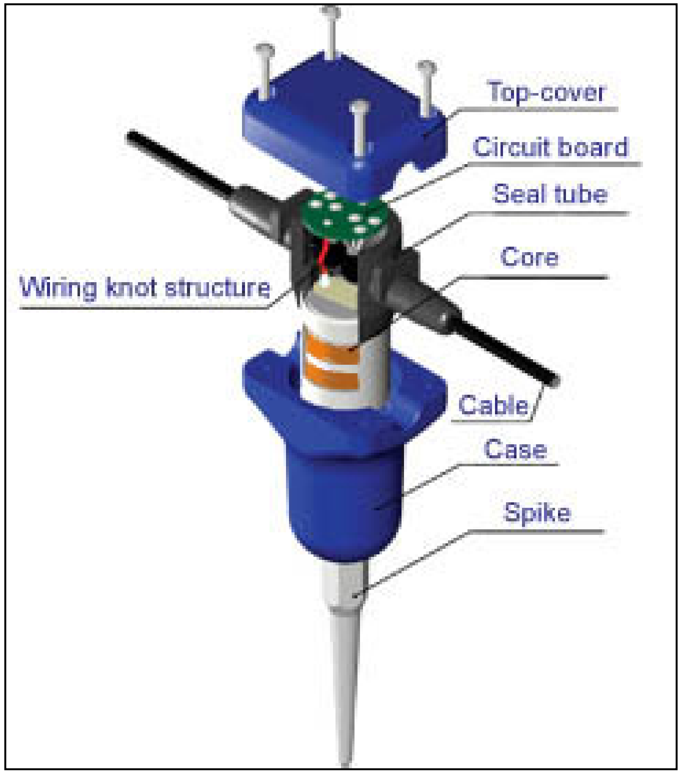
marine airgun array



dragoset, tle 2000

land receivers - geophone



output

spring-mounted magnet
moving in a coil = voltage
~ particle velocity

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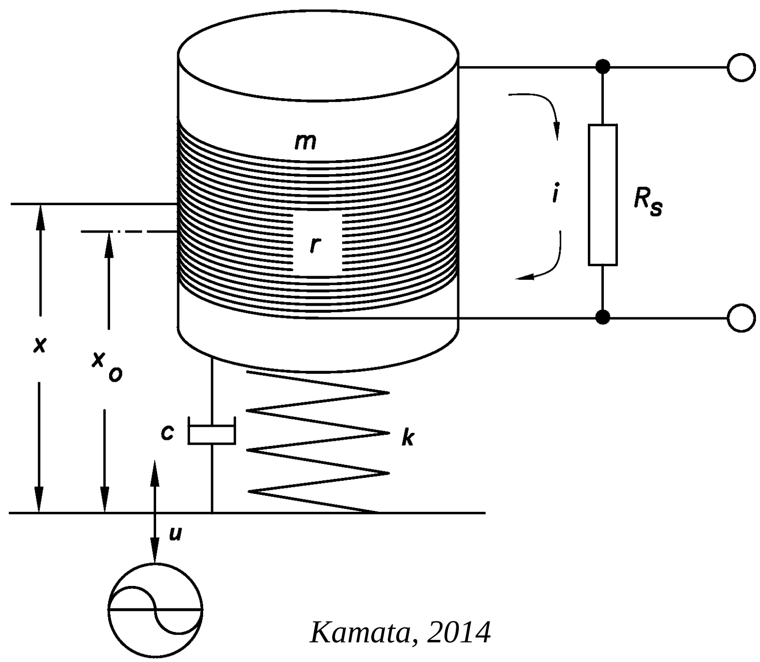
land receivers - geophone

$$e(t) = K/\omega \; e^{-\sigma(t-t_0)} \sin(\omega(t-t_0)) \, H(t-t_0) \quad \text{volts}$$



Kamata, 2014

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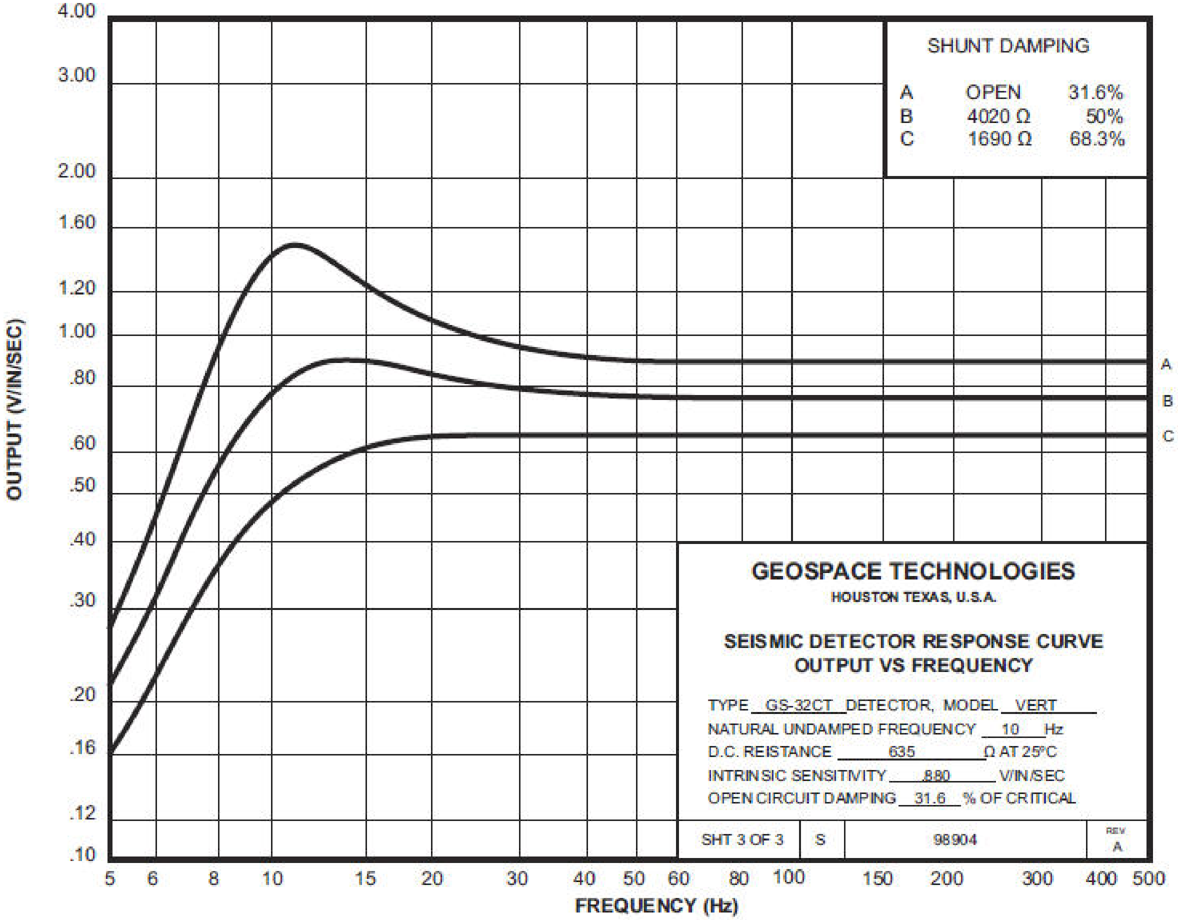
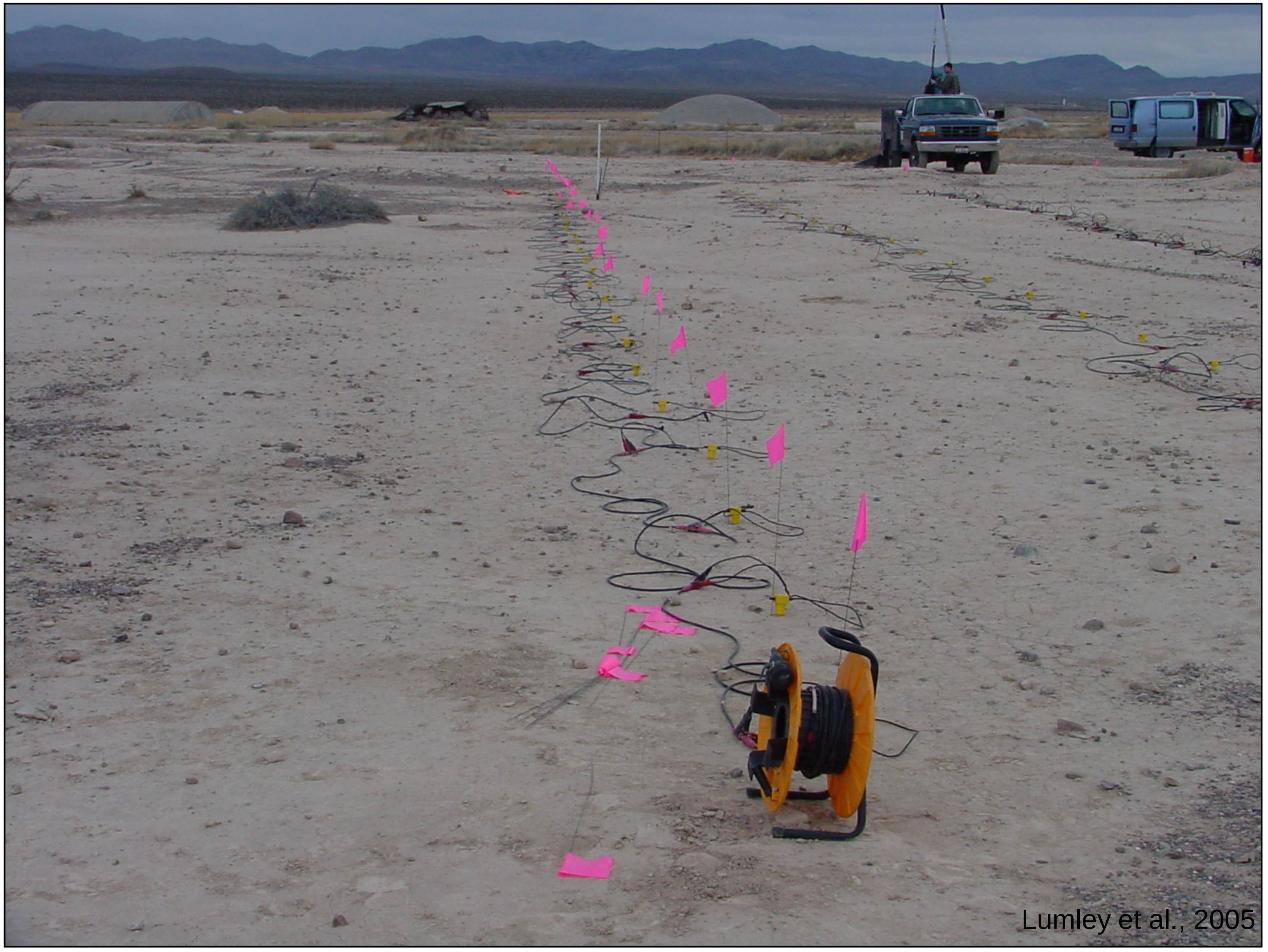
geophone response



Geospace

land receiver array


Lumley et al., 2005

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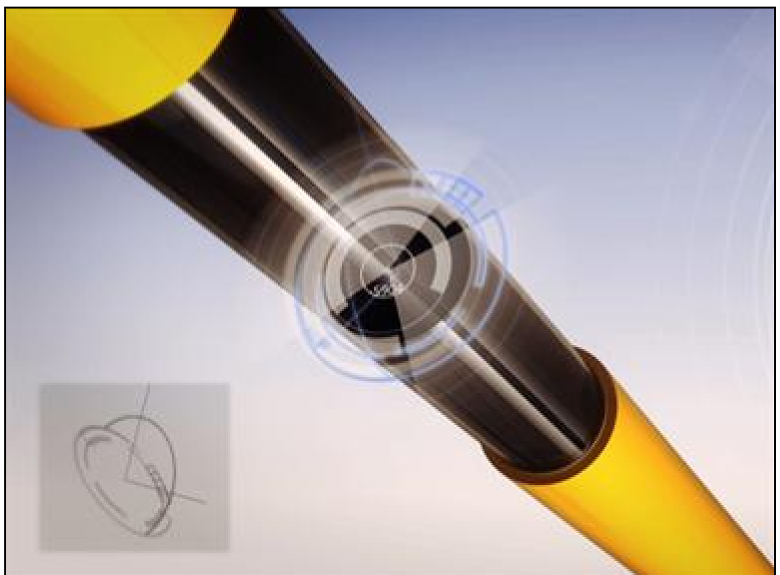
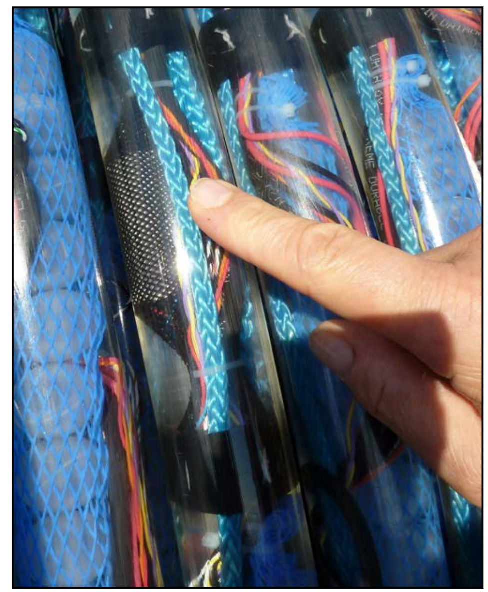
marine receivers - hydrophone

piezoelectric material
generates a voltage when stressed/strained
~ pressure



Sercel



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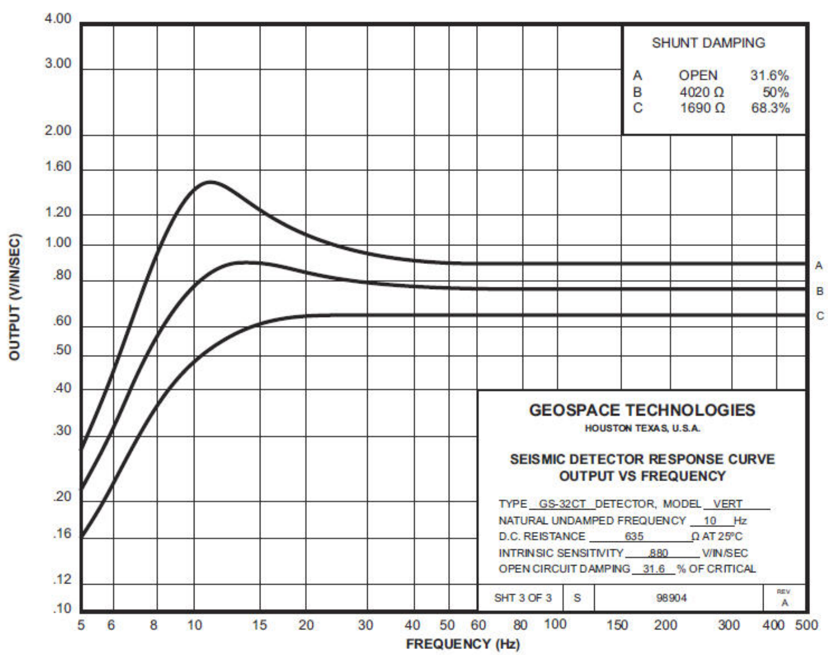
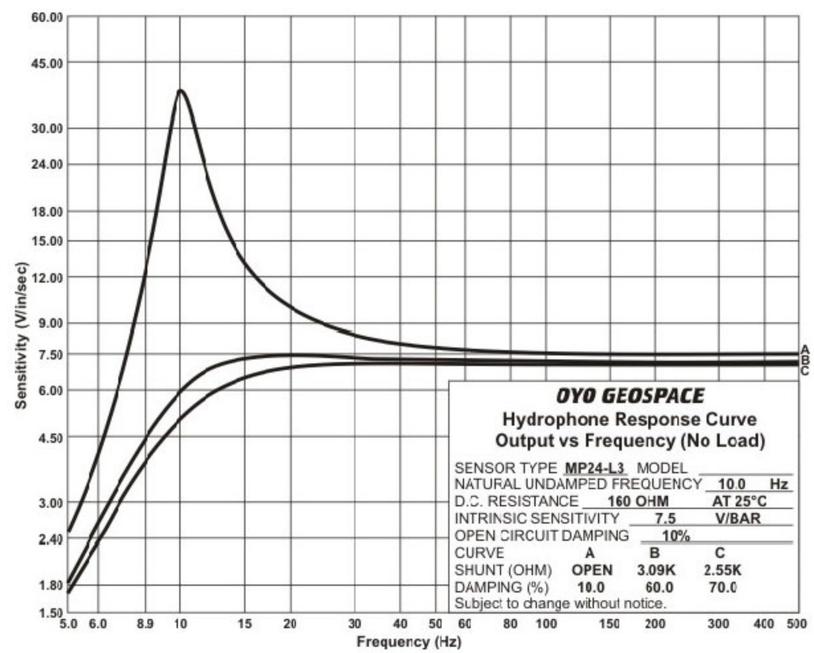
geophone + hydrophone response

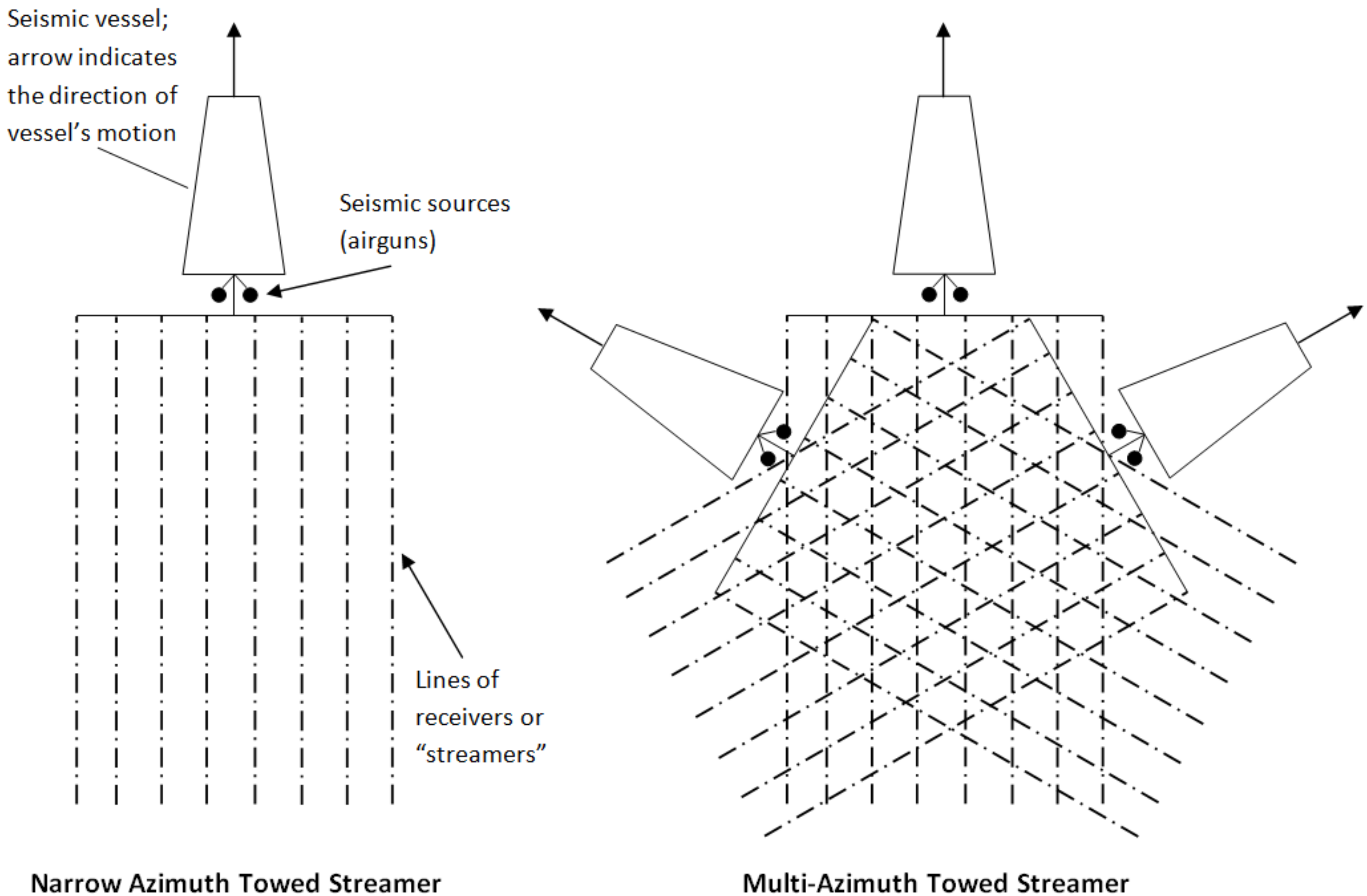




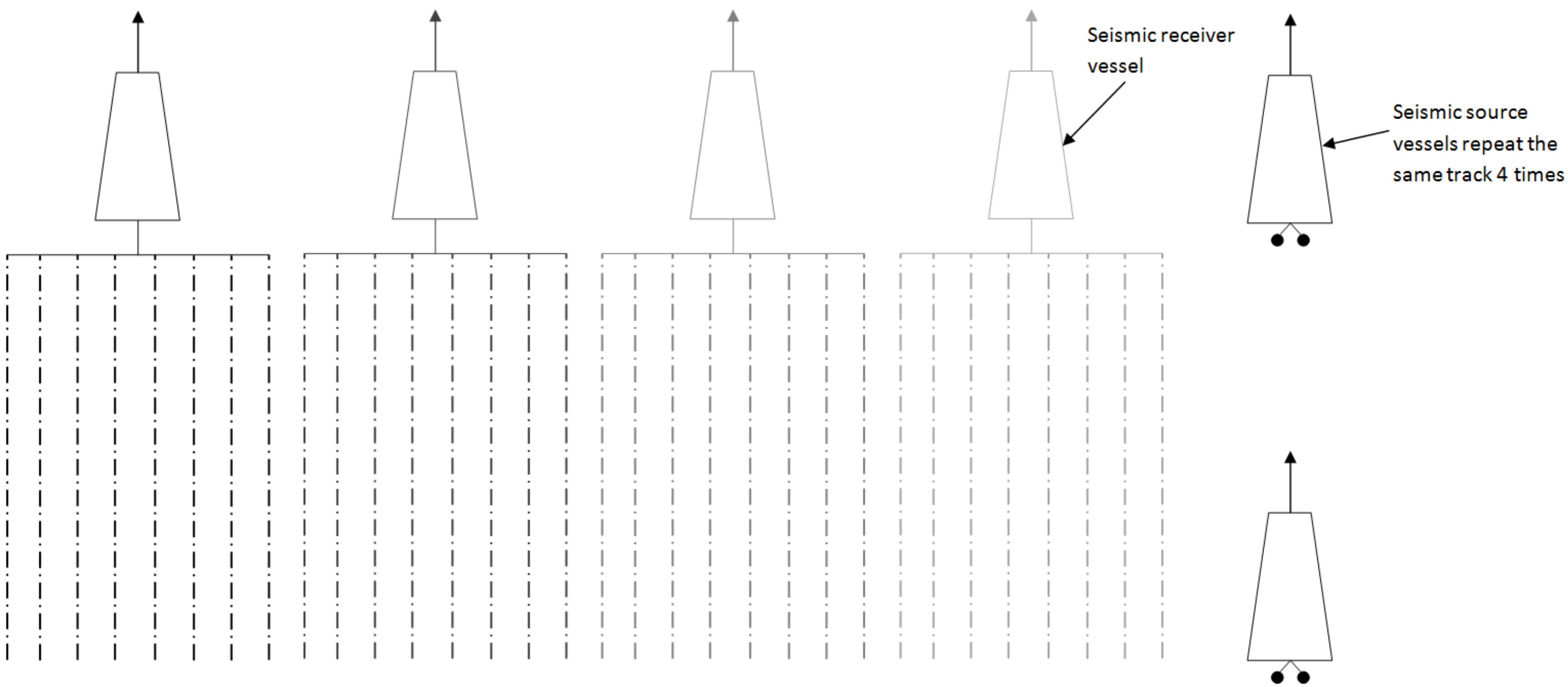
Geospace

seismic boat – streamer deck

fugro


Seismic vessel;
arrow indicates
the direction of
vessel's motion
Seismic sources
(airguns)
Lines of
receivers or
"streamers"
Narrow Azimuth Towed Streamer
Multi-Azimuth Towed Streamer

Wikipedia

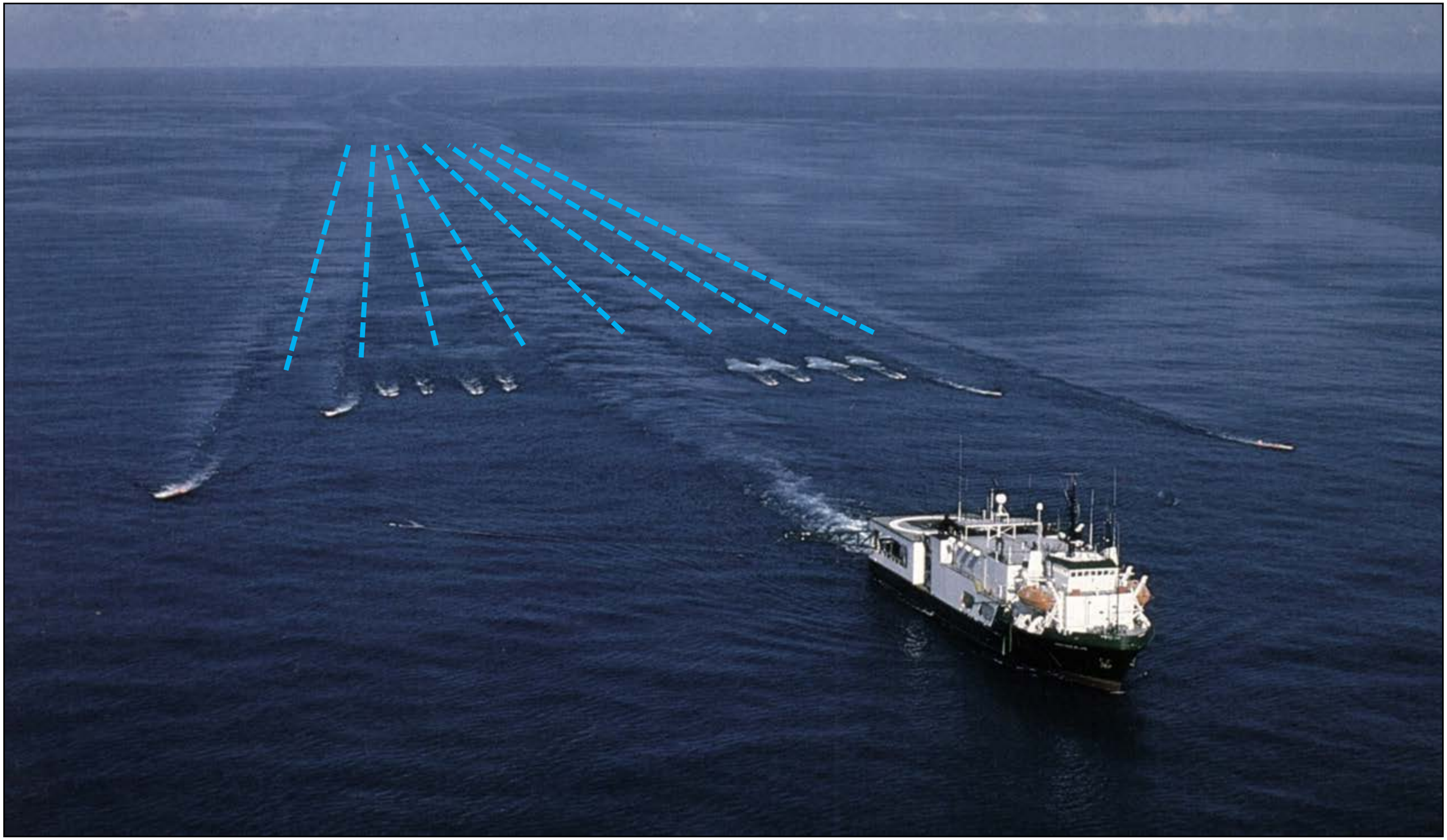


Wide Azimuth Towed Streamer

Seismic receiver vessel repeats 4 parallel tracks to give the effect of a survey with 4 x as many receivers; arrows indicates the direction of each vessel's motion

Wikipedia

marine receiver array



after Dragoset, TLE, 2005

Marine seismic acquisition

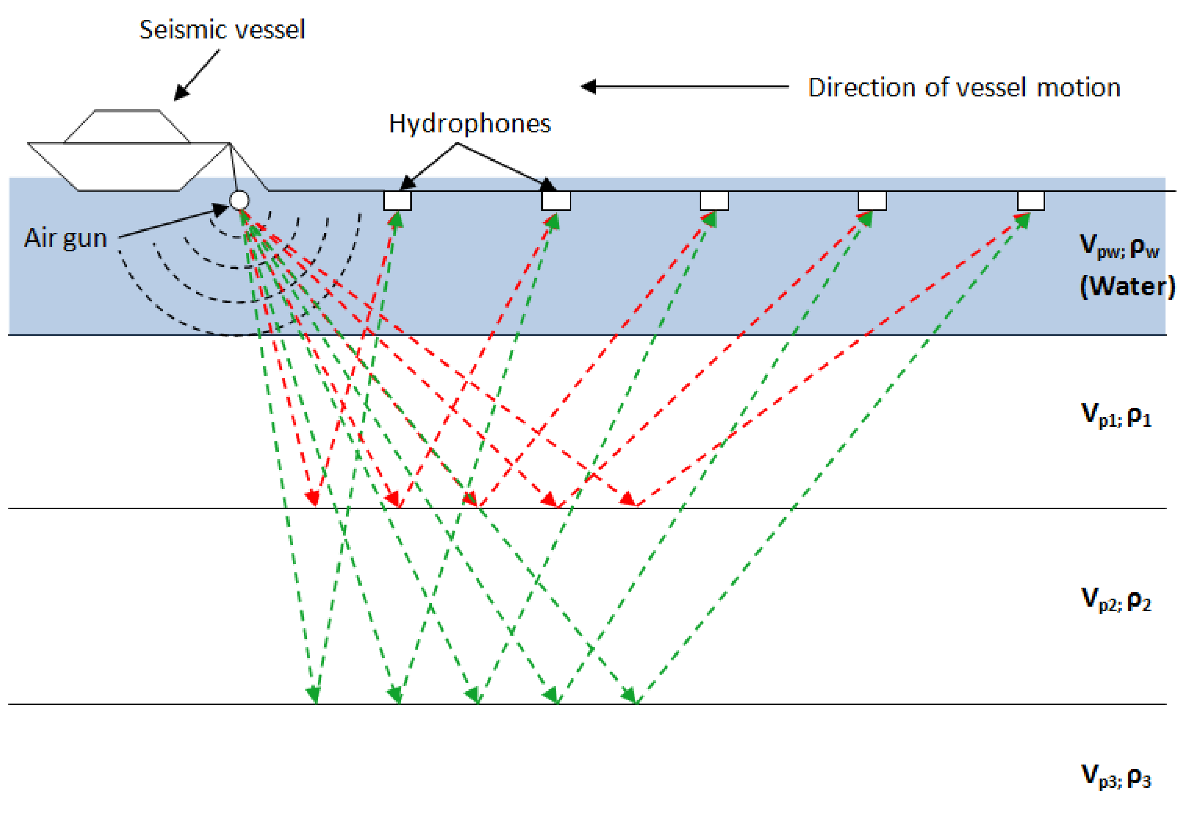


Diagram of a marine towed streamer seismic survey with the raypaths that result from a single shot by an airgun into a streamer containing 5 hydrophones.
--- = raypaths to first reflector; --- = raypaths to second reflector;

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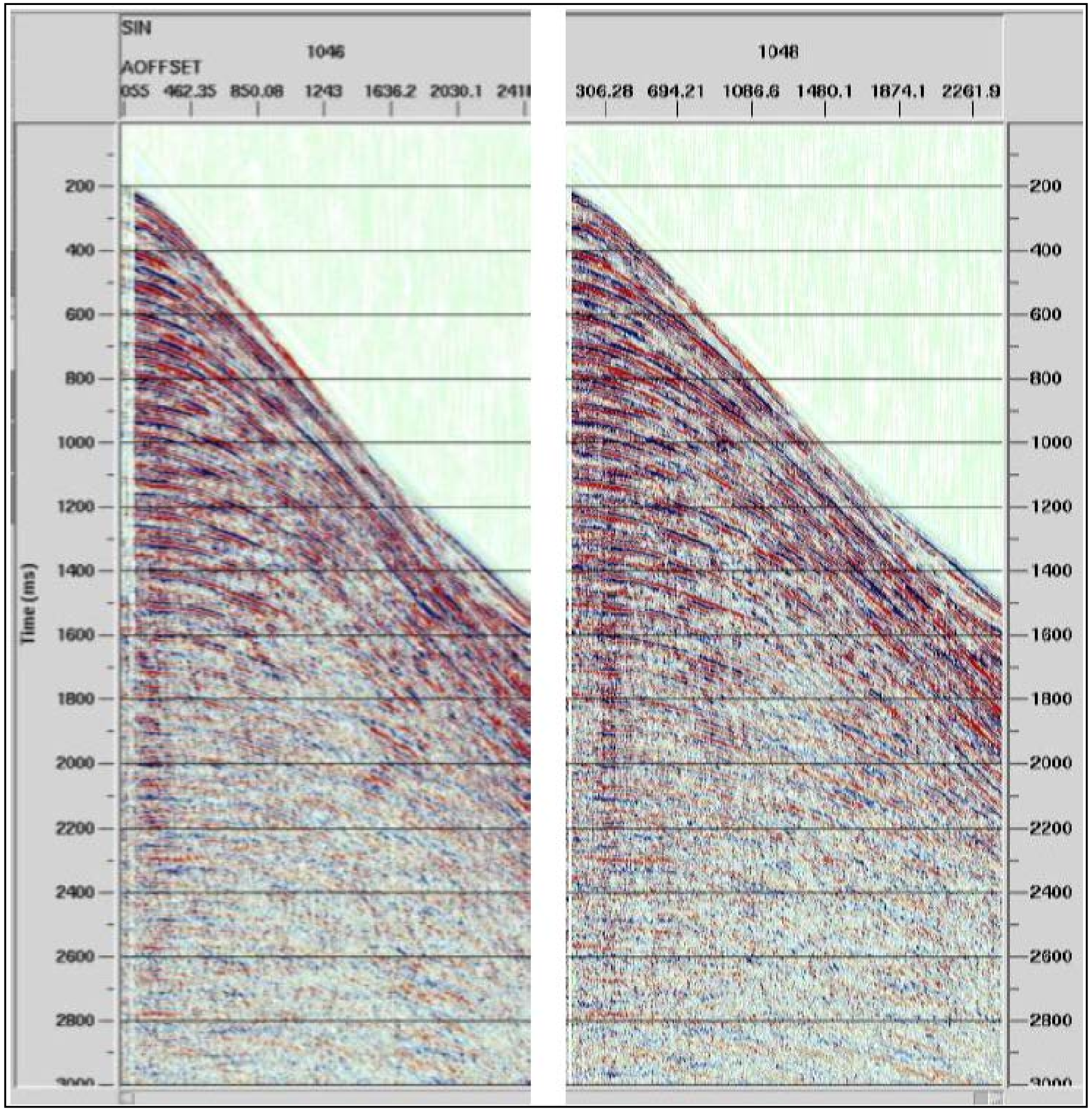
real shot gathers



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marine vessel processing room

lindsey sharp, fugro

Rock and Fluid Physics

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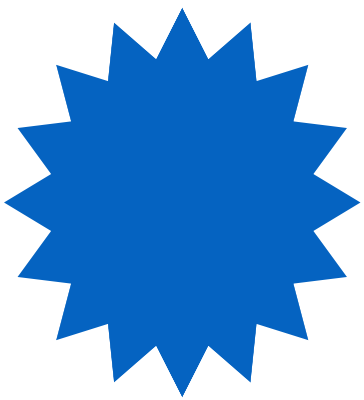
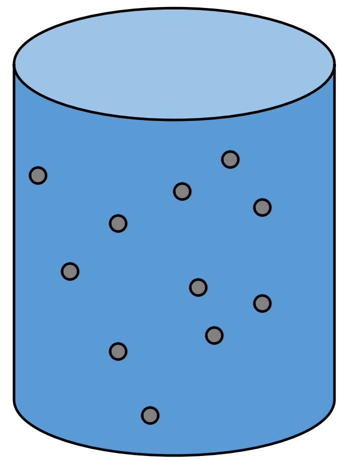
sponge



porous rock



Lumley

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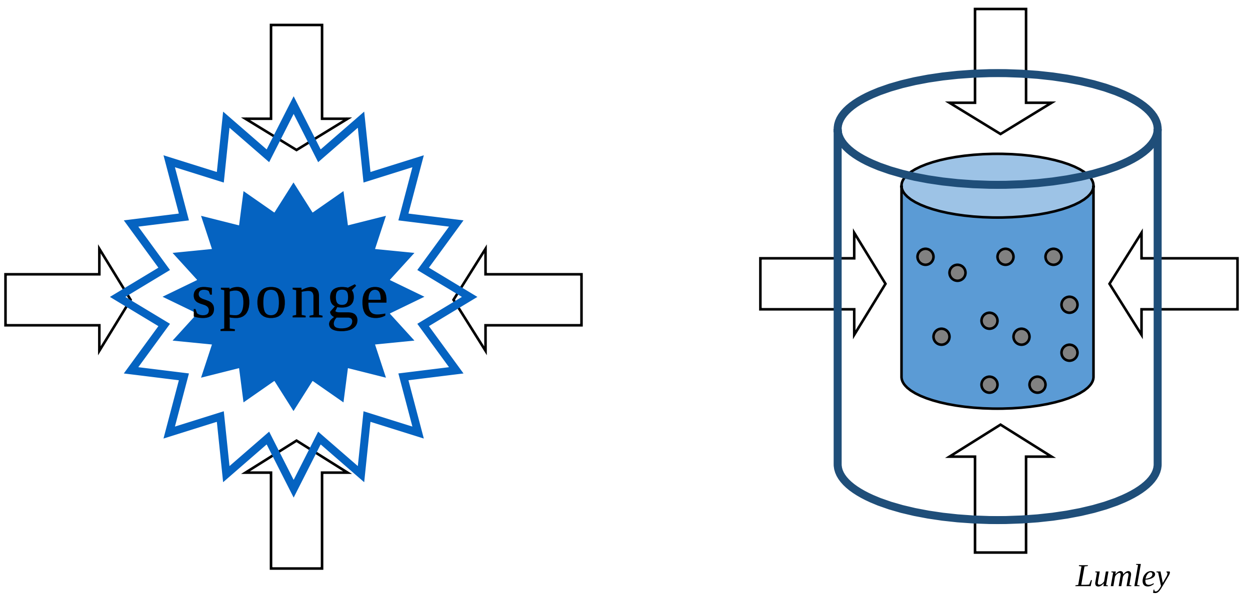
compression

- sensitive to rock compressibility
- sensitive to both pore fluids & pressure



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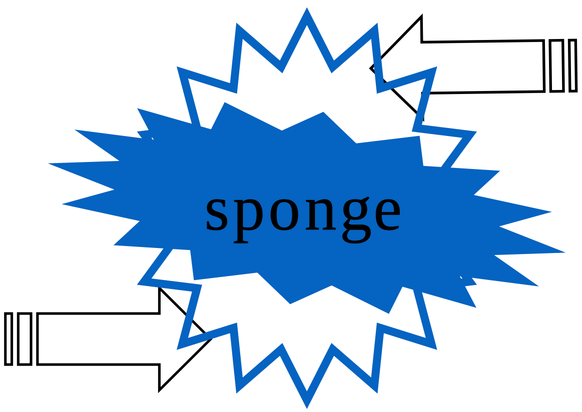
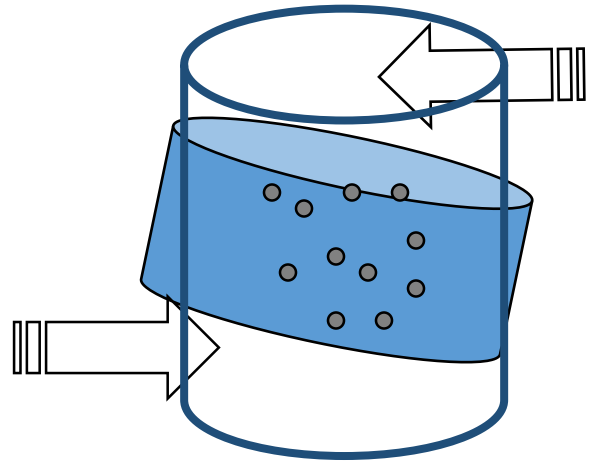
shear

- sensitive to rock shear strength
- sensitive to pore pressure but not fluids





Lumley

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seismic velocity and impedance

- **Two types of velocity: v_p and v_s**
  - P-waves $v_p = \alpha = \text{sqrt}\{ (K + 4G/3)/\rho \}$
  - S-waves $v_s = \beta = \text{sqrt}\{ G/\rho \}$

- ***Z* = impedance = velocity * density = *v* * ρ**
  - K = *bulk modulus (stiffness)* $= \lambda + 2\mu/3$
  - G = *shear modulus (shear strength)* $= \mu$
  - ρ = *density*

