Fereidoon Vasheghani and Larry Lines

University of Calgary

The Seismic Quest for Heavy Oil Viscosity

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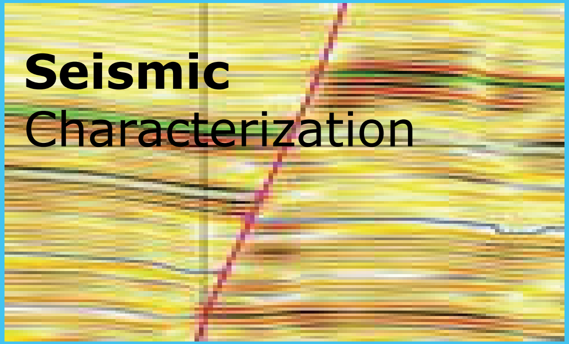
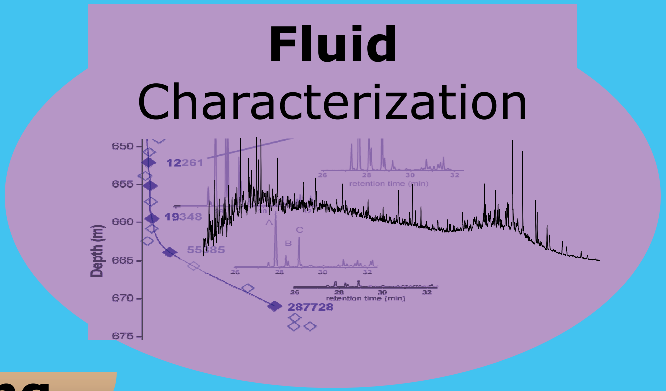
Outline

- Reservoir characterization
- Viscoelasticity
- Q versus viscosity and temperature
- Estimation of Q
- Modeling results
- Crossborehole field data results
- Conclusions

Reservoir Characterization

- 1. Build geological model using seismic, well logs, core analyses in a reservoir simulator
- 2. History match production data, 4D seismic, fluid & sand production to model reservoir
- 3. Simulate reservoir to predict and design recovery mechanisms





Reservoir Engineering

Numerical Simulation

Optimization

Monitor

Production

Flow Dynamics

Enhanced heavy oil production involves lowering the oil viscosity.

Why Viscoelastic?

- Heavy oils, which play a significant role in today's oil industry, have high viscosities, closer to solid viscosities.
- Recent studies have shown that wave propagation in the reservoir is affected by the viscosity.
- Elastic assumption excludes the time dependent response of the porous media. This is true for perfectly elastic media, but:

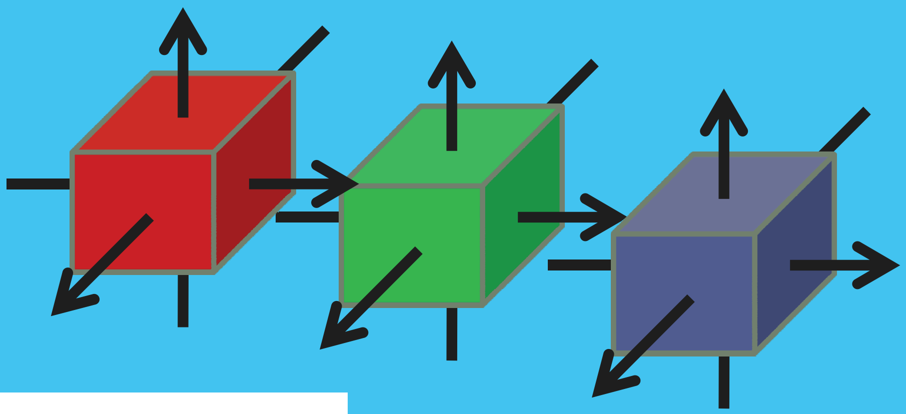
  Is the Earth a perfectly elastic medium?

  NO

- Rocks absorb and convert (i.e. attenuate) energy.

