Viscosity Estimation Using Seismic Inversion

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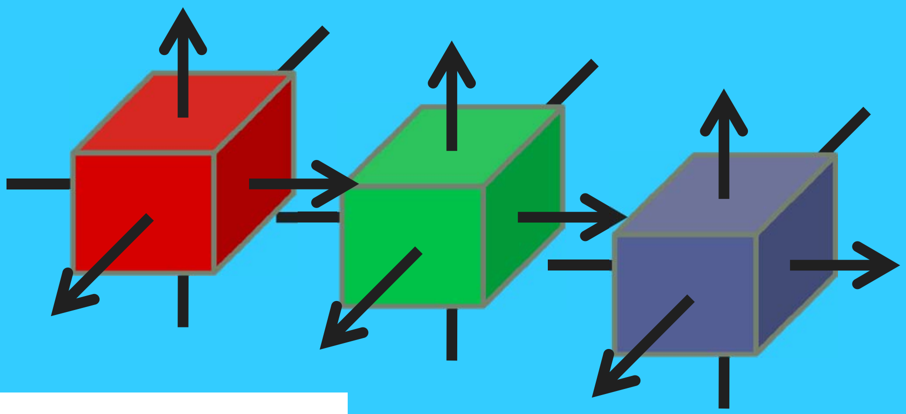
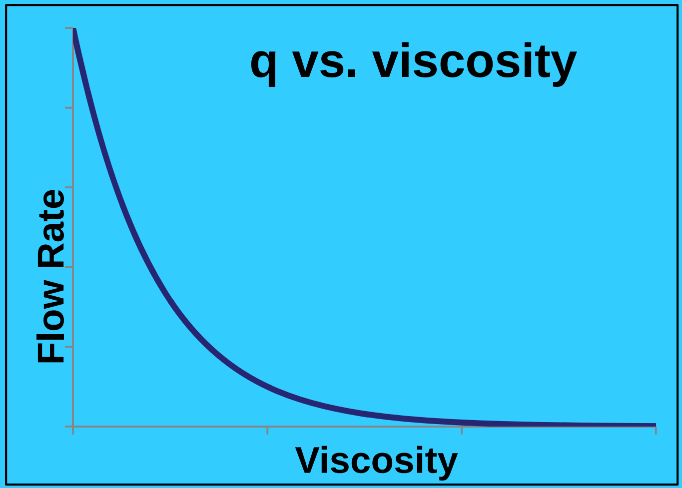
Enhanced heavy oil production involves lowering the oil viscosity.

Reservoir Engineering Importance
(ref. Vasheghani, 2008)



- **Darcy's Law, q=flow rate**



$$q = \frac{kA}{\mu}\frac{\partial P}{\partial x}$$

q: flow rate
k: permeability
A:cross sectional area
μ: viscosity
P: pressure

Viscosity changes with:
 Temperature (thermal mechanisms)
 Gas saturation (cold production)

General Methodology

- Estimate Seismic-Q with a series of inversion methods
- Transform Q values to viscosity values with the use of rock physics relations in Biot Squirt Theory (BISQ), as described by Dvorkin et al. (1994).
- Much of this research is found in detail in the 2011 PhD thesis of Fereidoon Vasheghani entitled "*Estimating heavy oil viscosity from seismic data*".

Inversion Methods Applied to Estimate Seismic-Q

- Traveltime tomography to estimate seismic velocity and ray paths.
- Q-tomography to estimate Q in the subsurface.
- Full waveform inversion using initial models from tomography.

Definition of Q, quality factor

- Solution to wave equation for damped harmonic oscillation

$$A(x,t) = A_0 e^{i(k' x - \omega t)}$$

with complex wavenumber, $k' = k + i\alpha$

$$A(x,t) = A_0 e^{-\alpha x} e^{i(kx - \omega t)}$$

where α is the absorption coefficient.

Definition of Q, the quality factor

- Relation of Q to absorption and wavelength (Toksöz and Johnston, 1981)

$$\frac{1}{Q(\omega)} = \frac{1}{2\pi}\frac{\Delta E}{E} = \frac{1}{2\pi}\frac{\Delta(A^2)}{A^2} = \frac{1}{\pi}\frac{\Delta A}{A}$$

where ΔE is the energy change over one wavelength

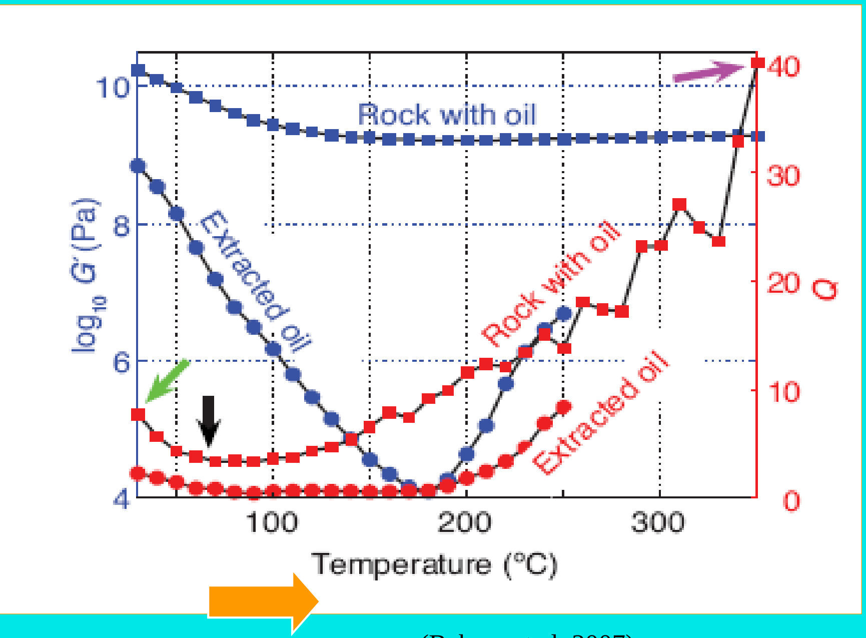
$$\frac{1}{Q(\omega)} = \frac{1}{\pi}\frac{A_0(1-e^{-\alpha\lambda})}{A_0} \cong \frac{\alpha\lambda}{\pi}$$

$$Q(\omega) \cong \frac{\pi}{\alpha\lambda}$$

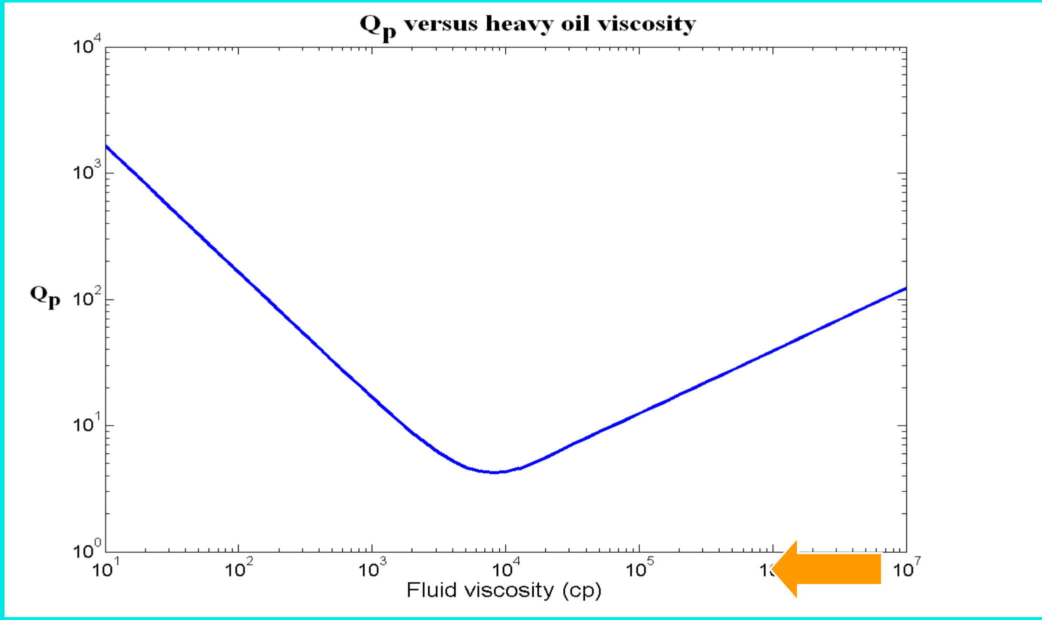
Rock Physics: Lab results & BISQ (Biot + Squirt flow model)

Measured in lab

Theoretical values



(Behura et al, 2007)



- Both lab measurements and BISQ calculations show that quality factor decrease to a minimum then increases with viscosity (temperature).