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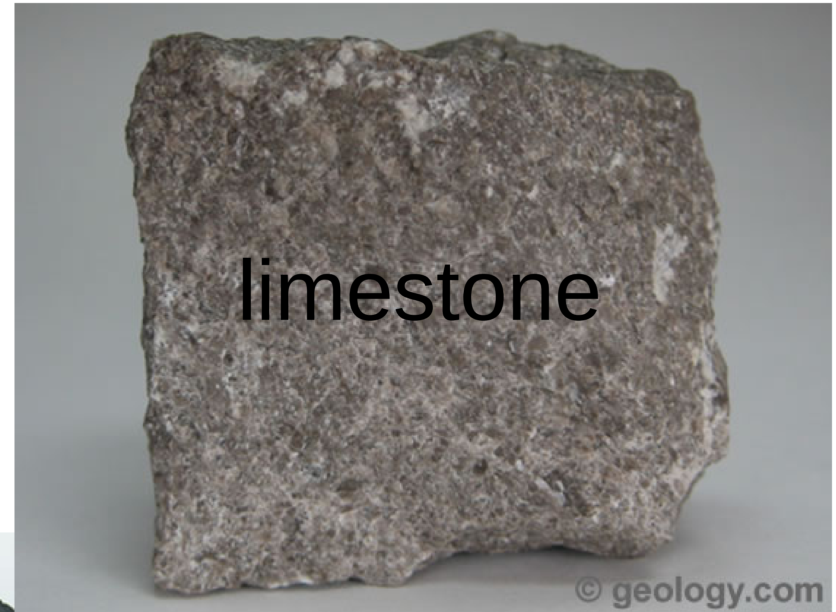
sedimentary rocks



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hydrocarbon reservoirs

- sediments deposited into oceans
- sediments contain organic material (plant matter)
- buried, compressed and cooked in earth
  - ***coal*** *formed at low P, low T*
  - ***oil*** *formed at med P, med T, ie. the "oil window"*
  - ***gas*** *formed under various P,T conditions*

- rock pores contain fluids (water, oil, gas…)

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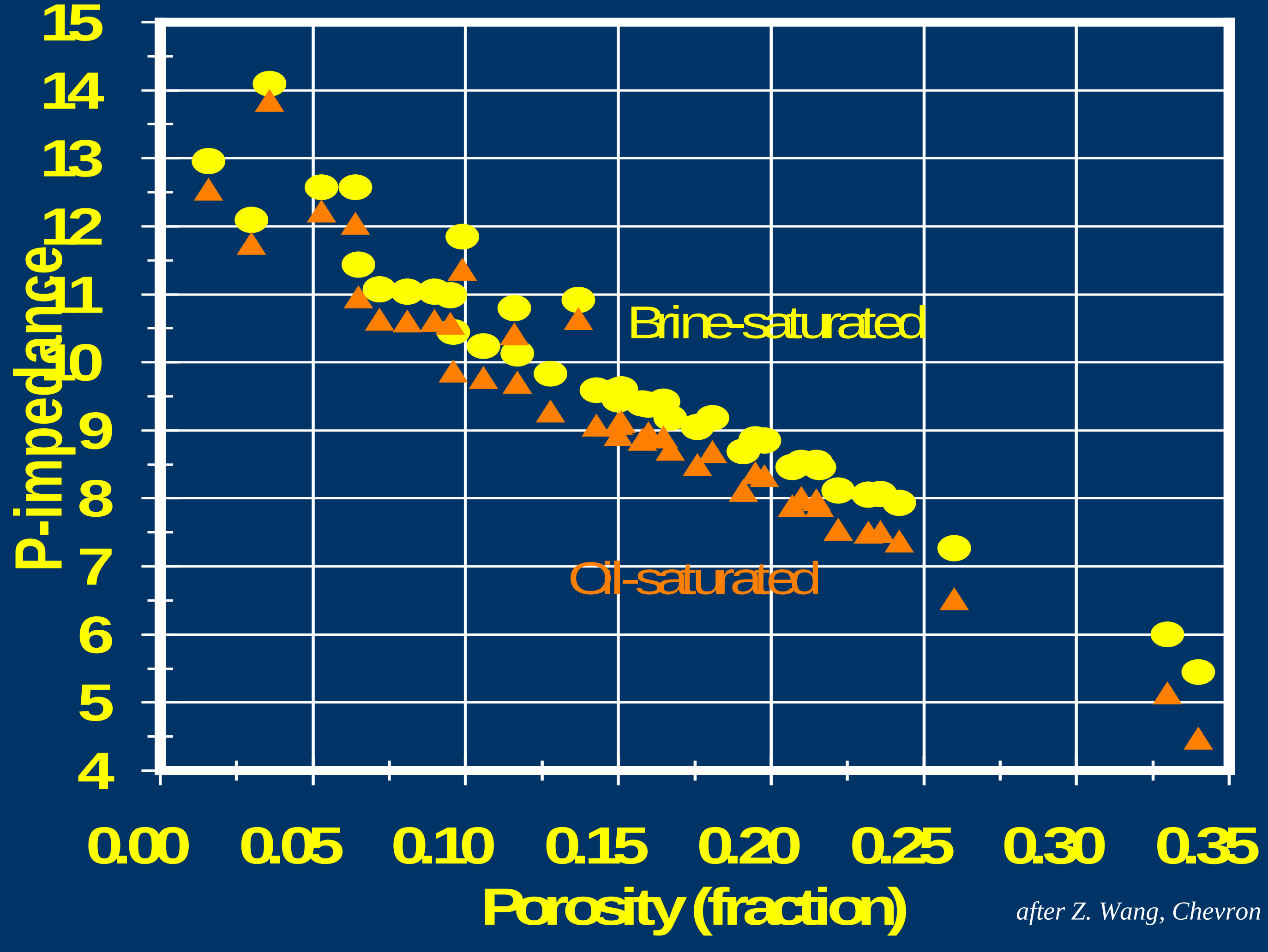
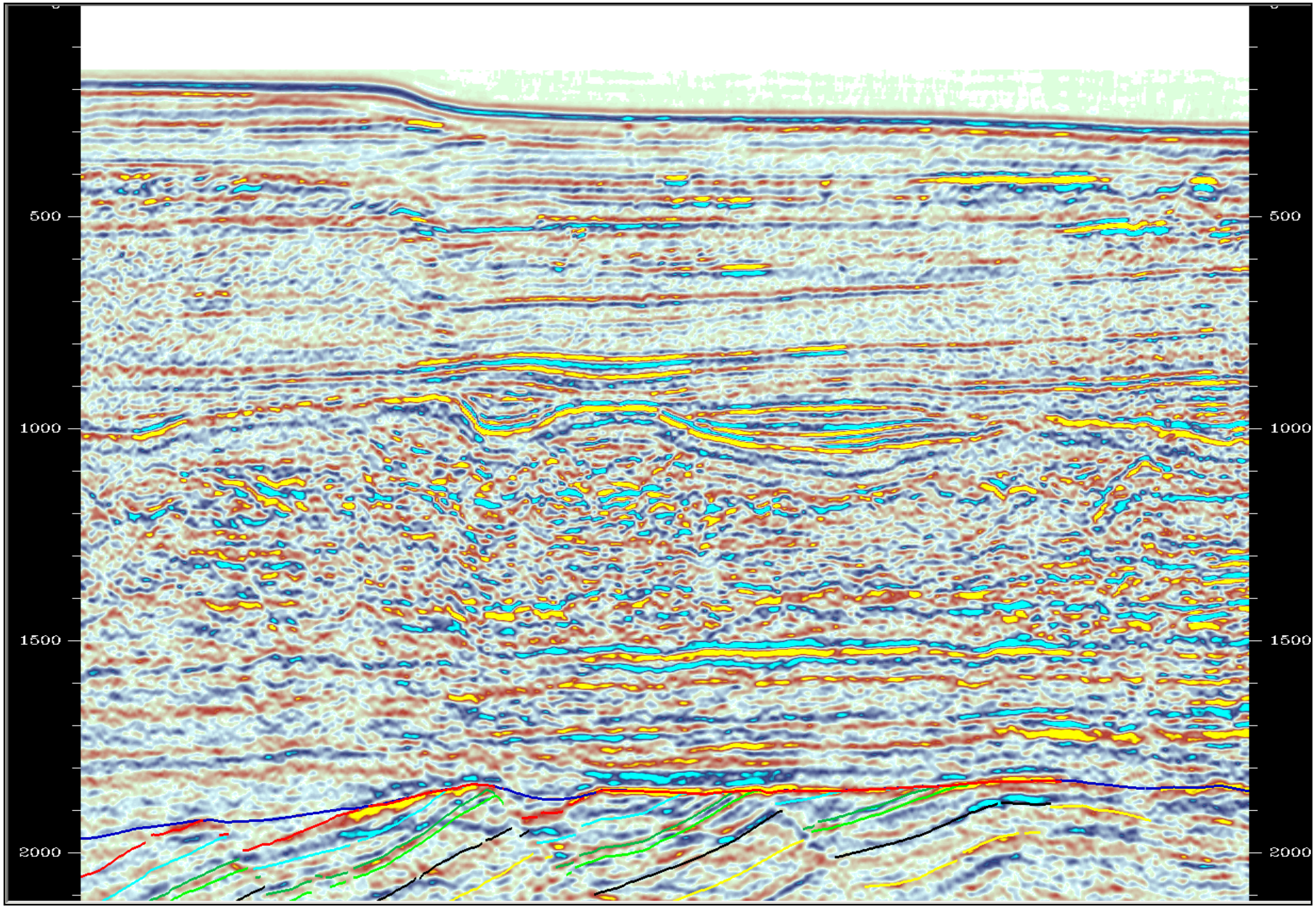
Gulf Coast and Alaska Sand Samples



after Z. Wang, Chevron

Seismic Image – 2D *cross-section*



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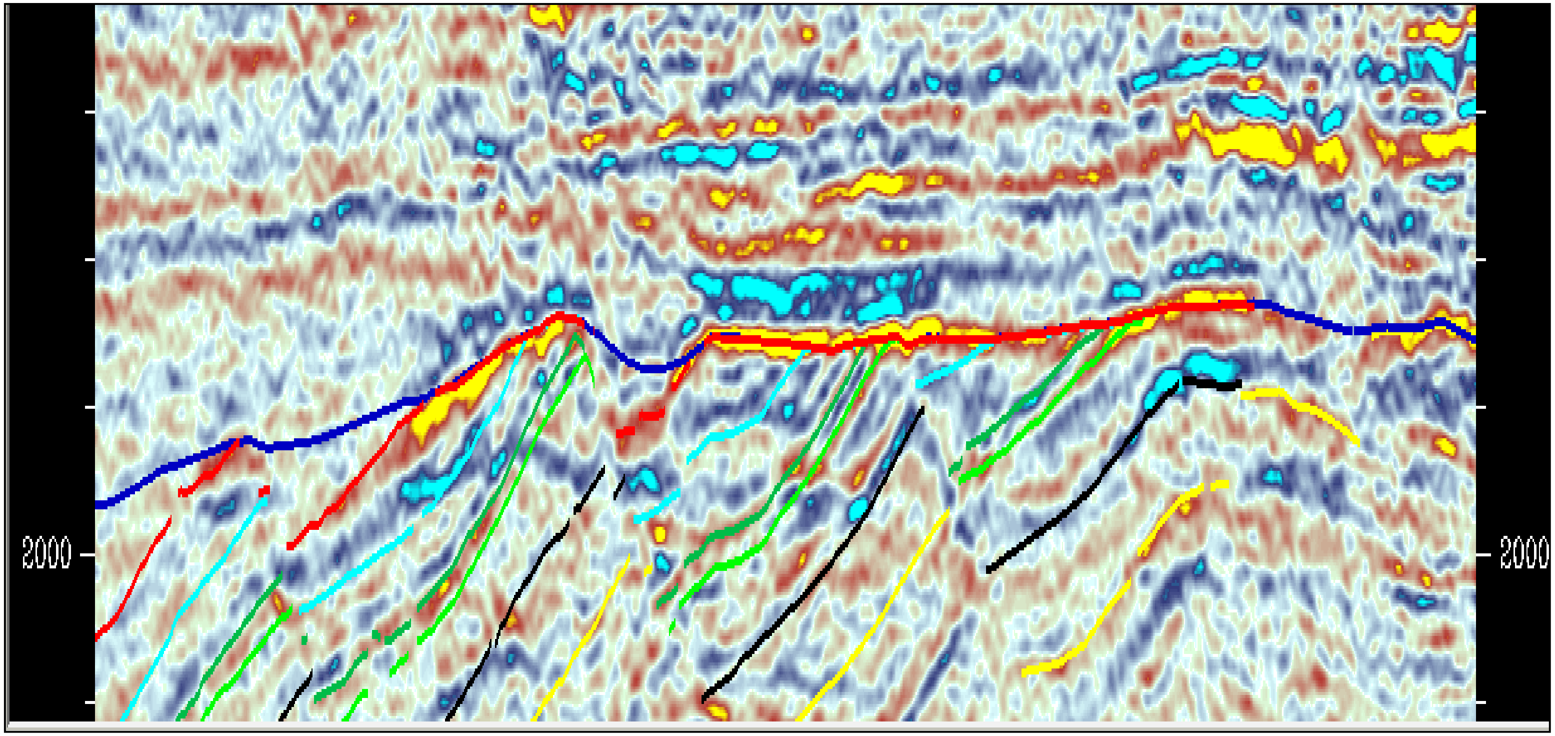
Seismic Image – *zoom on reservoirs*



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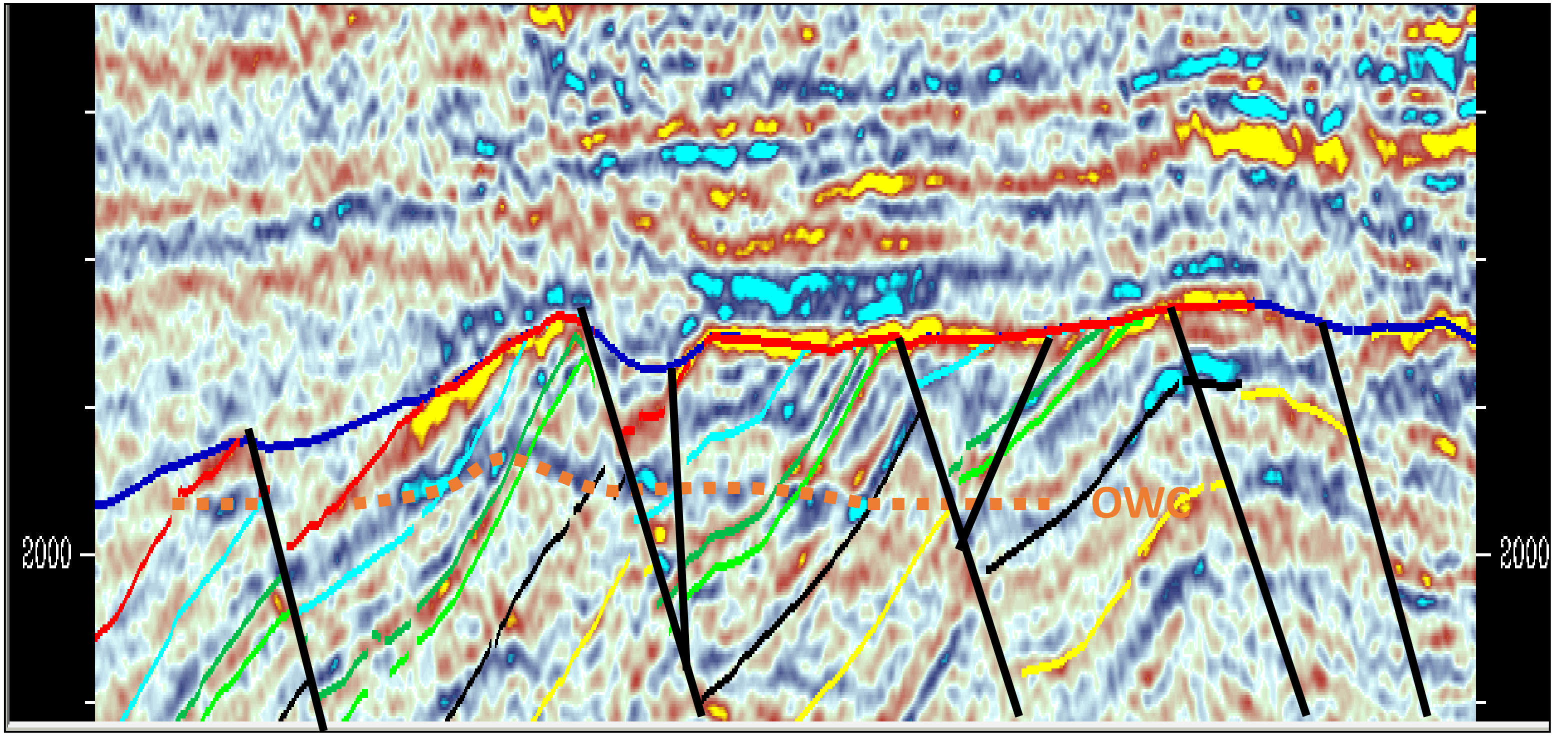
Seismic Image – *zoom on reservoirs*



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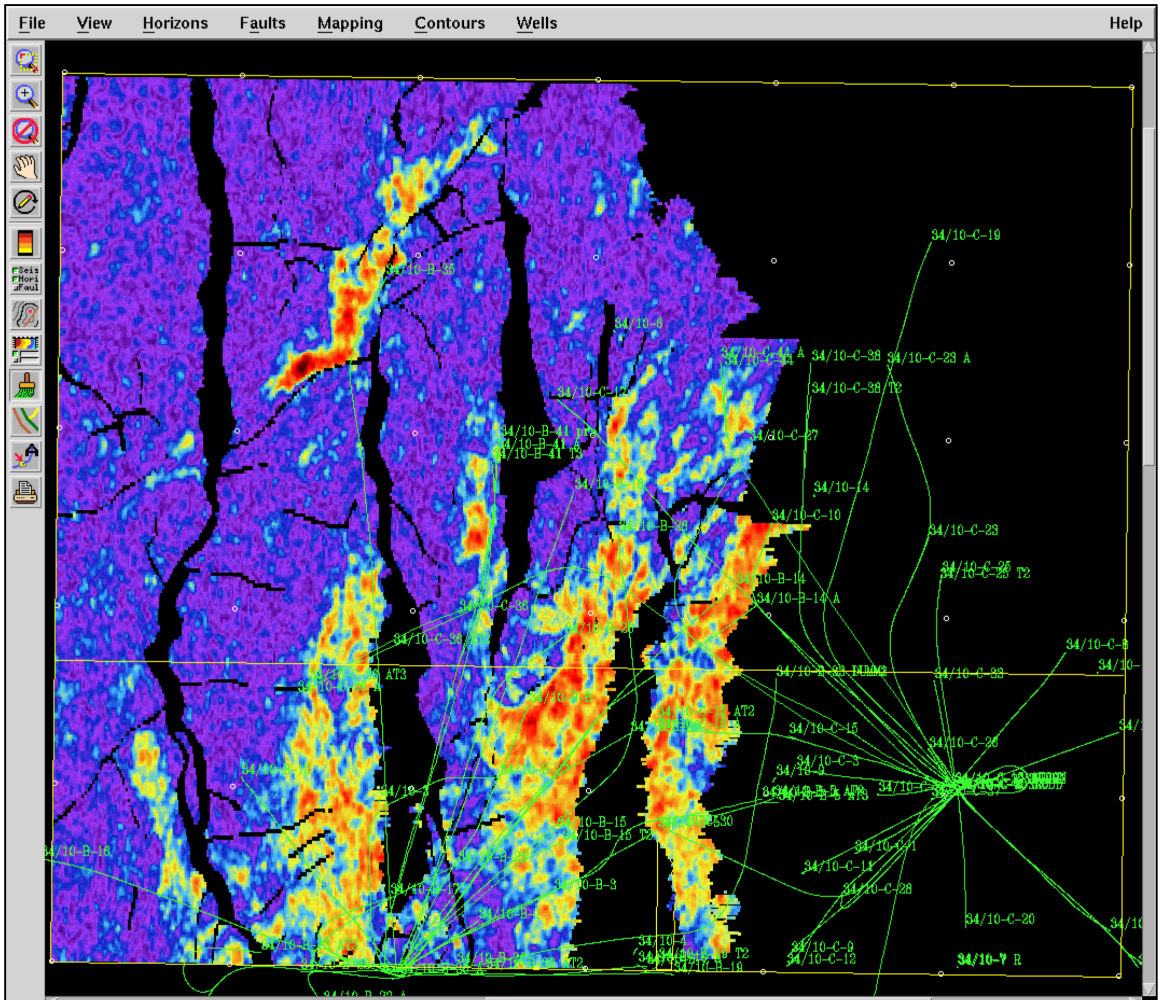
Seismic Image – 3D *amplitude map extracted along top of reservoir structure*



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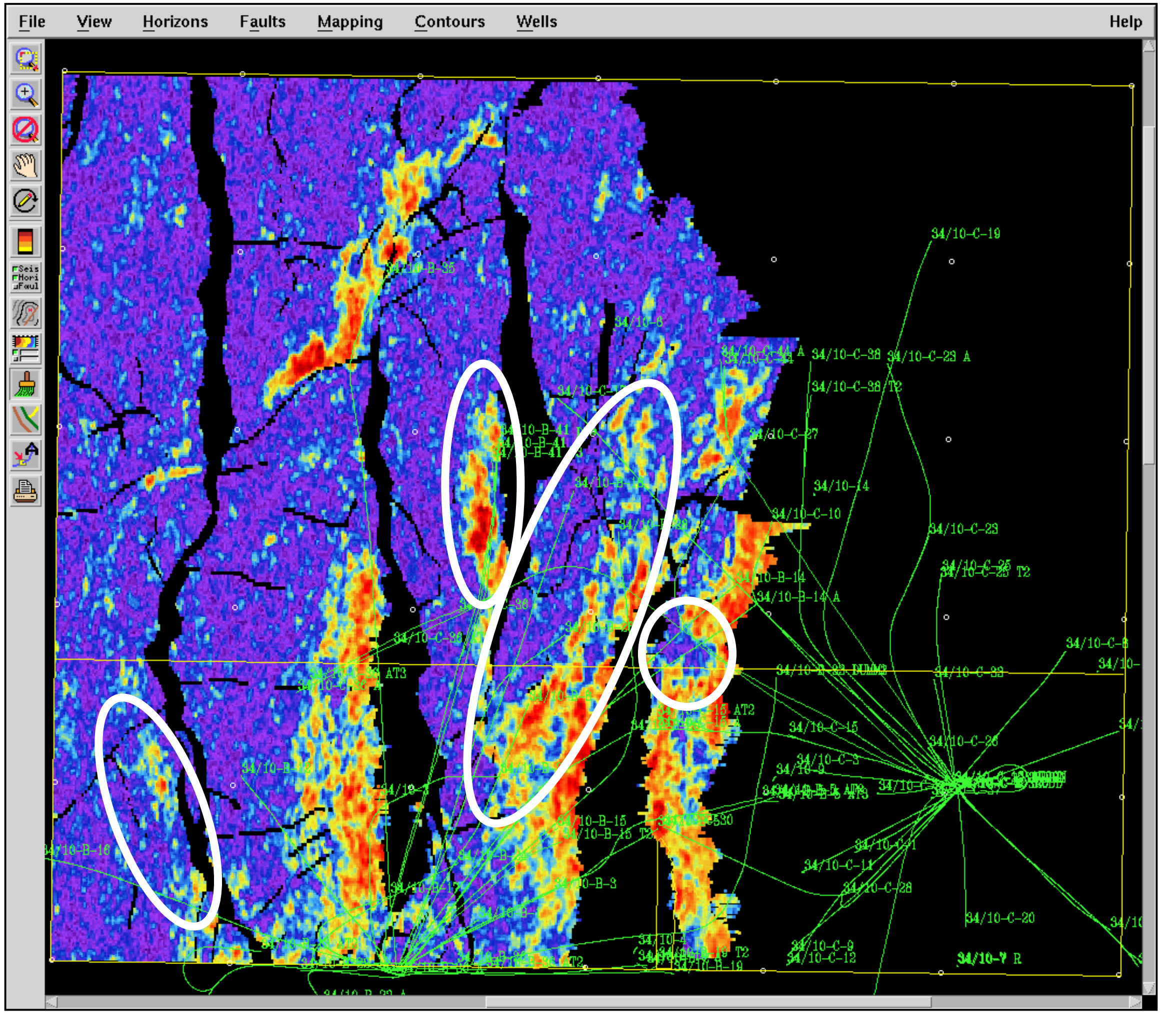
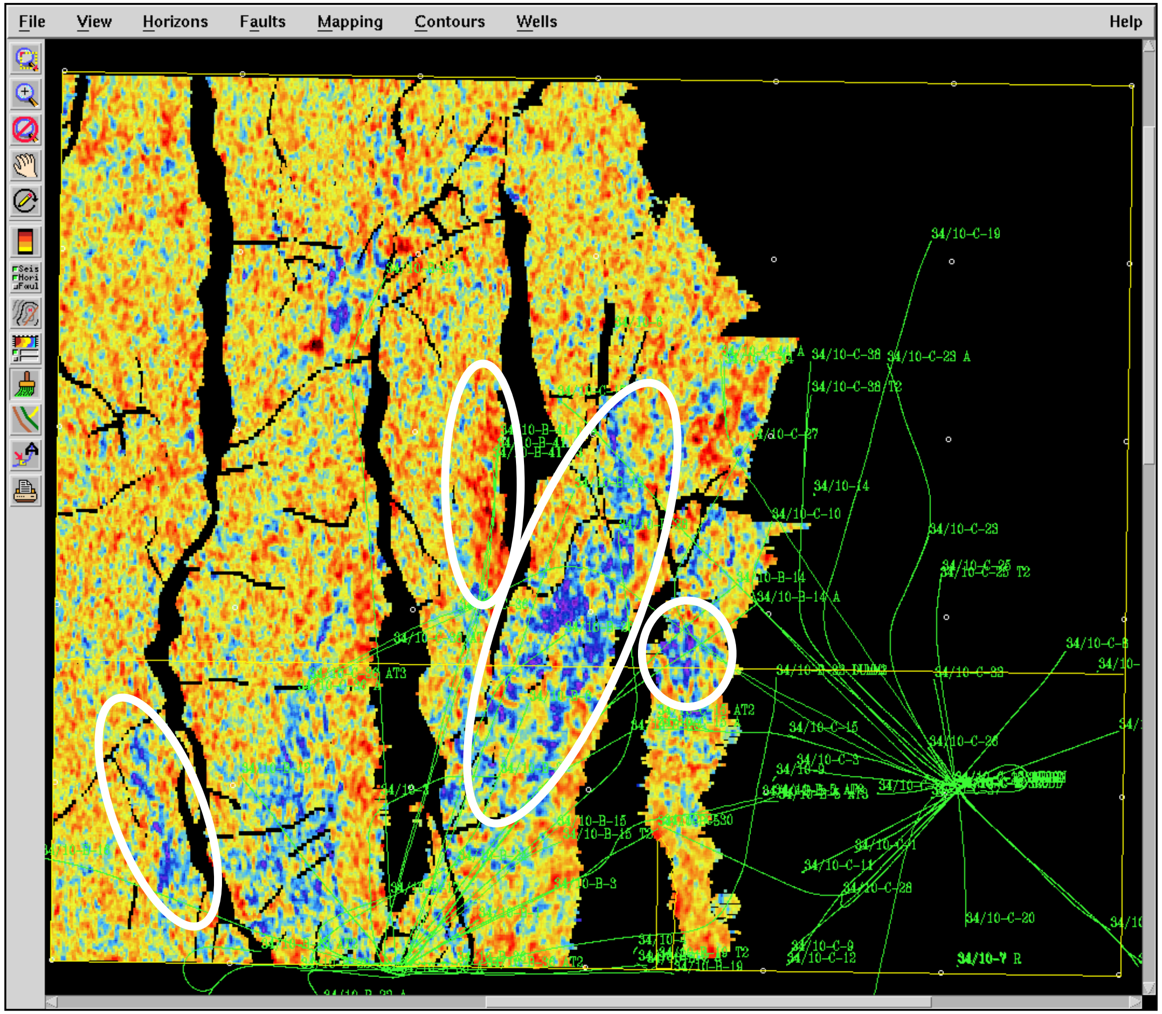
Seismic Image – TIME 2 *amplitude map extracted along top of reservoir structure*



Lumley

Seismic Image – 4D *difference map extracted along top of reservoir structure*



Lumley

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Rock Physics
core measurements

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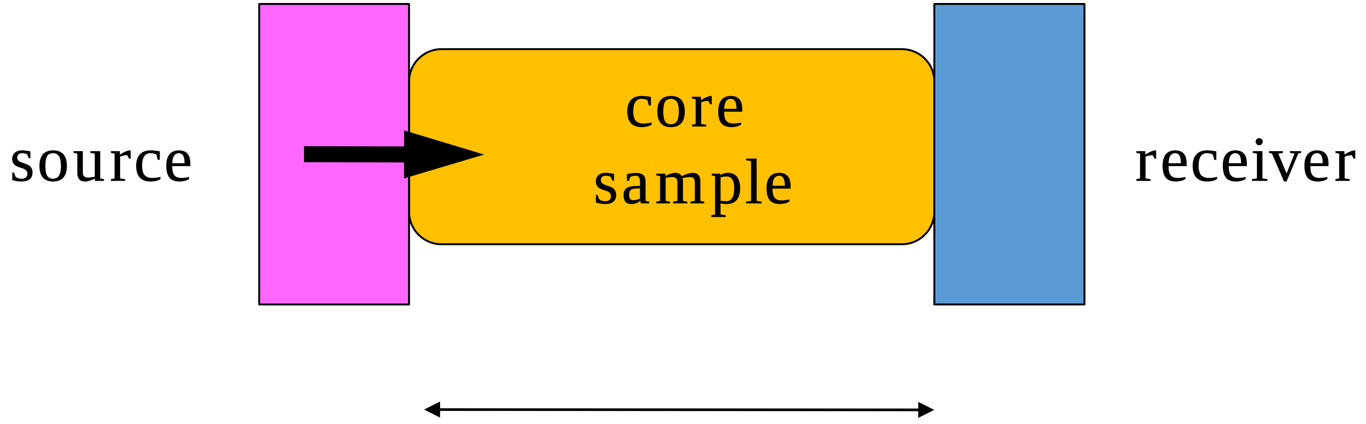
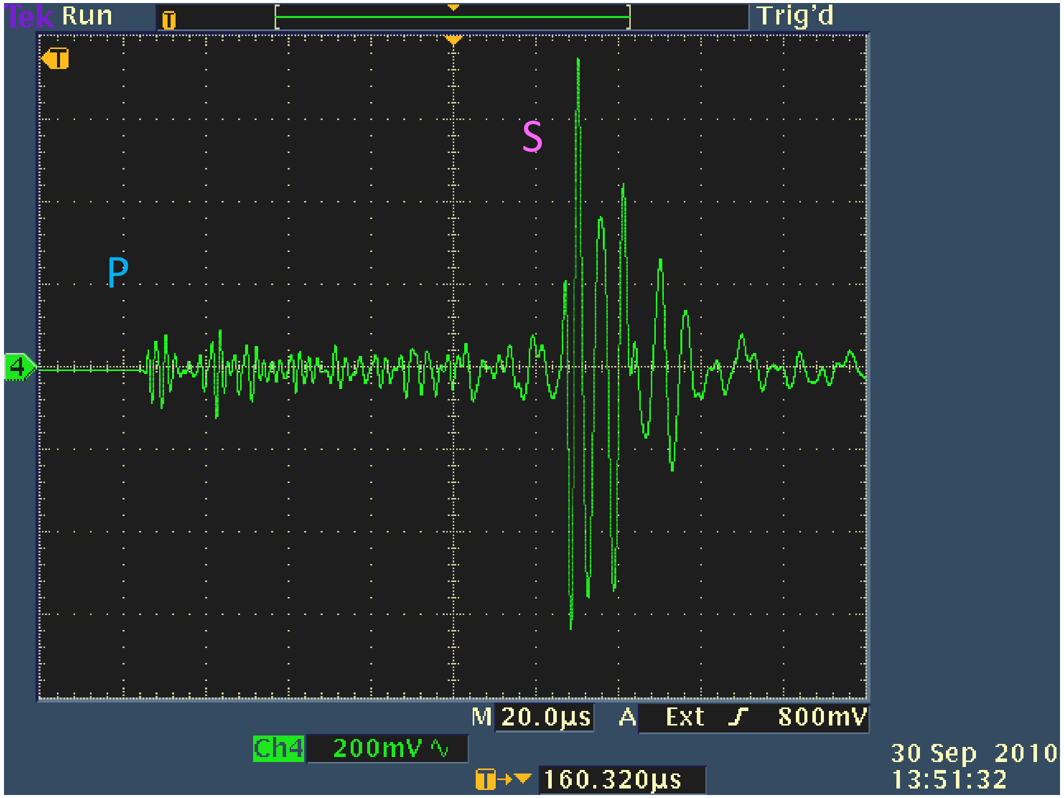


$$v = d / t$$

rock physics lab

Curtin University



M. Lebedev, Curtin

Velocity Equations

$$Vp = \sqrt{\frac{K + \frac{4}{3} G}{\rho}}$$

P-wave velocity

$$Vs = \sqrt{\frac{G}{\rho}}$$

S-wave velocity

$$Ip = \rho * Vp$$

P-wave impedance

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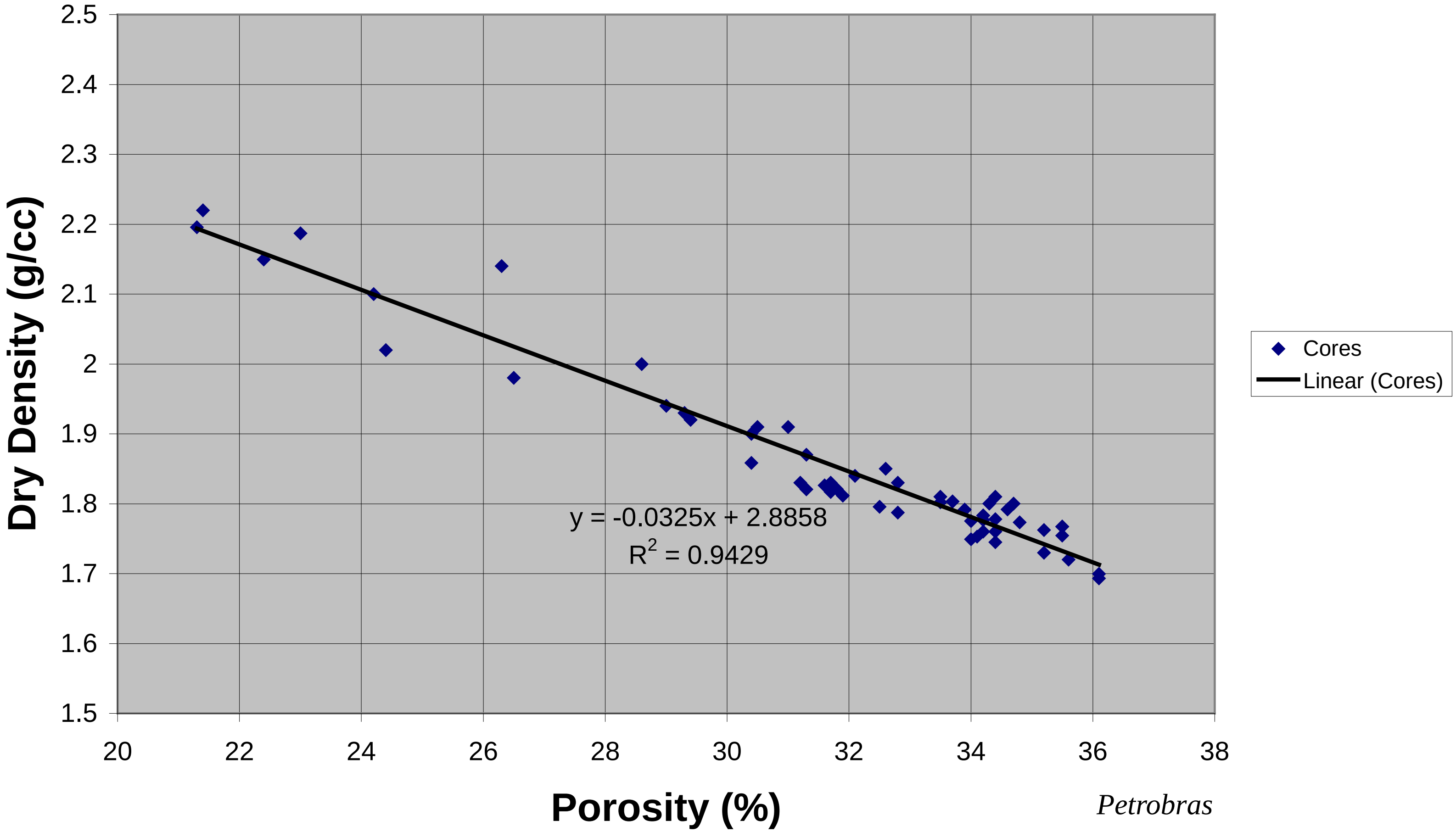
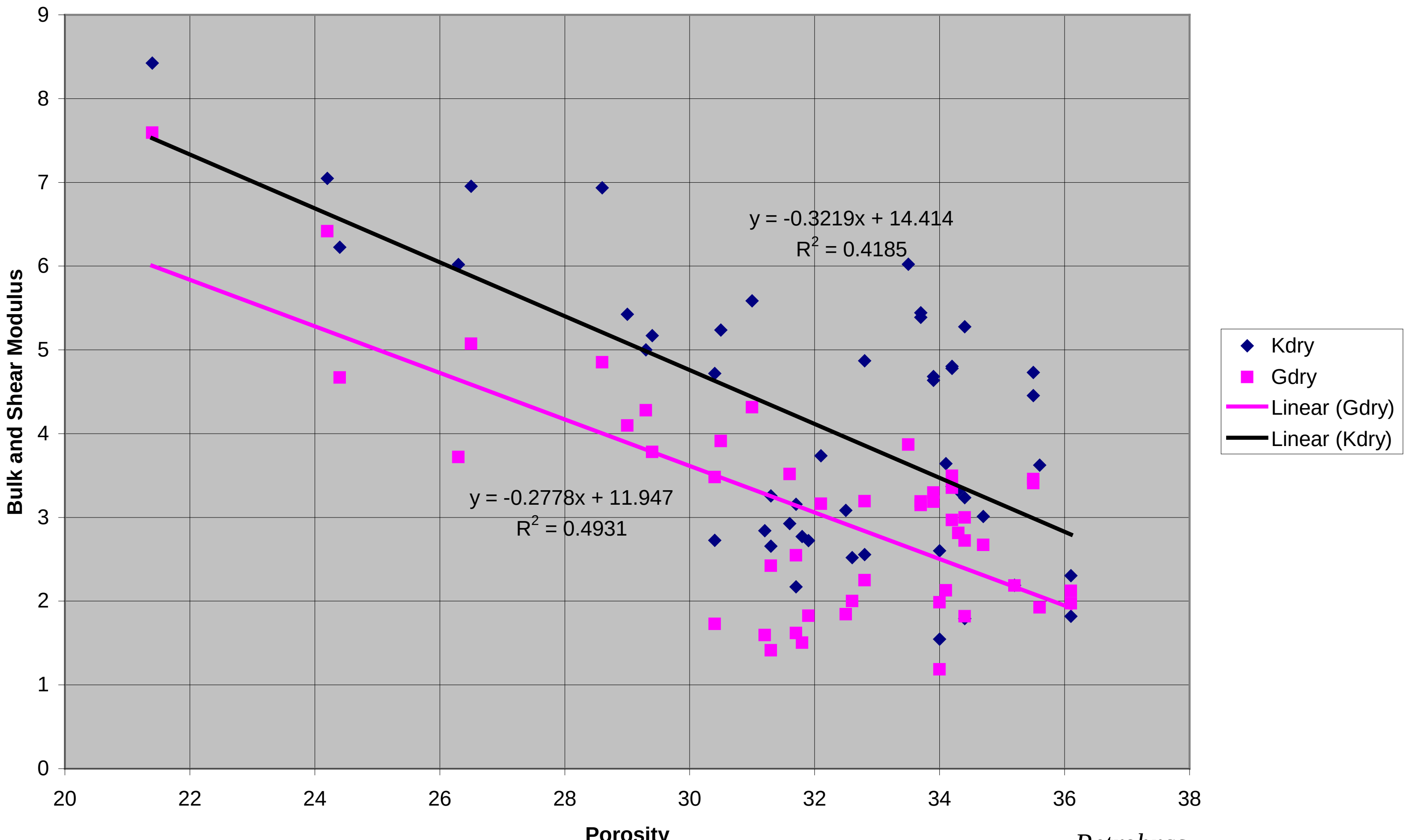
Density versus φ