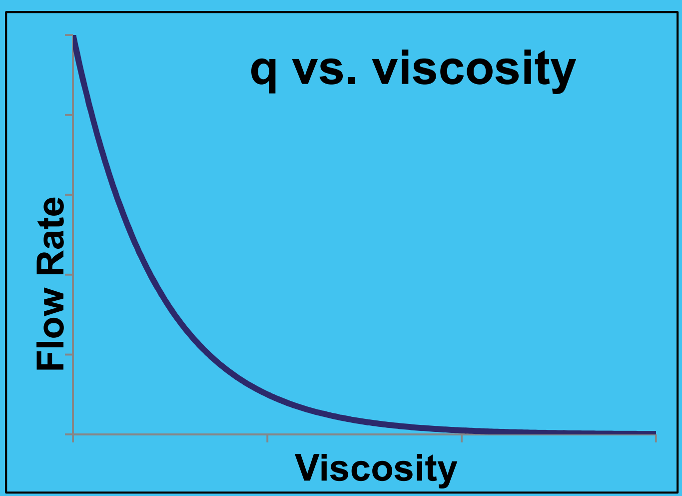
Reservoir Engineering Importance
(ref. Vasheghani, 2008)

- **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)

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)

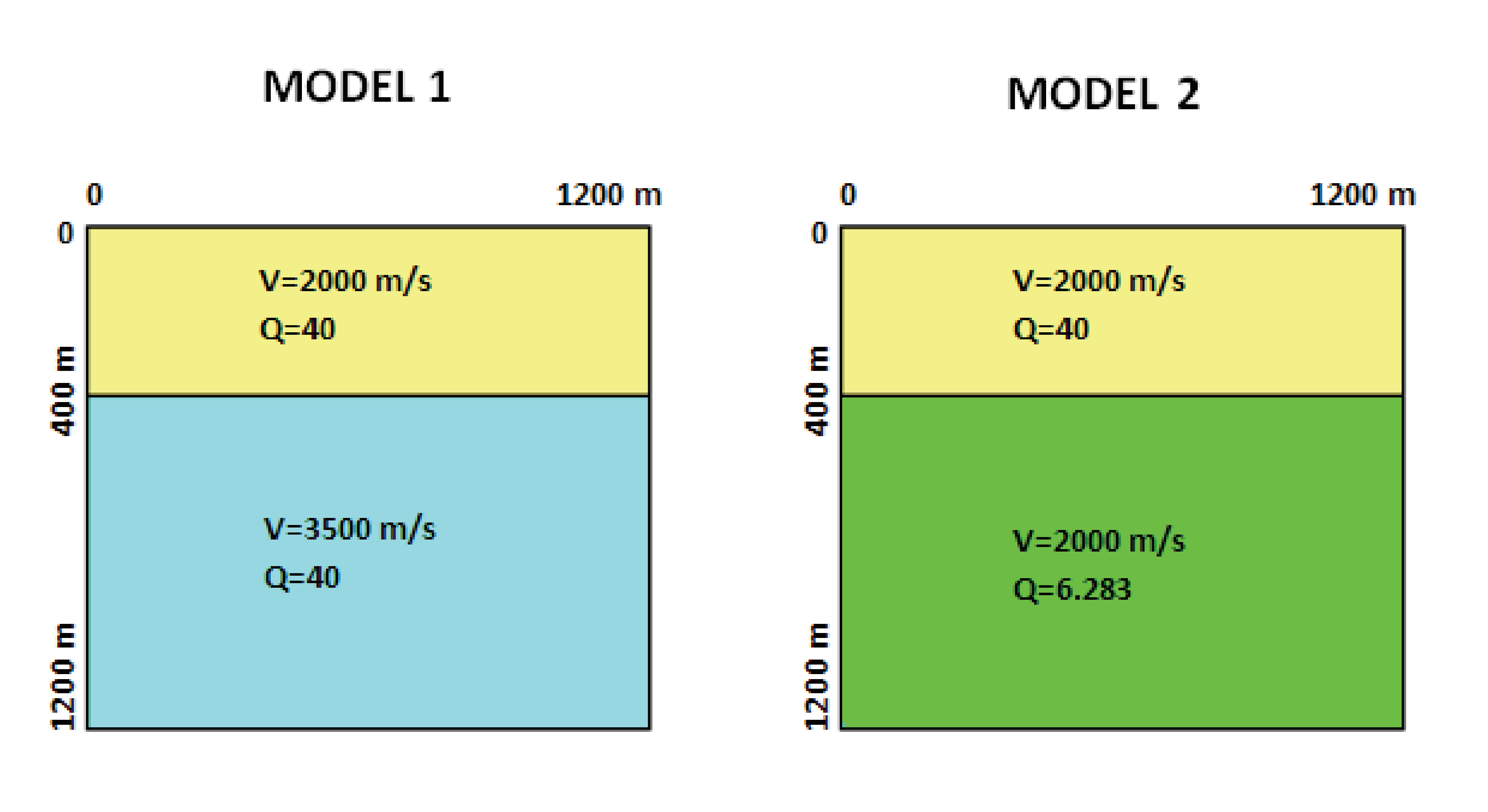
$$\frac{1}{Q(\omega)} = \frac{1}{2\pi}\frac{\Delta E}{E} = \frac{1}{2\pi}\frac{\Delta(A^2)}{A^2} = \frac{1}{\pi}\frac{\Delta A}{A}$$