Model-based Inversion
(Lines and Treitel, 1984, among others)

- Define model parameters, x.
- Compute model response, f.
- Compare f to data values, y.
- Minimize e=y-f, "error of fit".
- We can minimize e (often in a least squares sense). $e^T e$
- Solve for parameter change vector,

$$A\Delta x = b = y - f^{0}$$

Jacobian Matrix

- The Jacobian matrix, A, is a rectangular matrix of size n by p and its cost of computation can control the cost of the inversion.
- n =no. of data points
- p = no. of model parameters:

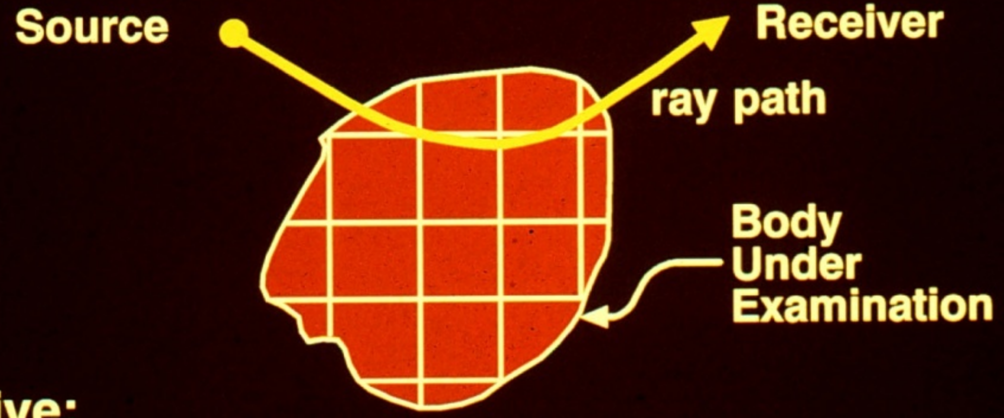
$$A_{ij} = \frac{\partial f_i}{\partial x_j}$$

Use Seismic-Q to Estimate Fluid Viscosity

- Heavy oil viscosity can be estimated using seismic-Q measurements.
- We shall discuss the use of two inversion methods to estimate Q:
  - Q-tomography
  - Full waveform inversion for Q.

TOMOGRAPHY

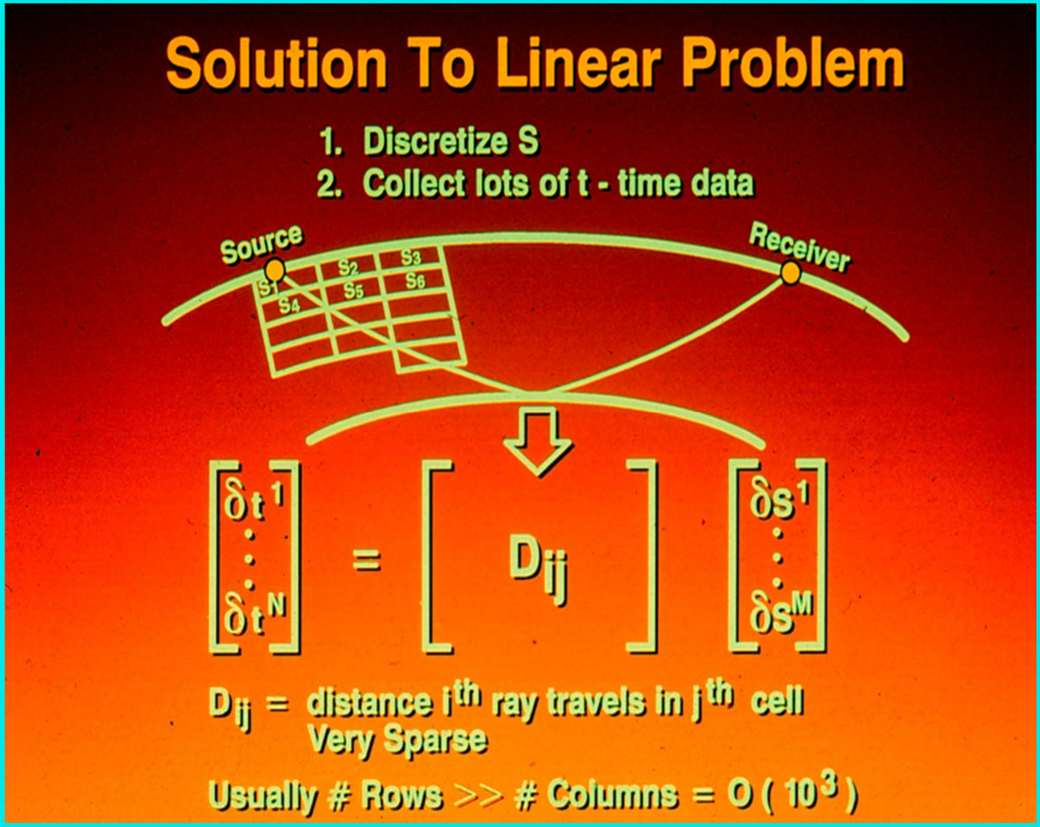
- **Definition:**
  The word "tomography" means section (Greek word "tomos") drawing ("graphy").



- **Objective:**
  Given the set of observations gathered near the surface of a body, reconstruct the material properties within the body.

Traveltime Tomography

- A type of model-based inversion where ray tracing is used to compute seismic traveltimes.



Comparison of Traveltime and Attenuation Tomography

- Traveltime equations

$$\mathbf{Ds} = \mathbf{t}$$

- Attenuation (Centroid Method (Quan and Harris, 1997)