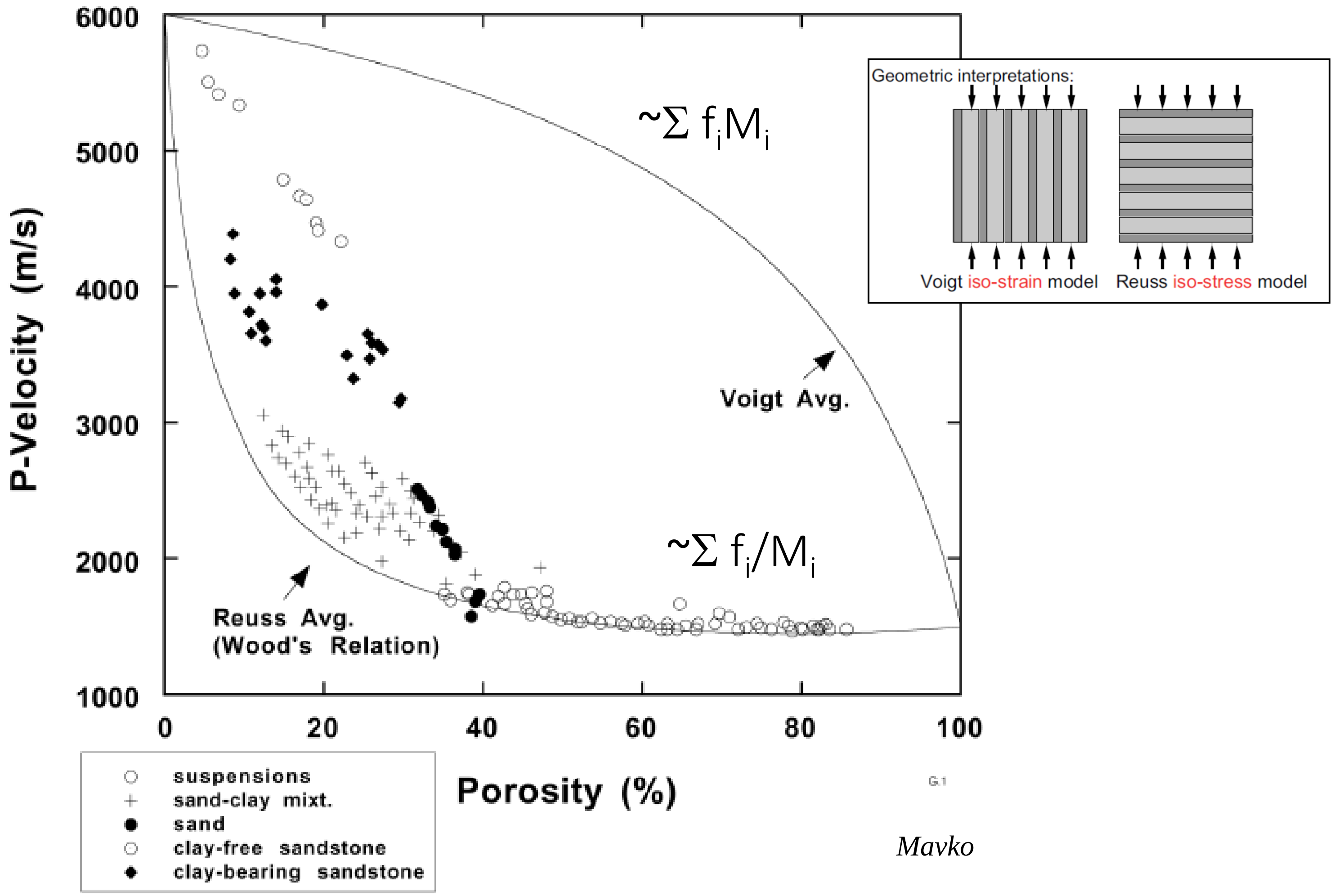
Petrobras

K, G versus φ



Petrobras

Voigt and Reuss bounds



Mavko

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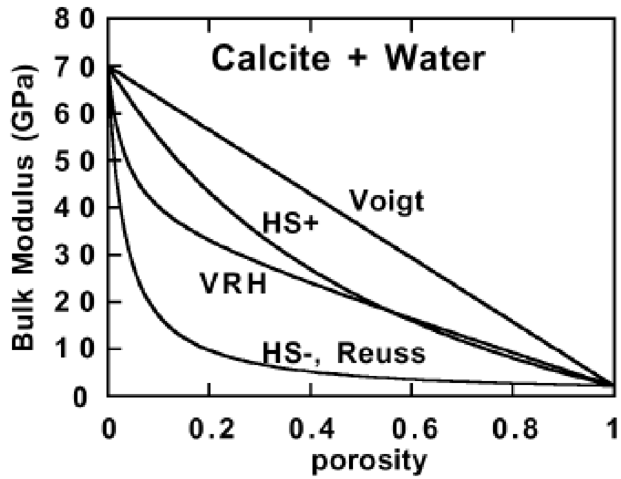
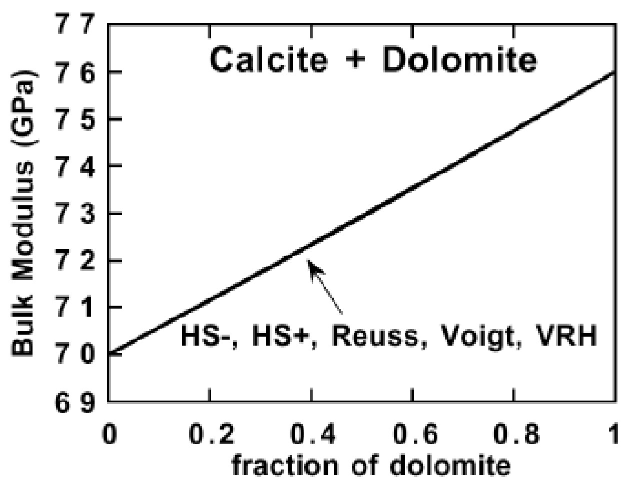
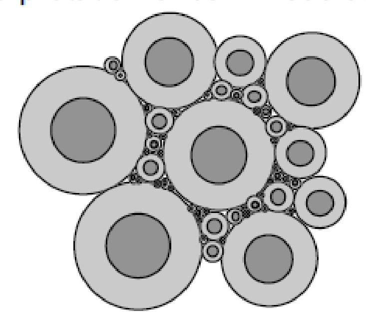
Hashin-Shtrikman bounds





Interpretation of bulk modulus:



Mavko

Hashin-Shtrikman bounds

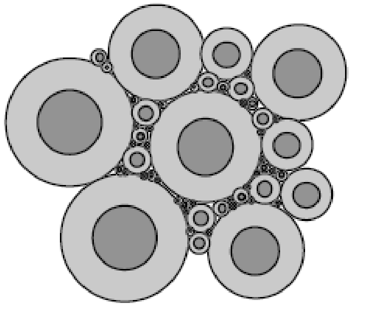
of 2 materials:

$$K^{HS\pm} = K_1 + \frac{f_2}{(K_2 - K_1)^{-1} + f_1\left(K_1 + \frac{4}{3}\mu_1\right)^{-1}}$$

$$\mu^{HS\pm} = \mu_1 + \frac{f_2}{(\mu_2 - \mu_1)^{-1} + \frac{2f_1(K_1 + 2\mu_1)}{5\mu_1\left(K_1 + \frac{4}{3}\mu_1\right)}}$$

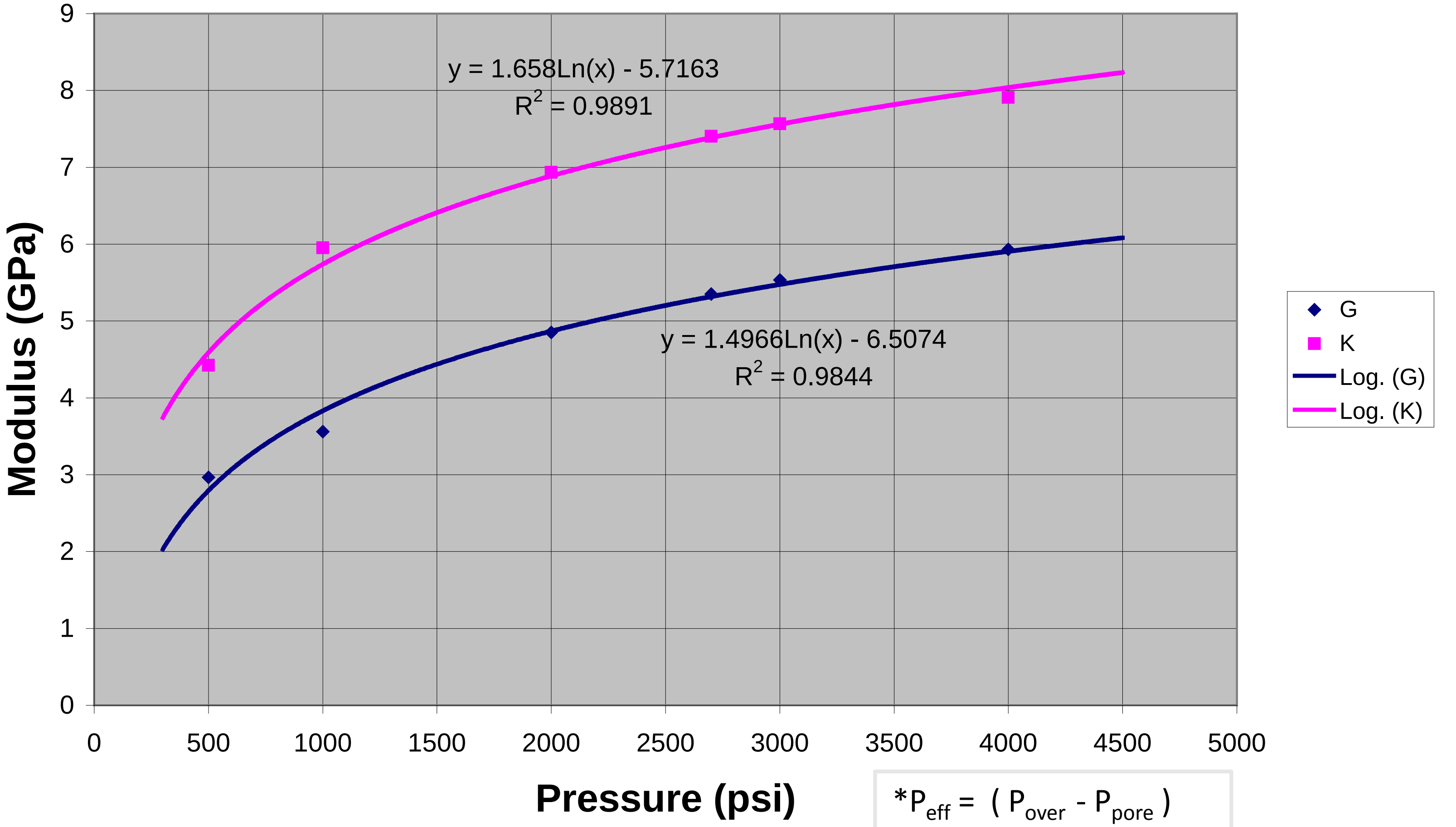
where subscript 1 = shell, 2 = sphere. f_1 and f_2 are volume fractions.

Interpretation of bulk modulus:



Mavko

K, G versus P_{eff}*



*P_{eff} = (P_{over} - P_{pore})

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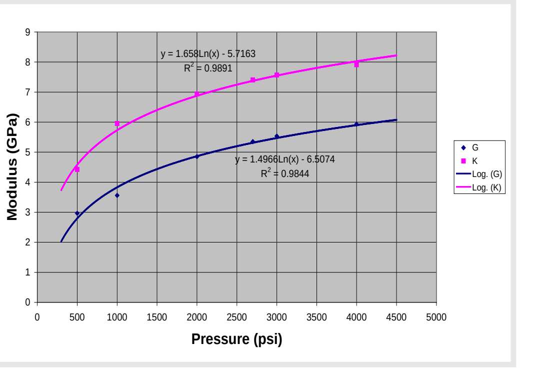
velocity-pressure curves



- Hertz-Mindlin…
  - $K_{dry} = f(\, c, \varphi_c, K_g, G_g, P_{eff}\,)^{1/3}$
  - *theoretical basis, but doesn't fit data in practice*
- Polynomial, Exponential…
  - $K_{dry} = c_o + c_1 x + c_2 x^2 + \ldots + c_n x^n$; c_i *coeffs* ; $x = P_{eff}$
  - $V_{dry} = c_o + c_1 x + c_2\, e^{-a\,x}$; a, c_i *coeffs* ; $x = P_{eff}$
  - *Exponential fits data better than poly and has some theory basis*
- Logarithmic…
  - $K_{dry} = c_o + c_1\, Ln(x)$; c_i *coeffs* ; $x = P_{eff}$
  - *Logarithmic fits data better than above, no theory basis (yet)…*

A new velocity-pressure model

$$K = A - Be^{-CP_{eff}} - De^{-EP_{eff}}$$

Saul & Lumley, GJI 2013

Where A, B, C, D and E are all positive constants,
with the constraint:

(A-B-D) = K(Peff=0) calculated from: $K_{eff} = \left[\frac{\phi_c}{K_f} + \frac{1-\phi_c}{K_m}\right]^{-1}$

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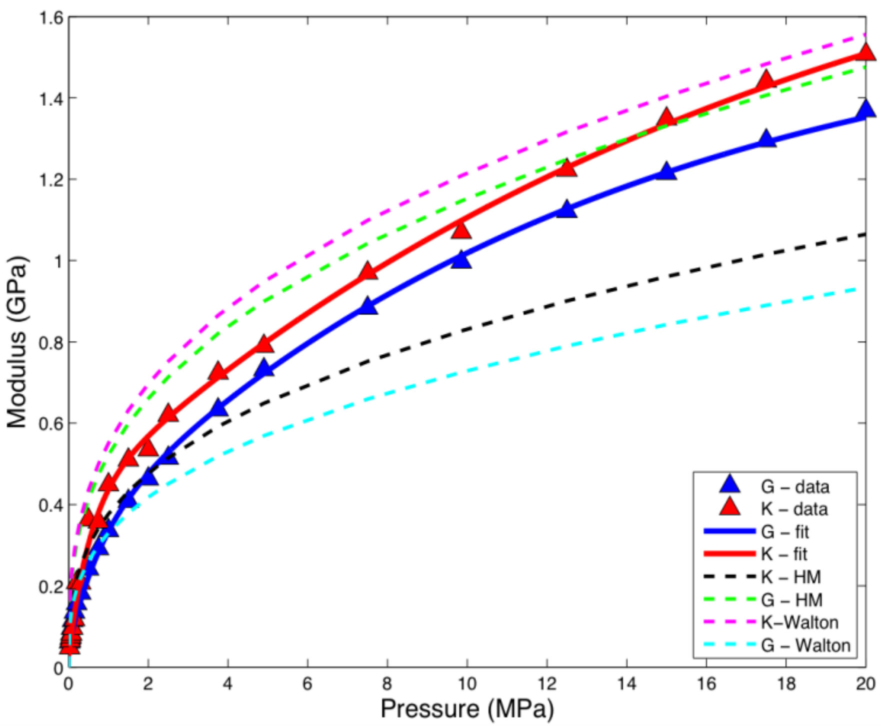
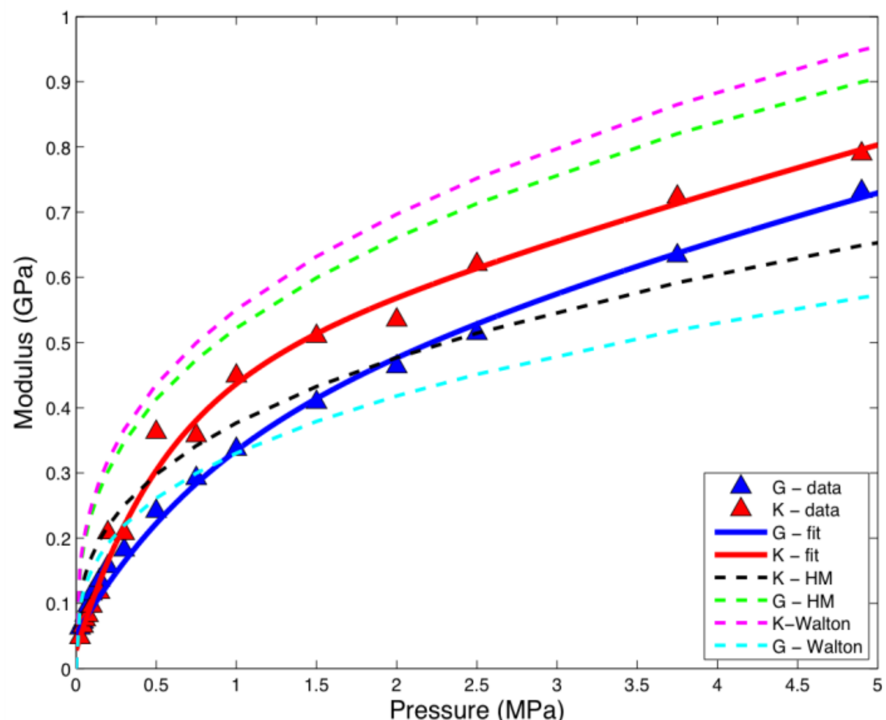
Fit to core data...

Bulk and Shear moduli – SL, HM, Walton smooth

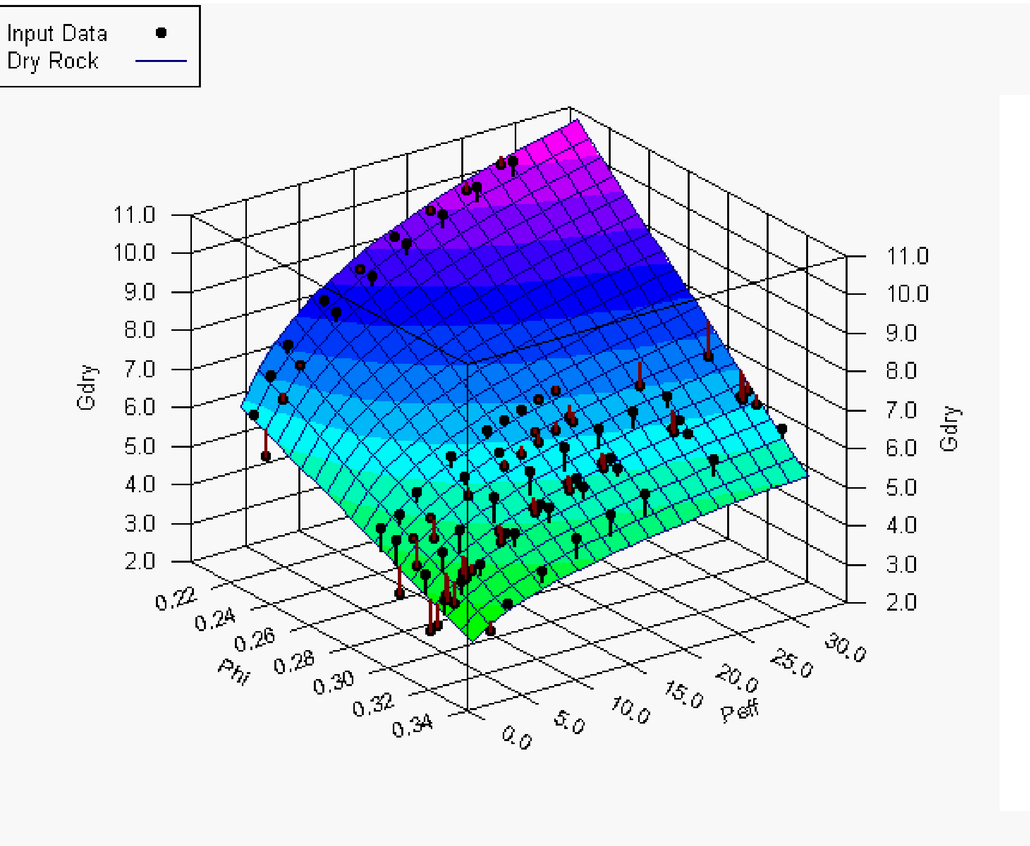


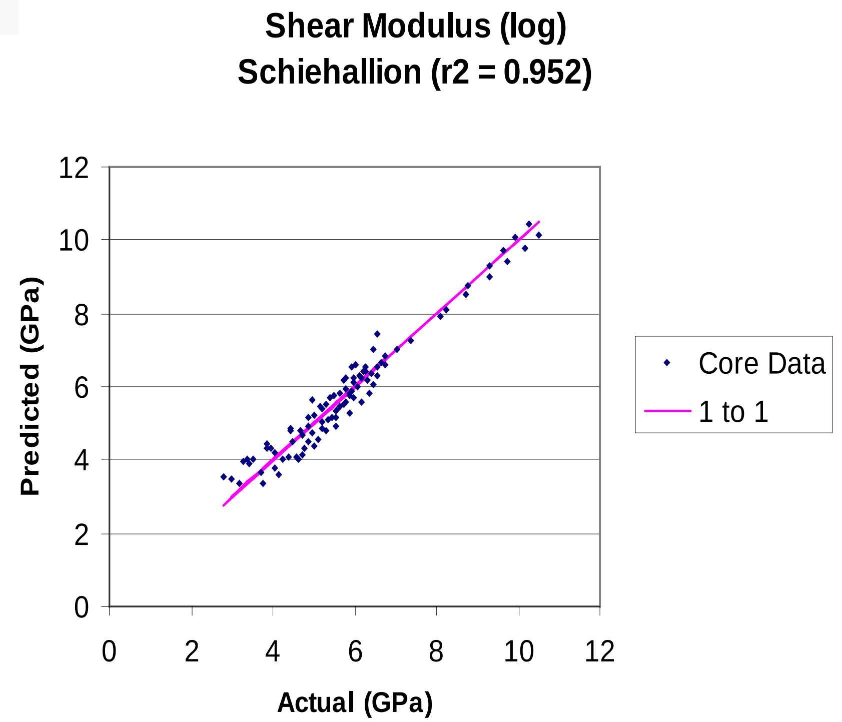


Saul & Lumley, 2011

For Contact models - ϕ_c variable, C = 20−34 ϕ +14 ϕ^2 (Murphey, 1982), α = 0,1

2D surface fit for Gdry(f, P_{eff})





Meadows et al., 2005

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Fluid properties vary with P,T

* PVT data; * Empirical, eg. Batzle & Wang (1992); * Equations of State...

eg. Span-Wagner, GERG-2004 etc.

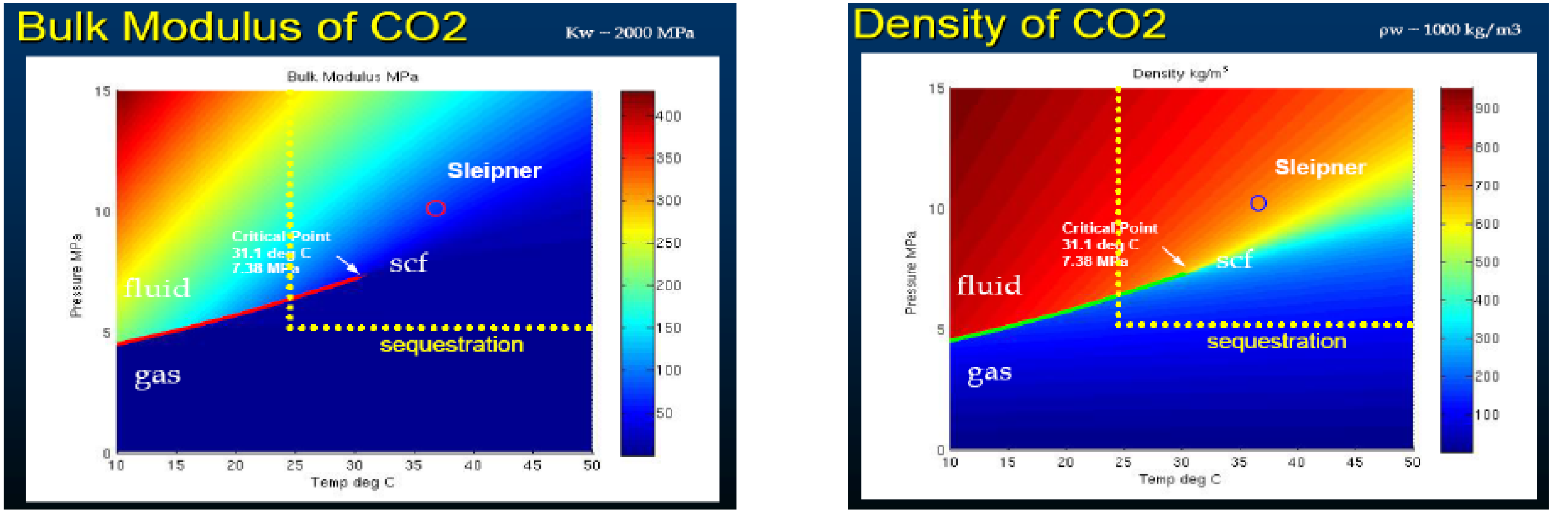

Figure 1: (a) Bulk modulus (left) and (b) density (right) of CO_2 under various pressure and temperature conditions (Lumley et al., 2008).

Lumley

Fluid mixing equations

Wood's equation:

$$1/K_{fluid} = \sum S_i / K_i$$

Effective fluid modulus

S_i is the i^{th} fluid saturation
such that $\Sigma S_i = 1$
K_i is the i^{th} fluid modulus
ρ_i is the i^{th} fluid density

Note: (S_i/K_i) averaging leads to the Reuss lower bound
($S_i * K_i$) averaging leads to the Voigt upper bound

$$\rho_{sat} = \rho_{dry} + \phi \sum S_i \rho_i$$

Bulk density

Lumley

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Gassmann Equation

Gassmann Equation:

$$K_{sat} = K_{dry} + A/B$$

Saturated bulk modulus

$$A = (1 - K_{dry}/K_m)^2$$

$$B = \frac{\phi}{K_{fluid}} + \frac{1-\phi}{K_m} - \frac{K_{dry}}{(K_m)^2}$$

K_m is the matrix (grain) modulus
ϕ is the porosity
K_{fluid} is the effective fluid modulus

$$G_{sat} = G_{dry}$$

Shear modulus

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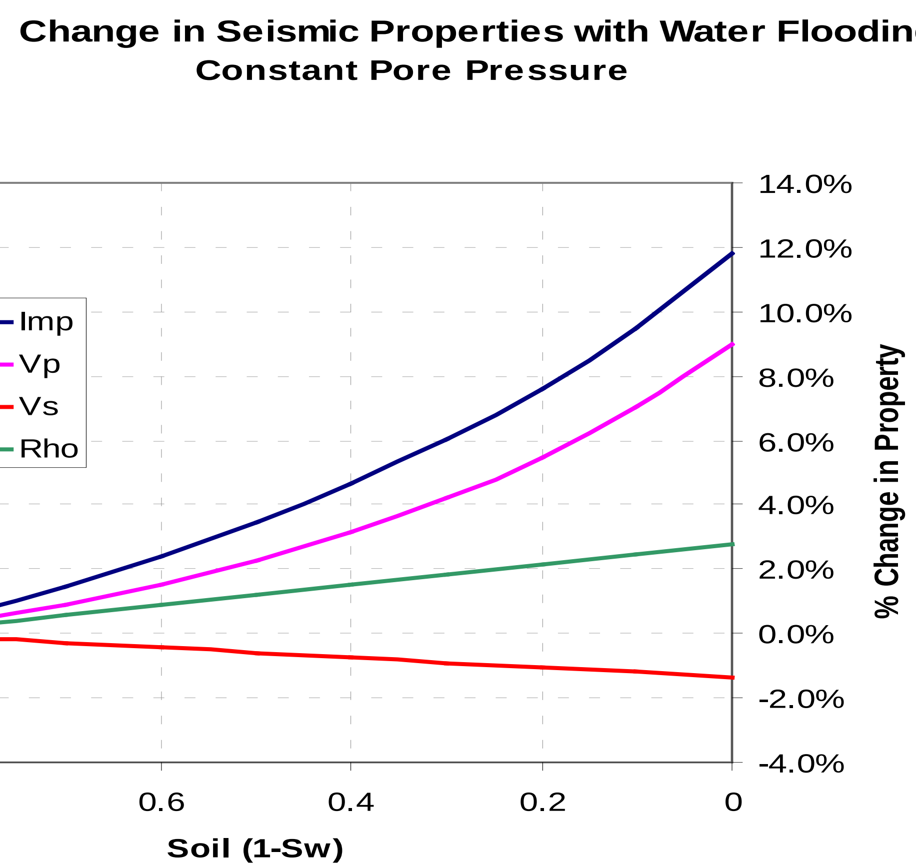
Velocity-saturation curves



Lumley et al.

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Patchy Saturation

Hill's equation:

$$1/M_{patchy} = \sum S_i / M_i$$

Patchy rock modulus

S_i is the i^{th} fluid saturation such that $\Sigma S_i = 1$

$$M_i = K_{i(sat)} + 4G/3$$

Effective rock modulus

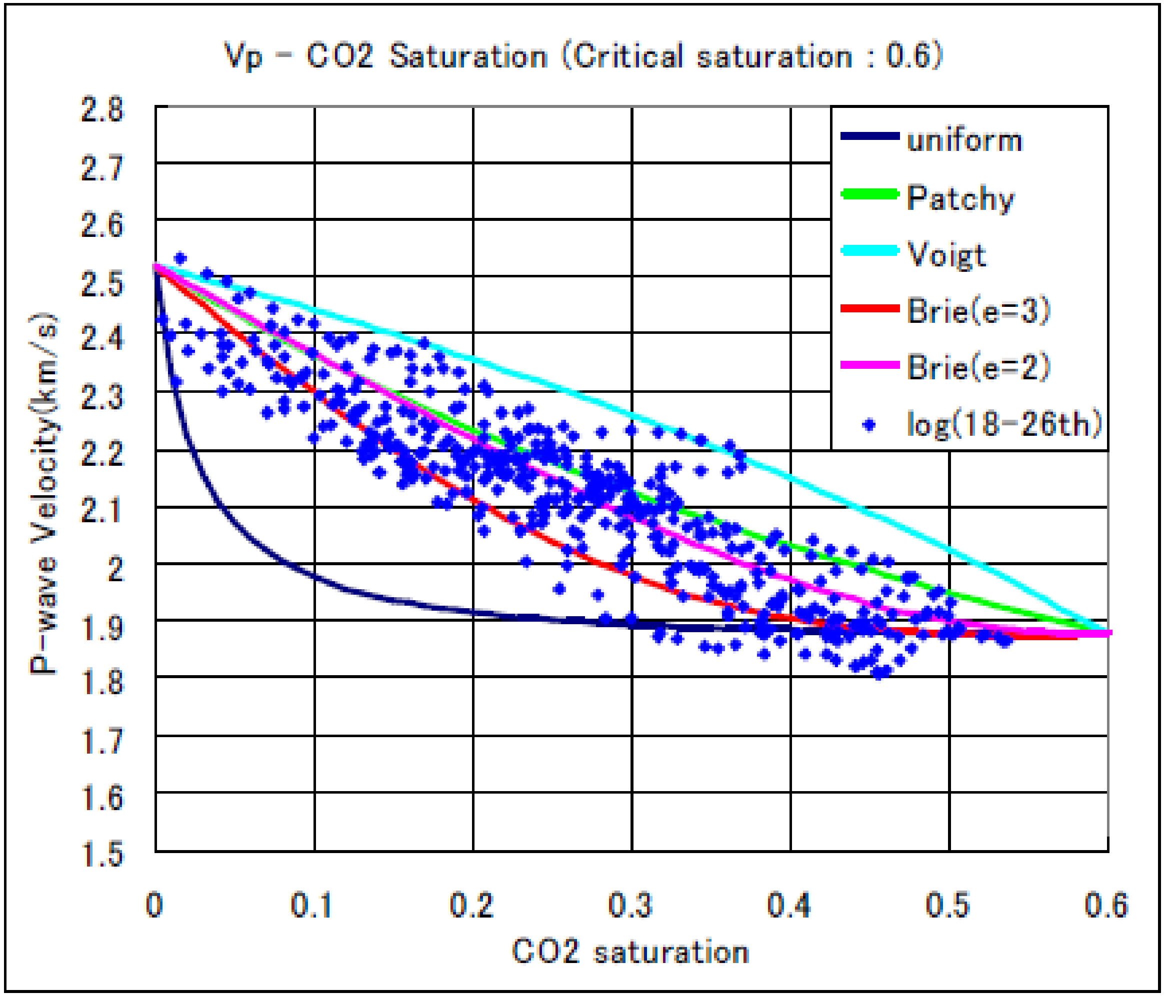
M_i is the i^{th} rock modulus saturated with 100% fluid "i".

Substitute M_{patchy} directly into V_p equation.

(i.e., no Gassmann involved).

Lumley

velocity-saturation curves



Konishi, OYO

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Rock Physics properties from well logs

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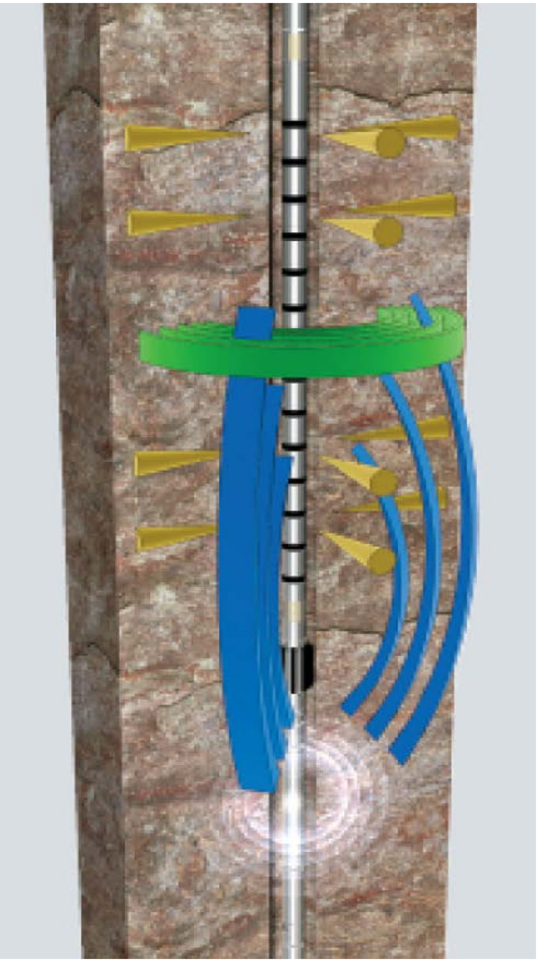
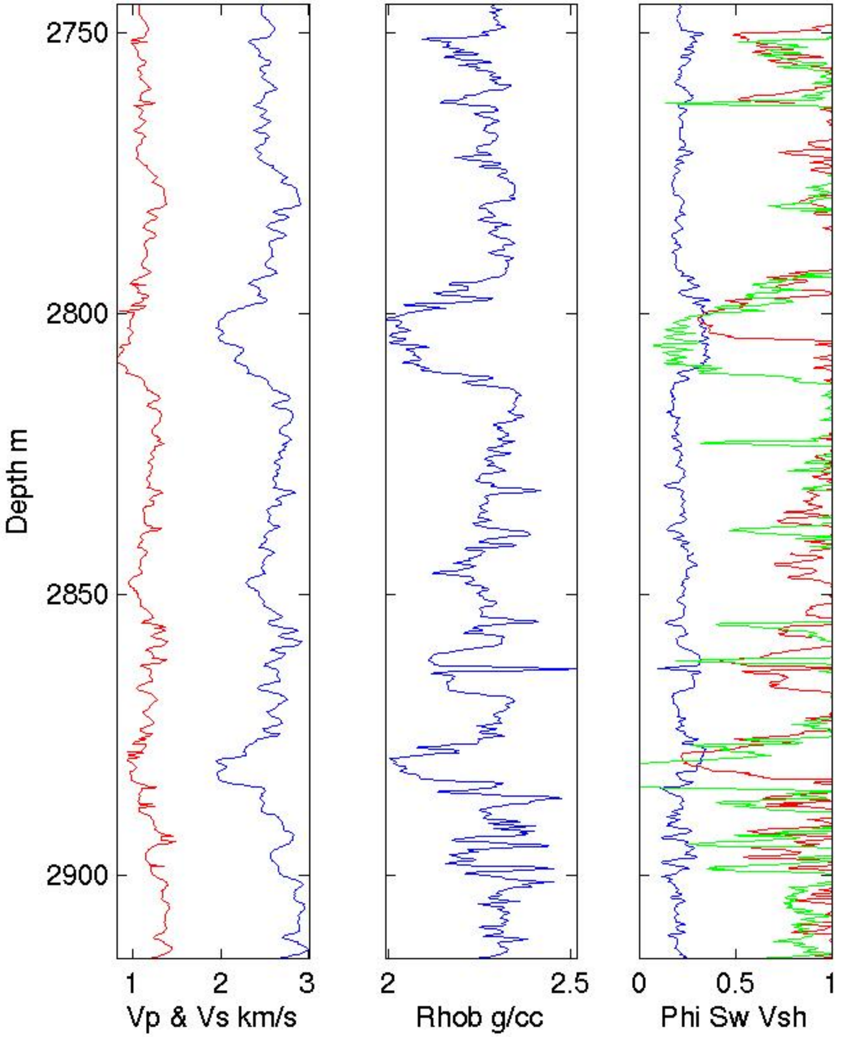
Seismic logging tools



Schlumberger



Lumley et al.

Velocity Equations

well logs

$$Vp = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

P-wave velocity

$$Vs = \sqrt{\frac{G}{\rho}}$$

S-wave velocity

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Velocity Equations

calculate

$$Vp = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

P-wave velocity

$$Vs = \sqrt{\frac{G}{\rho}}$$

S-wave velocity

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Velocity Equations

inverse Gassmann

$$Vp_{dry} = \sqrt{\frac{K_d + \frac{4}{3}G}{\rho_d}}$$

P-wave velocity

$$Vs_{dry} = \sqrt{\frac{G}{\rho_d}}$$

S-wave velocity

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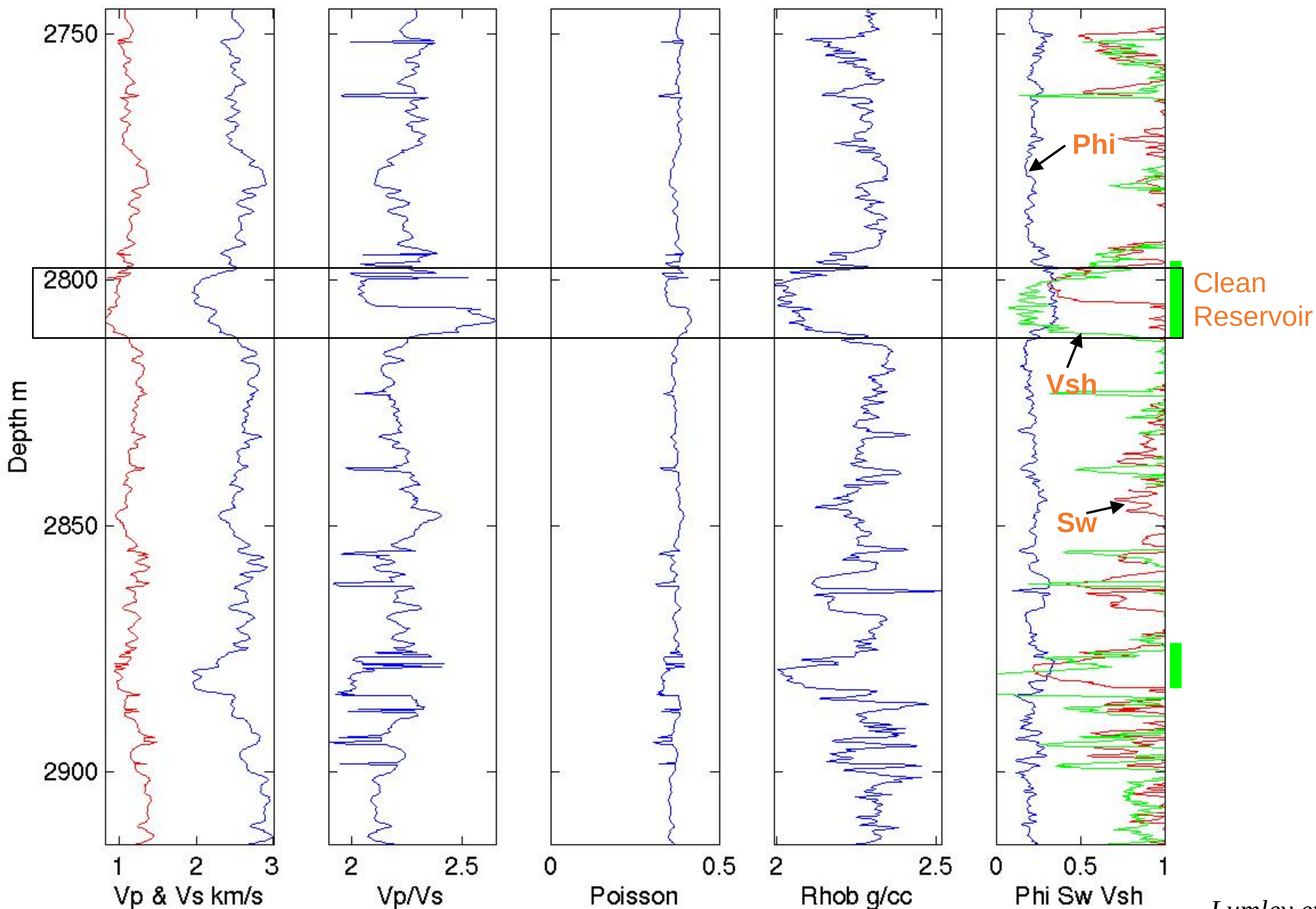
Well #1 logs… Full Reservoir Interval



Lumley et al.

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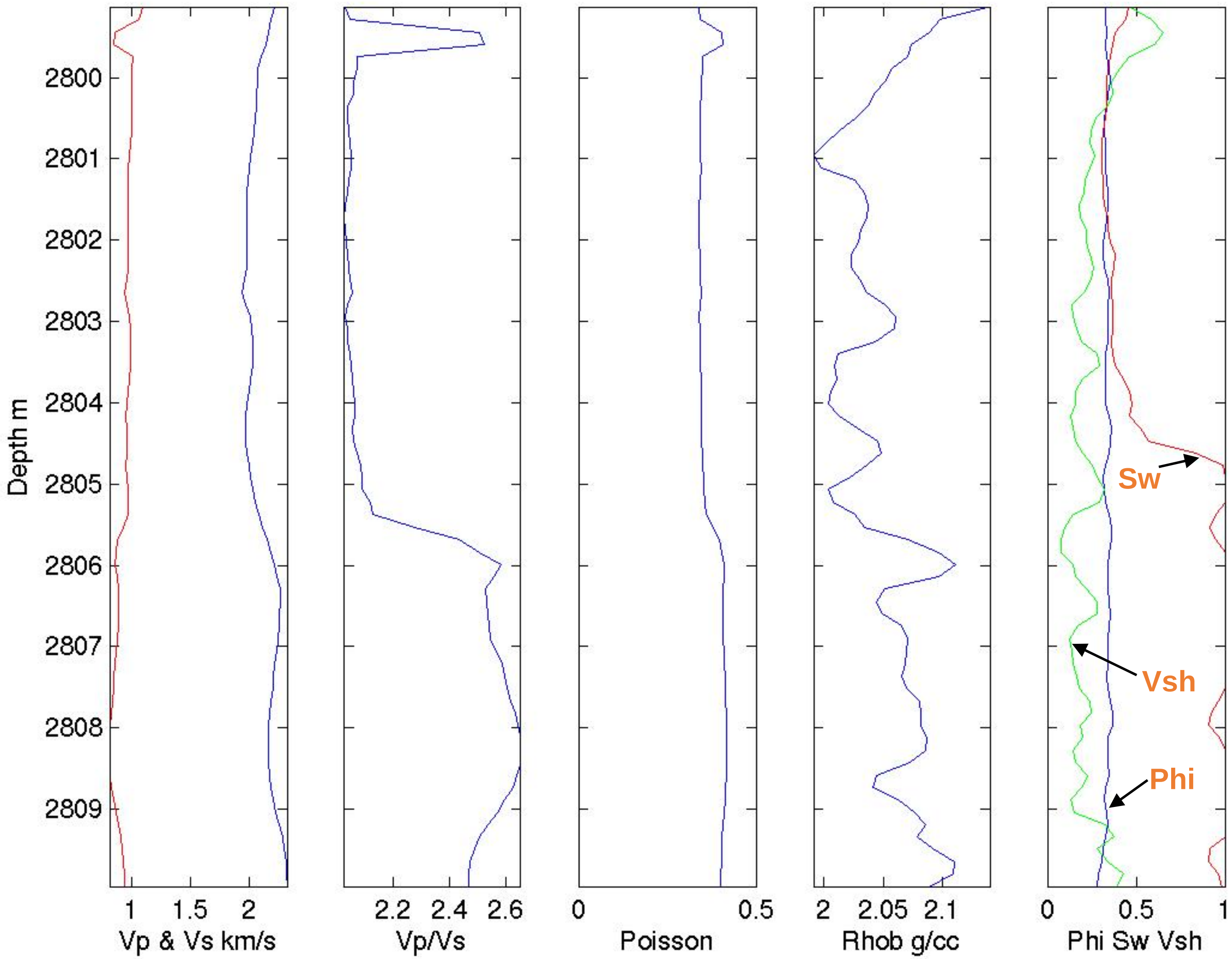
Well #1 Zoom on Upper Reservoir Interval

Upper Zone 2799 – 2810 m



Lumley et al.