where ΔE is the energy change over one wavelength

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

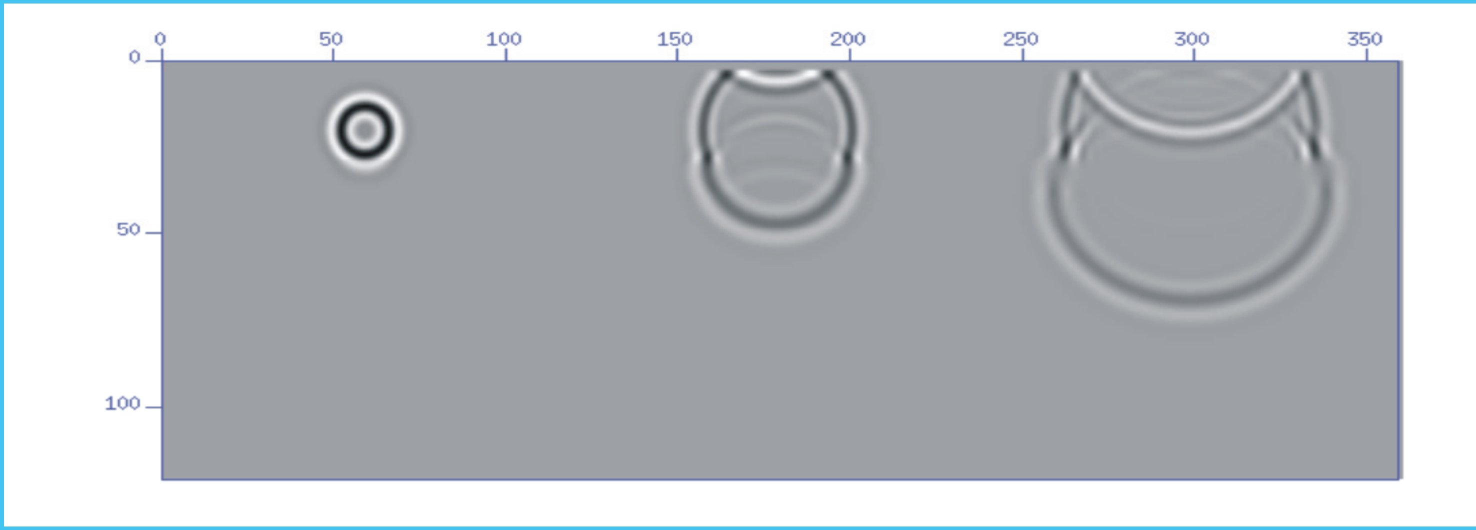
$$Q(\omega) \cong \frac{\pi}{\alpha\lambda}$$

Reflections on Q: Models to illustrate reflections due to impedance and Q contrasts (CSEG Recorder, 2008).