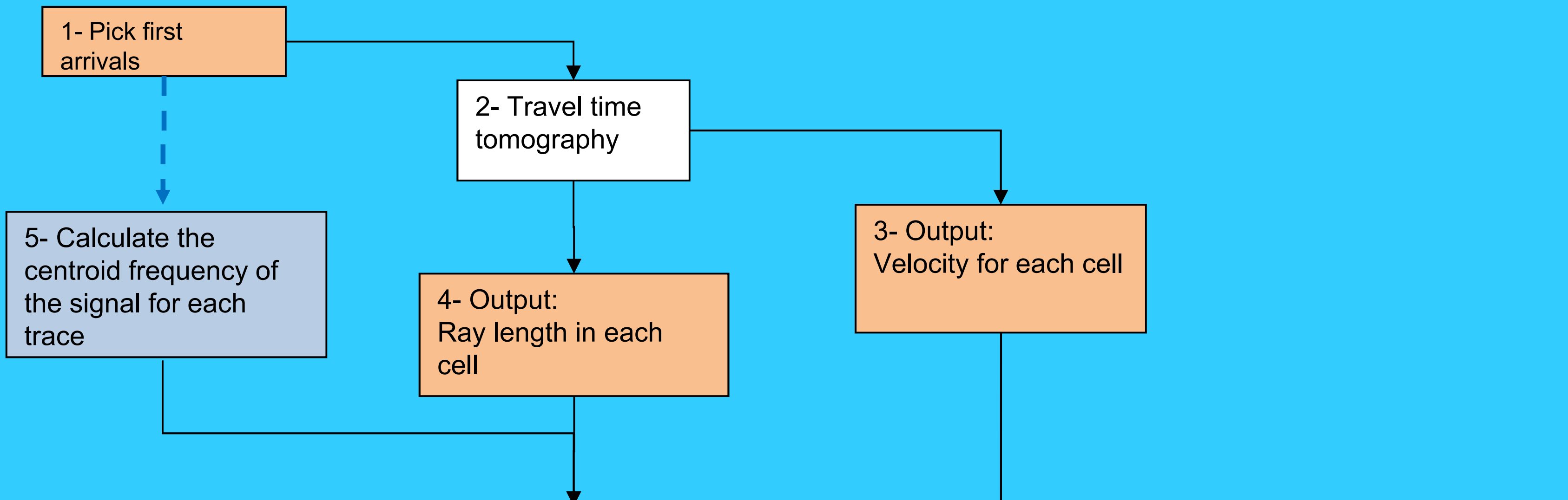
$$\mathbf{D}\alpha_0 = \mathbf{f}_s - \mathbf{f}_r$$

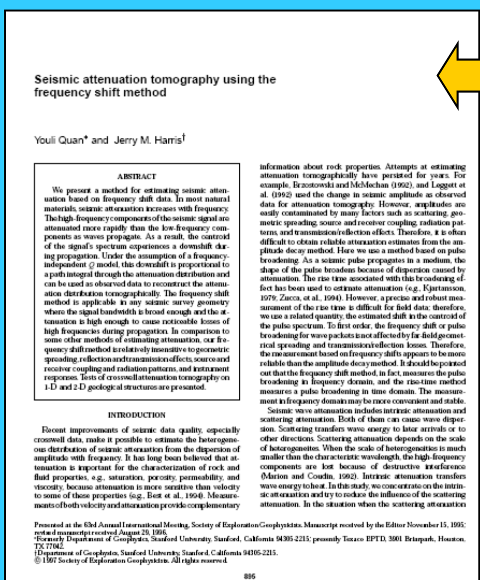
α_0 = attenuation coefficient/frequency

f_s = centroid frequency at source normalized by variance

f_r = centroid frequency at receiver normalized by variance

Methodology





Seismic attenuation tomography using the frequency shift method

Youli Quan* and Jerry M. Harris†

ABSTRACT

We present a method for estimating seismic attenuation based on frequency shift data. In most natural materials, seismic attenuation increases with frequency. The high-frequency components of the seismic signal are attenuated more rapidly than the low-frequency components as waves propagate. As a result, the centroid of the signal's spectrum experiences a downshift during propagation. Under the assumption of a frequency-independent Q model, this downshift is proportional to a path integral through the attenuation distribution and can be used as observed data to reconstruct the attenuation distribution tomographically. The frequency shift method is applicable in any seismic survey geometry where the signal bandwidth is broad enough and the attenuation is high enough to cause noticeable losses of high frequencies during propagation. In comparison to some other methods of estimating attenuation, our frequency shift method is relatively insensitive to geometric spreading, reflection and transmission effects, source and receiver coupling and radiation patterns, and instrument responses. Tests of crosswell attenuation tomography on 1-D and 2-D geological structures are presented.

INTRODUCTION

Recent improvements of seismic data quality, especially crosswell data, make it possible to estimate the heterogeneous distribution of seismic attenuation from the dispersion of amplitude with frequency. It has long been believed that attenuation is important for the characterization of rock and fluid properties, e.g., saturation, porosity, permeability, and viscosity, because attenuation is more sensitive than velocity to some of these properties (e.g., Best et al., 1994). Measurements of both velocity and attenuation provide complementary information about rock properties. Attempts at estimating attenuation tomographically have persisted for years. For example, Brzostowski and McMechan (1992), and Leggett et al. (1992) used the change in seismic amplitude as observed data for attenuation tomography. However, amplitudes are easily contaminated by many factors such as scattering, geometric spreading, source and receiver coupling, radiation patterns, and transmission/reflection effects. Therefore, it is often difficult to obtain reliable attenuation estimates from the amplitude decay method. Here we use a method based on pulse broadening. As a seismic pulse propagates in a medium, the shape of the pulse broadens because of dispersion caused by attenuation. The rise time associated with this broadening effect has been used to estimate attenuation (e.g., Kjartansson, 1979; Zucca, et al., 1994). However, a precise and robust measurement of the rise time is difficult for field data; therefore, we use a related quantity, the estimated shift in the centroid of the pulse spectrum. To first order, the frequency shift or pulse broadening for wave packets is not affected by far-field geometrical spreading and transmission/reflection losses. Therefore, the measurement based on frequency shifts appears to be more reliable than the amplitude decay method. It should be pointed out that the frequency shift method, in fact, measures the pulse broadening in frequency domain, and the rise-time method measures a pulse broadening in time domain. The measurement in frequency domain may be more convenient and stable.

Seismic wave attenuation includes intrinsic attenuation and scattering attenuation. Both of them can cause wave dispersion. Scattering transfers wave energy to later arrivals or to other directions. Scattering attenuation depends on the scale of heterogeneites. When the scale of heterogeneities is much smaller than the characteristic wavelength, the high-frequency components are lost because of destructive interference (Marion and Coudin, 1992). Intrinsic attenuation transfers wave energy to heat. In this study, we concentrate on the intrinsic attenuation and try to reduce the influence of the scattering attenuation. In the situation when the scattering attenuation