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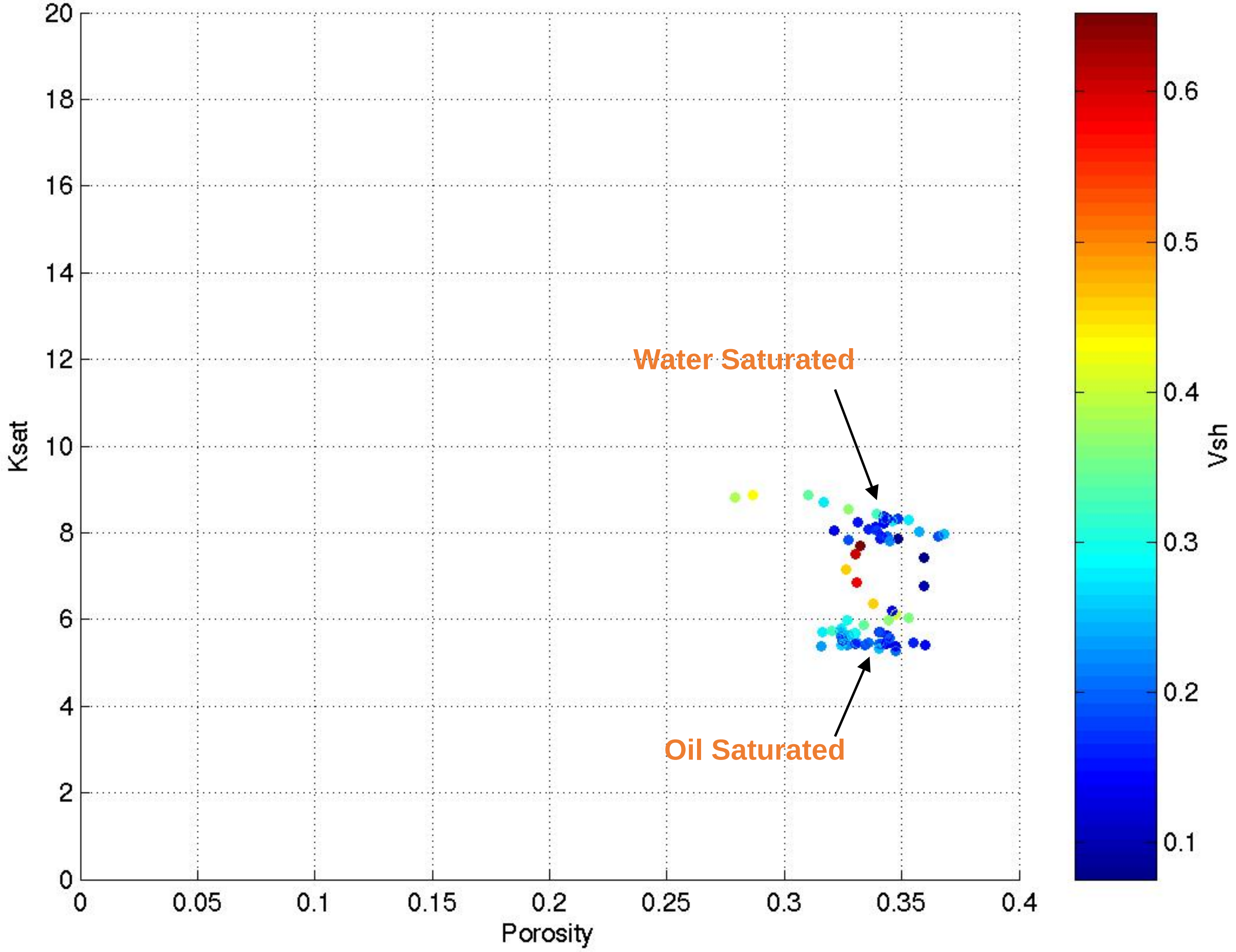
Well #1 Ksat… Upper Reservoir Interval

Upper Zone 2799 – 2810 m



Lumley et al.

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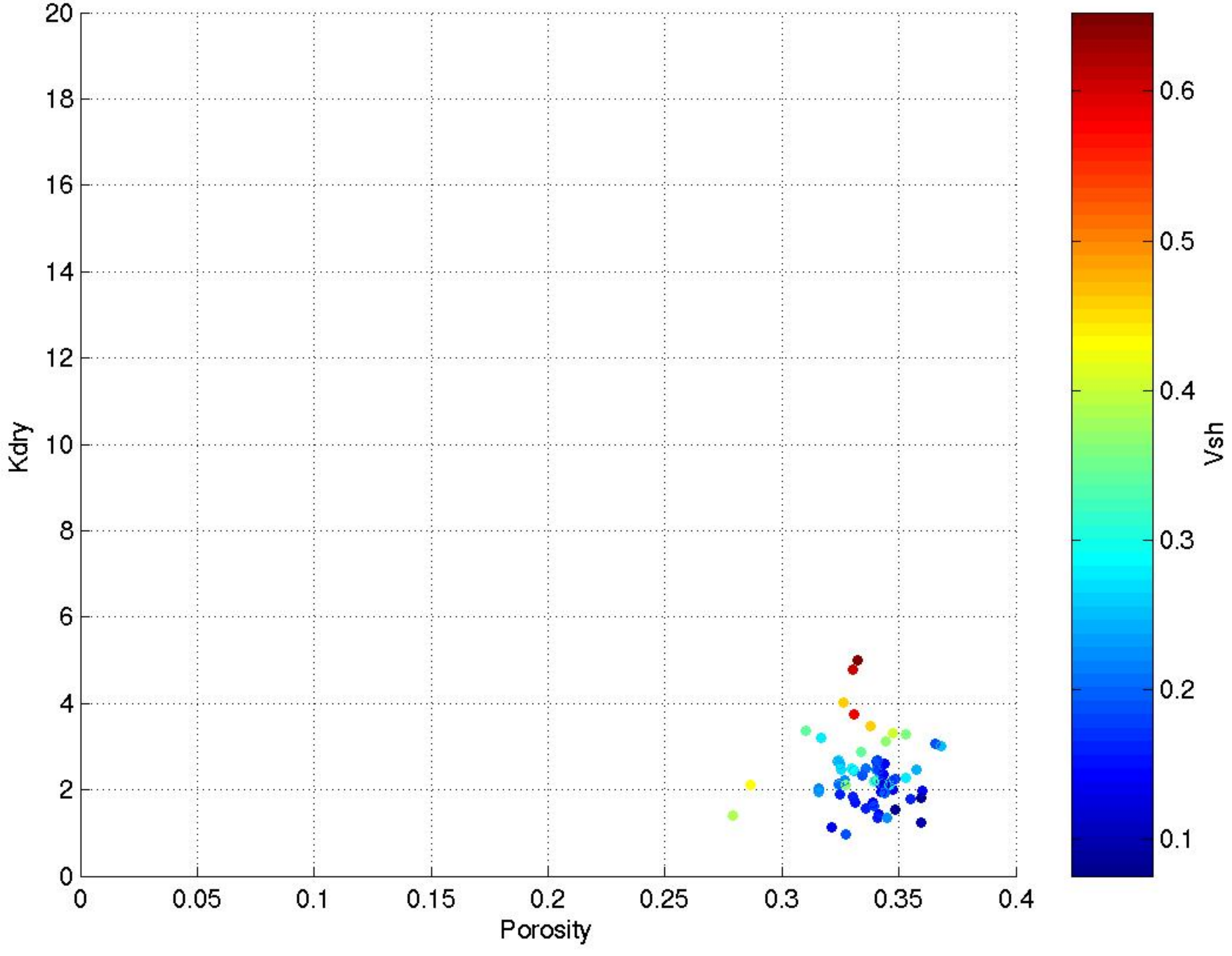
Well #1 Kdry… Upper Reservoir Interval

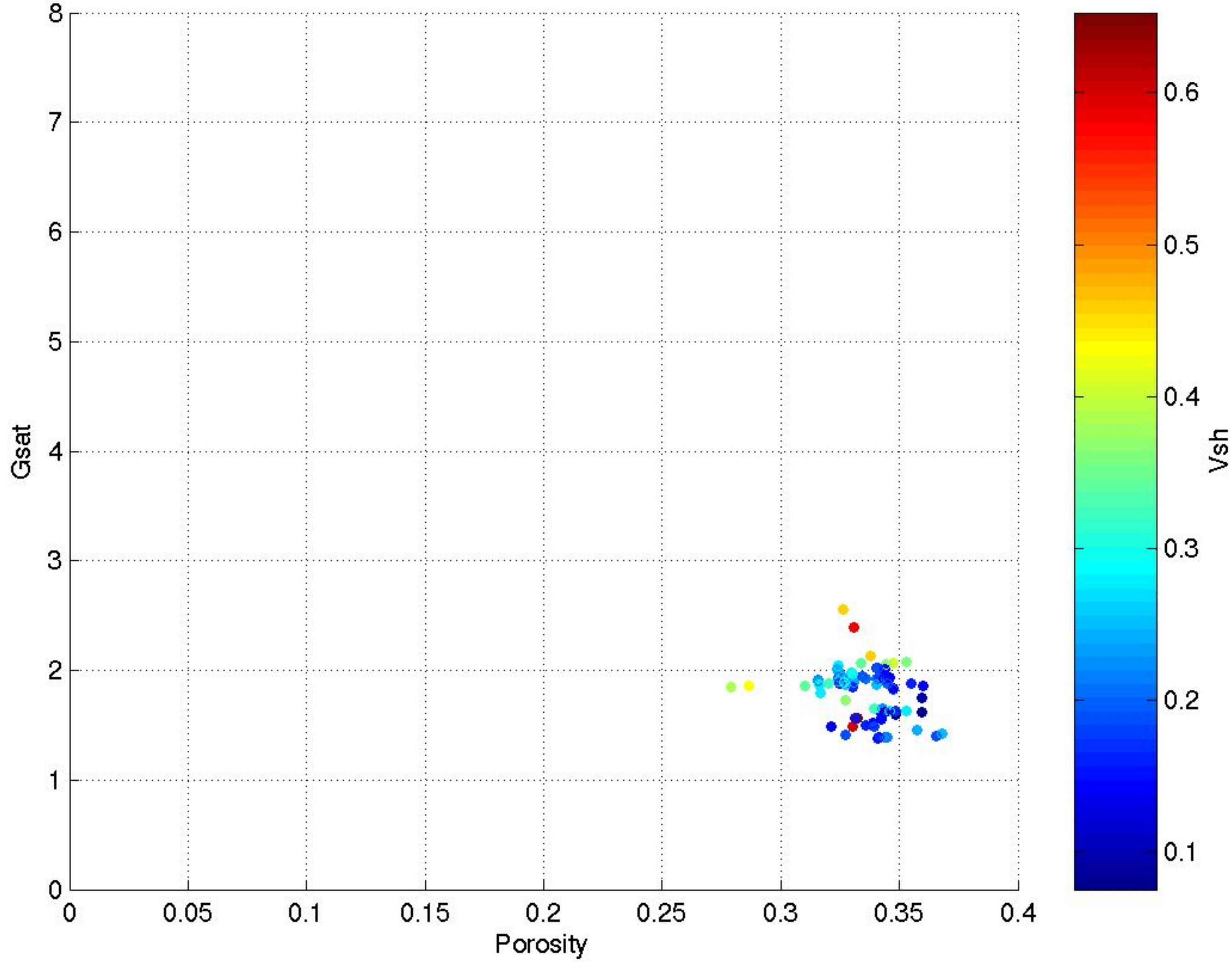
Upper Zone 2799 – 2810 m



Lumley et al.

Well #1 Gsat… Upper Reservoir Interval

Upper Zone 2799 – 2810 m



Lumley et al.

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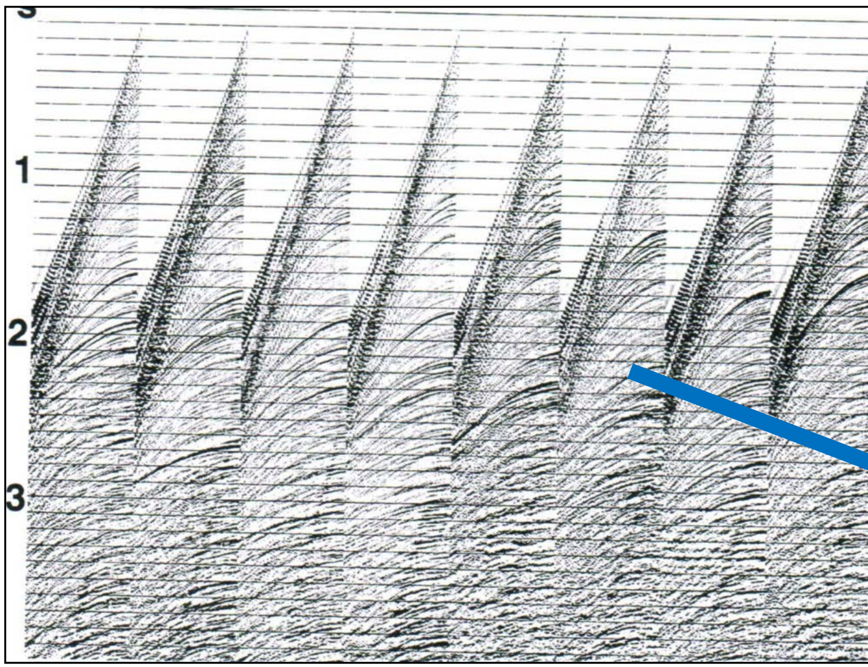
3D + 4D Seismic Imaging

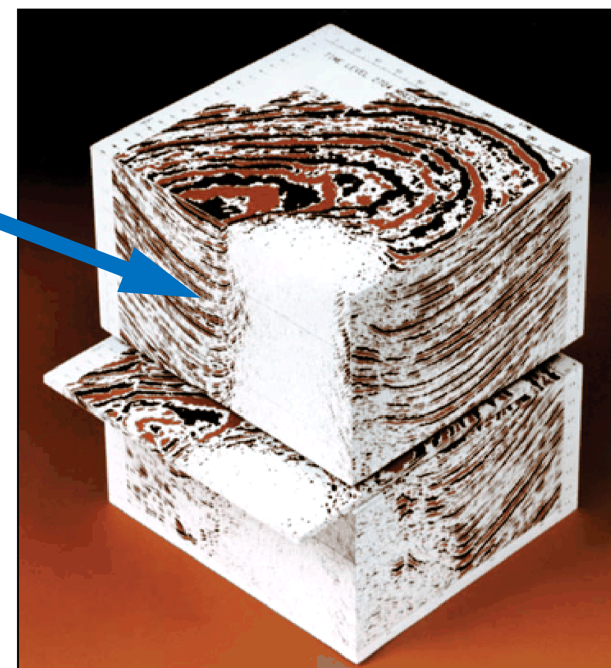
david.lumley@utdallas.edu

3D seismic imaging

so how do we go from this…



to this… ?



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Scalar wave equation modeling

$$d = Fm$$

$$(v^2 \nabla^2 - \partial_{tt}) P(\underline{x},t) = 0$$

$$m = v(\underline{x})$$

$$F = \nabla^2 - \partial_{tt}$$

$$d = P(\underline{x},t)$$

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Full waveform inversion

$$m = F^{-1} d$$

$$\min\ e^2 = w_d^2 (d - Fm)^2 + w_m^2 (m - m_o)^2 + \ldots$$

subject to constraints: $\nabla m \approx 0$ *etc…*

F *WEQ modeling operator*

m *2D/3D velocity model*

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WEQ imaging + velocity analysis

$$\mathcal{R} \sim \nabla m \sim (F^*F)^{-1} F^*d \;\sim\; Fs \times F^*_m d \,|_{ic}$$

min $\mathcal{E}^2$ = *Image Quality…*

subject to constraints: $\nabla_x \mathcal{R} \approx 0$ *etc…*

F^* *WEQ imaging (adjoint) operator*

m *2D/3D velocity model*

$\mathcal{R}$ *migrated reflectivity image*

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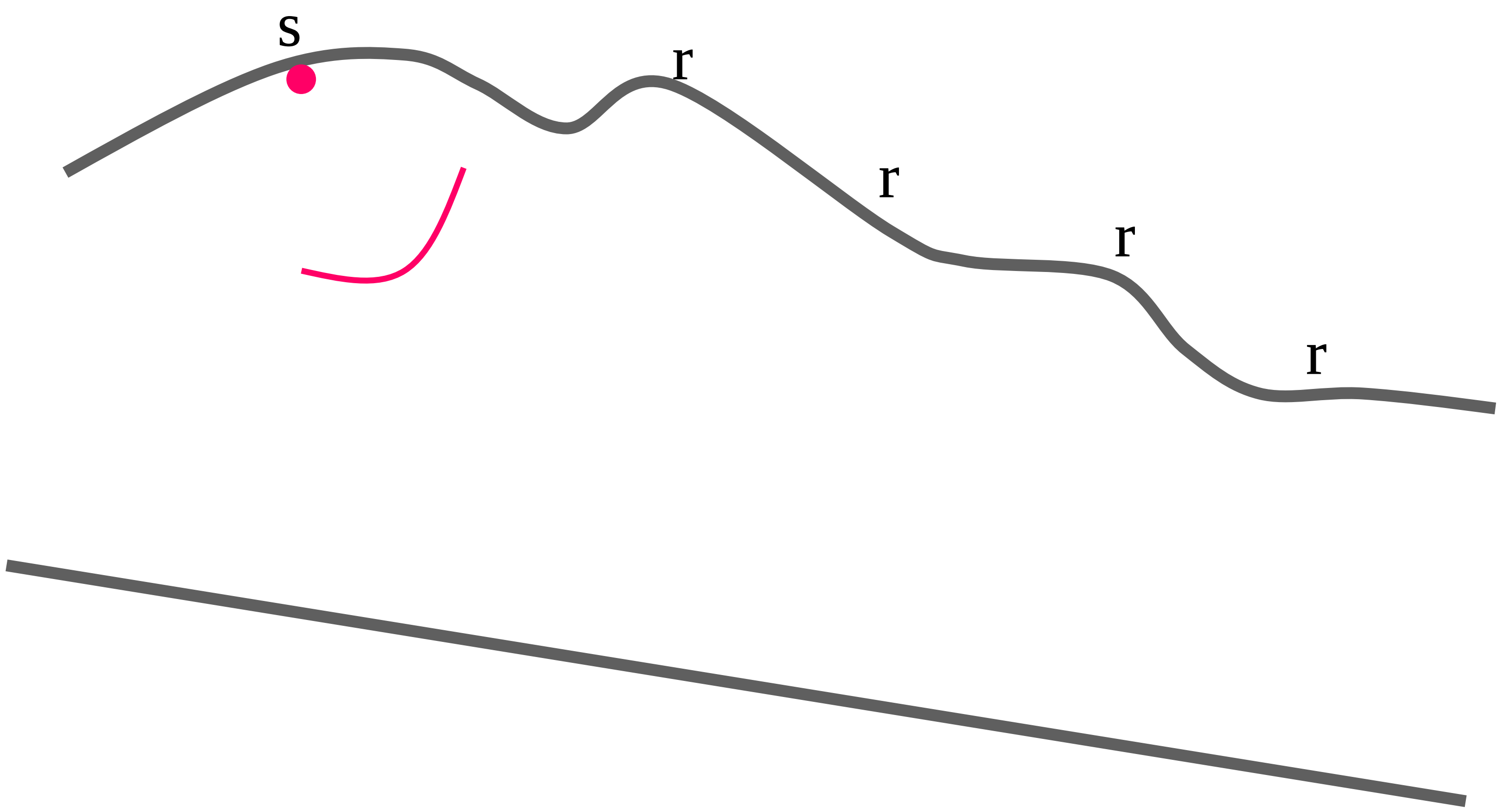
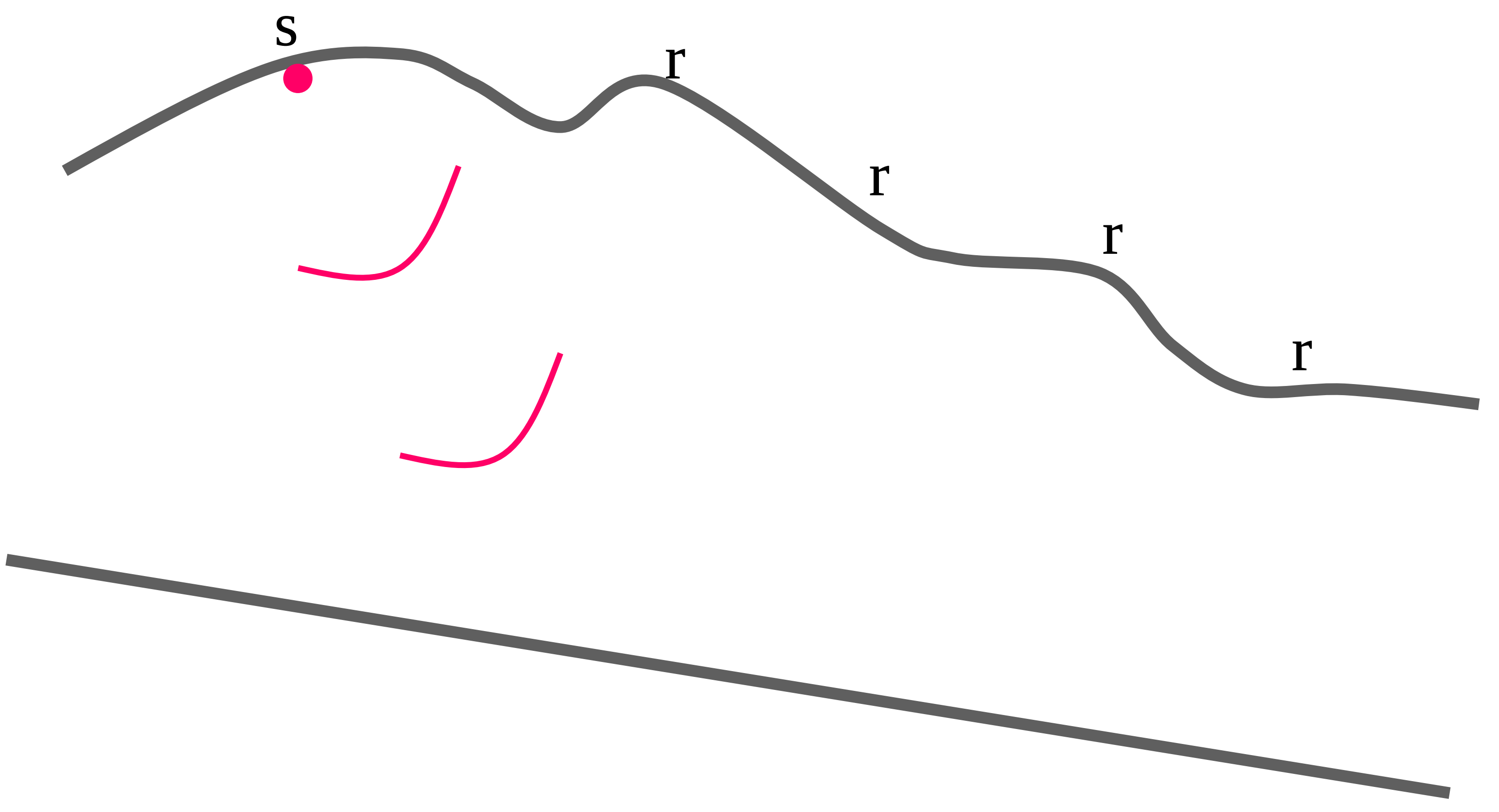
prestack modeling



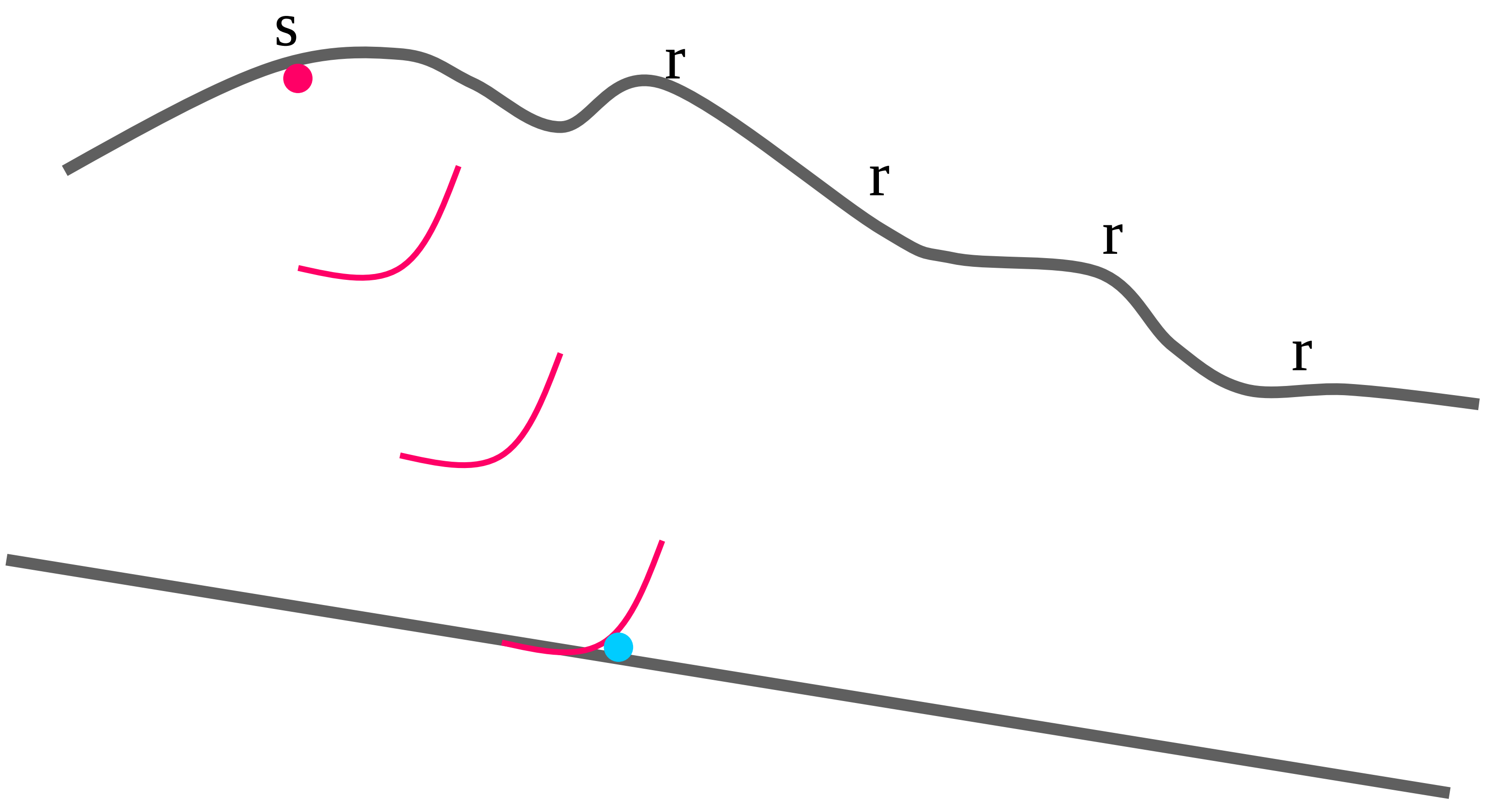
david.lumley@utdallas.edu

prestack modeling



david.lumley@utdallas.edu

prestack modeling



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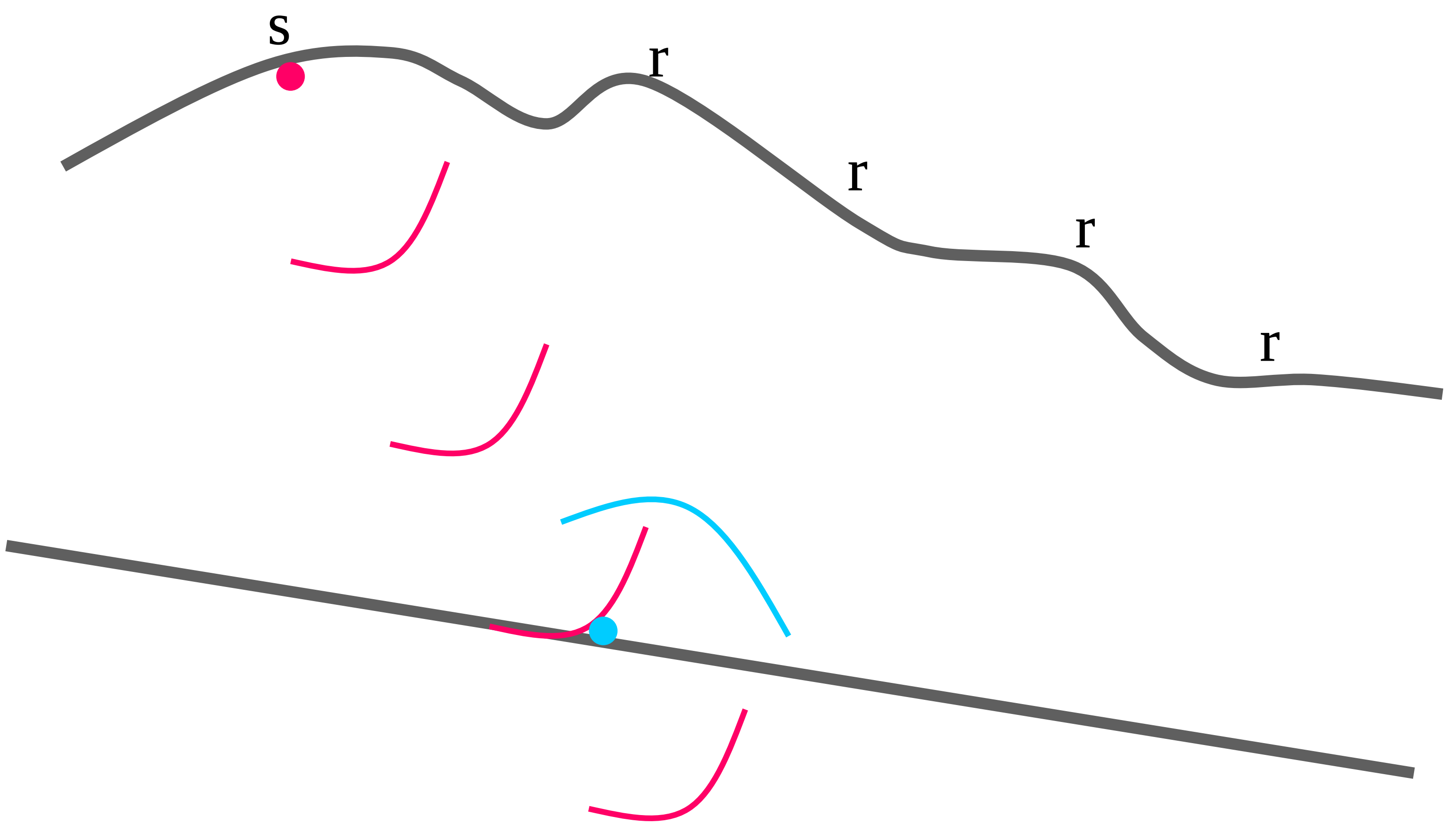
prestack modeling



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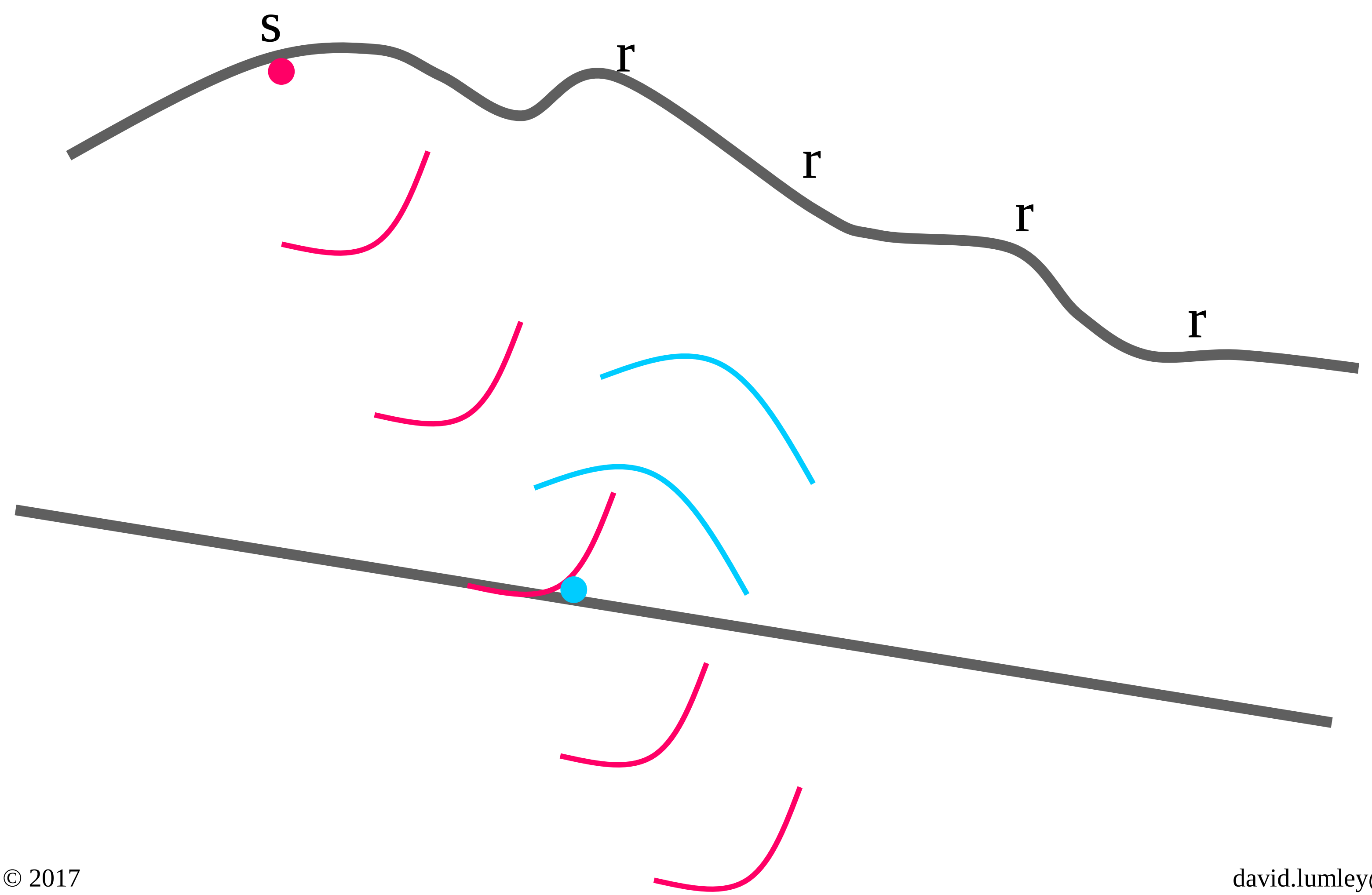

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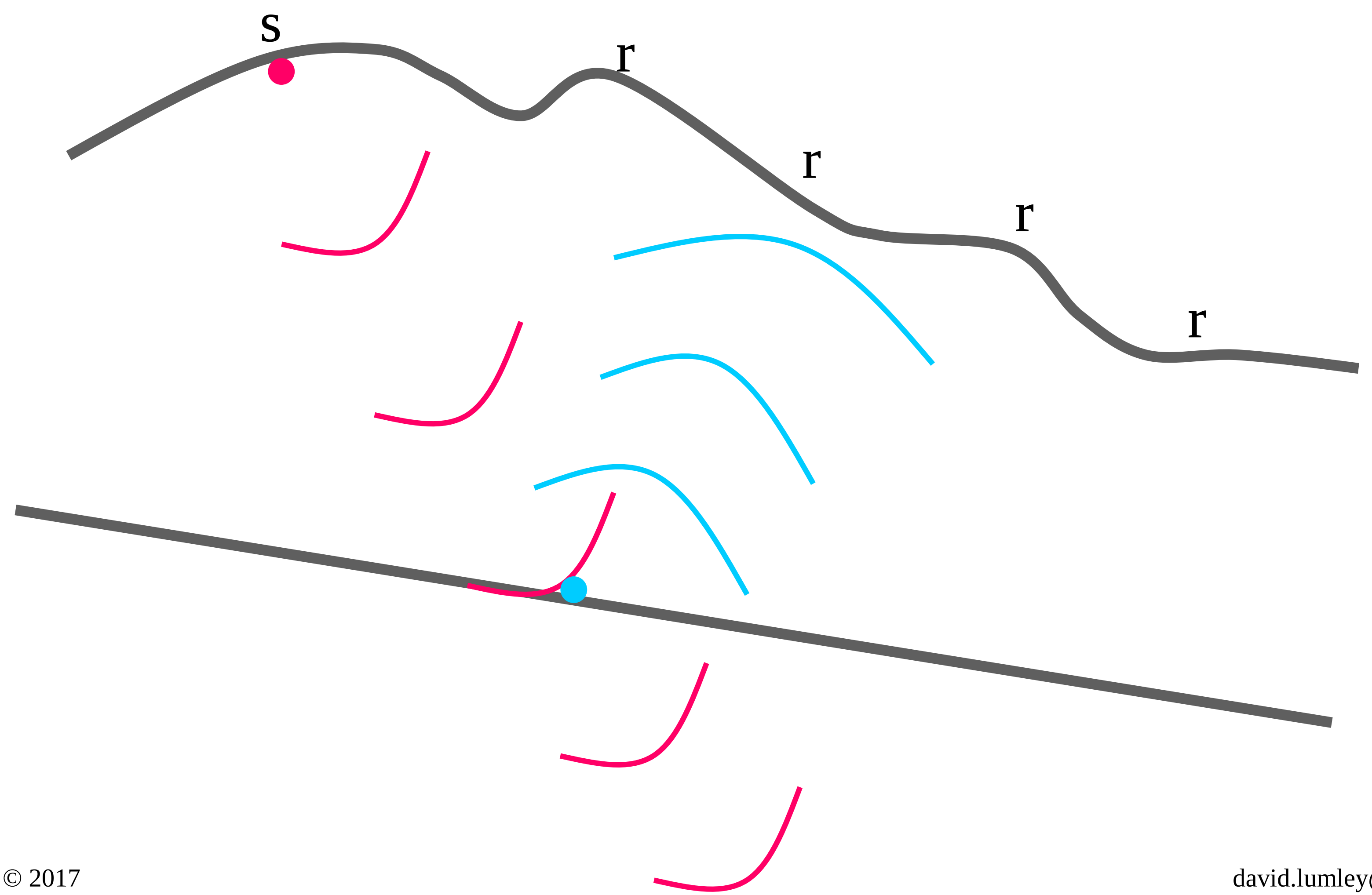
prestack modeling



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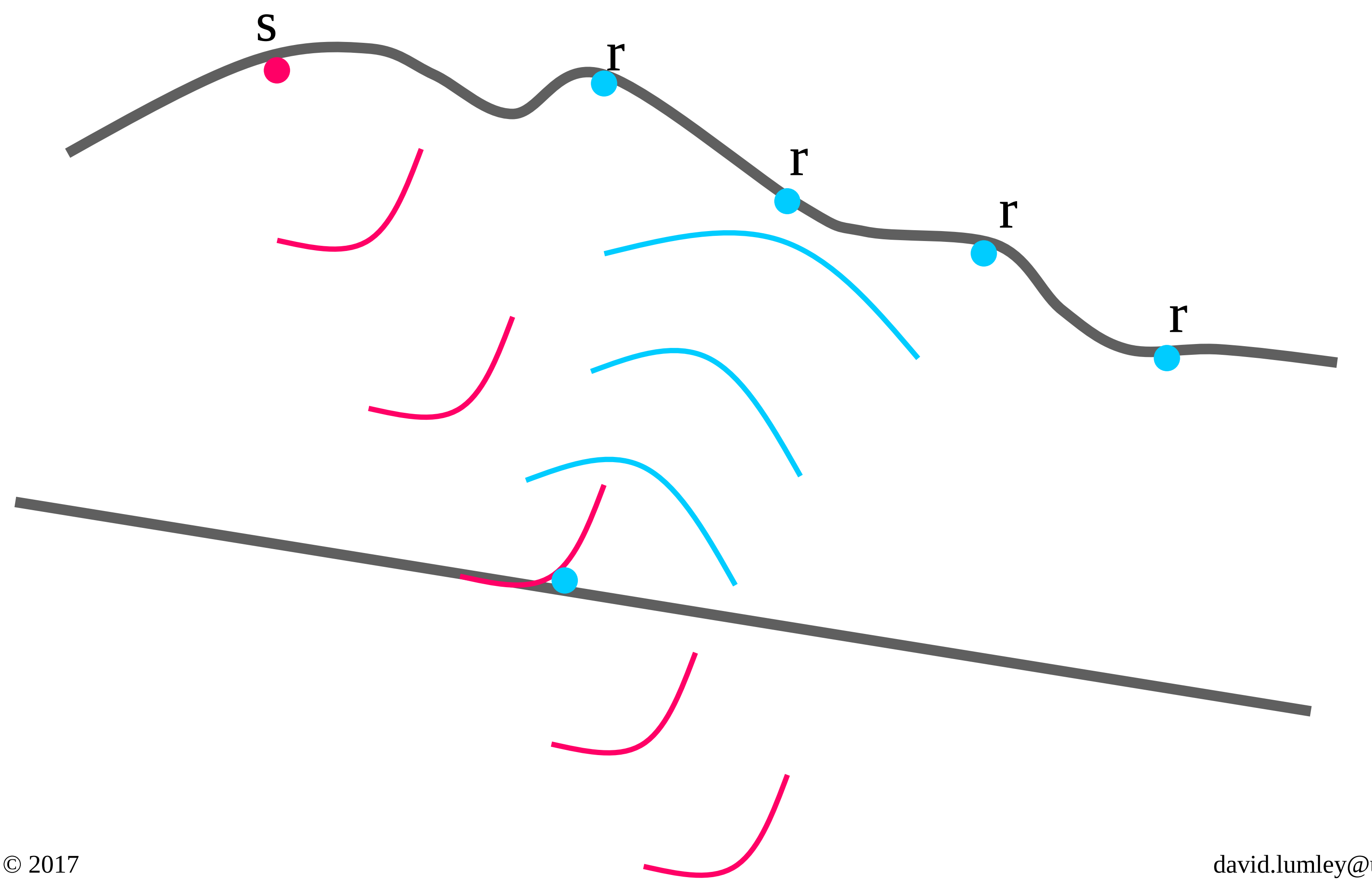