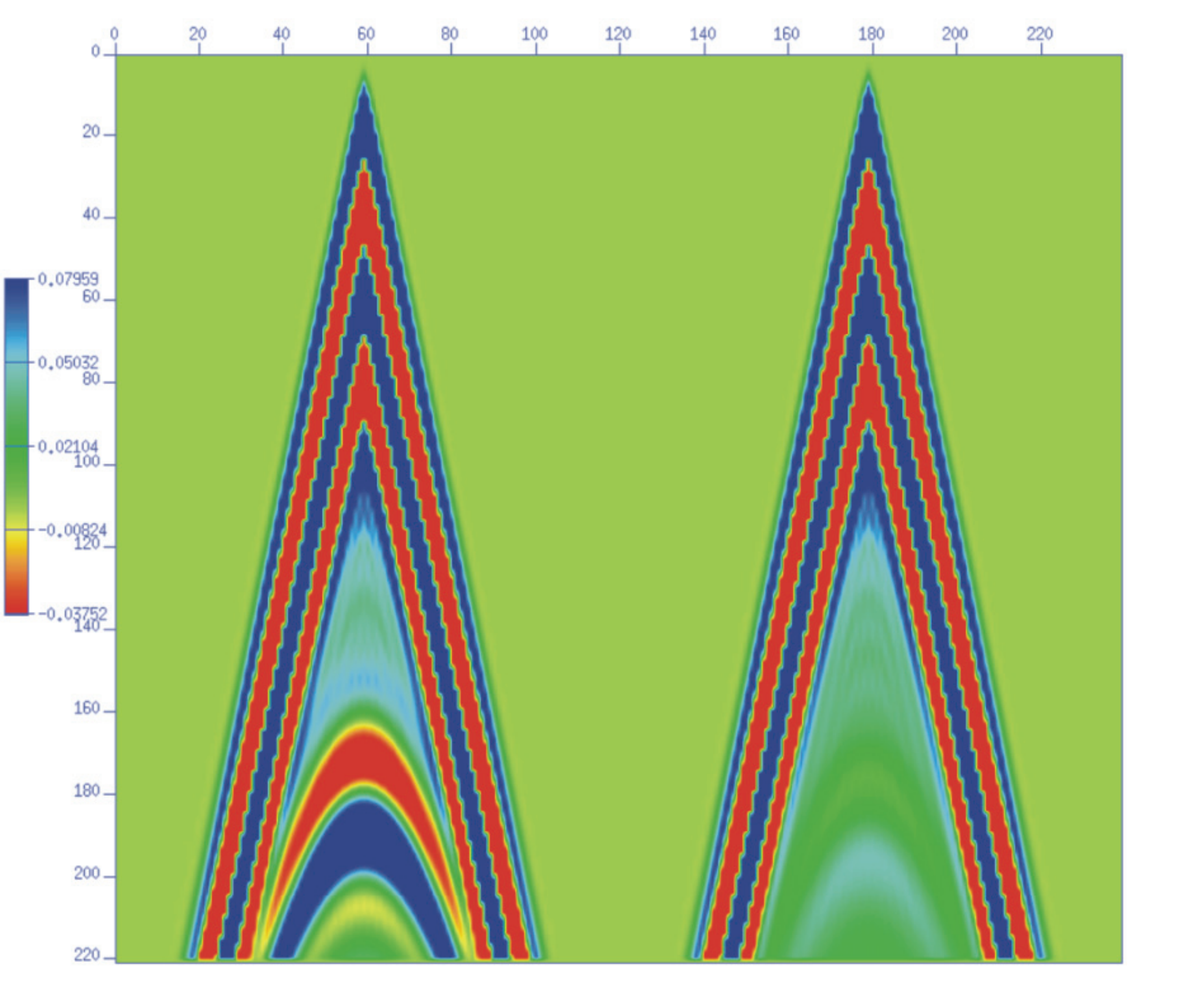
Finite-difference modeling using Carcione's modeling codes

- Finite-difference codes (Fortran 90) from Carcione (2007) can be used to model the effects of Q.



Reflection seismograms for models 1 and 2.

- Source depth= 250m
- Source offset = 600m
- Receiver depths = 260m
- Lateral receiver spacing =10 m
- Wavelet peak delayed 20 ms from onset
- Note that both model responses have reflections at about 165 ms
- From “Reflections on Q” by Lines et al. (2008).
- Stand by for CREWES presentation by Chris Bird



Viscoelasticity

- Viscoelastic behavior is a time dependent, mechanical non instantaneous response of a material body to variations of applied stress (Carcione, 2007).

- To formulate the viscoelastic behavior, springs (elastic) and dashpots (viscous) can be used as the components of viscoelasticity.