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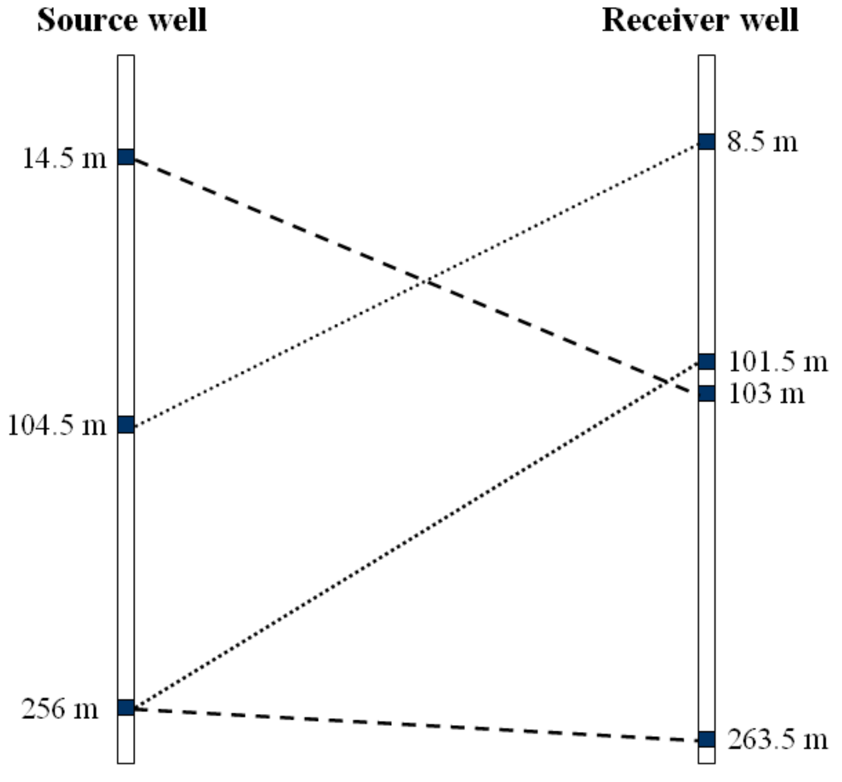
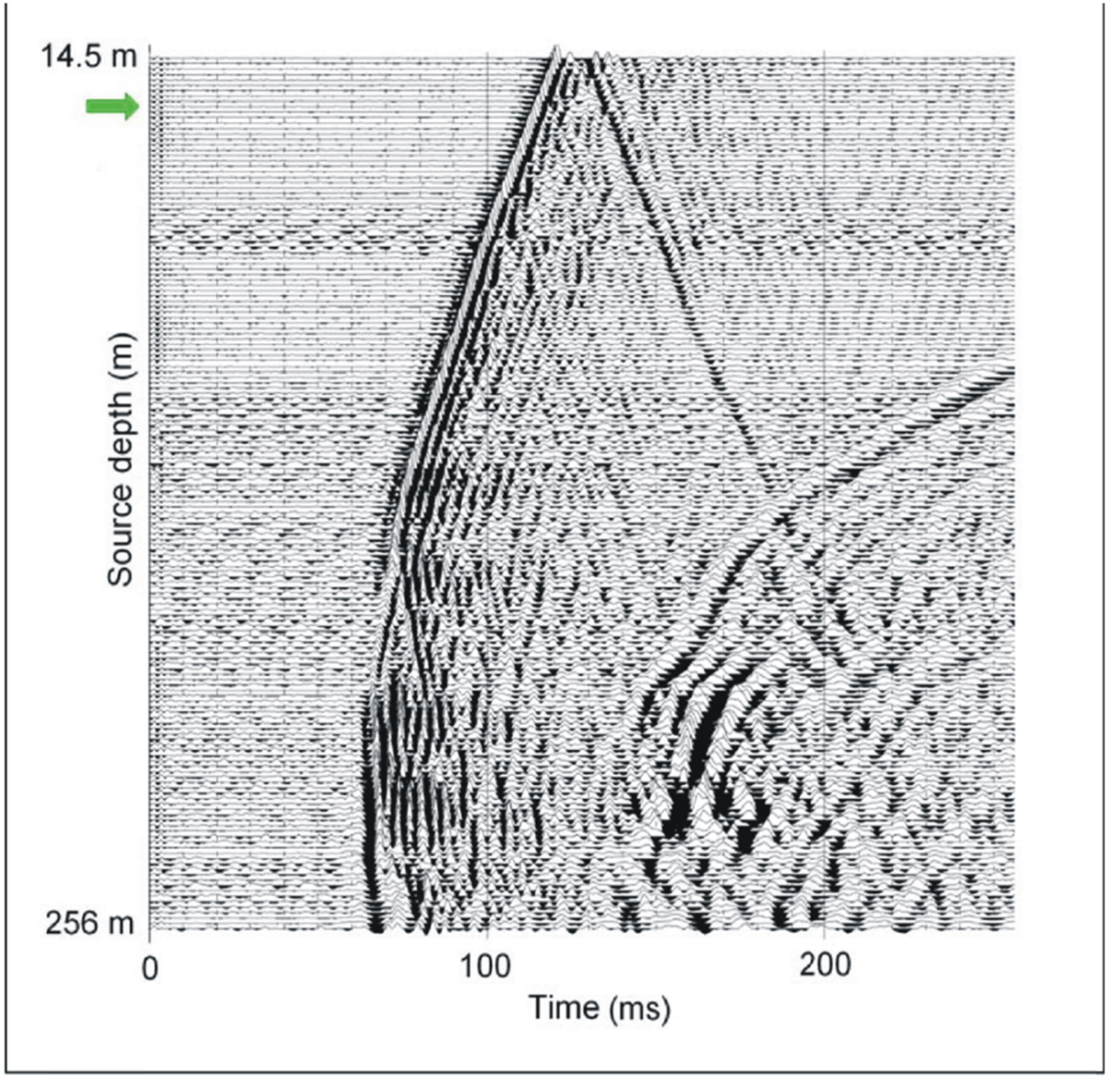
(Quan and Harris, 1997)

Crosswell Acquisition Parameters

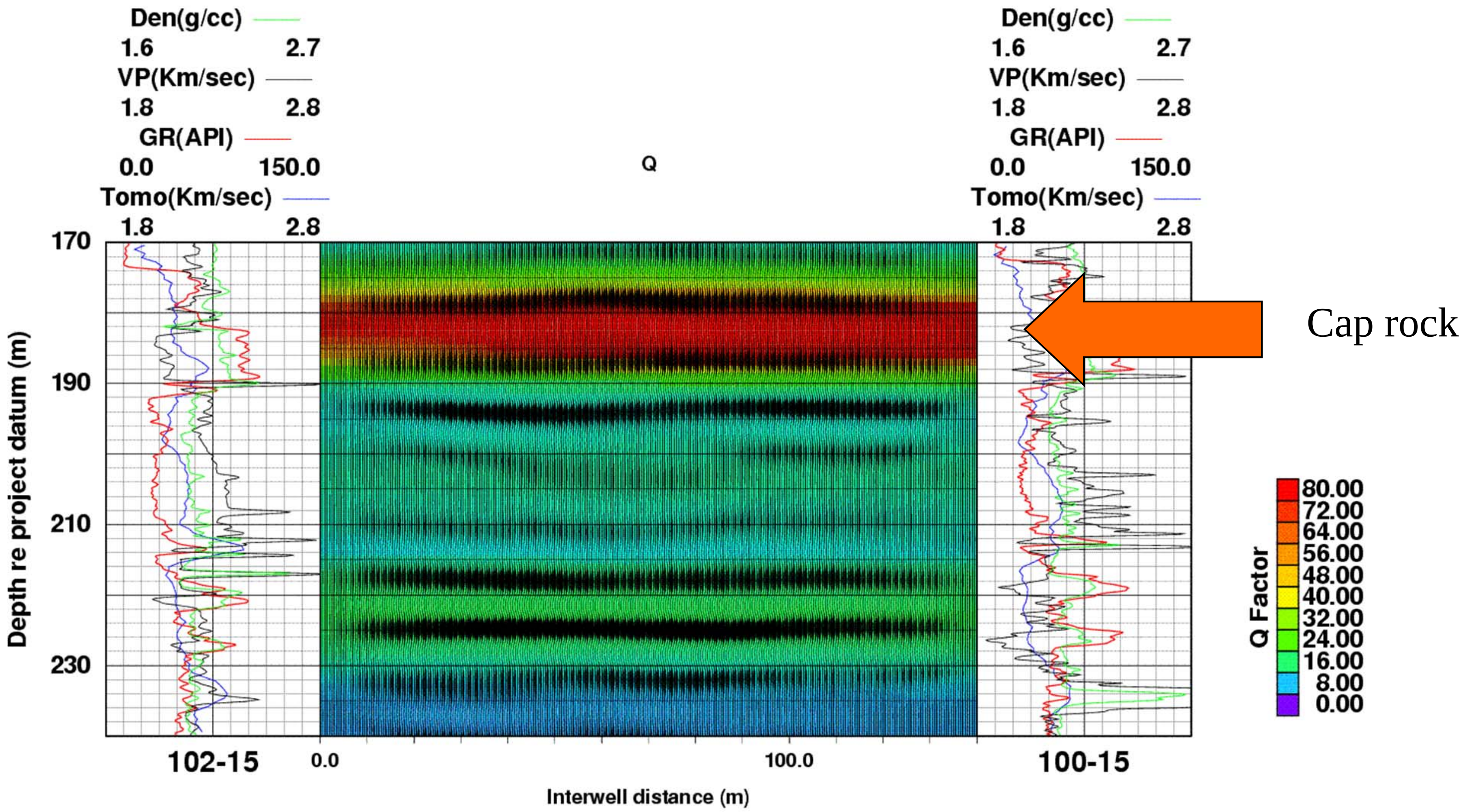


Well spacing	140 m
Receiver spacing	1.5 m
Source spacing	1.5 m
Frequency range	30-600 hz
Dominant frequency	420 Hz
Zone of interest	188-218 m