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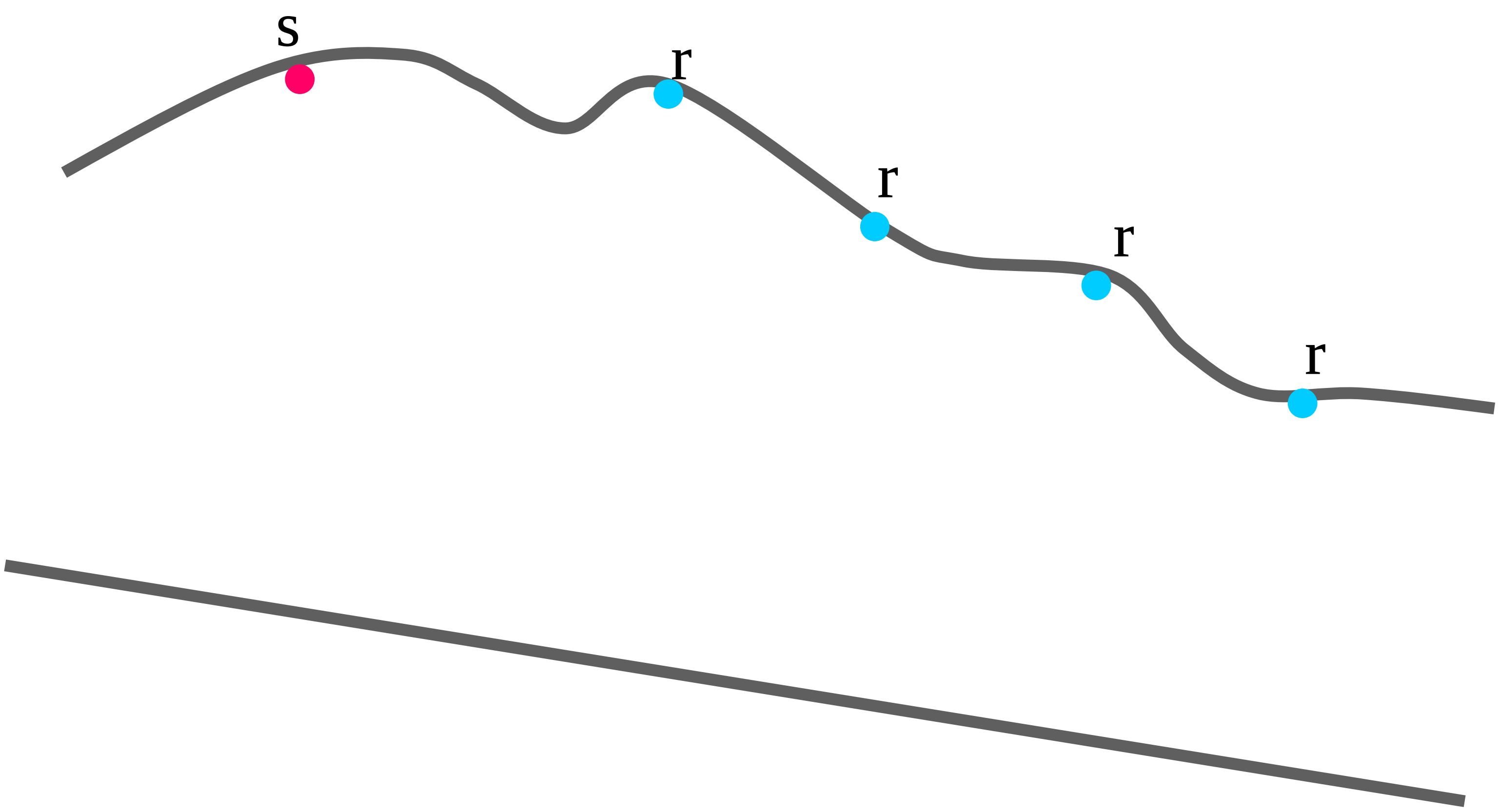
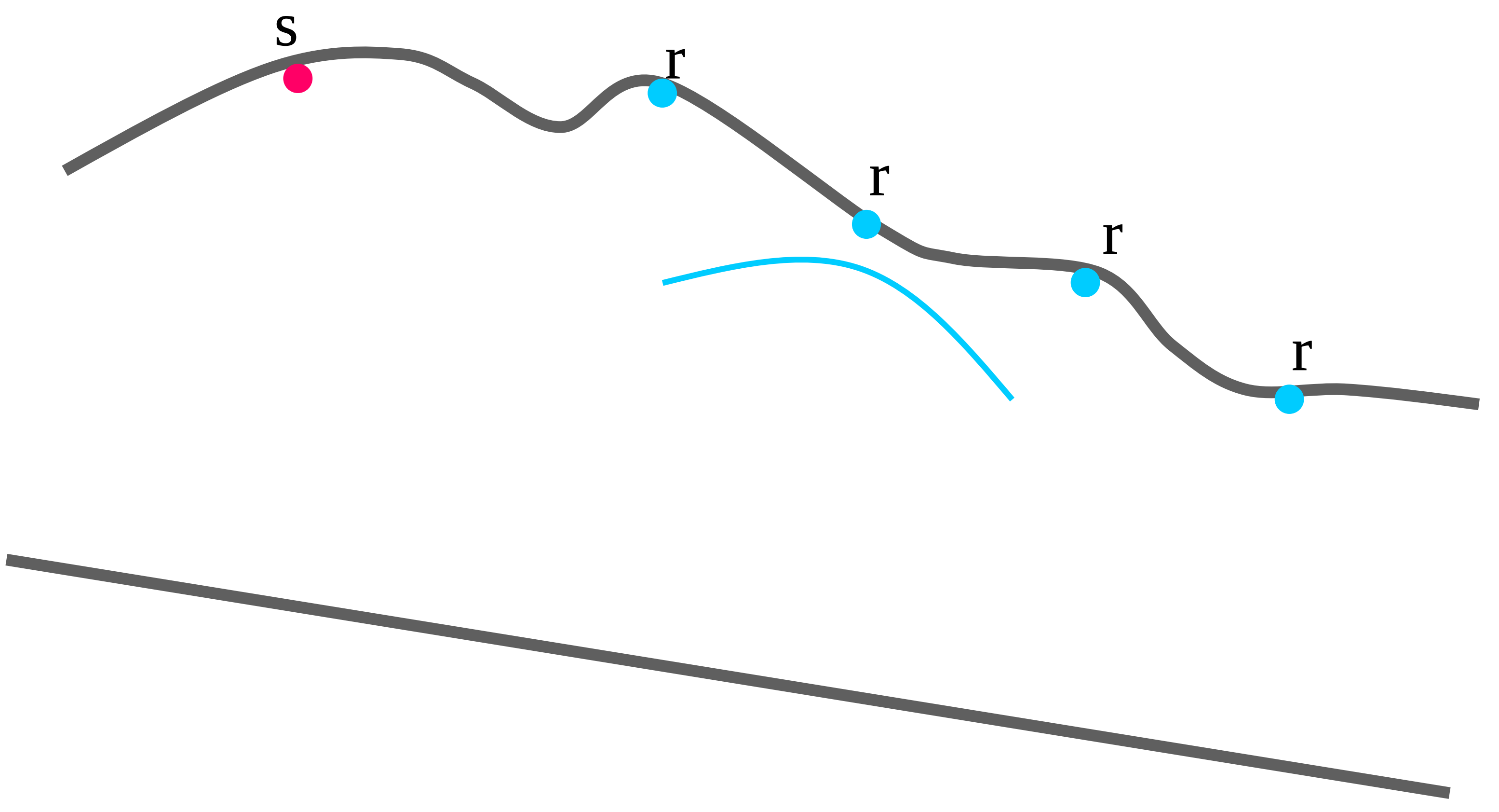
prestack imaging*



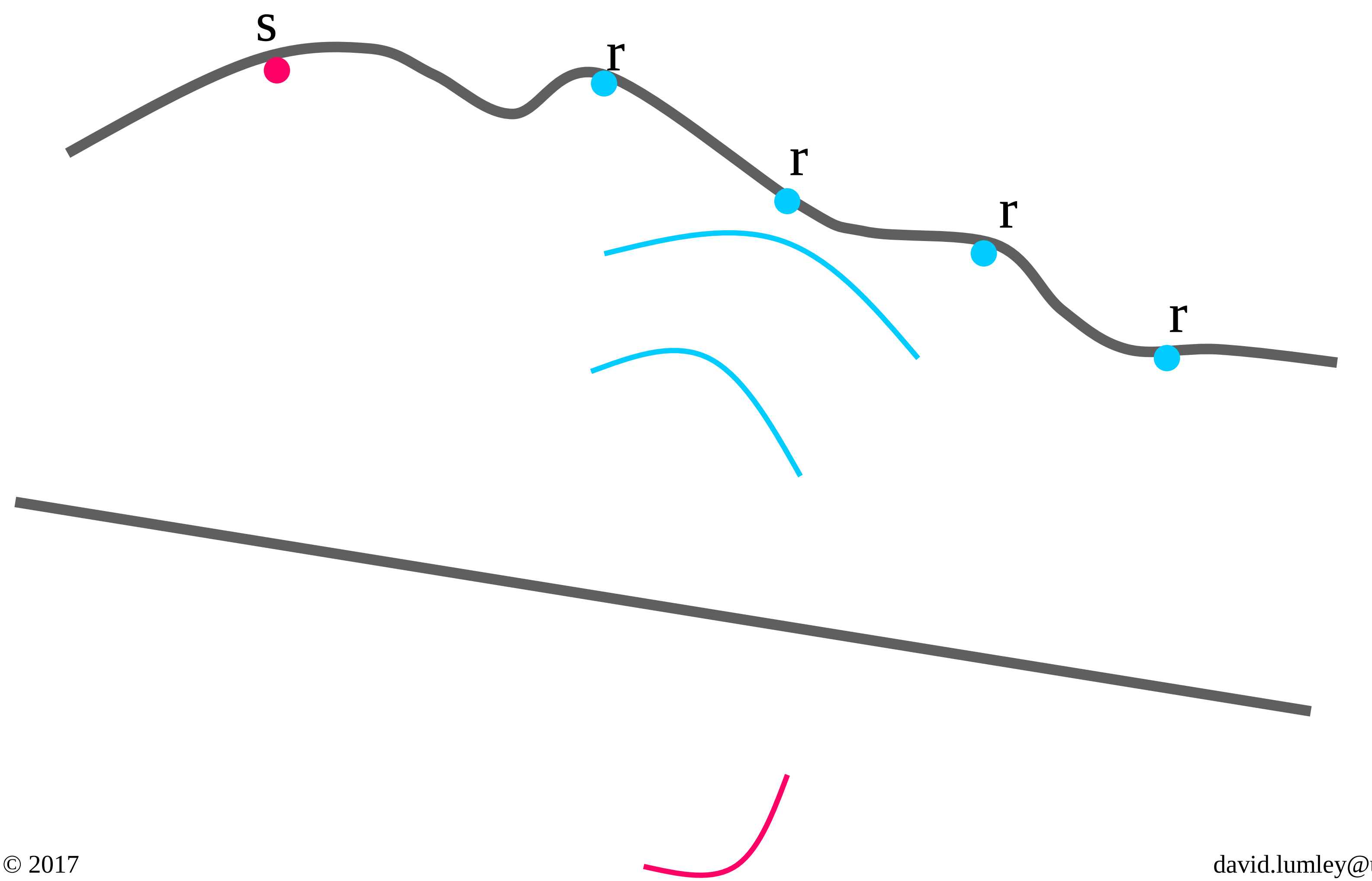
 david.lumley@utdallas.edu

prestack imaging



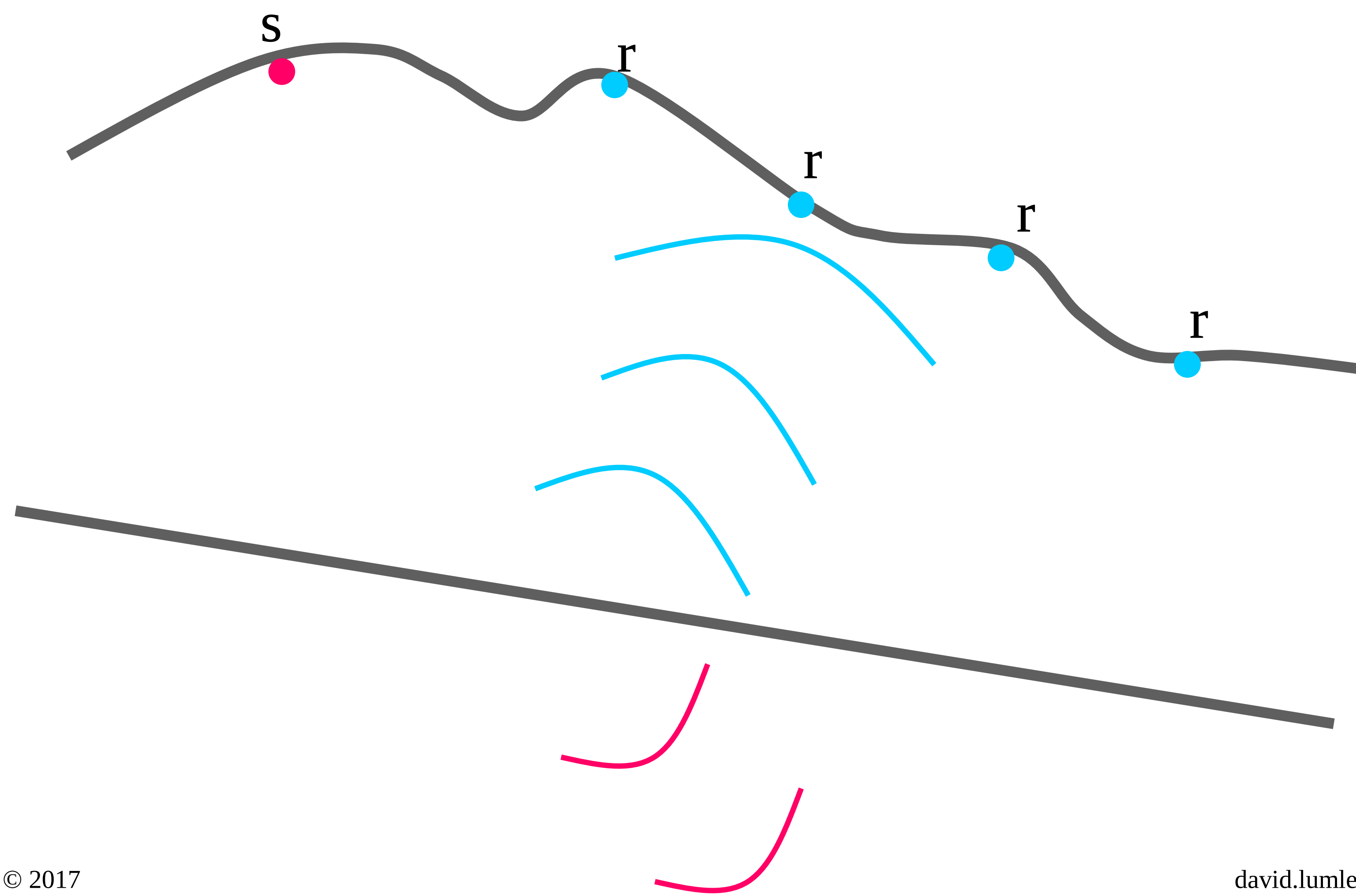
david.lumley@utdallas.edu

prestack imaging

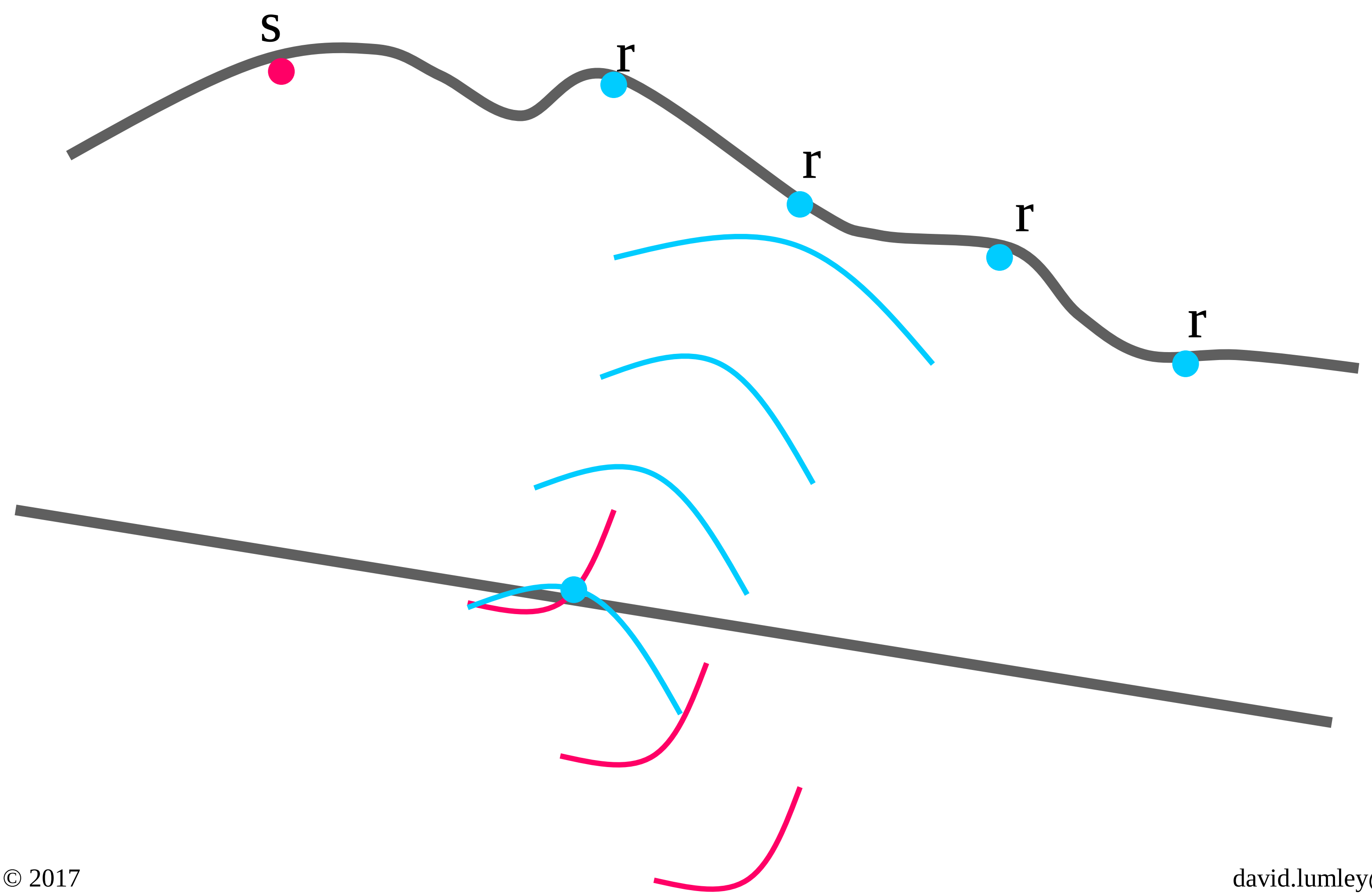


david.lumley@utdallas.edu

prestack imaging



prestack imaging



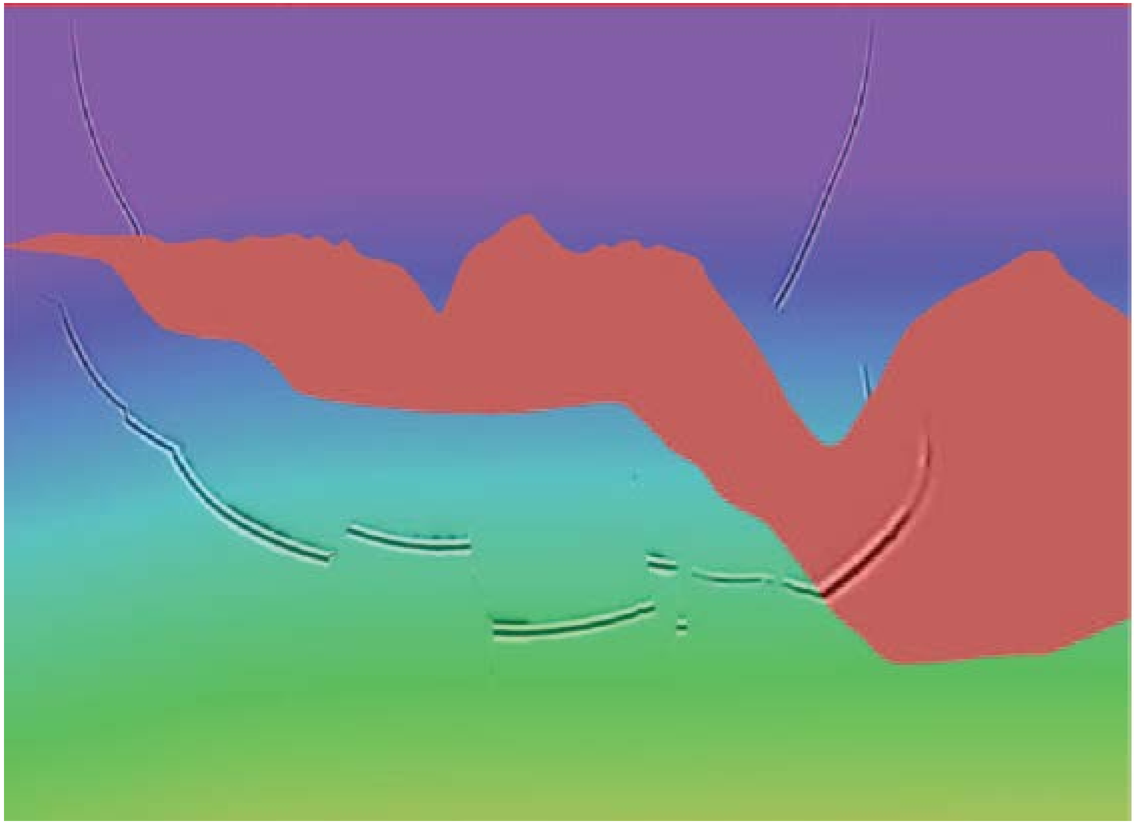
Imaging methods

- Different ways to solve the wave equation:

$$\{ \nabla^2 - \partial_{tt}/v^2 \} P(x,t) = 0$$

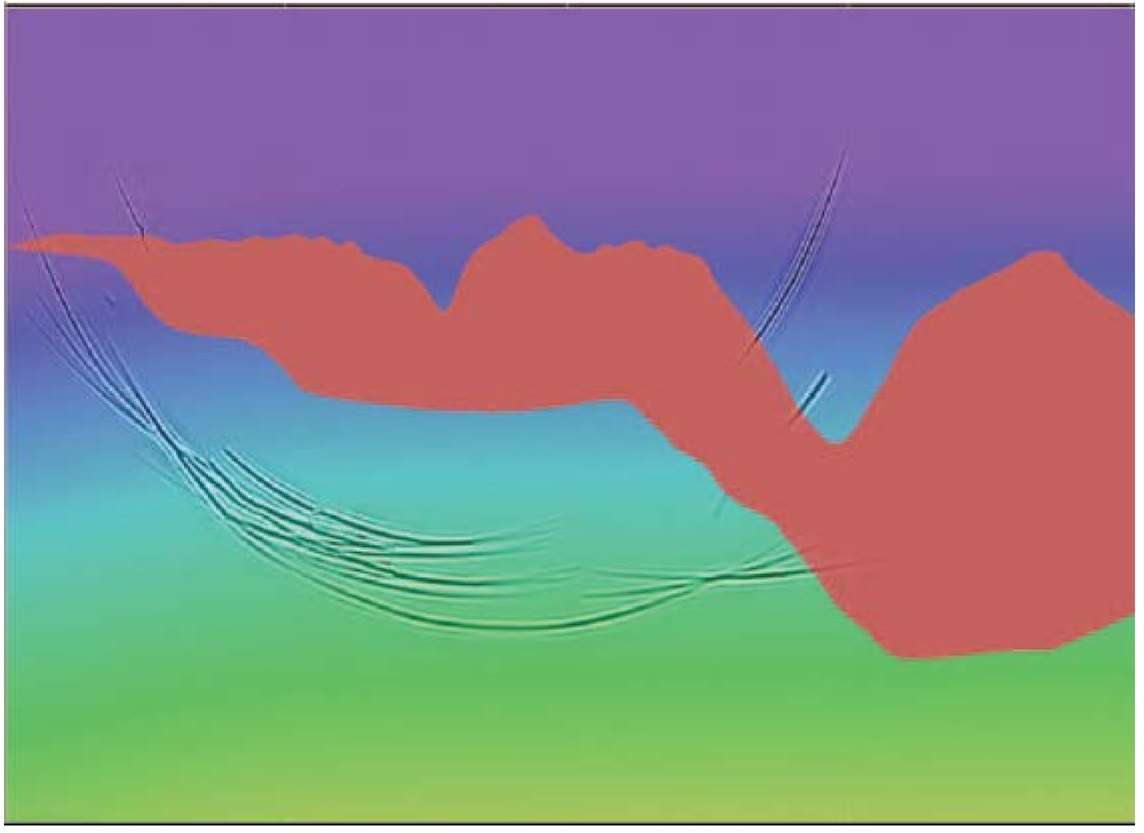
- Kirchhoff/rays/beams: *by Integral (summation) methods*
- Frequency-domain: *by Fourier/Laplace transforms*
- Finite Difference: *by FD/FEM operators*
- Hybrid methods: *any combinations of the above*

Kirchhoff



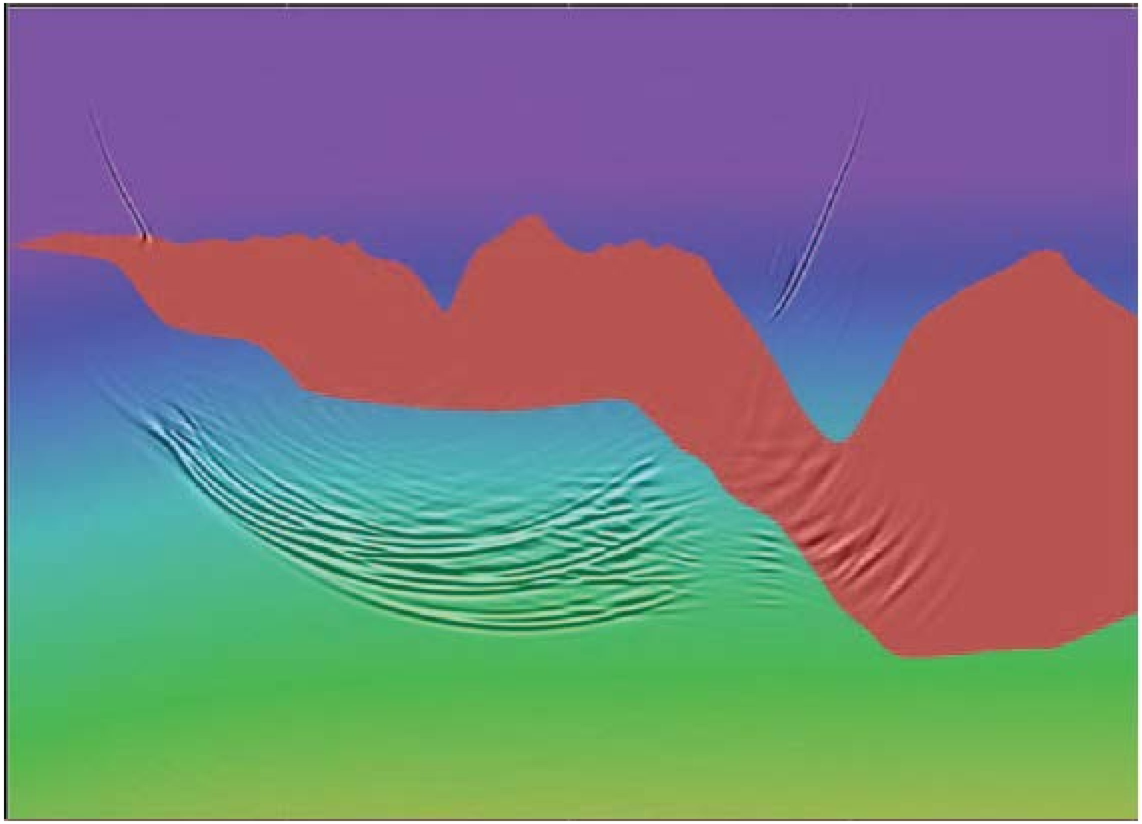
Etgen et al. (2009)

Gaussian Beam



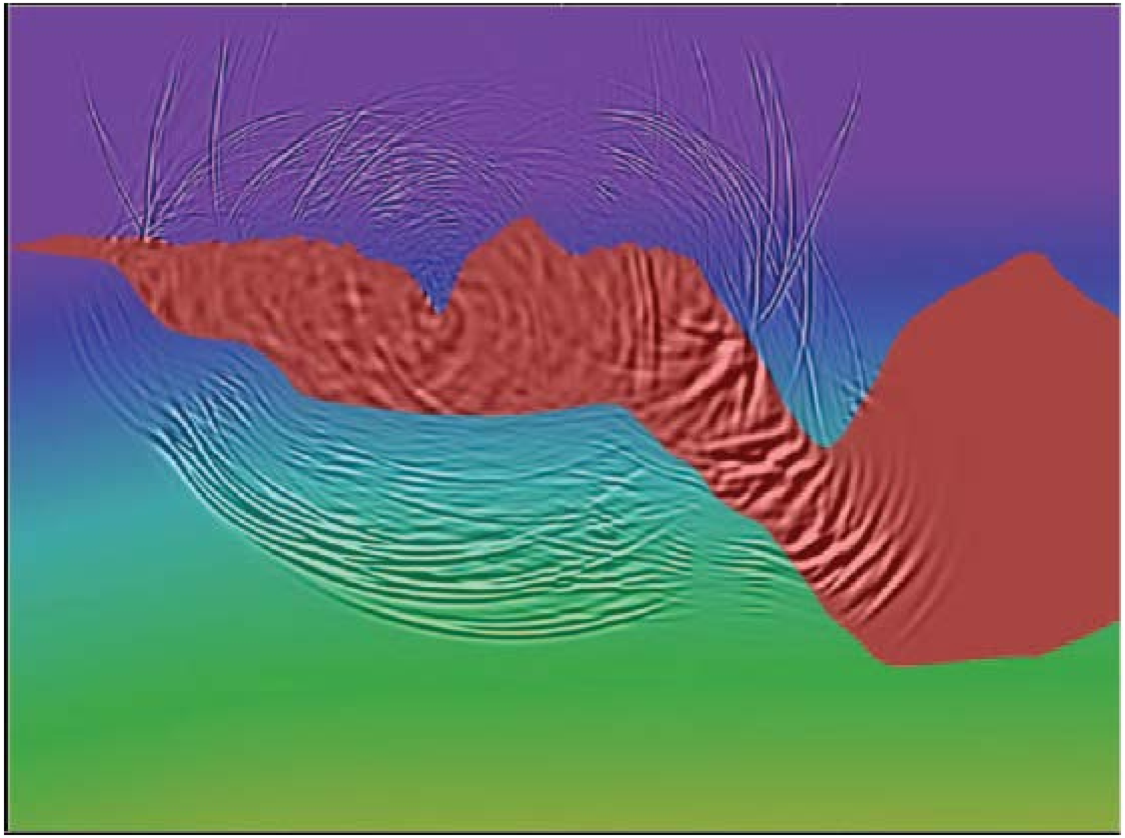
Etgen et al. (2009)

WEM (1-way)



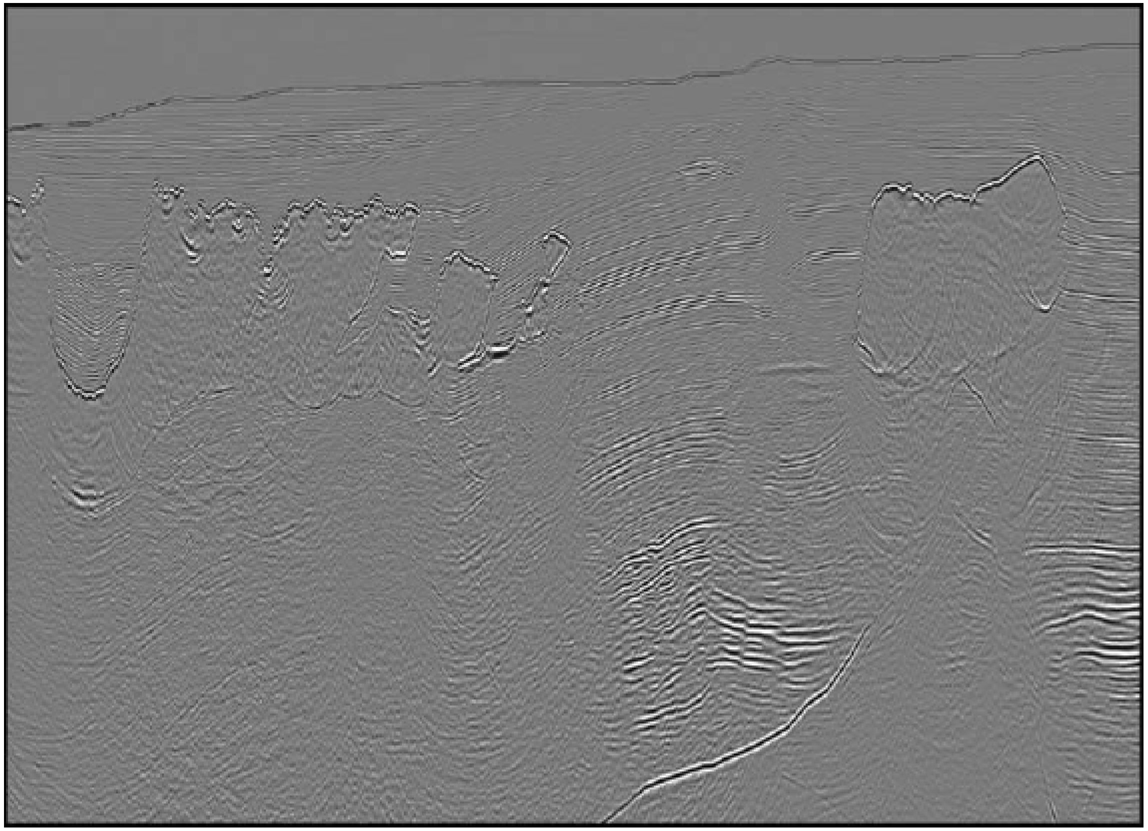
Etgen et al. (2009)

Reverse-time (RTM)



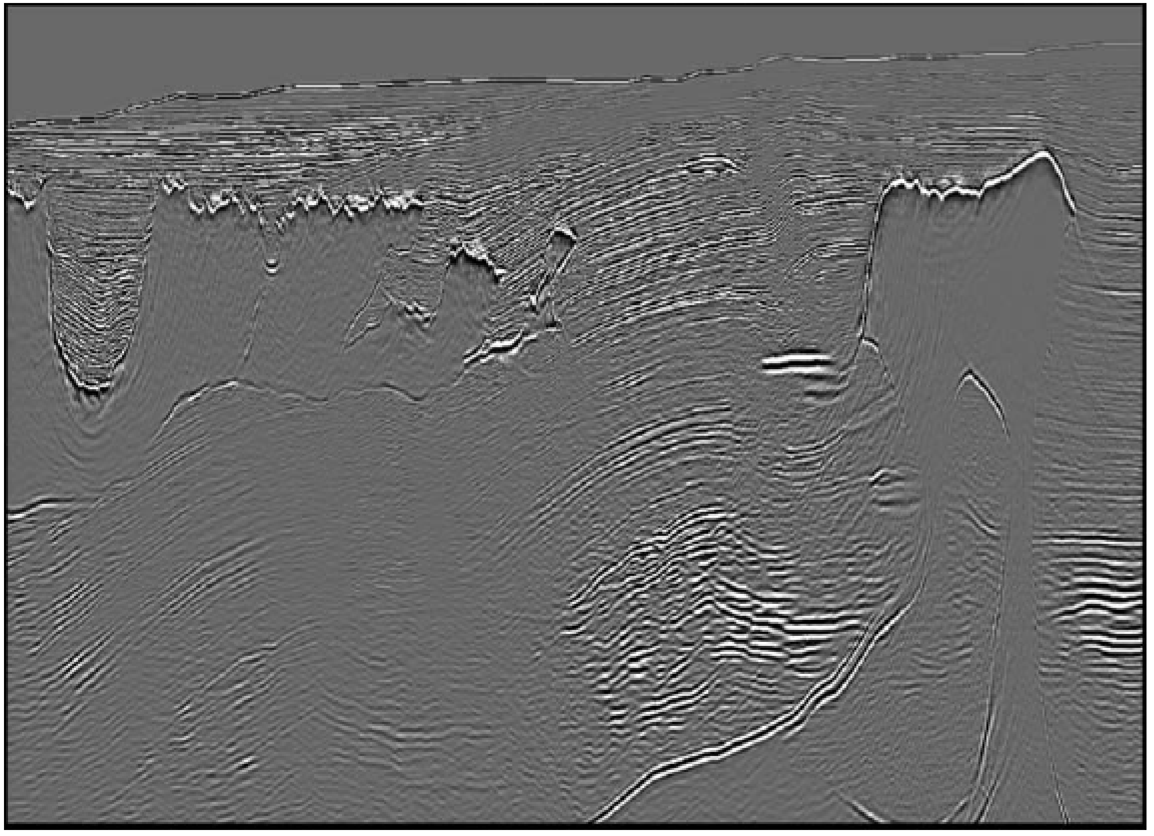
Etgen et al. (2009)

Kirchhoff



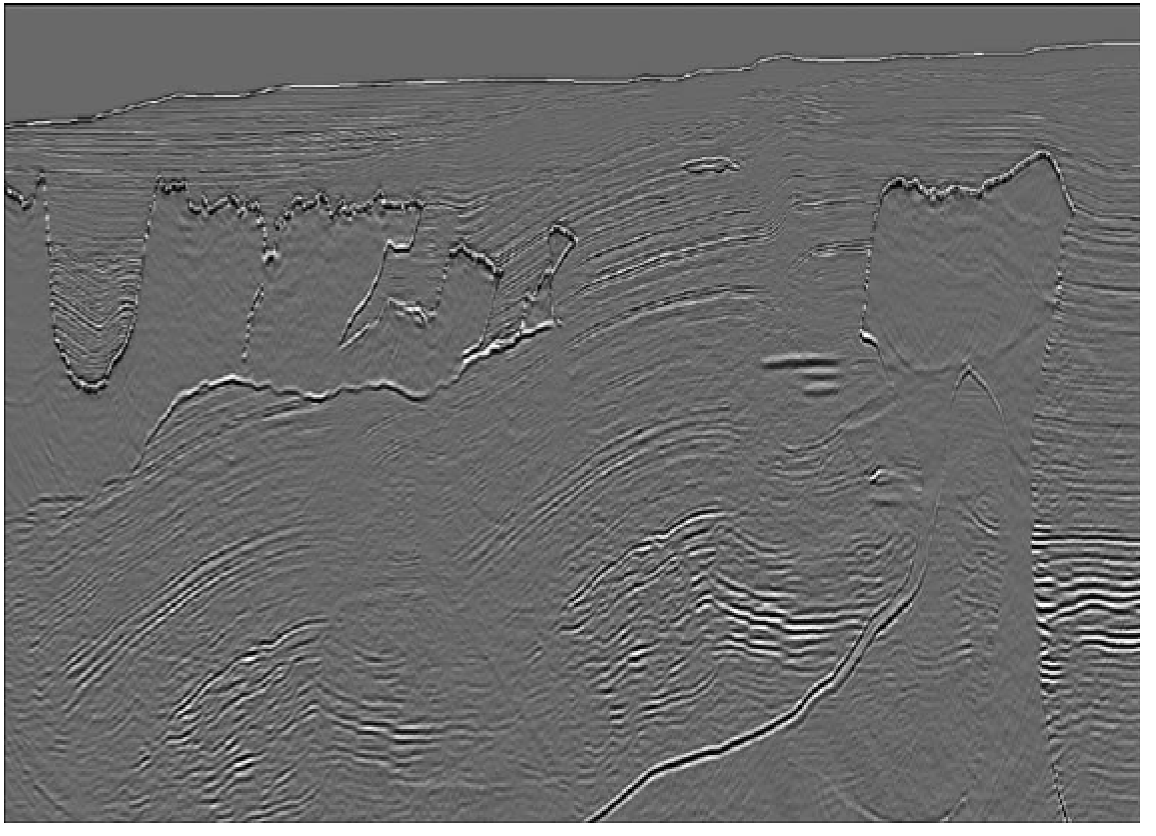
Etgen et al. (2009)