- based on configuration, we achieve different responses:
  - **Maxwell**
  - **Kelvin-Voigt**
  - **Zener**

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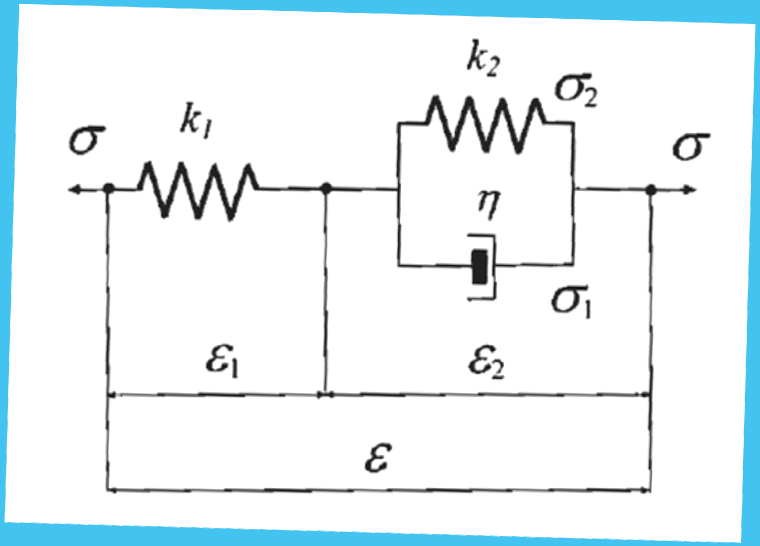
Zener's Model

- A spring and a Kelvin-Voigt component in series
- Provides a more realistic representation of earth



(from Carcione, 2007).

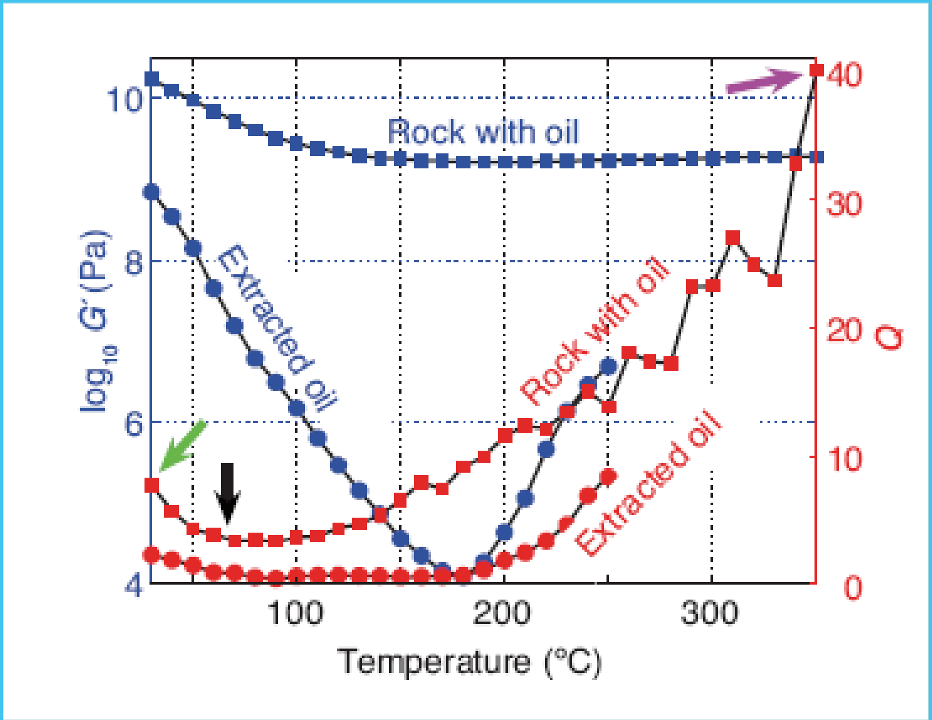
$$\sigma + \tau_\sigma \partial_t \sigma = M_r(\epsilon + \tau_\epsilon \partial_t \epsilon)$$

$$Q(\omega) = \frac{1 + \omega^2 \tau_\epsilon \tau_\sigma}{\omega(\tau_\epsilon - \tau_\sigma)}$$

$$M_r = \frac{k_1 k_2}{k_1 + k_2}$$

$$\tau_\sigma = \frac{\eta}{k_1 + k_2} \qquad \tau_\epsilon = \frac{\eta}{k_2} \geq \tau_\sigma$$