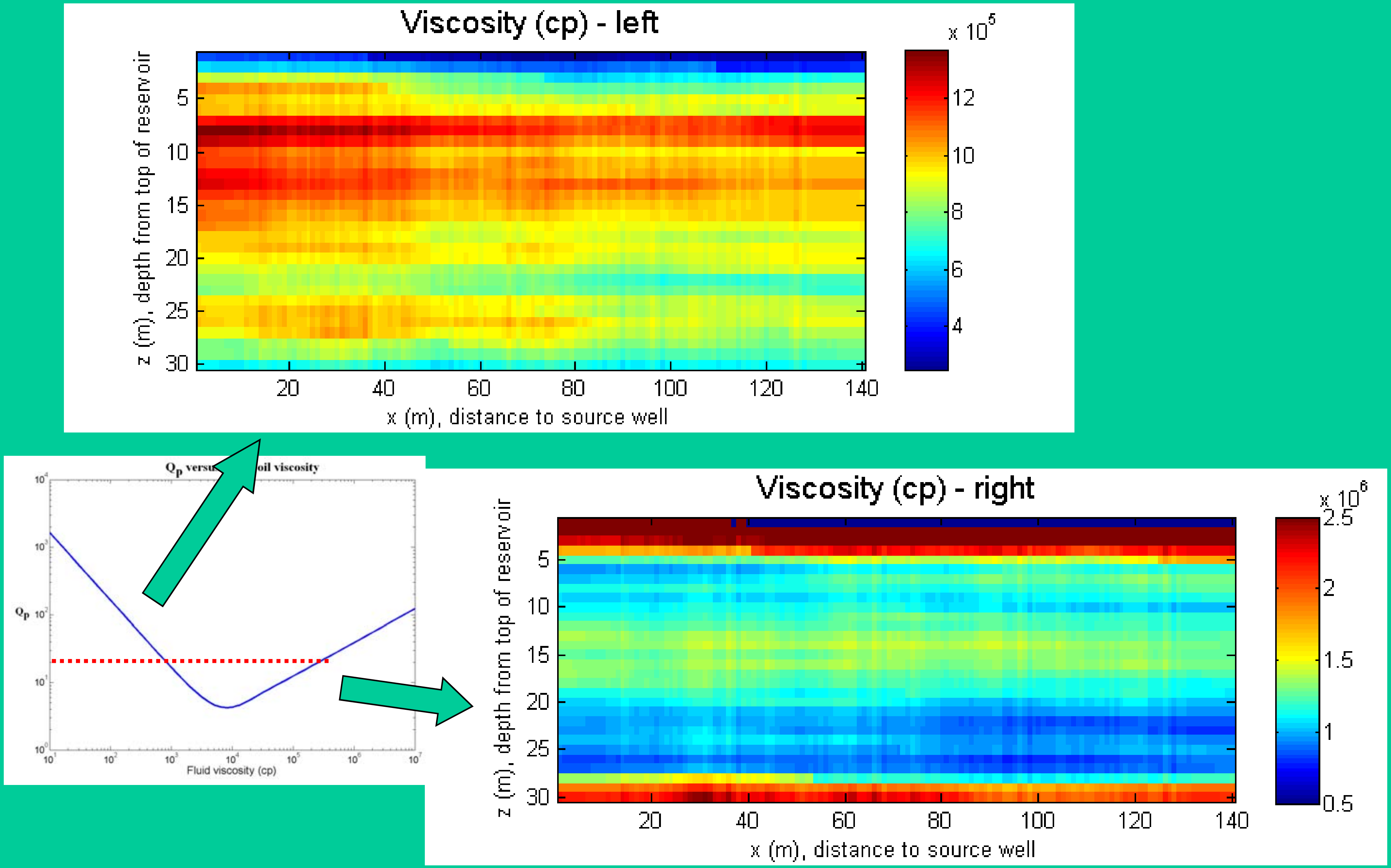
Crosswell Receiver Gather: Receiver Depth 205m



Quality factor



Viscosity: ambiguity

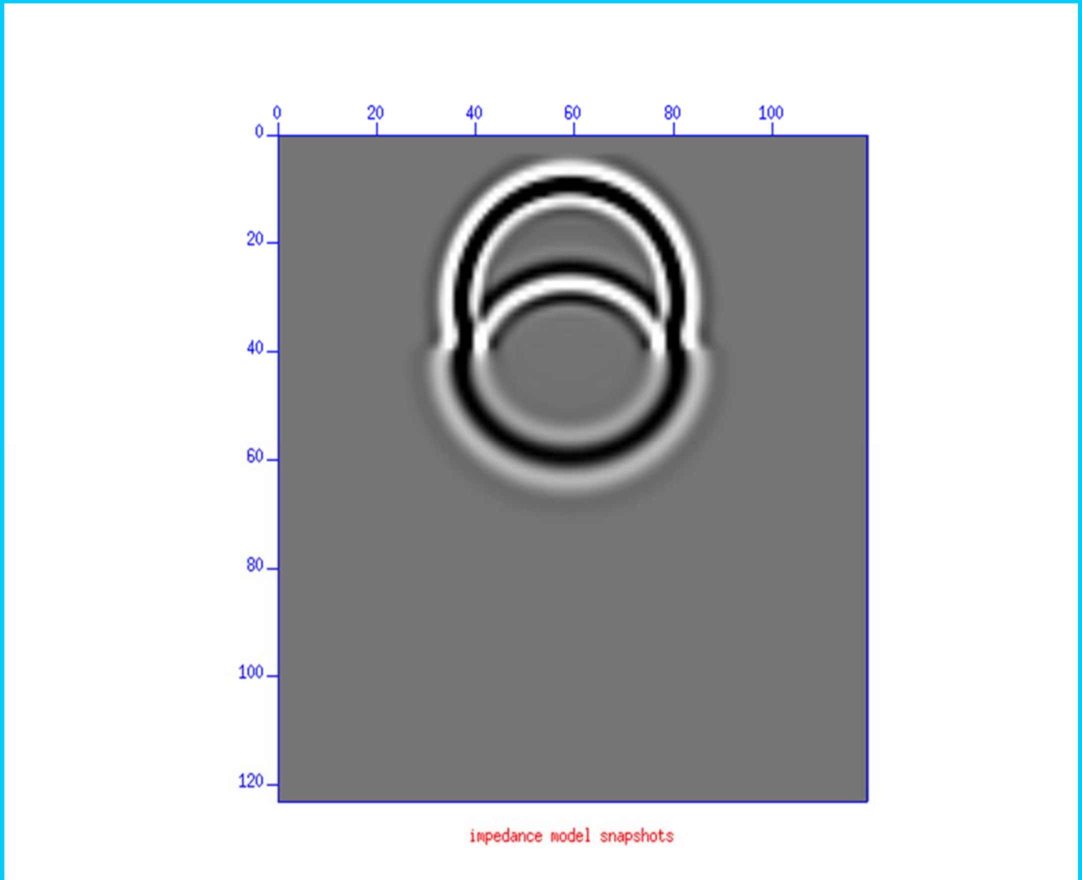


Full waveform inversion for estimation of seismic-Q

A model-based inversion method.