Gaussian Beam



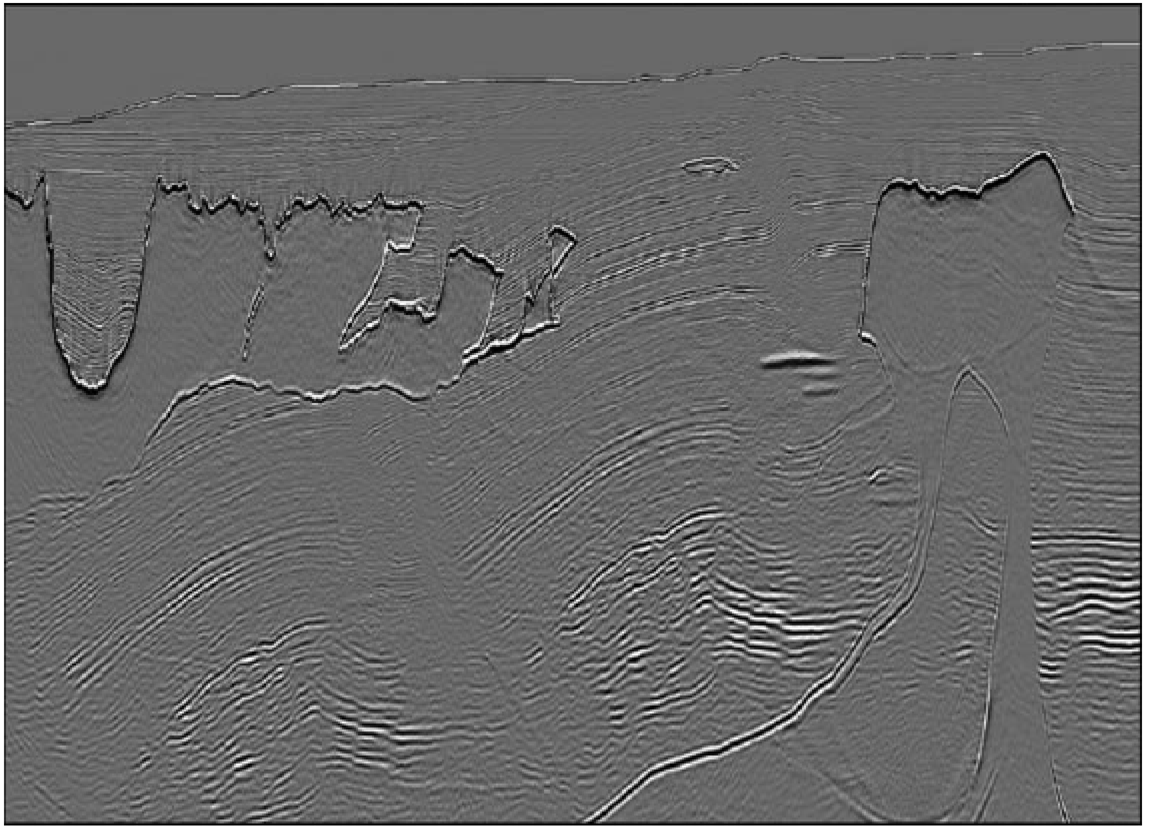
Etgen et al. (2009)

WEM (1-way)



Etgen et al. (2009)

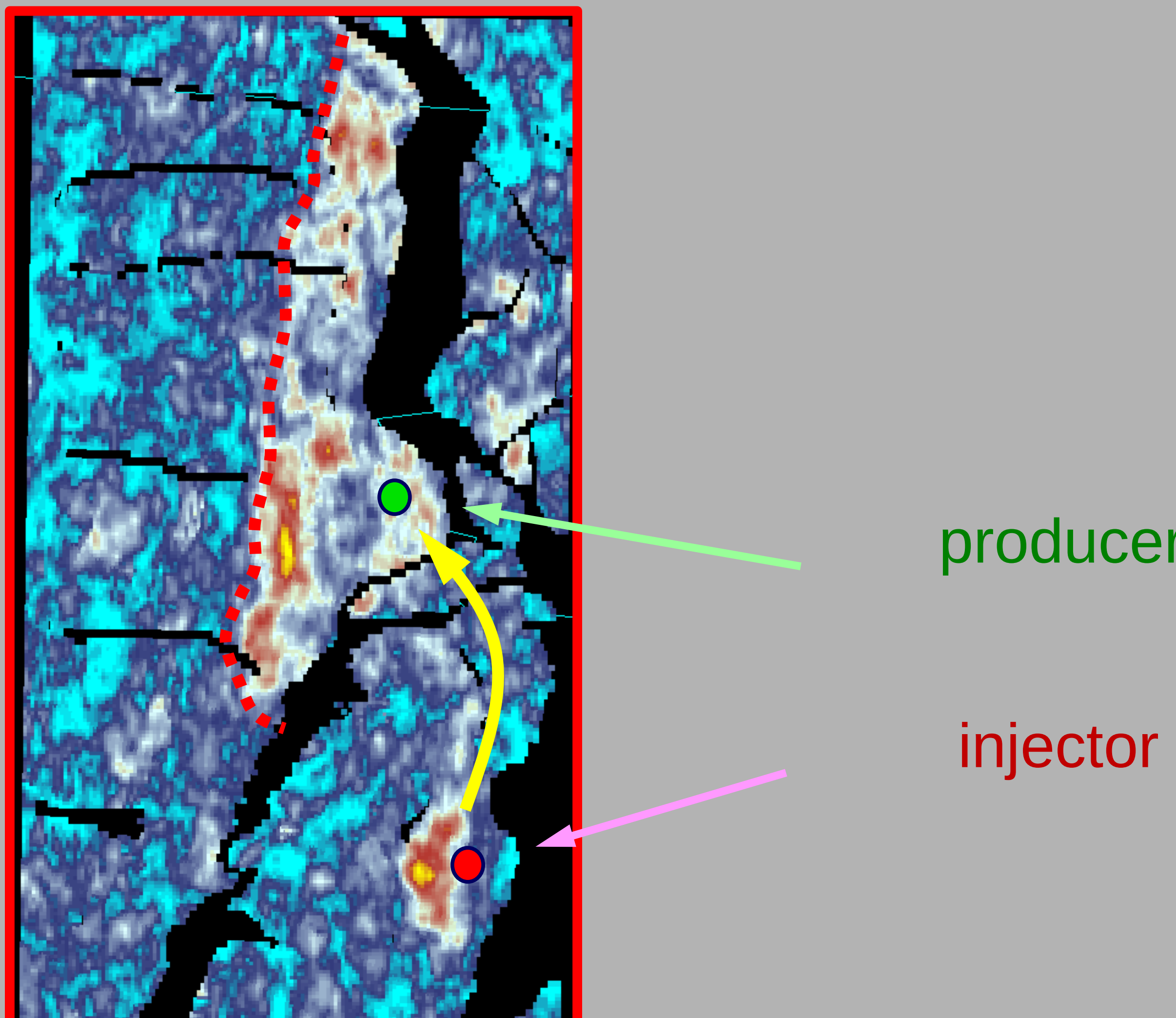
Reverse-time (RTM)(2-way)



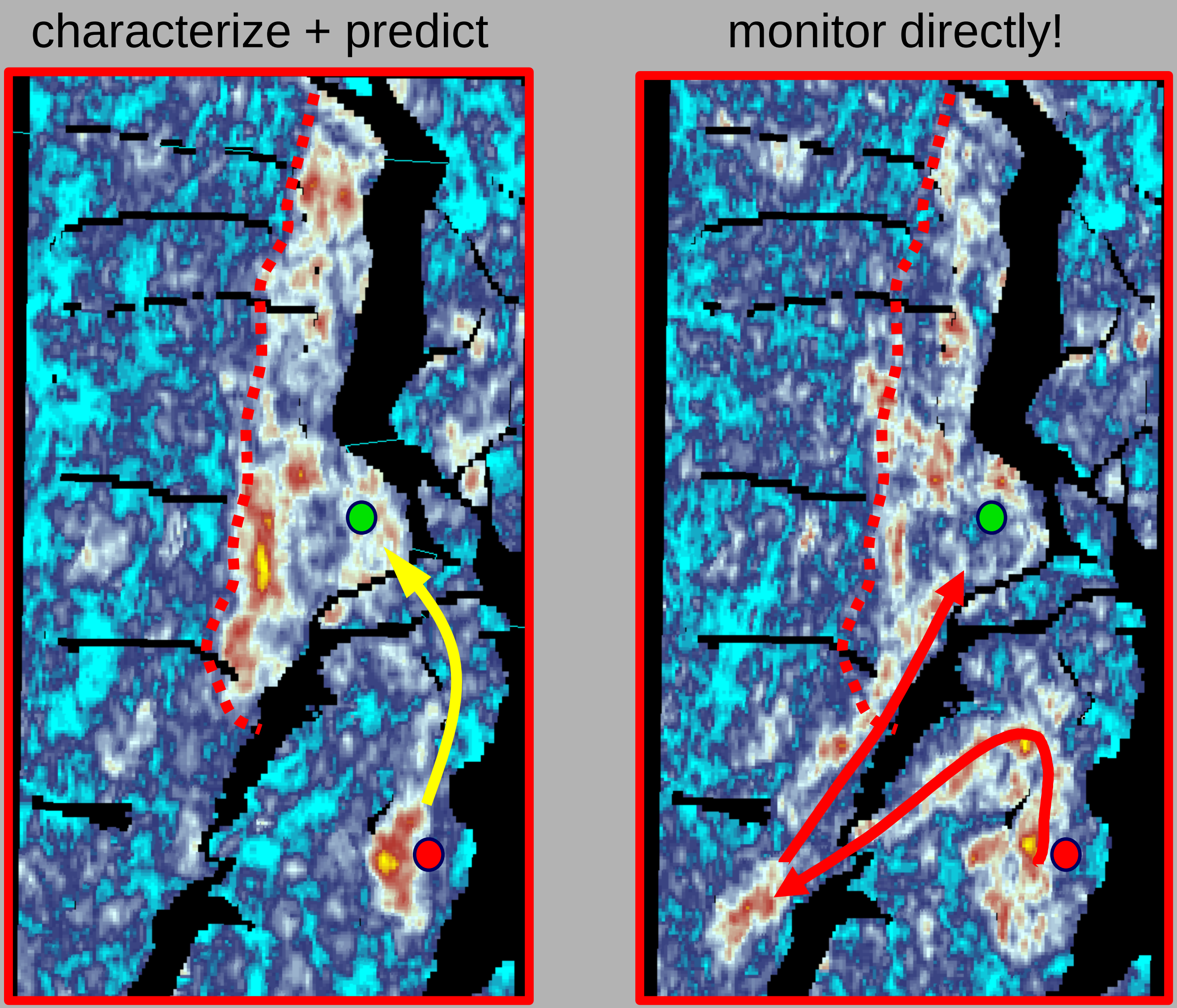
Etgen et al. (2009)

Monitoring Production

characterize + predict

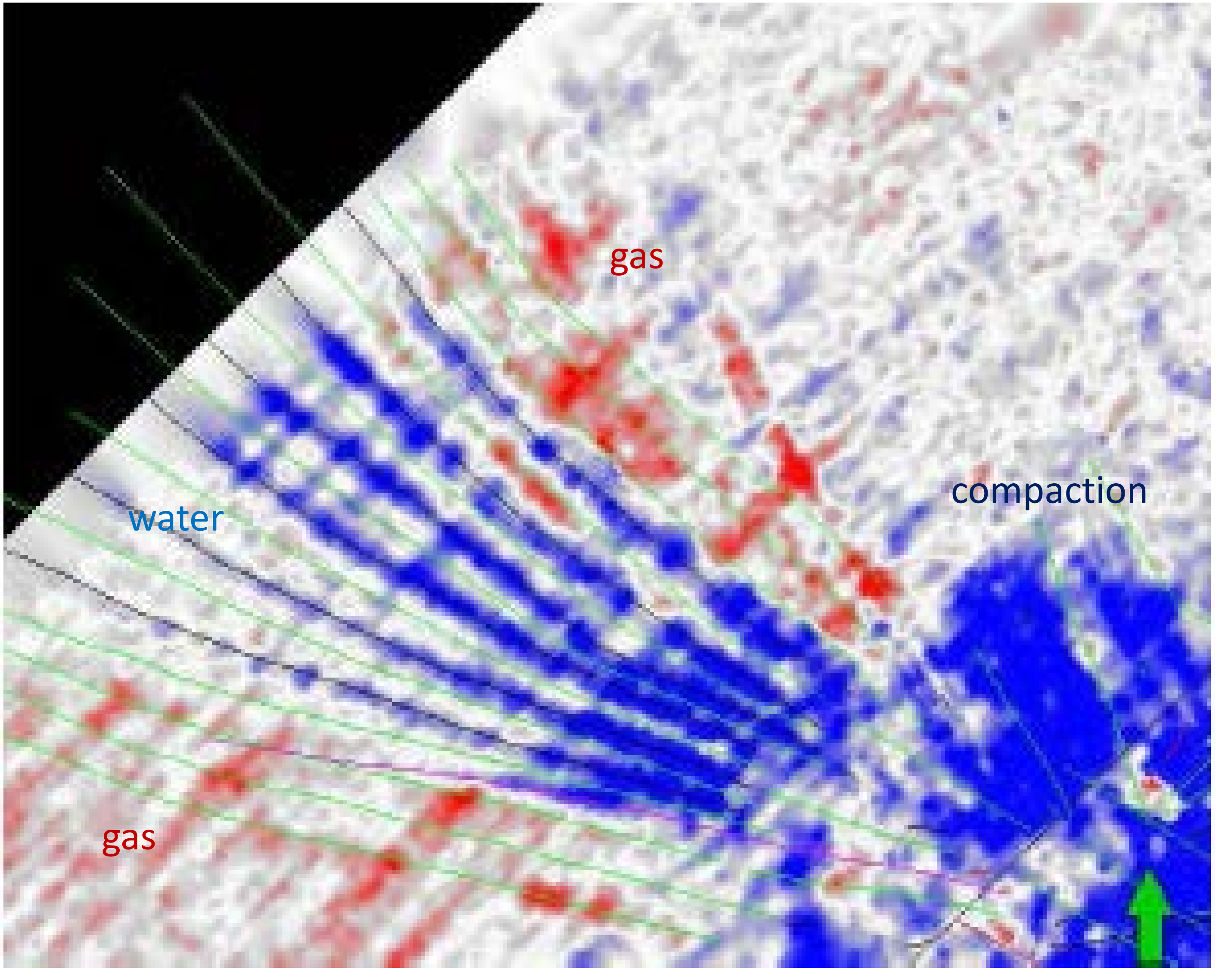


Monitoring Production



Statoil

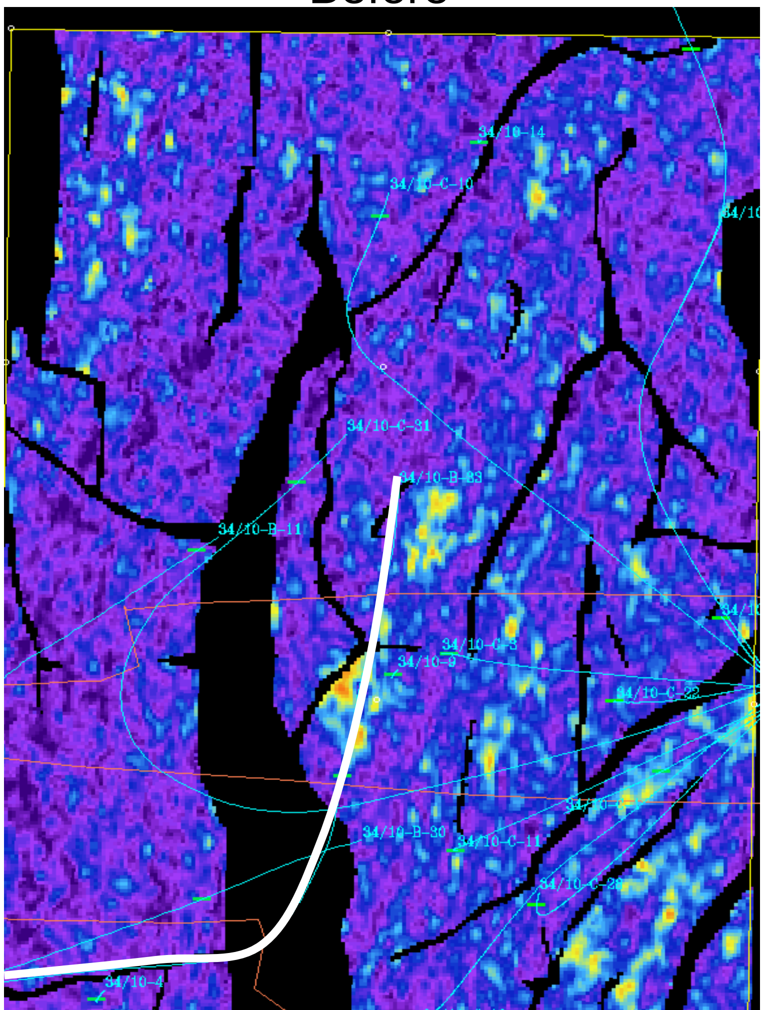
Fractured chalk reservoir



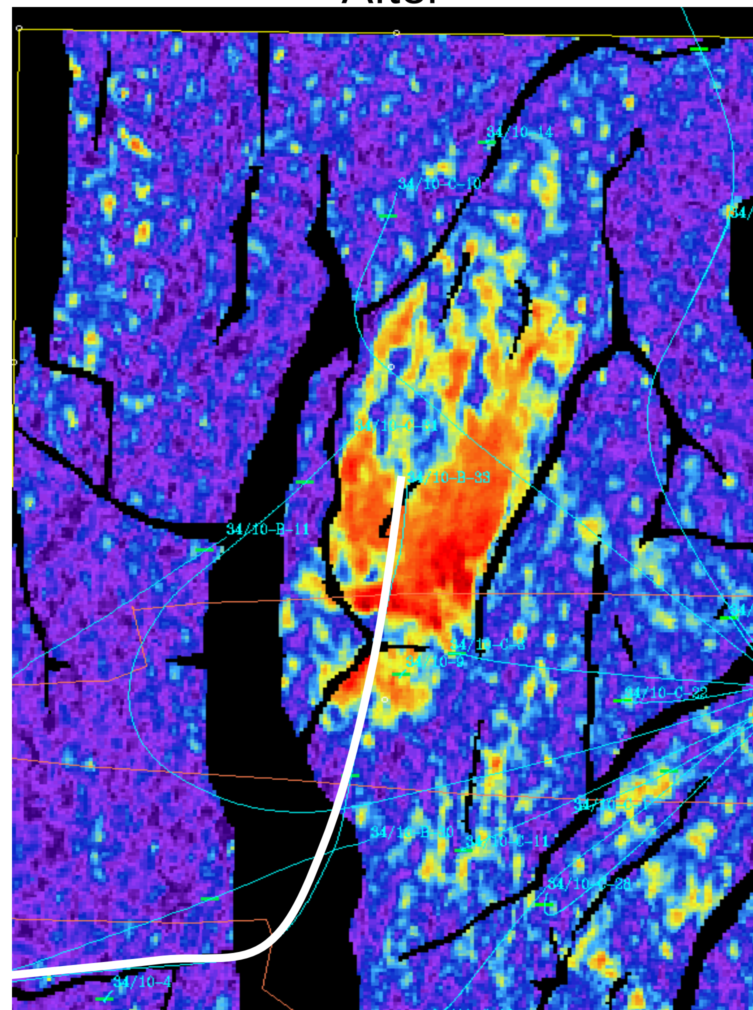
Gommesen et al., 2007

4D Seismic Pressure Anomaly

Before



After



Lumley et al.

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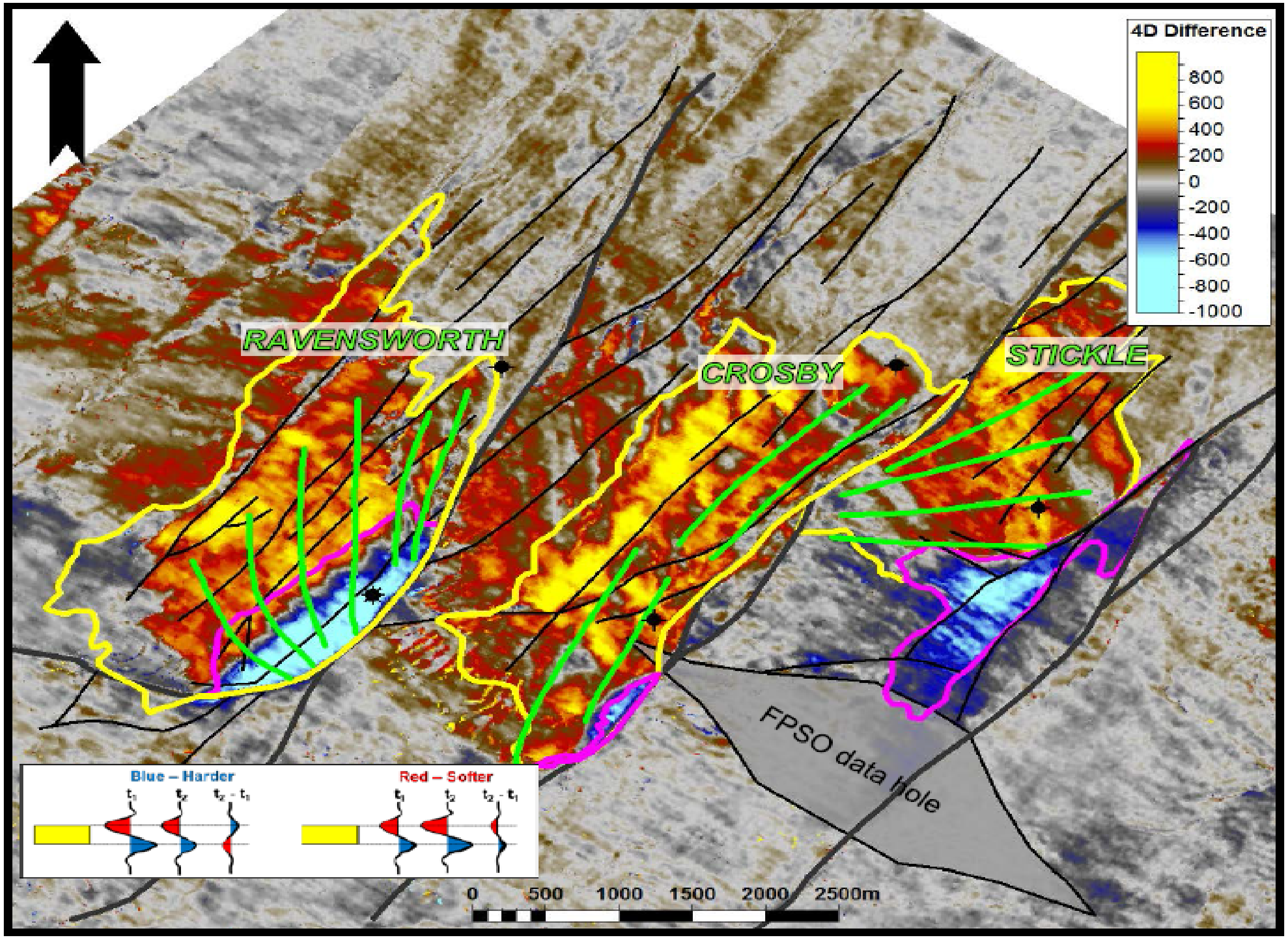
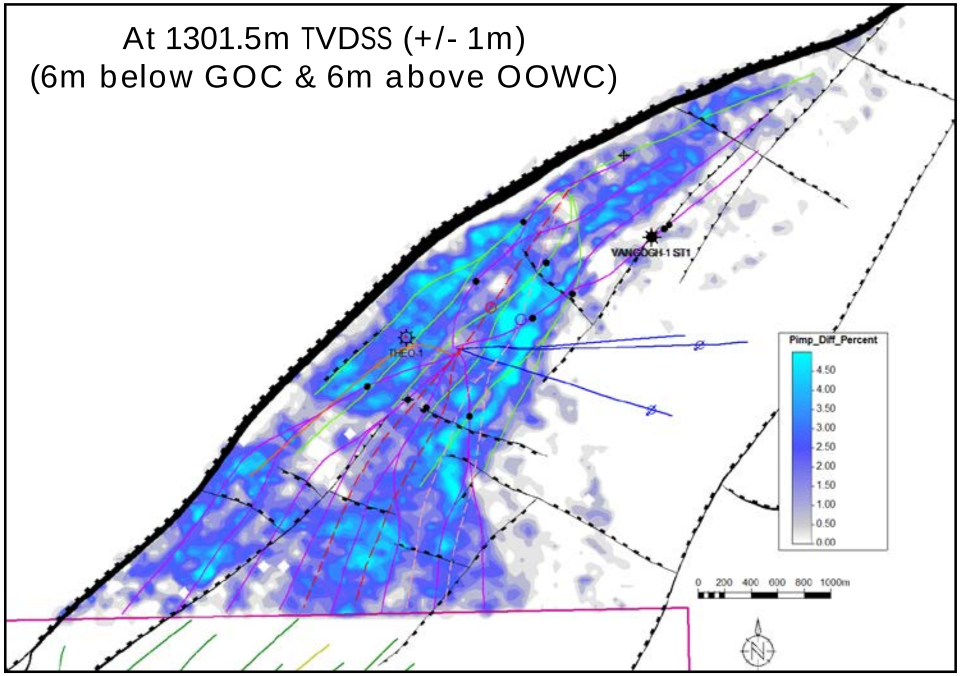
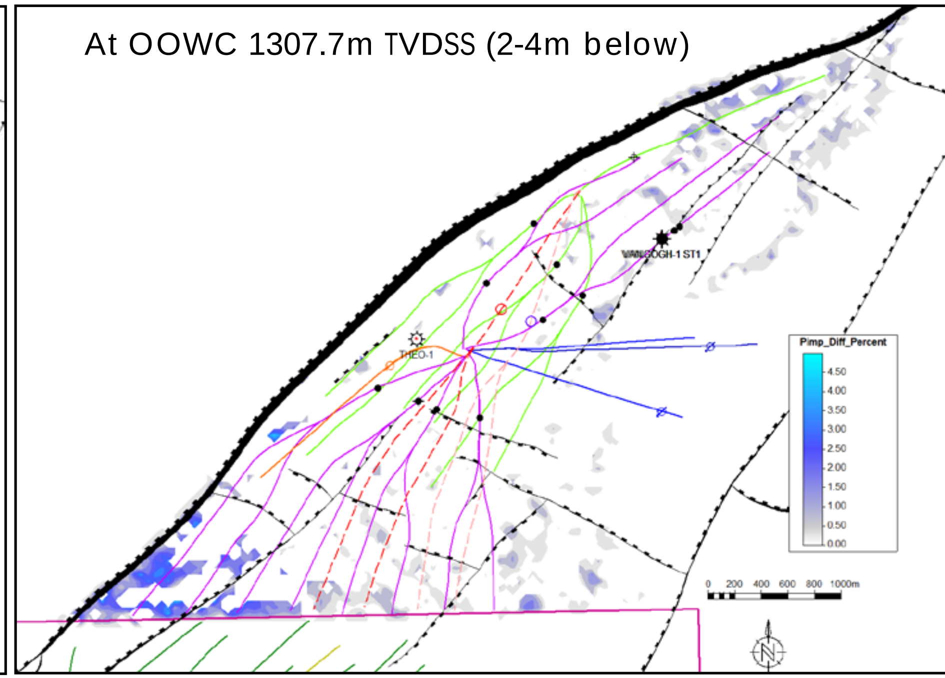
Full Angle Stack
Monitor minus Baseline



ASEG-PESA 2015 4D Seismic over the Pyrenees Fields: Duncan, et al.

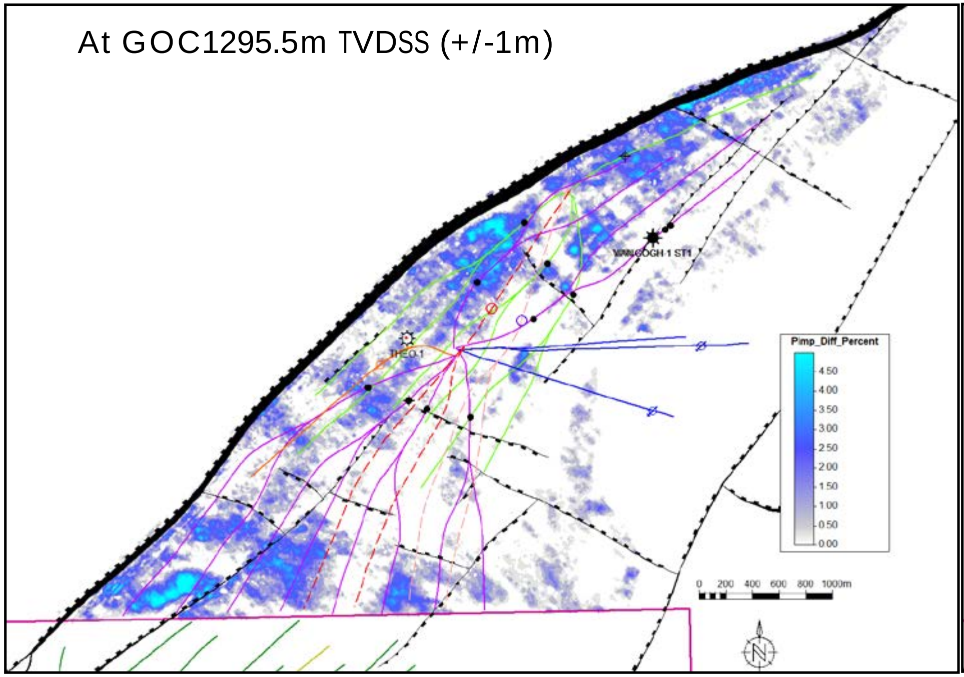
van GOGH: P-IMP $4D_{DIFF}$ %

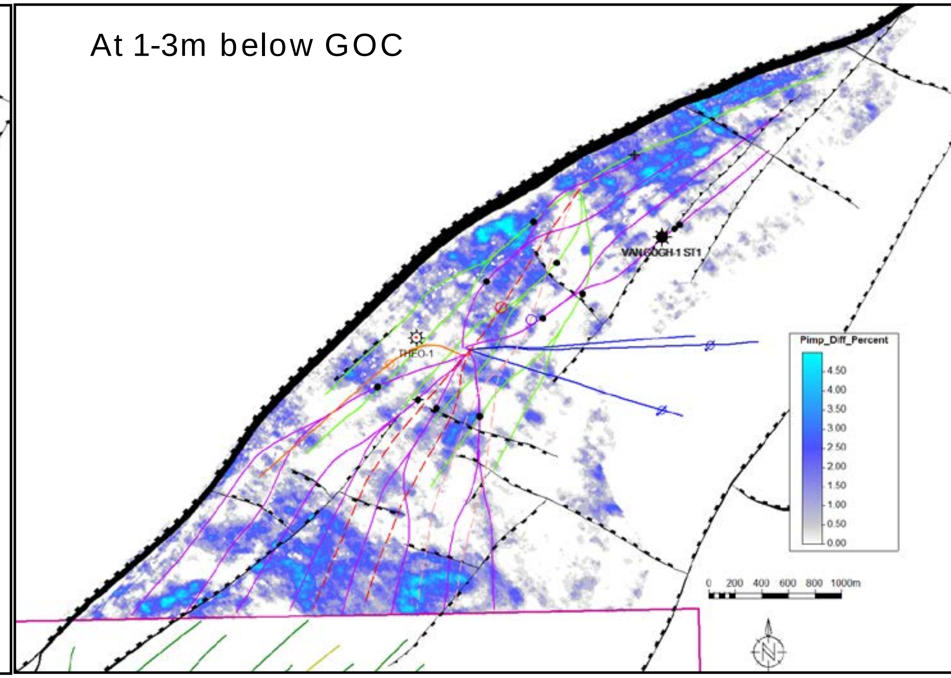




Bouloudas et al., Quadrant, 2015

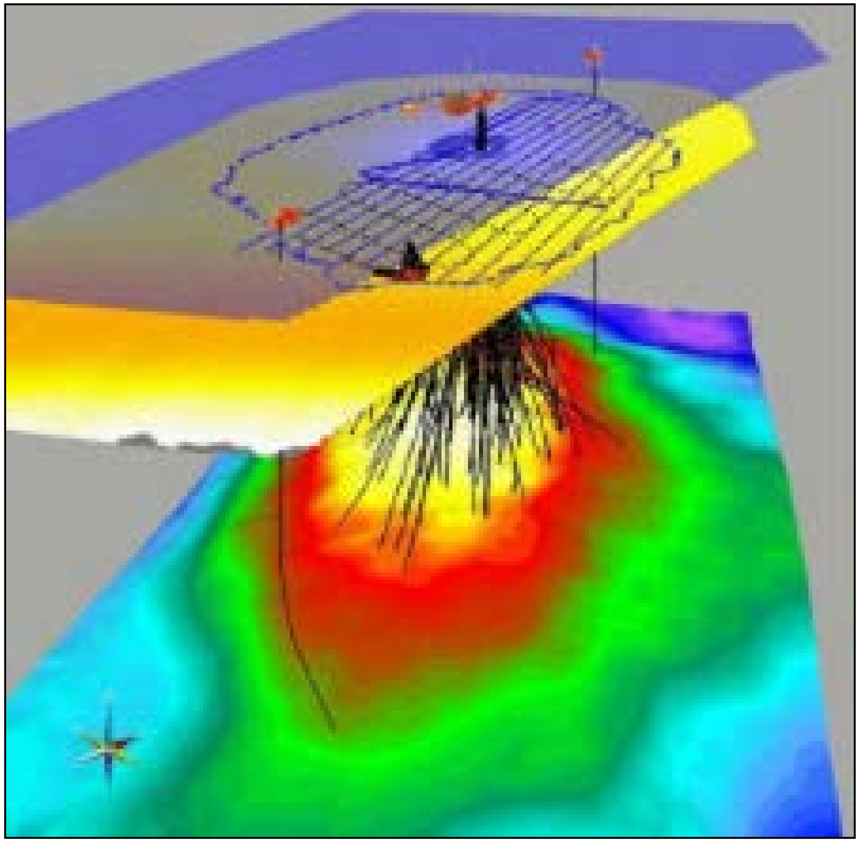
van GOGH: P-IMP 4D$_{DIFF}$ %



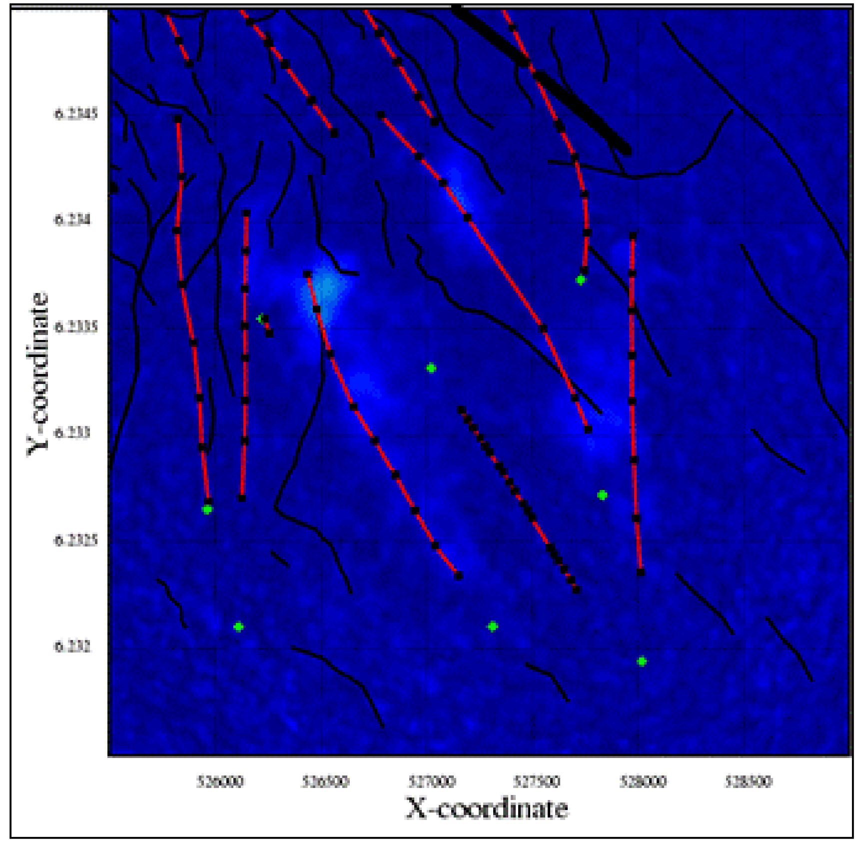


Bouloudas et al., Quadrant, 2015

Valhall permanent seafloor array



Barkved et al., 2004



courtesy BP

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3D + 4D Seismic Inversion

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Inverse theory (inversion)

$d = F(m)$; $m = F^{-1}(d)$

d = data
m = model
F = physics

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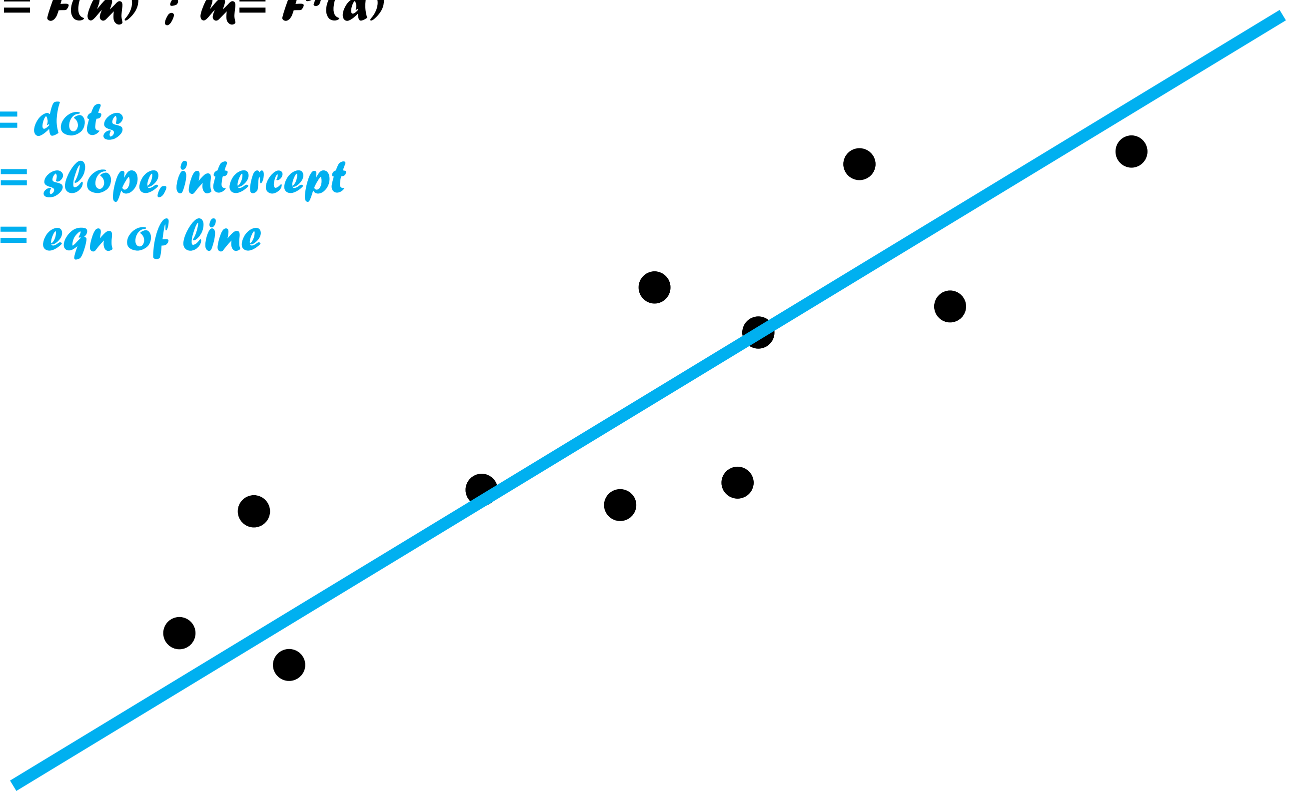
Inverse theory (inversion)