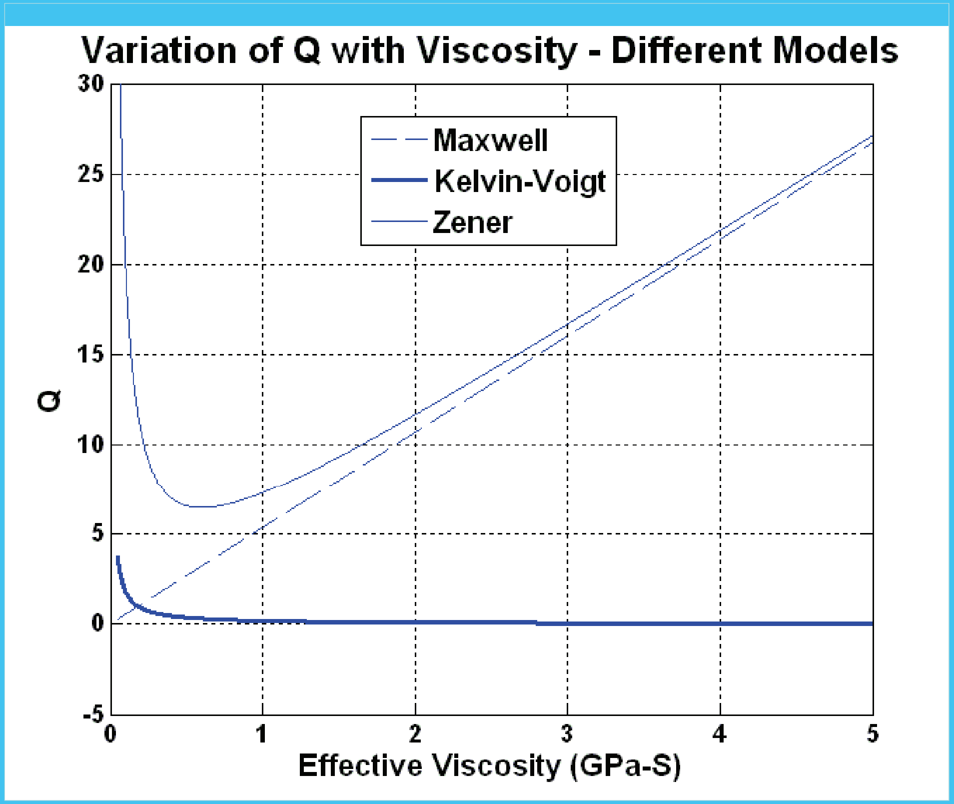
Q vs. Viscosity and Temperature

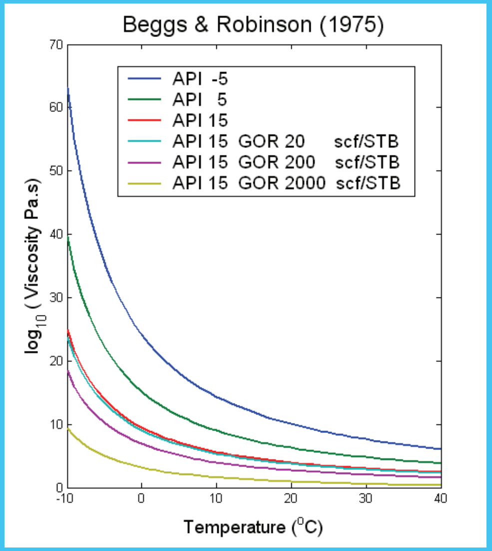


(from Behura et al., 2007).

- Frequency of signal: 12.6 Hz.
- Q at room temperature for the Uvalde carbonate rock with 25% porosity is about 5.
- With increasing temperature, Q reaches a minimum of around 4 and increases to a value of 40 at about 350°C.

Q vs. Viscosity and Temperature





- Frequency of signal: 25 Hz.