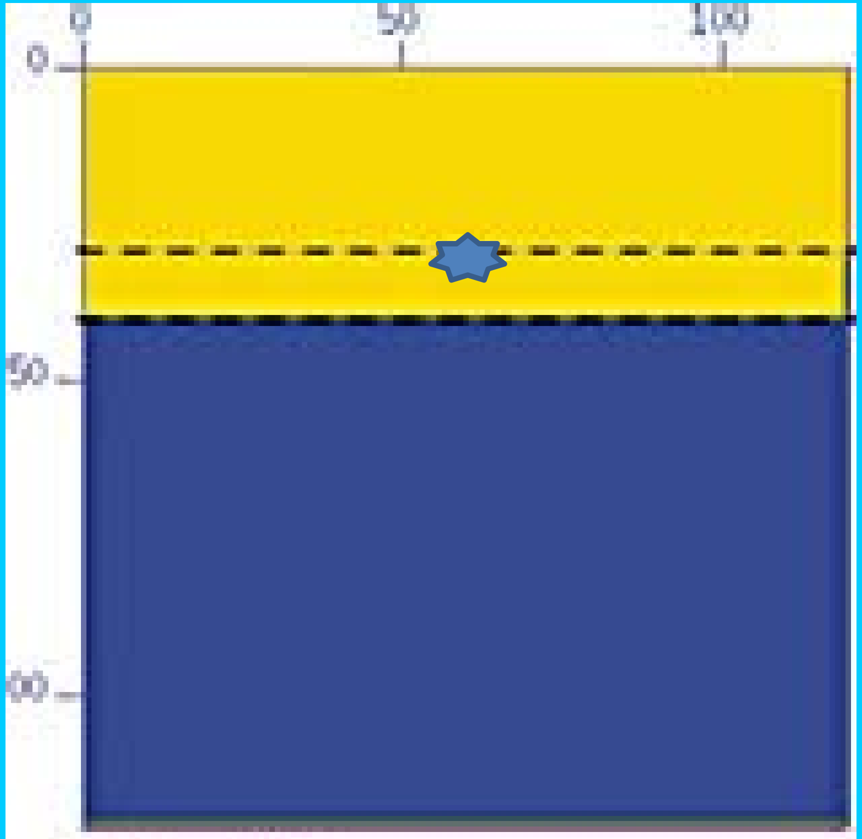
Finite-difference modeling

- Tests were done using finite-difference Fortran code from Carcione (2007).



Two-layer model to illustrate reflections due to impedance and Q contrasts

- Use Shot at grid point (60,30)
- Use line of receivers at varying depths with receiver spacings of 1 grid point
- In models vary the impedance for yellow layer and blue layer



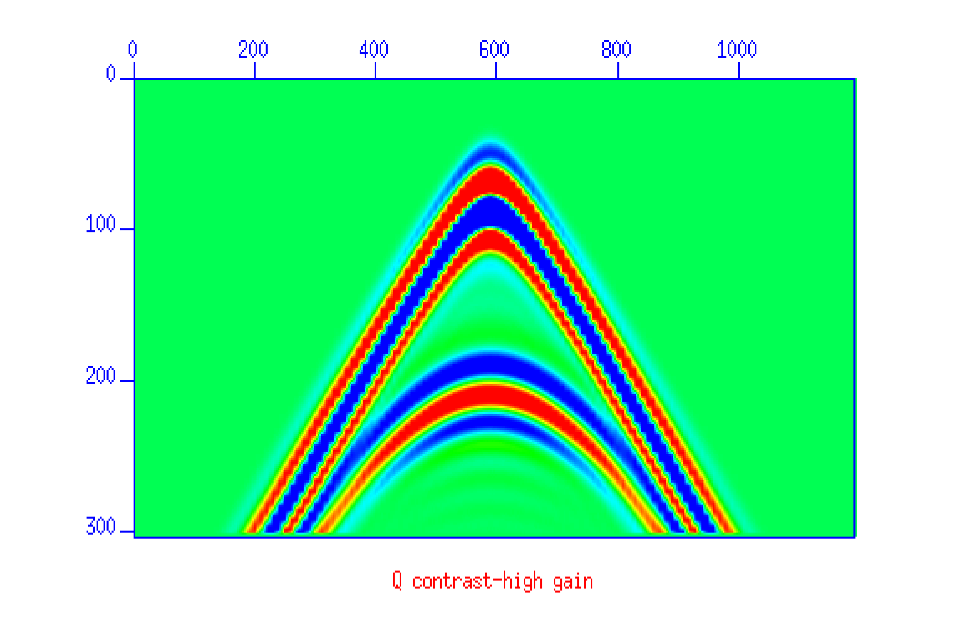
Model 1.

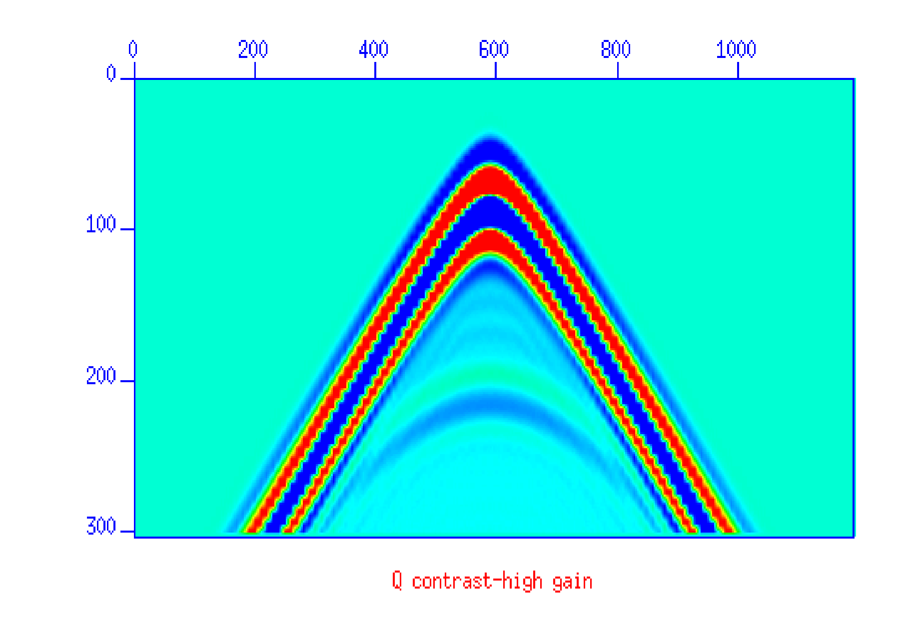
Reflections on Impedance

- The reflections from contrasts in the real component of impedance (density*velocity) will be much greater than reflections from Q contrasts.
- Consider case for source at grid (60,30) and line of receivers at row 25, giving rise to reflections.

Comparison of Impedance-only contrast and Q-only contrast

- Model 1 (left). Layer 1 impedance = 1500000; Layer 2 impedance= 5000000; Q = 210000 for both layers.
- Model 2 (right) Impedance constant; Layer 1, Q=210000; Layer 2 Q=2*pi. (Scale factor = 100.)