$d = F(m)\ ;\ m = F^{-1}(d)$

d= dots
m= slope, intercept
F = eqn of line



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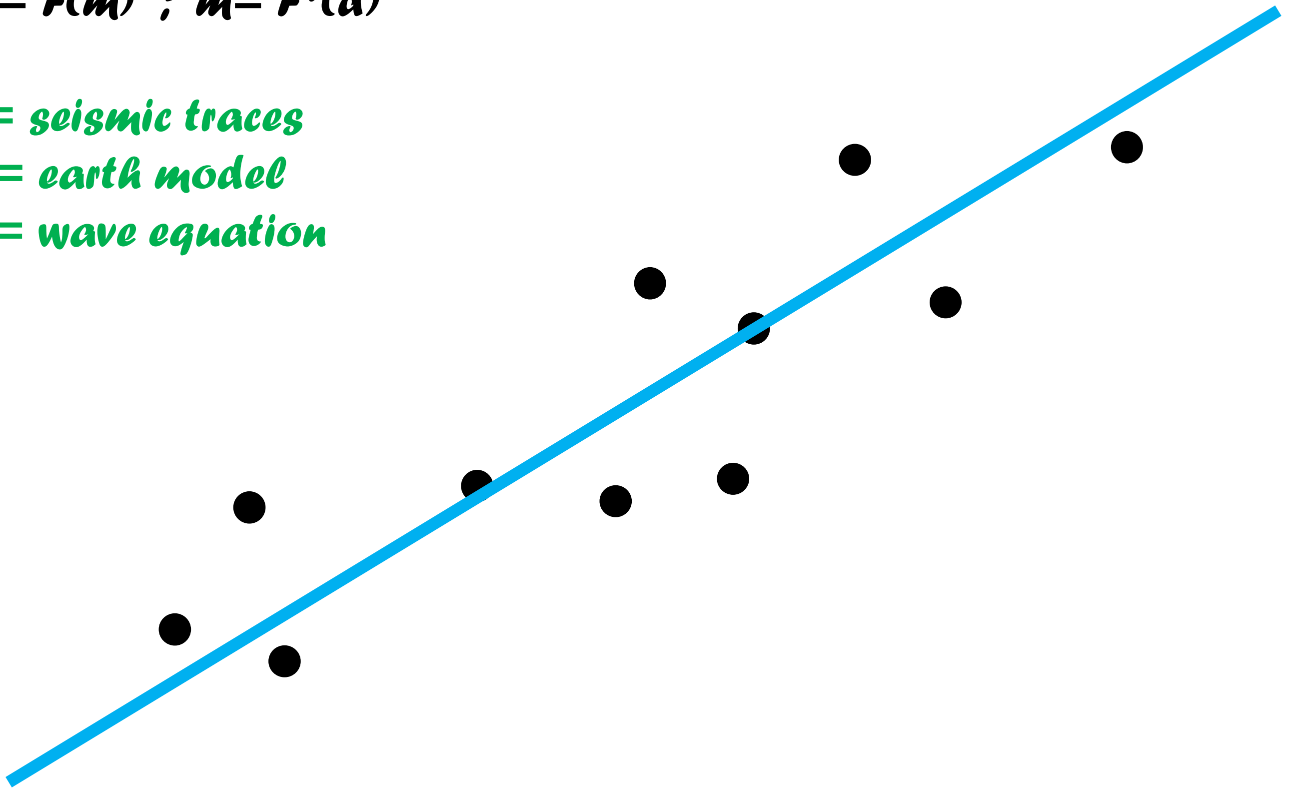
Inverse theory (inversion)

$d = F(m)$; $m = F^{-1}(d)$

d = seismic traces
m = earth model
F = wave equation



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Scalar wave equation modeling

$$d = Fm$$

$$(v^2 \nabla^2 - \partial_{tt})\, P(\underline{x},t) = 0$$

$$m = v(\underline{x})$$

$$F = \nabla^2 - \partial_{tt}$$

$$d = P(\underline{x},t)$$

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Full waveform inversion

$$m = F^{-1}d$$

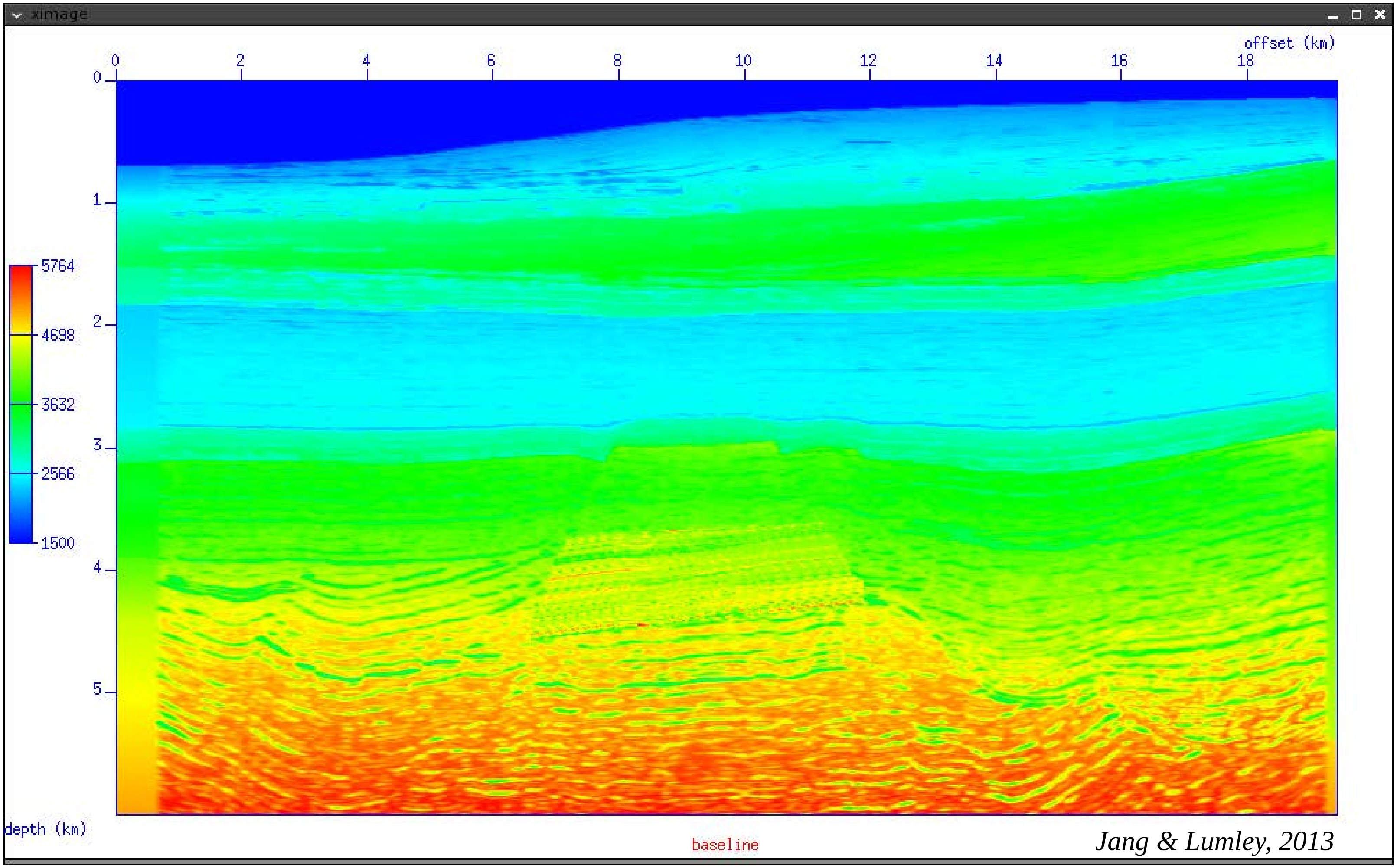
$$\min\ e^2 = w_d^2\,(d - Fm)^2 + w_m^2(m - m_o)^2 + \ldots$$

subject to constraints: $\nabla m \approx 0$ *etc…*

F — *2-way WEQ modeling operator*

m — *2D/3D elastic/velocity model*

True velocity model



Jang & Lumley, 2013

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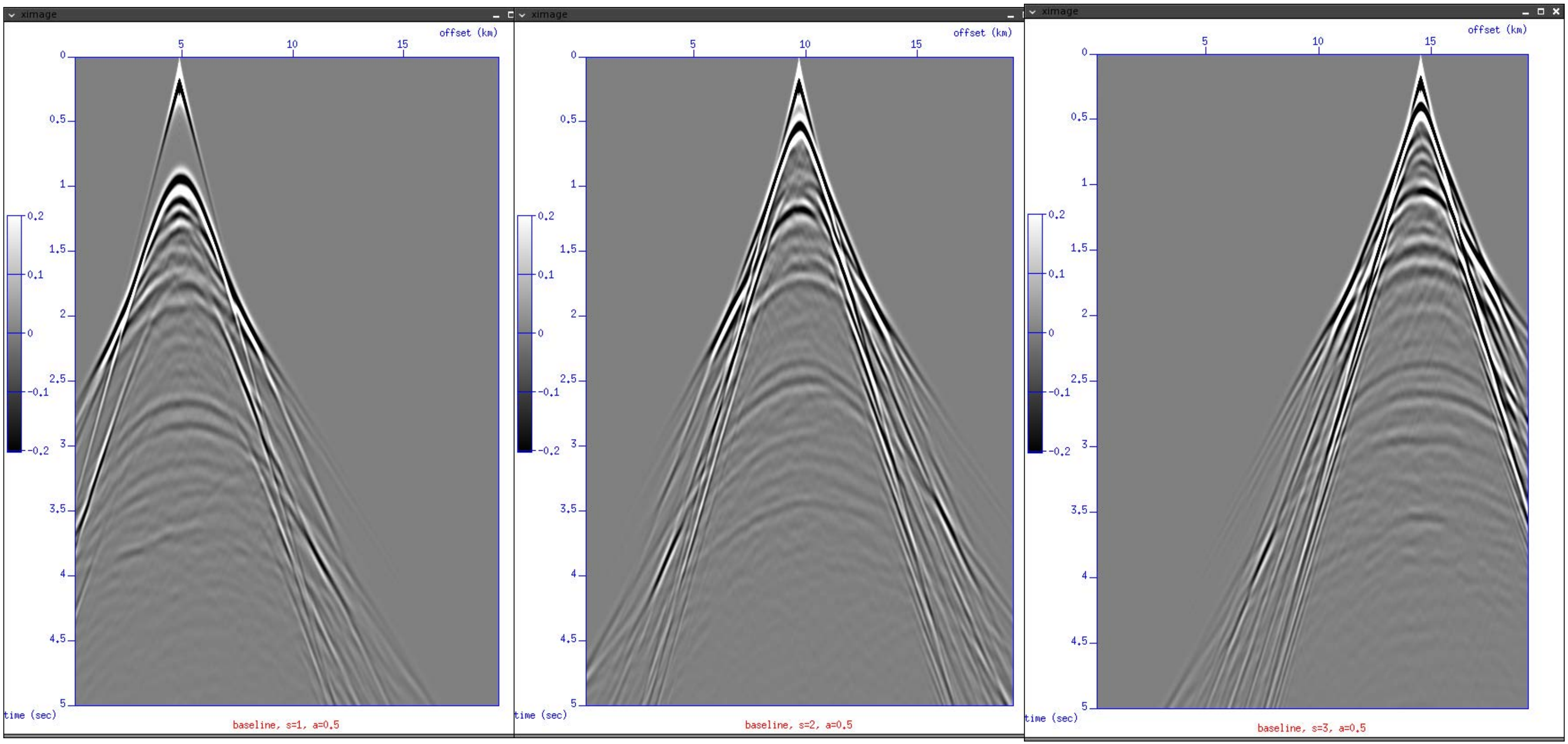
Seismic shot gathers



Jang & Lumley, 2013

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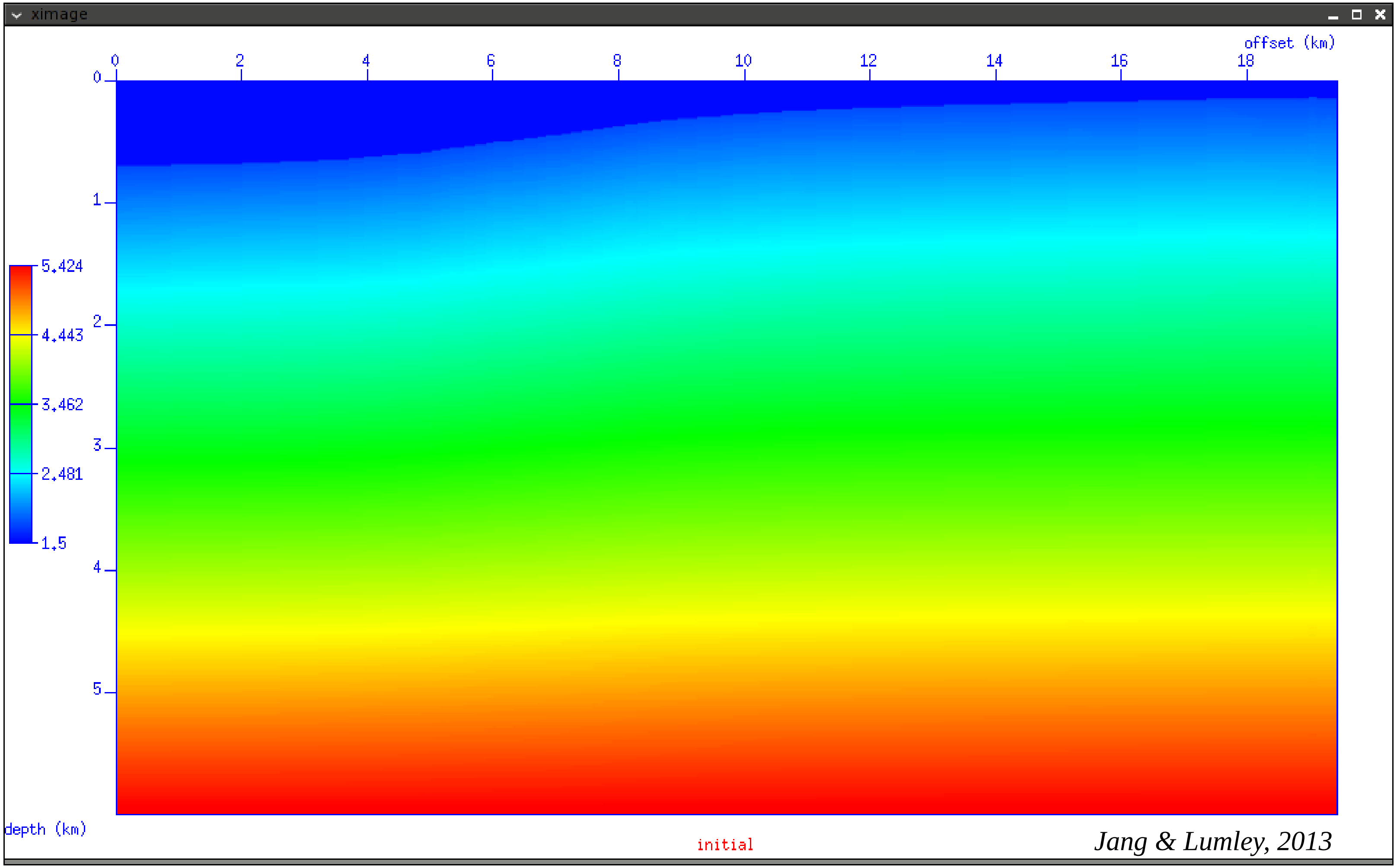
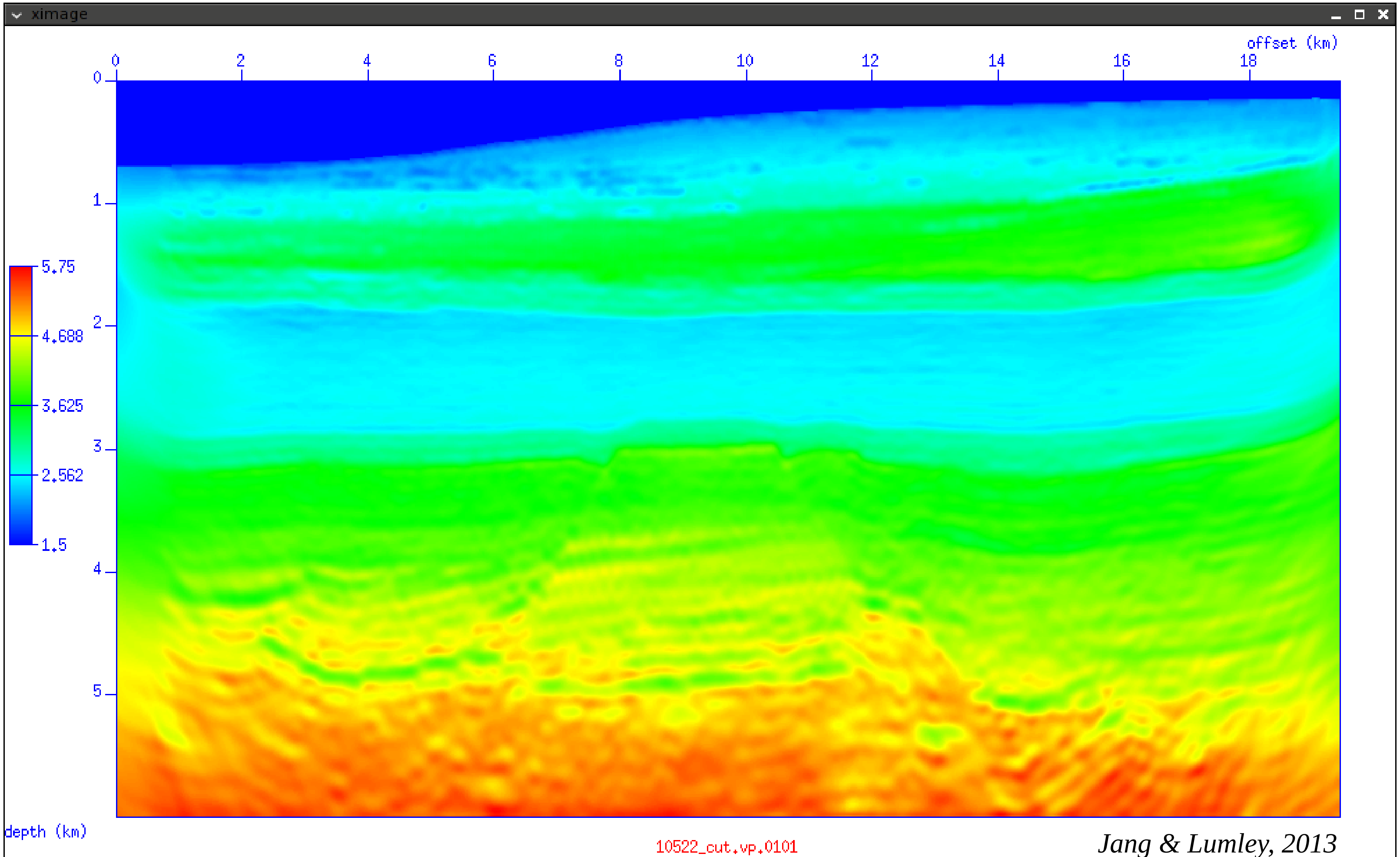
Initial velocity model



Jang & Lumley, 2013

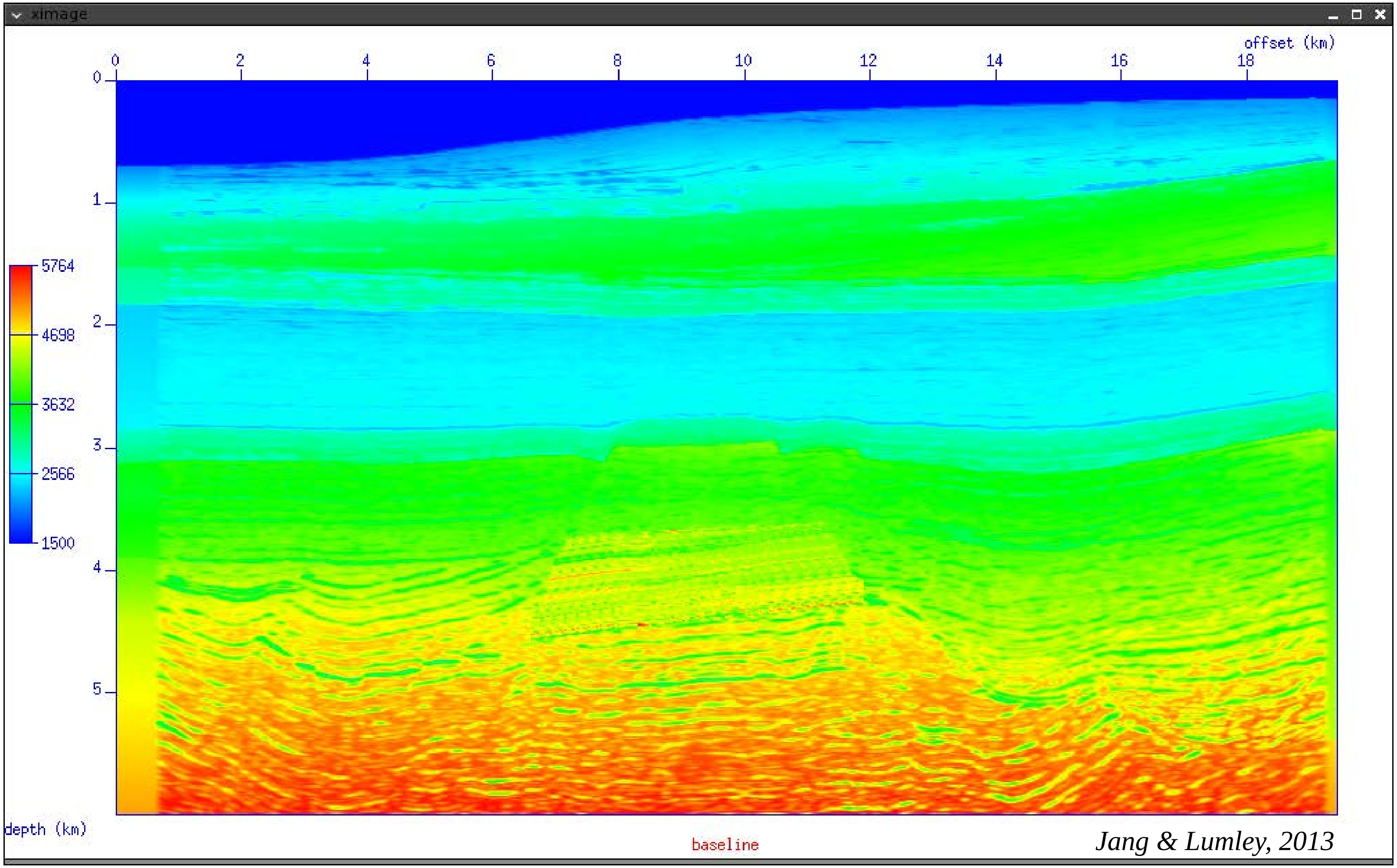
david.lumley@utdallas.edu

Inverted velocity model



Jang & Lumley, 2013

True velocity model



Jang & Lumley, 2013

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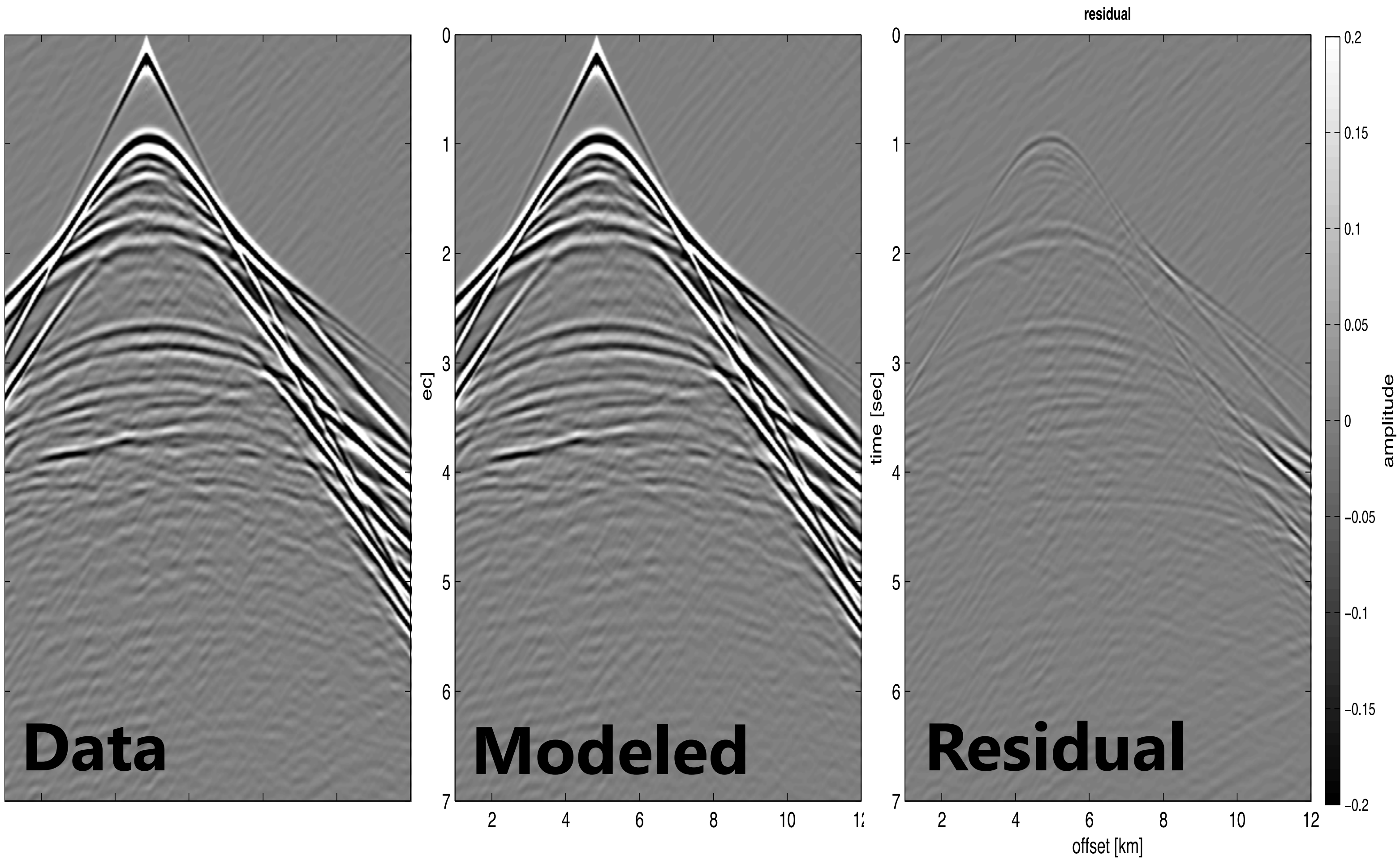
Seismic shot gathers



Jang & Lumley, 2013

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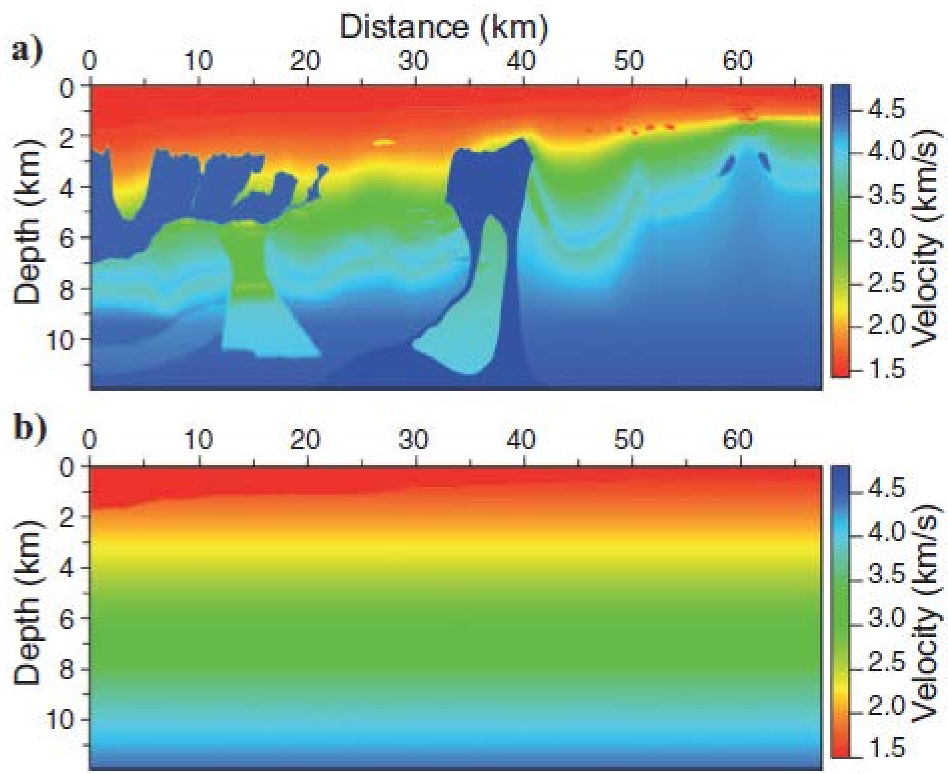
Full waveform inversion

true *model*

initial model



Shin & Cha 2009

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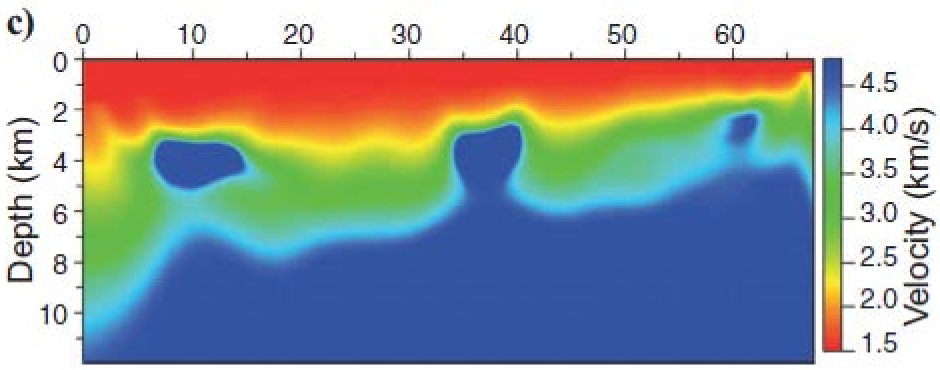
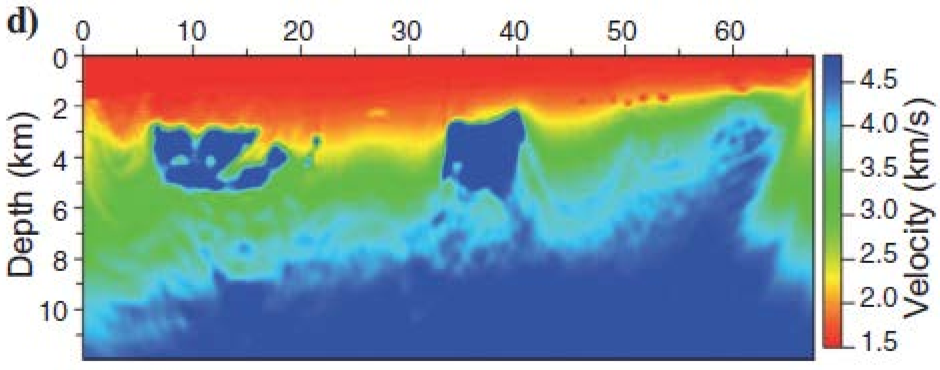
Full waveform inversion