Estimation of Q

Centroid Frequency

- Centroid frequency is defined as (Hedlin et al., 2002):

$$f_c = \frac{\int_0^\infty f A(f) df}{\int_0^\infty A(f) df}$$

- Quan and Harris (1997) estimated Q and solved a tomography problem in absorption $D\alpha' = \Delta f$

$$Q = \frac{\pi \sigma^2}{\Delta f} \frac{\Delta Z}{V}$$

$$\Delta Z = Z_2 - Z_1 \qquad \Delta f = f_{c2} - f_{c1} \qquad \sigma^2 = \frac{\int_0^\infty (f - f_{c1})^2 A(f) df}{\int_0^\infty A(f) df}$$

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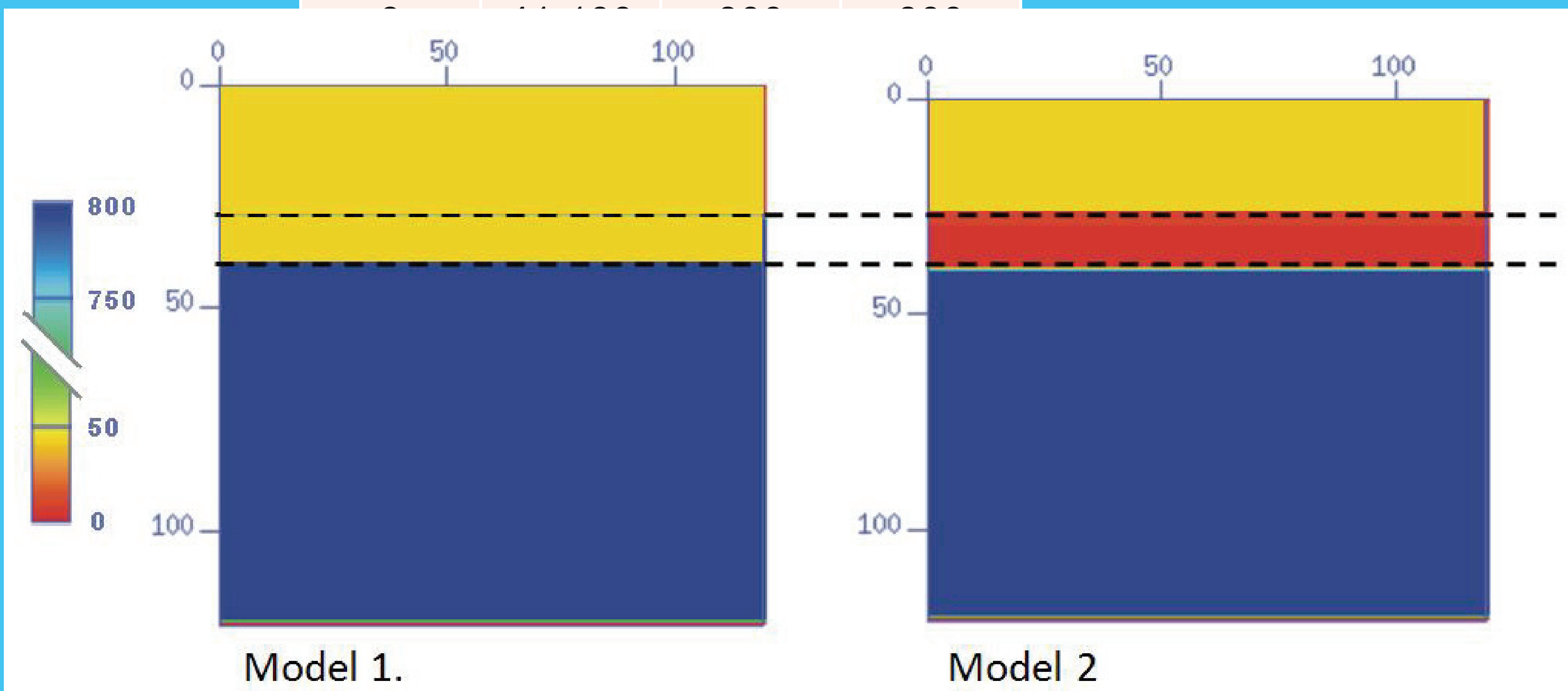
Synthetic Results - Models