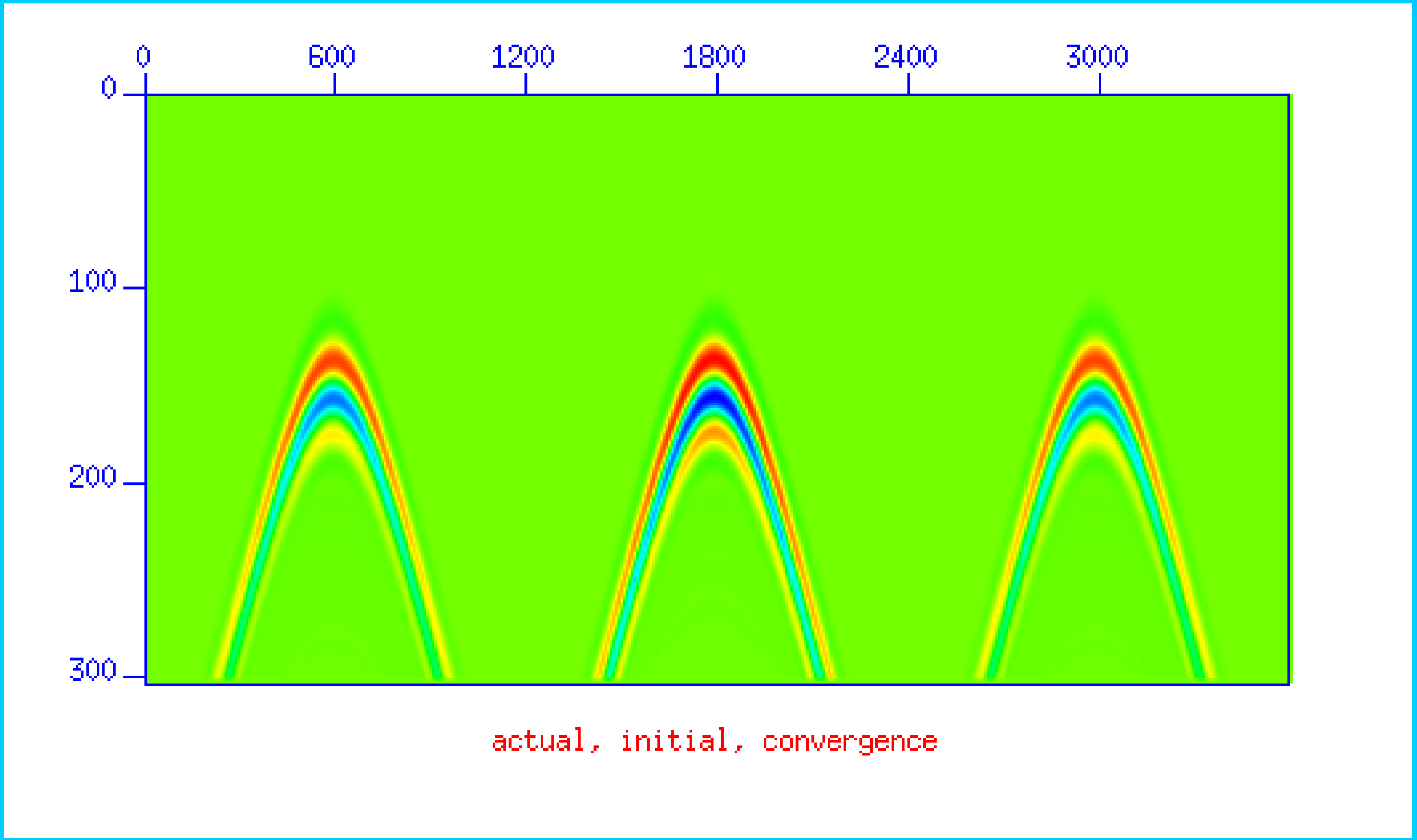


Use seismograms dominated by transmitted arrivals to estimate Q

- The reflections from contrasts in the real component of impedance (density*velocity) will be much greater than reflections from Q contrasts.
- Nevertheless all transmitted and reflected arrivals are used in full waveform inversion.

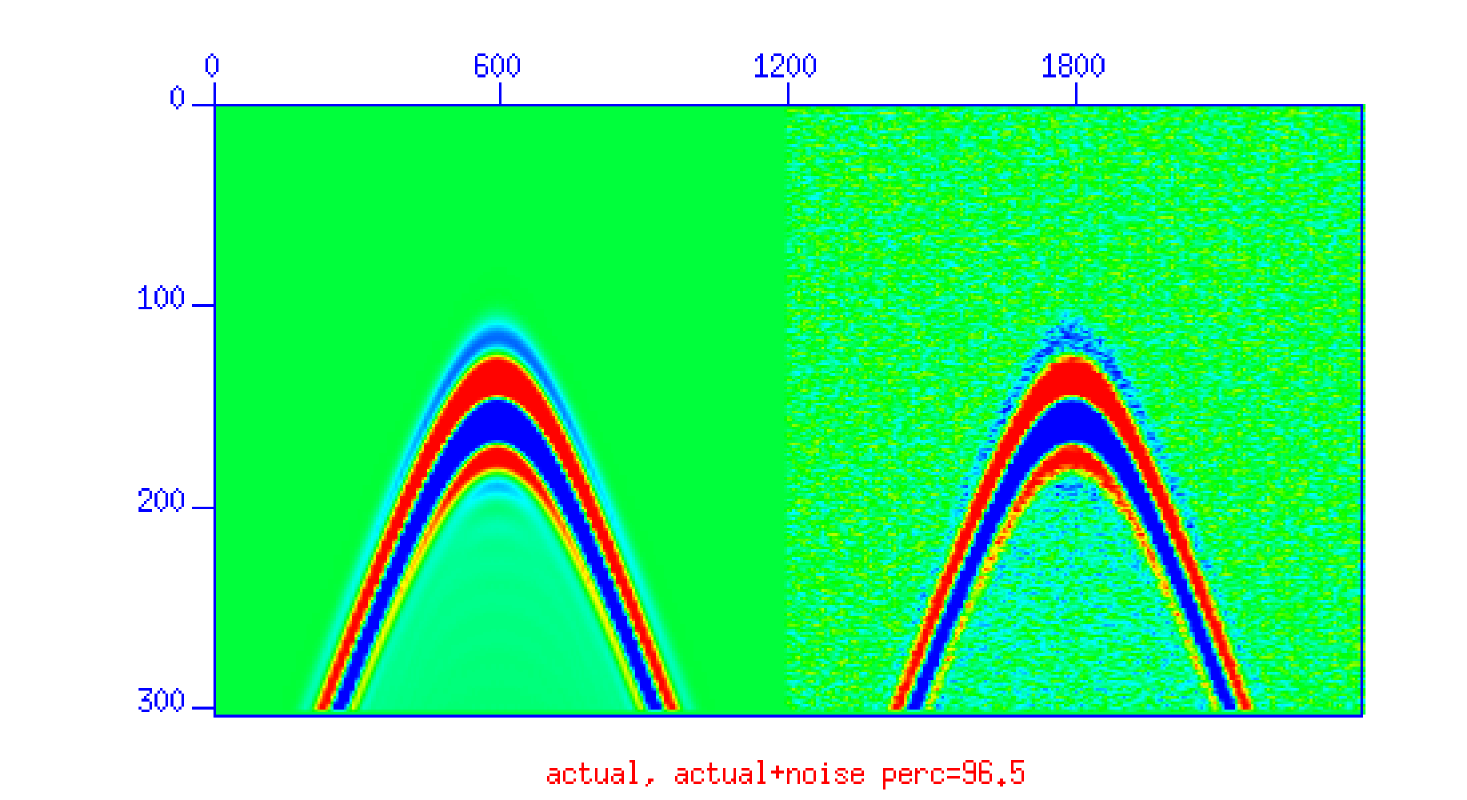
Convergence of Inversion

- Model responses for input data (Q=6.28), initial guess (Q=15), and converged answer (Q=6.09)(after 3 iterations).