Laplace



Laplace+Fourier

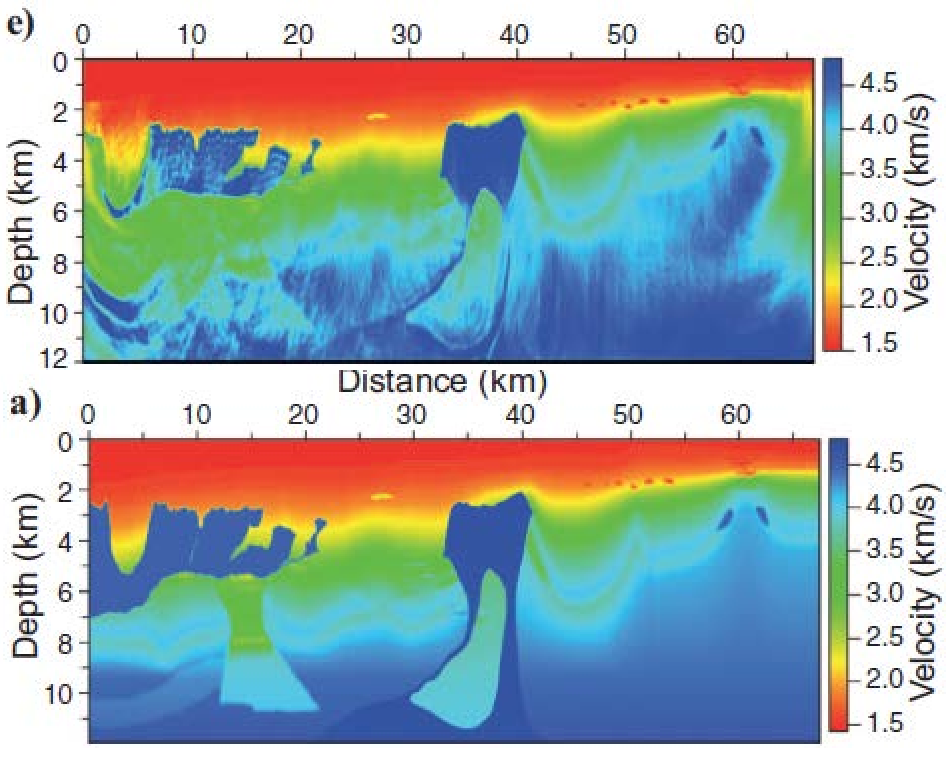


Shin & Cha 2009

Full waveform inversion

+Fourier

true model

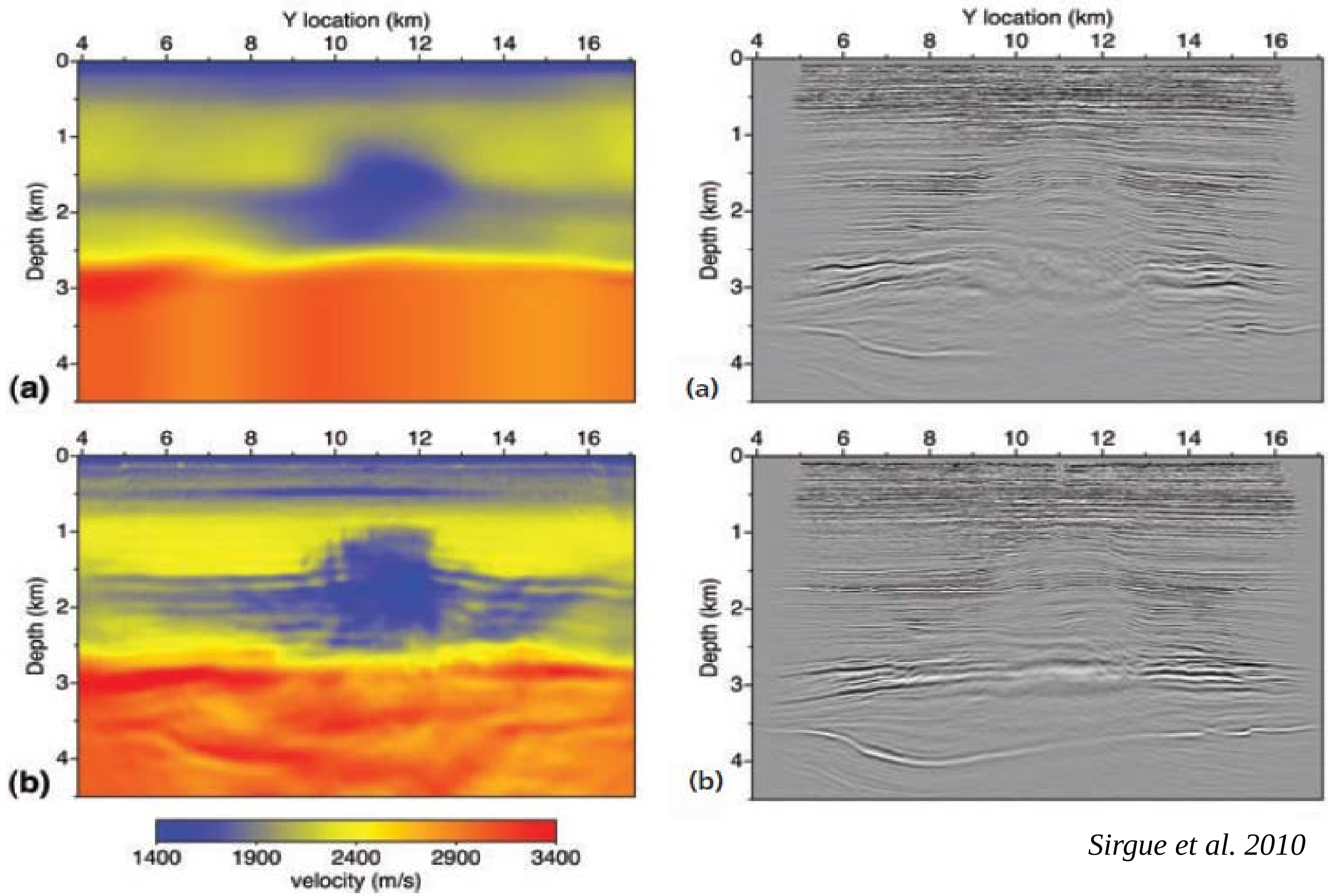


Shin & Cha 2009

Full waveform inversion

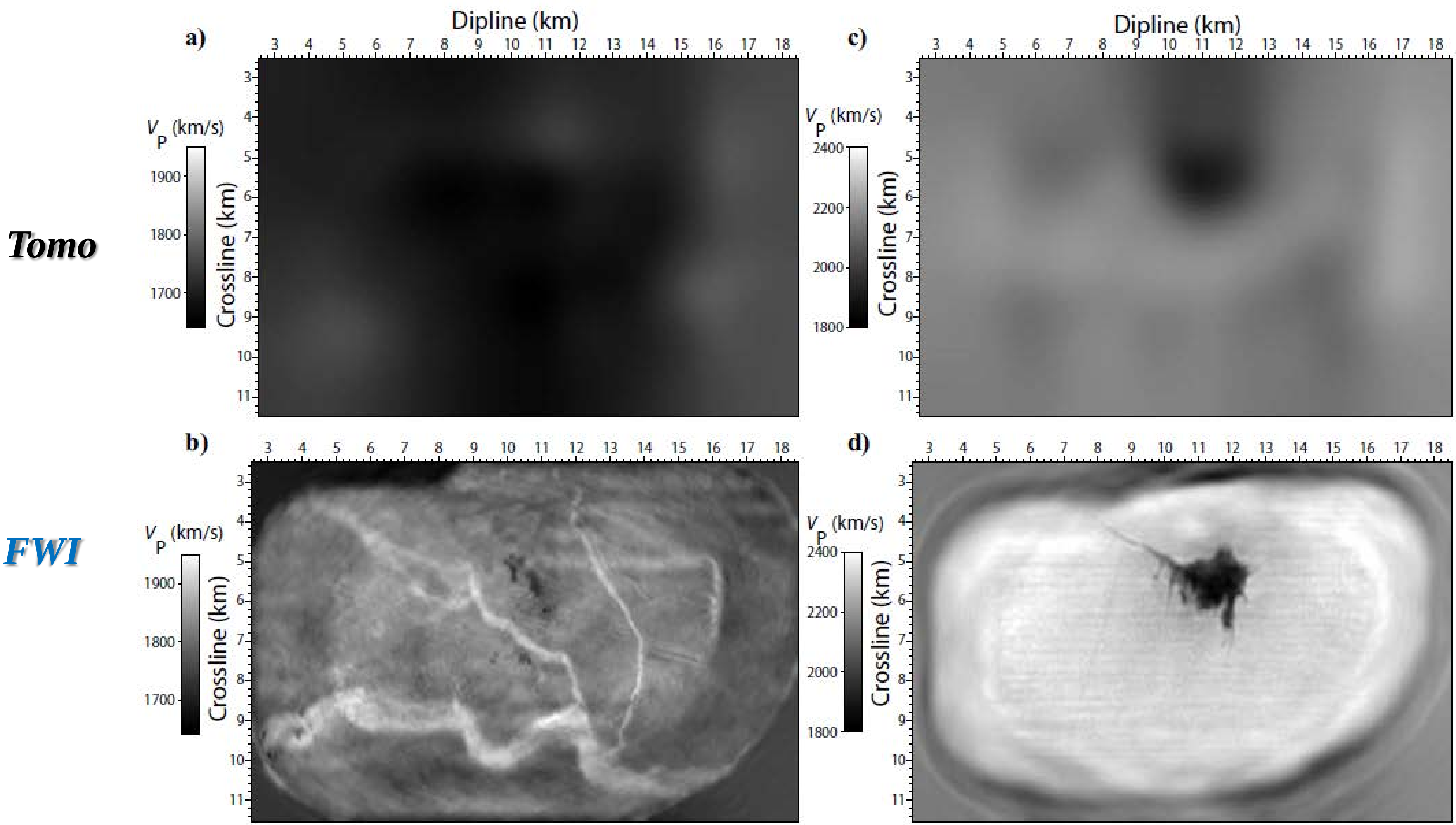
MVA

FWI



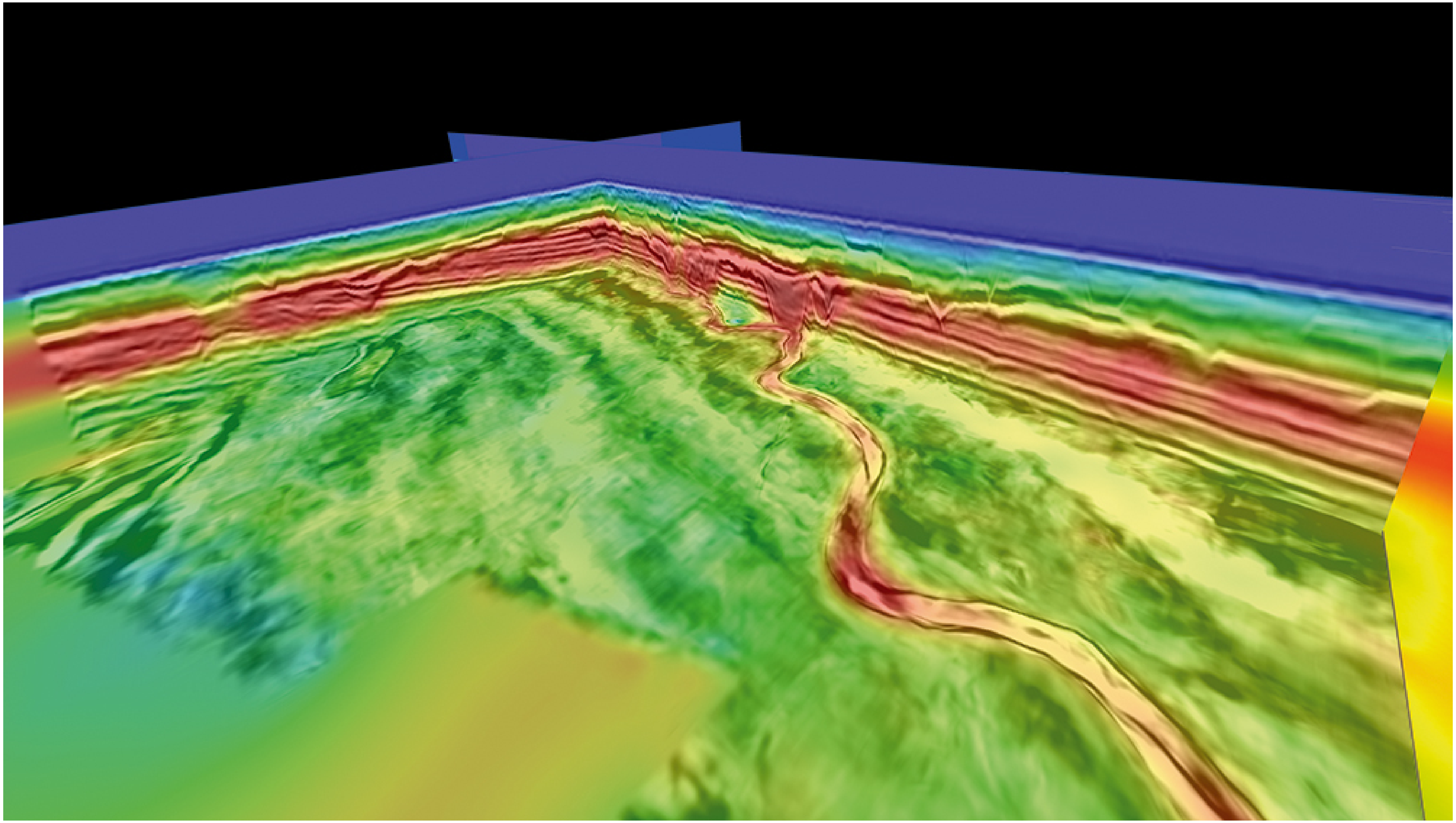
Sirgue et al. 2010

Full waveform inversion



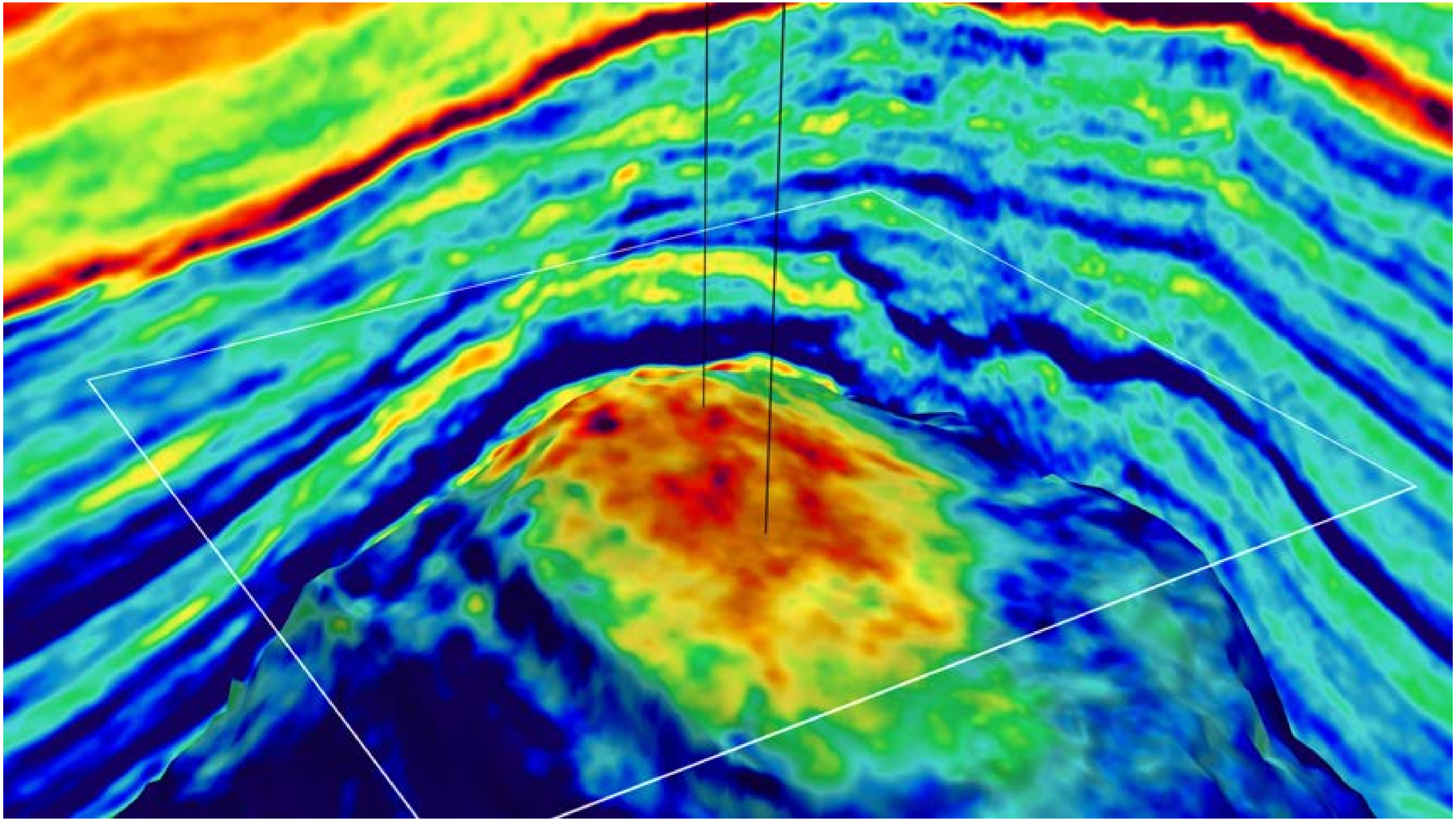
Sirgue & Barkved

Full waveform inversion



PGS

Full waveform inversion



PGS

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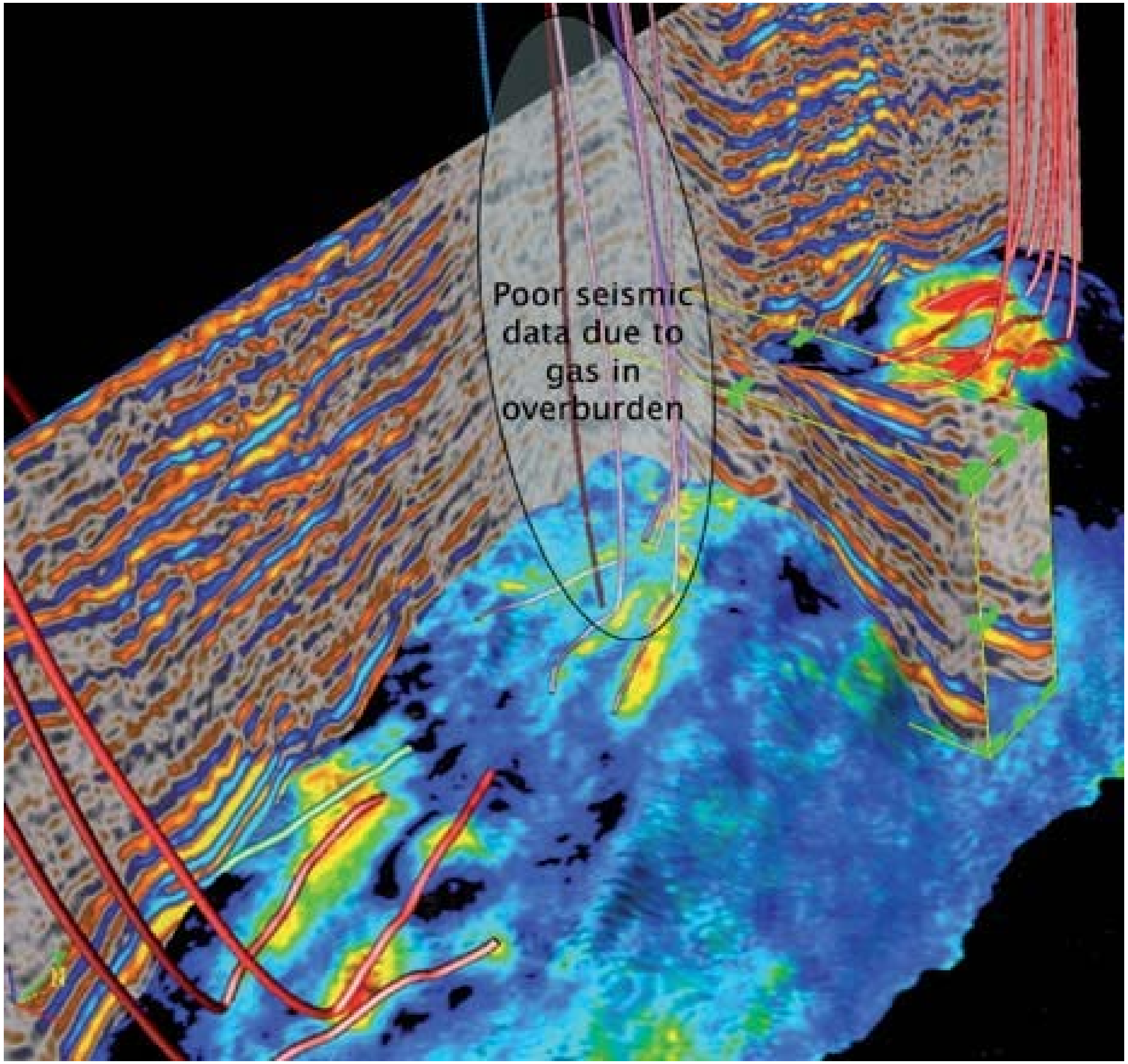
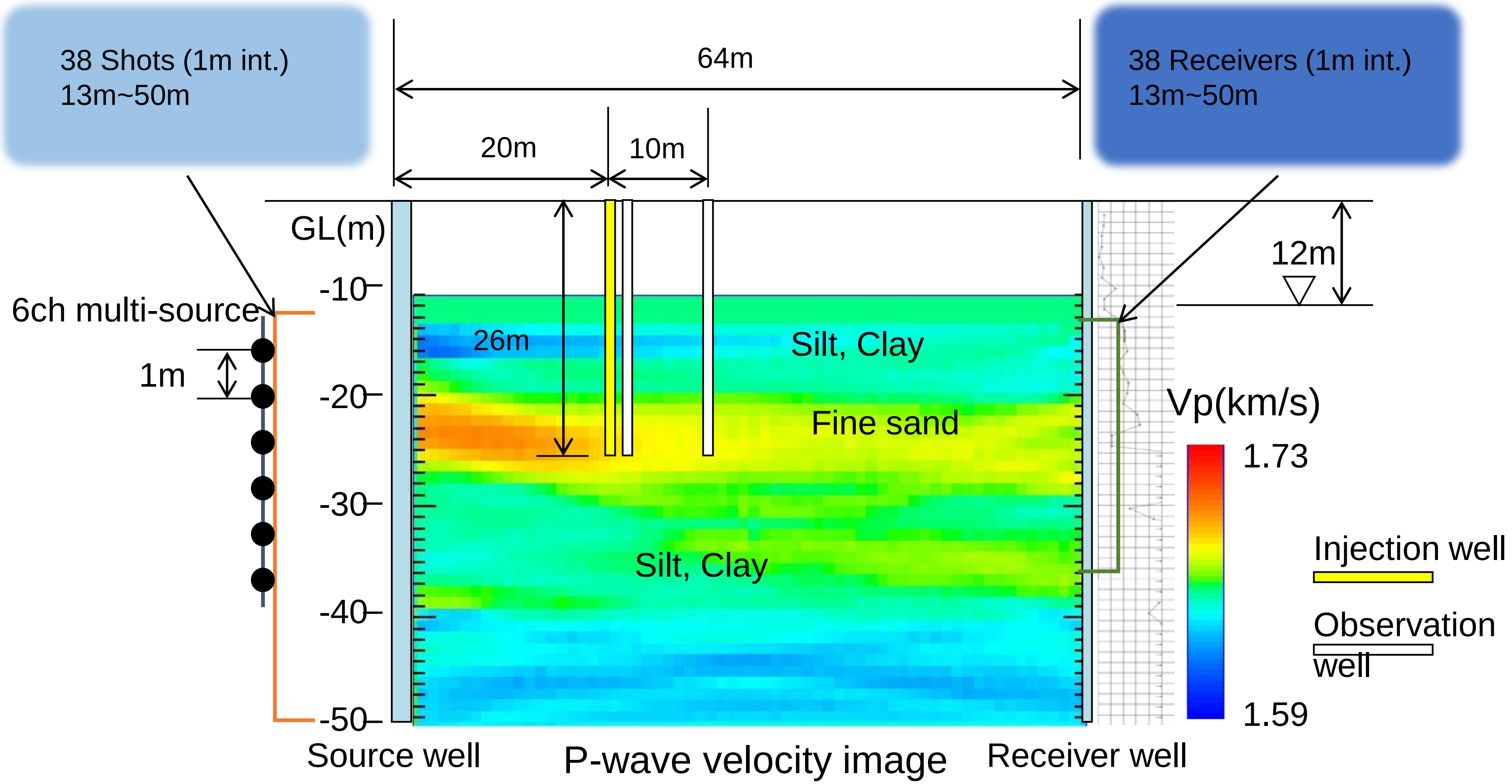
Full waveform inversion



Barkved et al., 2009

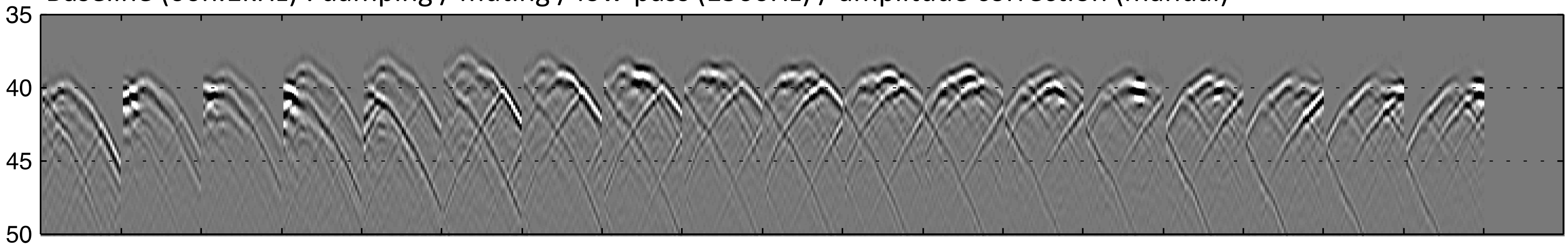
Cross-well FWI



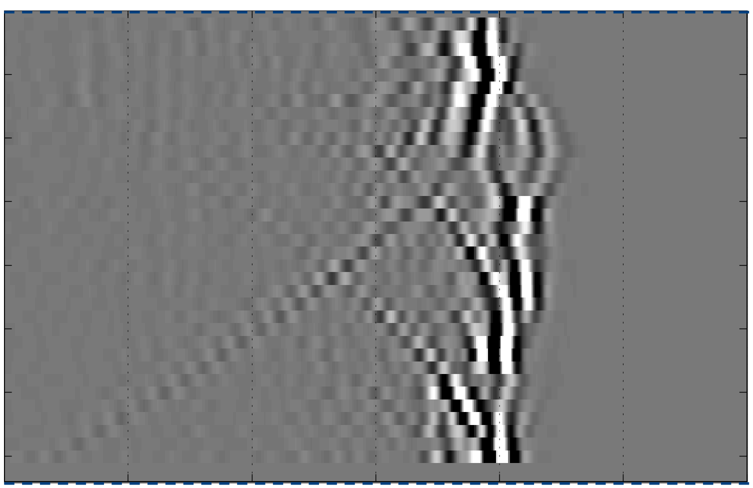
Kamei et al., 2016

Cross-well data (real)

Baseline (00h.1kHz) : damping / muting / low-pass (1500Hz) / amplitude correction (manual)



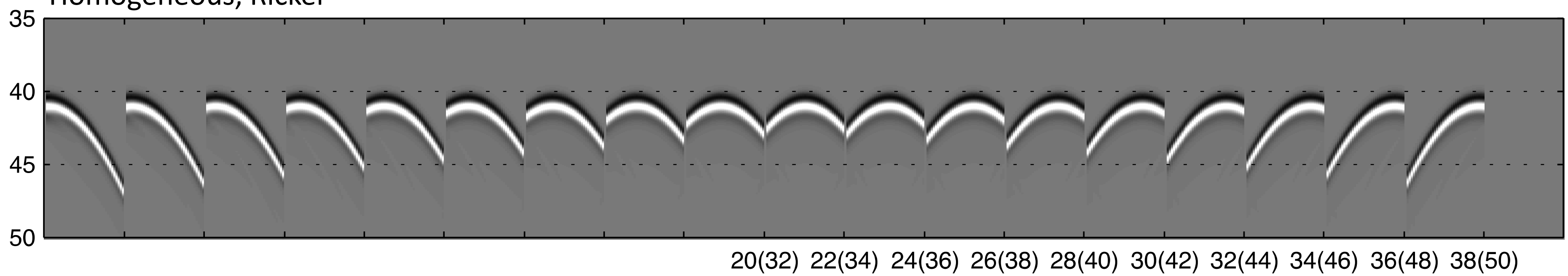
Same level section: Baseline (00h.1kHz)



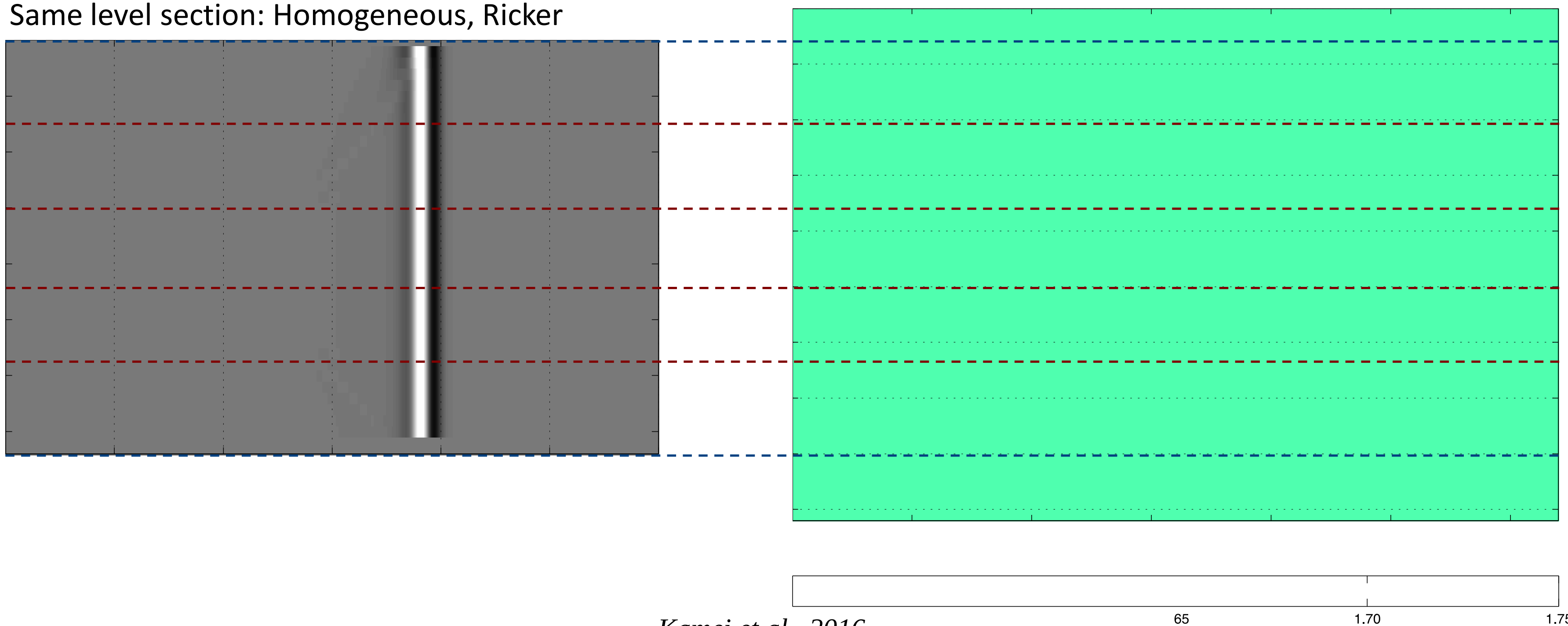
Kamei et al., 2016

Cross-well data (modelled)

Homogeneous, Ricker



Same level section: Homogeneous, Ricker



Kamei et al., 2016

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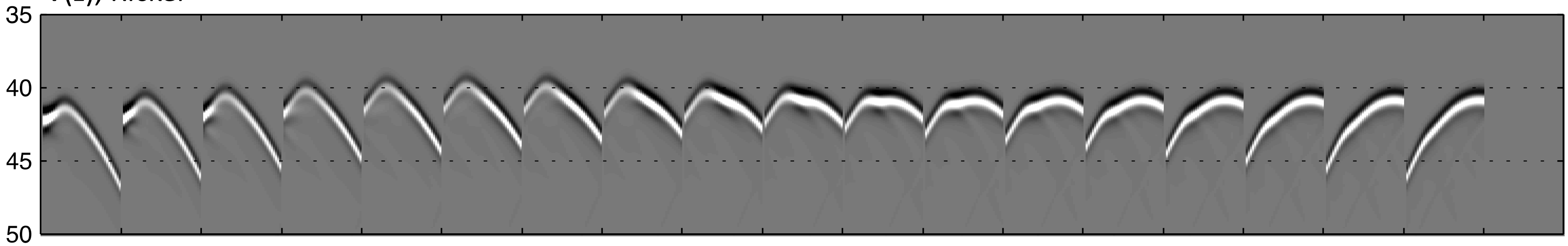
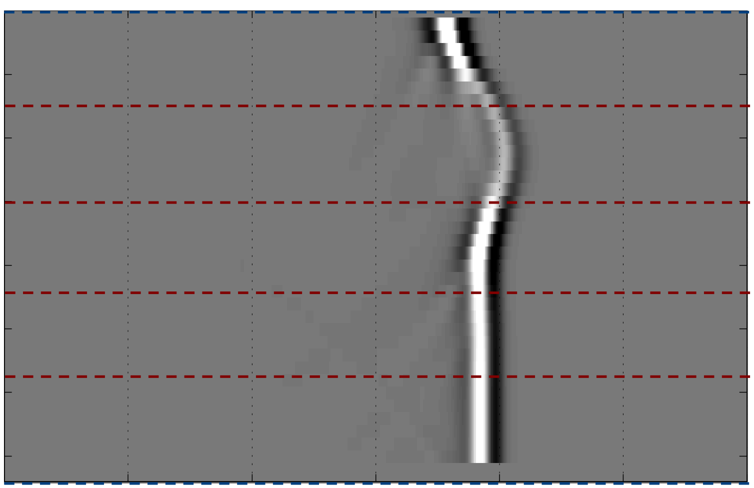
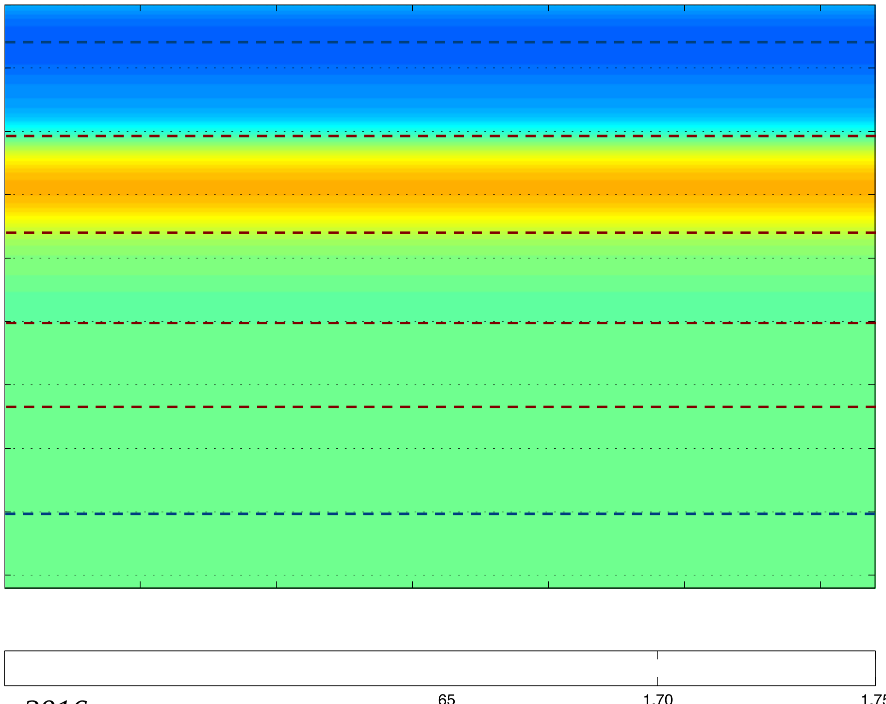
Cross-well data (modelled)

V(z), Ricker



Same level section: V(z), Ricker



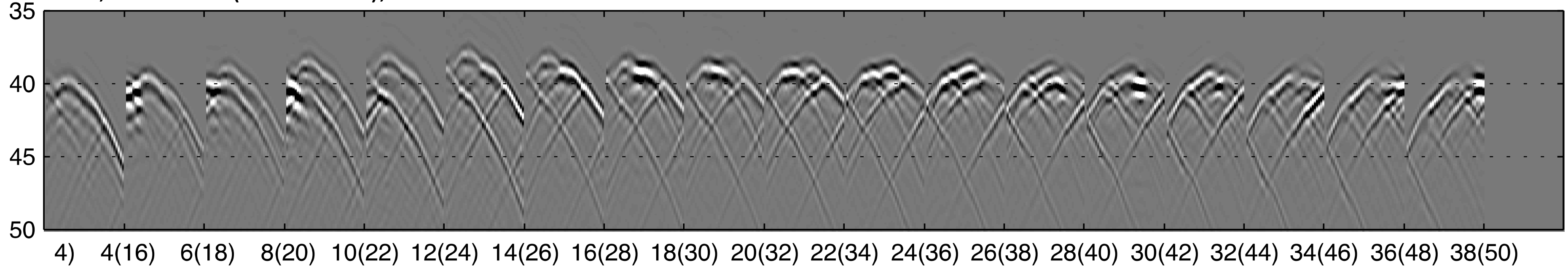


Kamei et al., 2016

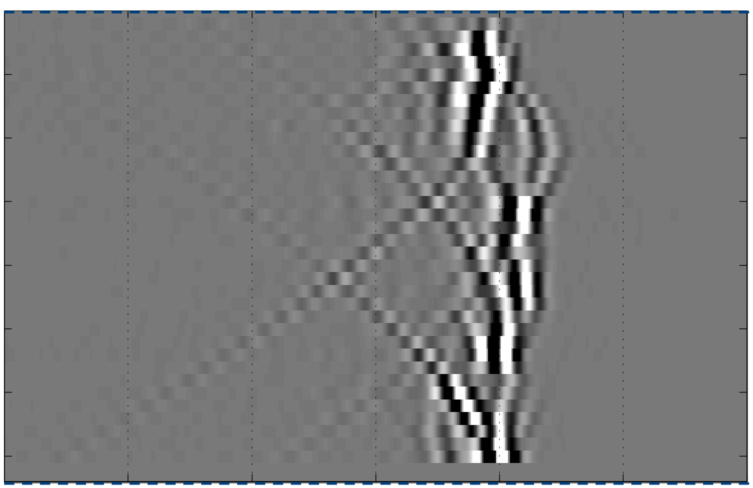
david.lumley@utdallas.edu

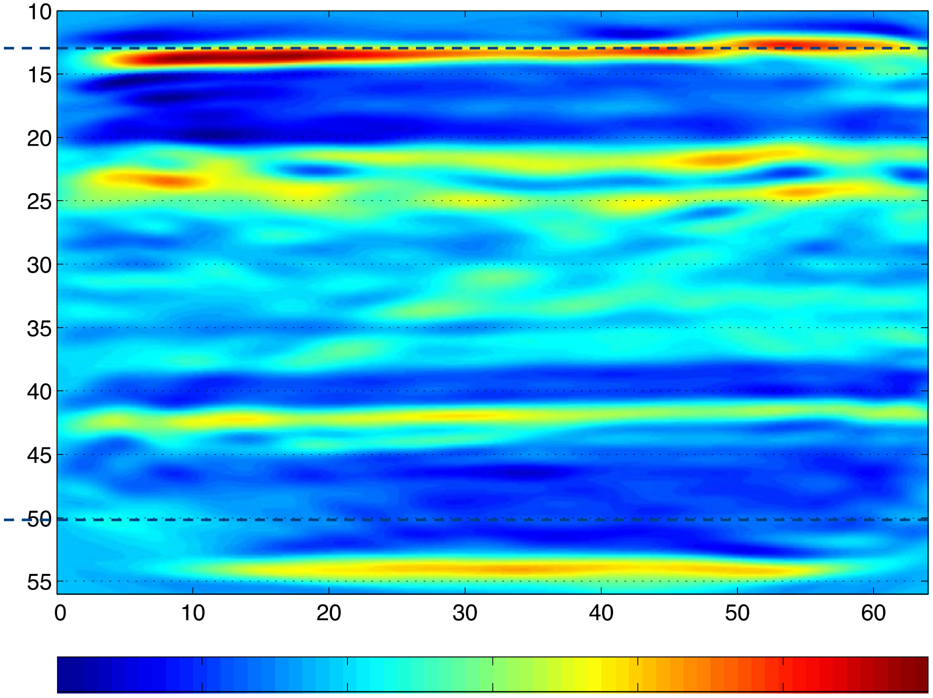
Cross-well data (modelled)

FWI, JOGMEC (smoothed), estimated source



Same level section: FWI, JOGMEC, estimated source





Kamei et al., 2016

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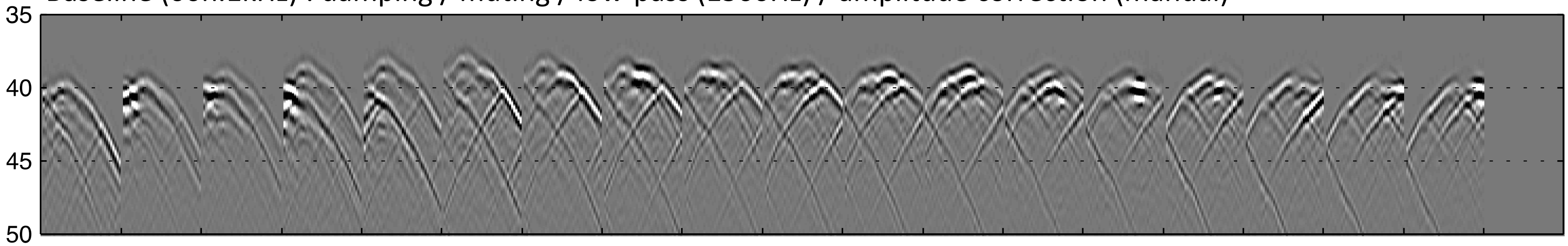
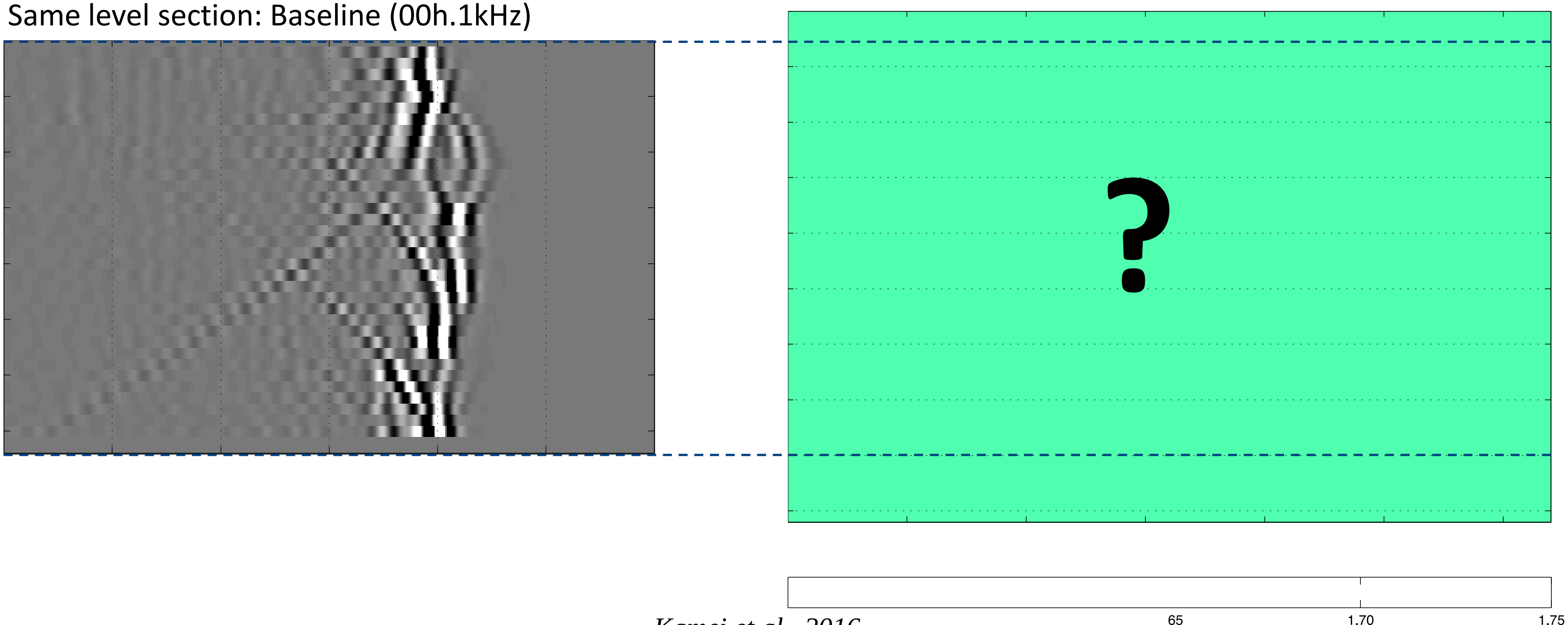
Cross-well data (real)

Baseline (00h.1kHz) : damping / muting / low-pass (1500Hz) / amplitude correction (manual)

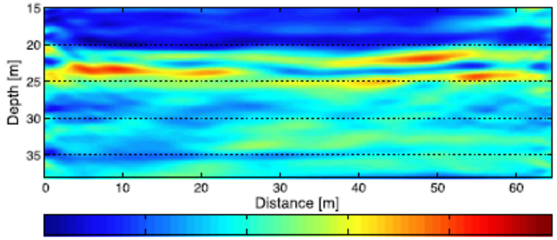


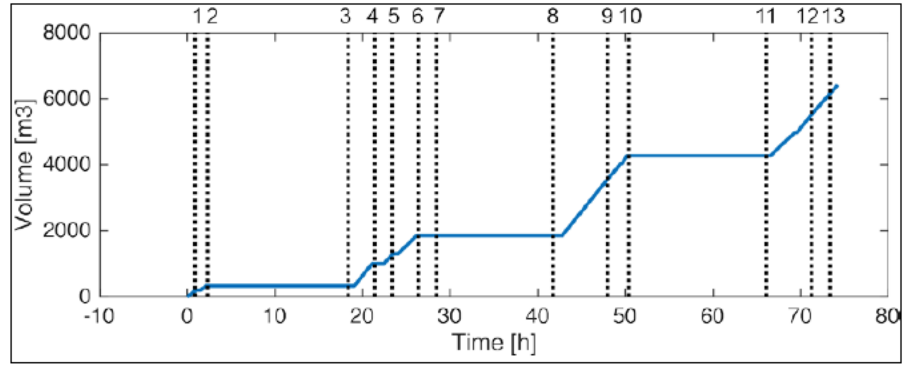
Same level section: Baseline (00h.1kHz)

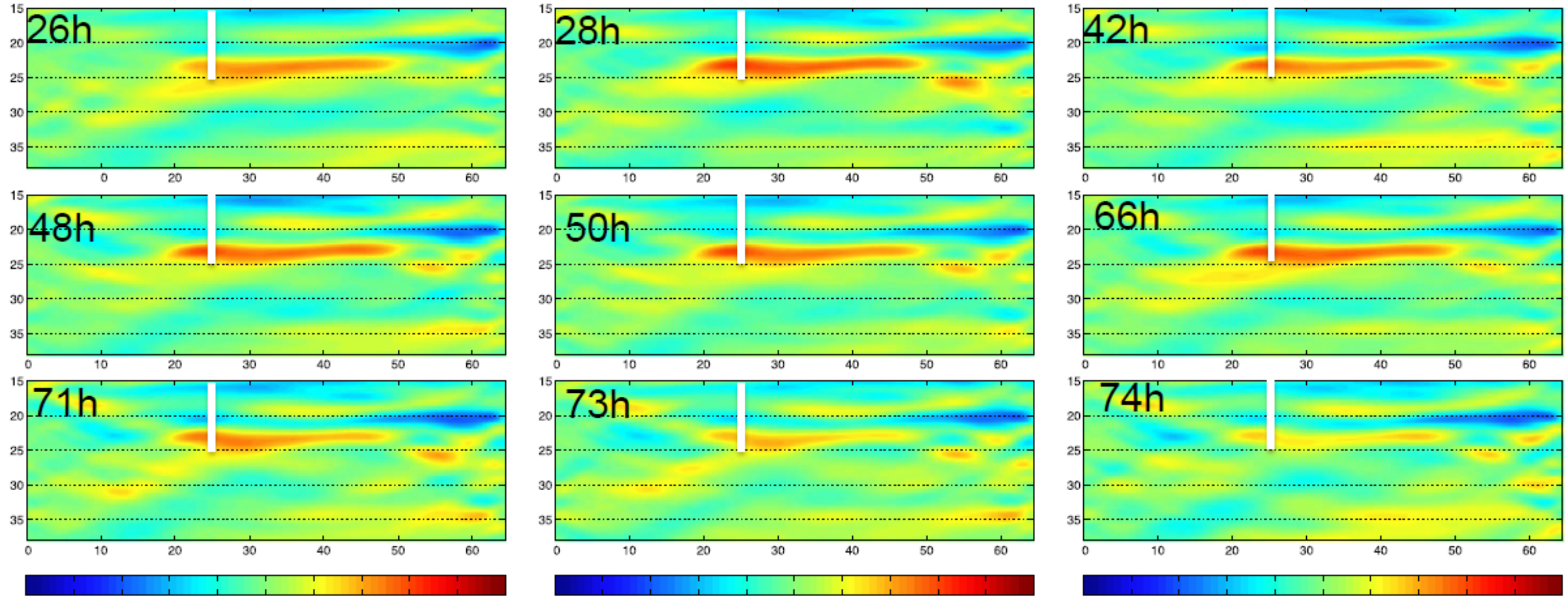


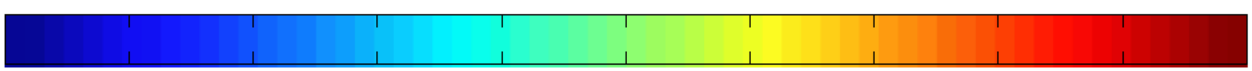
Kamei et al., 2016

4D FWI (real data)









Kamei et al., 2016

Full waveform inversion

- **Practical issues:**
  - *Very promising, but still a lot of R&D work to do… (us!)*
  - *Works well on 2D synthetics; 3D and real data much harder*
  - *Very computationally intensive (HPC)*
  - *Many approximations being made (acoustic, time-damping…)*
  - *Convergence and uniqueness issues*
  - *FWI result not guaranteed to give best image…*

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Why do we need HPC?

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Forward modeling/simulating waves

$$d = F\,m$$

seismic waves (data)

wave eqn operator (physics)

3D earth model

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Forward modeling (simulation)

$$d = F\,m$$

3D earth model(x:y:z:p) =
model($10^{3\text{-}4}$:$10^{3\text{-}4}$:$10^{3\text{-}4}$:$10^{0\text{-}1}$) = $10^{10\text{-}14}$ bytes
Memory= 10 GB - 100 TB

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Forward modeling (simulation)

$$\mathbf{d} = F\, m$$

↙

3D seismic data(s:r:t:c) =
data($10^{4\text{-}6}$:10^{4}:10^{4}:$10^{0\text{-}1}$) = $10^{13\text{-}16}$ bytes
Storage= 10 TB - 10 PB

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Forward modeling (simulation)

$$d = F\, m$$

Wave operator(fc:x:y:z:t:c) =

$weq(10^{1\text{-}2}:10^{3\text{-}4}:10^{3\text{-}4}:10^{3\text{-}4}:10^{4\text{-}5}:10^{0\text{-}1}) = 10^{14\text{-}20}$ *flops*

computation= 100 Tflops - 100 Exaflops

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3D Imaging (RTM)

$R = F^* d$

forall sources=1:$10^{4\text{-}6}$ {

fwd model the source wavefield;

reverse-time propagate the receiver wavefield;*

cross-correlate both wavefields;

add contribution to update the image }

Cost ~ $10^{4\text{-}6}$ x modeling = $10^{18\text{-}26}$ flops = $10^{0\text{-}8}$ Exaflops!

So we have to be clever about:

** approximating/accelerating wave operators (Clusters, GPUs…)*

** pre-compute/store/load wavefields etc. (memory, storage, i/o)*

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Full waveform inversion

$$m = F^{-1} d$$

$$\min \; \varepsilon^2 = w_d^2 (d - Fm)^2 + w_m^2 (m - m_o)^2 + \ldots$$

forall iterations=1:10^{1-3} {

apply the adjoint imaging operation $F^* d$;

estimate/update the earth model m;

forward model the simulated wavefield Fm;

compare to the recorded data d;

check convergence criteria ε^2 *}*

Cost ~ 10^{1-3} x imaging = 10^{19-29} flops = 10^{1-11} Exaflops!

So we have to be extremely clever (ie. we don't know how to do this yet!):

** approximating/accelerating wave operators (Clusters, GPUs…)*

** pre-compute/store/load wavefields etc. (memory, storage, i/o)*

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Seismic HPC Conclusions

- **Seismic modelling, imaging, and inversion maxes out on ALL key computational aspects:**

- Memory: *10 GB - 100 TB*
- Storage: *10 TB - 10 PB*
- FLOPs: *100 Tflops - 10^{11} Exaflops*
- I/O: *network bandwidth limits (eg. 120 Gb/s Infiniband)*

>> We need HPC!

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