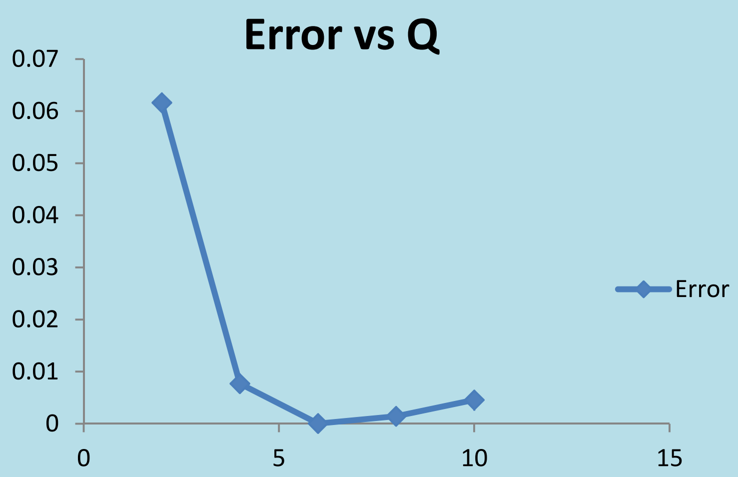


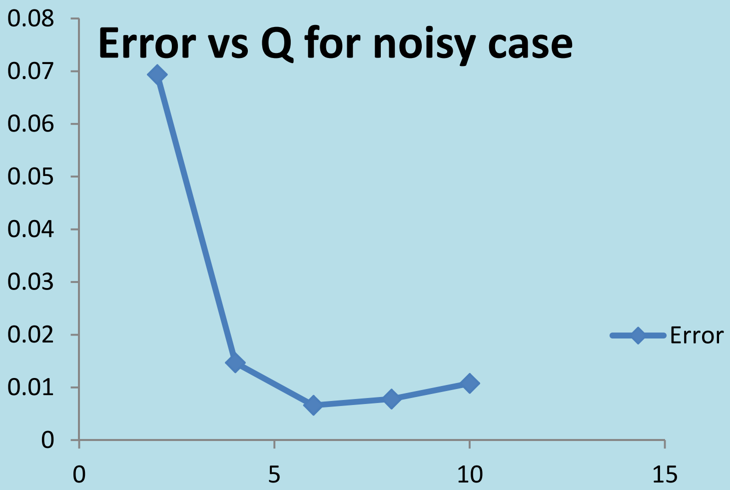
Effect of Modest Levels of Additive Noise on Full Waveform Inversion

- Compare inversion solutions for pure signal versus solutions with small amounts of noise (S/N in signal zone about 5).



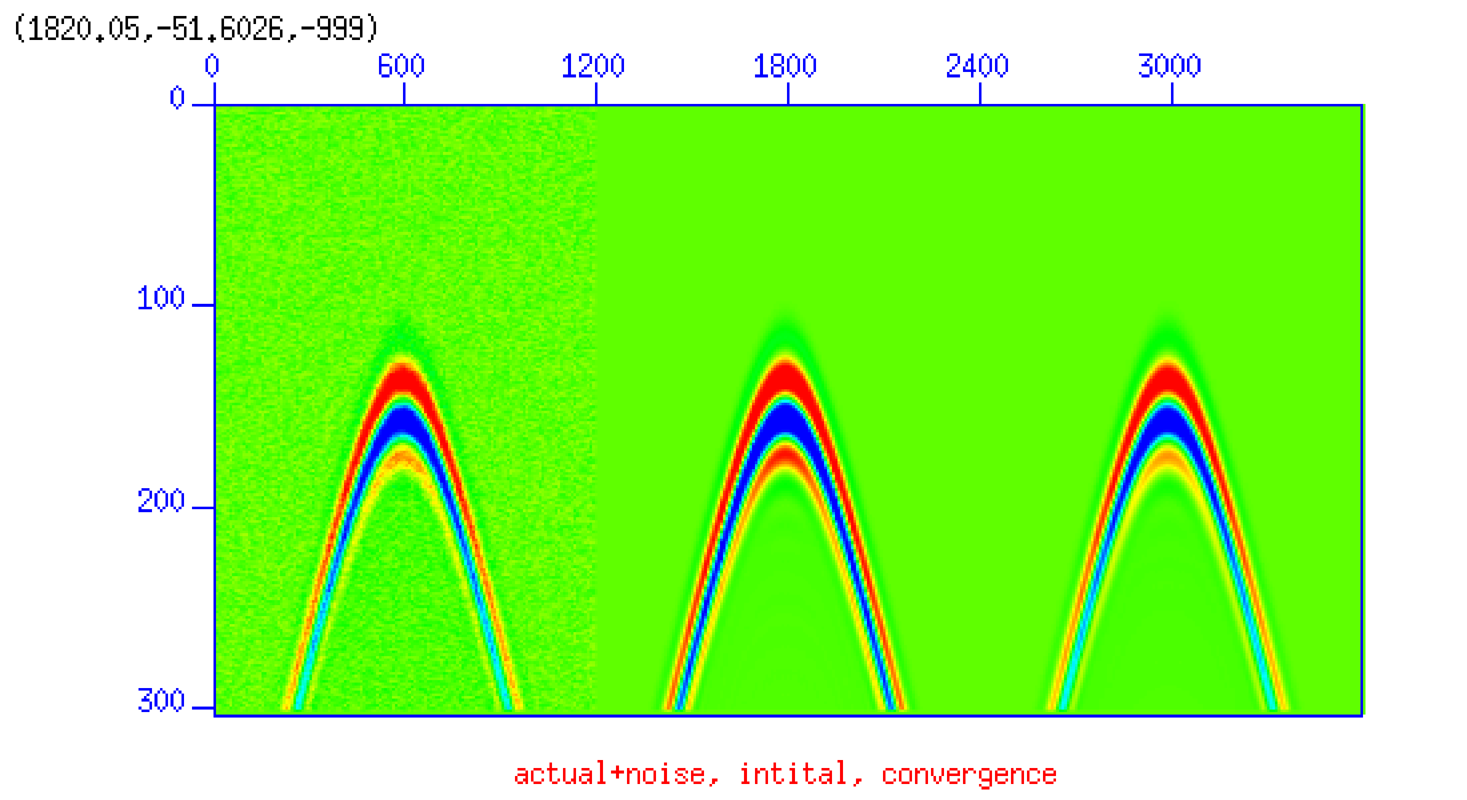
Error vs Q value





Convergence of Inversion

- Model responses for input data + noise (Q=6.28), initial guess (Q=15), and converged answer (Q=6.33)(after 3 iterations).



Preliminary Results

- Full waveform inversion for these simple Q-estimation problems is not overly sensitive to additive noise with zero mean.

$$A^T A\Delta x = A^T (b + n)$$

- $A^T n \rightarrow 0$ if noise, n, is random with zero mean.
- Error of data fit deteriorates slightly with noise but accuracy of Q estimate is consistent.

Conclusions

- Heavy oils are considered viscoelastic materials and their shear properties are important.
- Both theory and measurements show that Q has a decreasing-increasing behavior with viscosity.
- Q-tomography and full waveform inversion methods can be effectively used for Q-estimation.
- The inversion methods could be used in sequence with tomographic results being used as input for full waveform inversion.
- Full waveform inversion produces Q estimates based on the entire waveform. FWI appears to be robust for noisy data with moderate amounts of noise.
- More model and real data tests are needed.

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