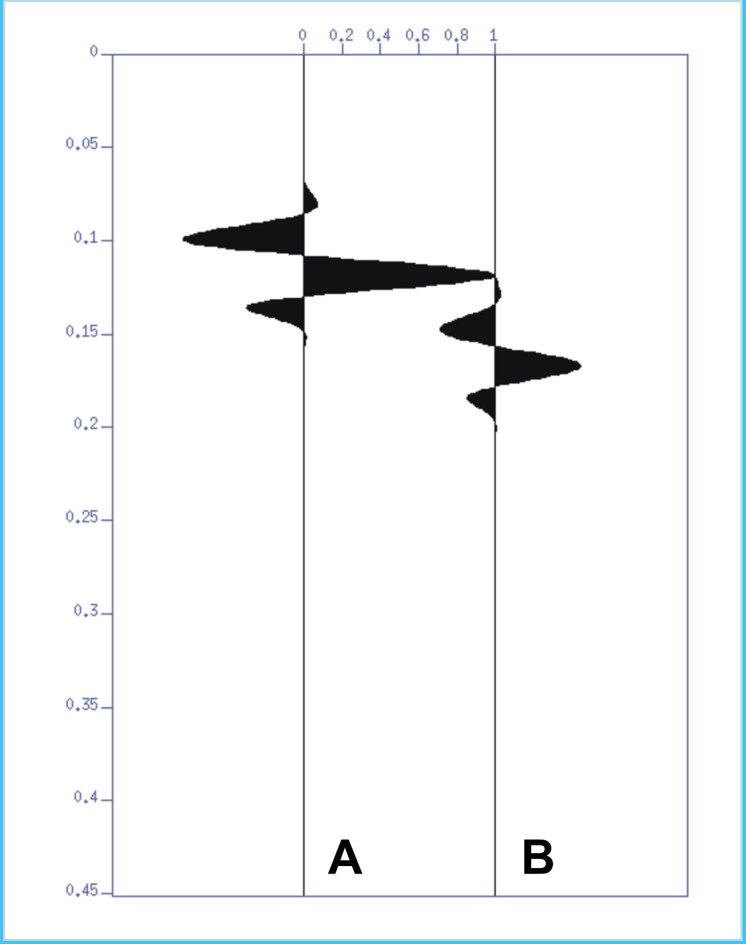
Layers	Cells	Q	
		Model 1	Model 2
1	1-30	40	40
2	31-40	40	3
[illegible]	[illegible]	[illegible]	[illegible]



Middle layer

Synthetic Results - Results

Pulses broaden and decay with propagation



Model 2:

Q = (40, 3, 800)

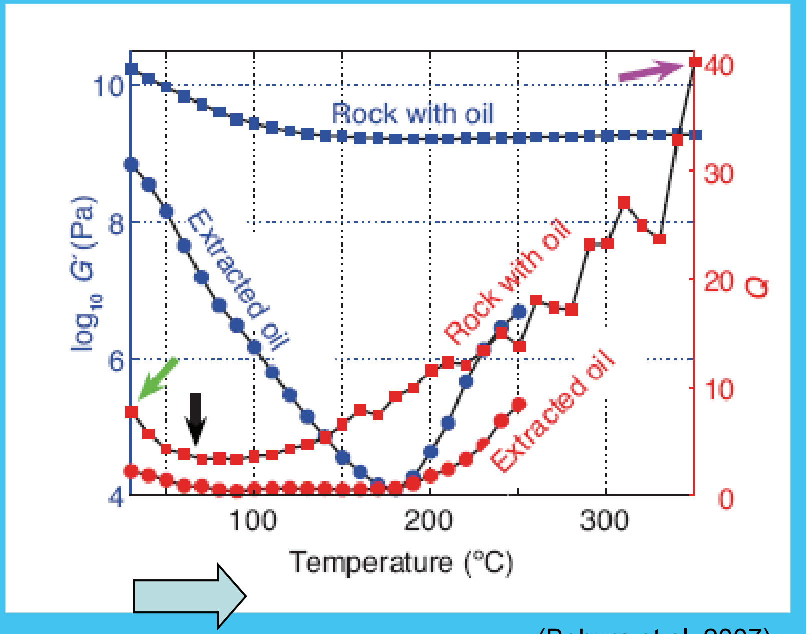
A: Top interface

B: Bottom interface

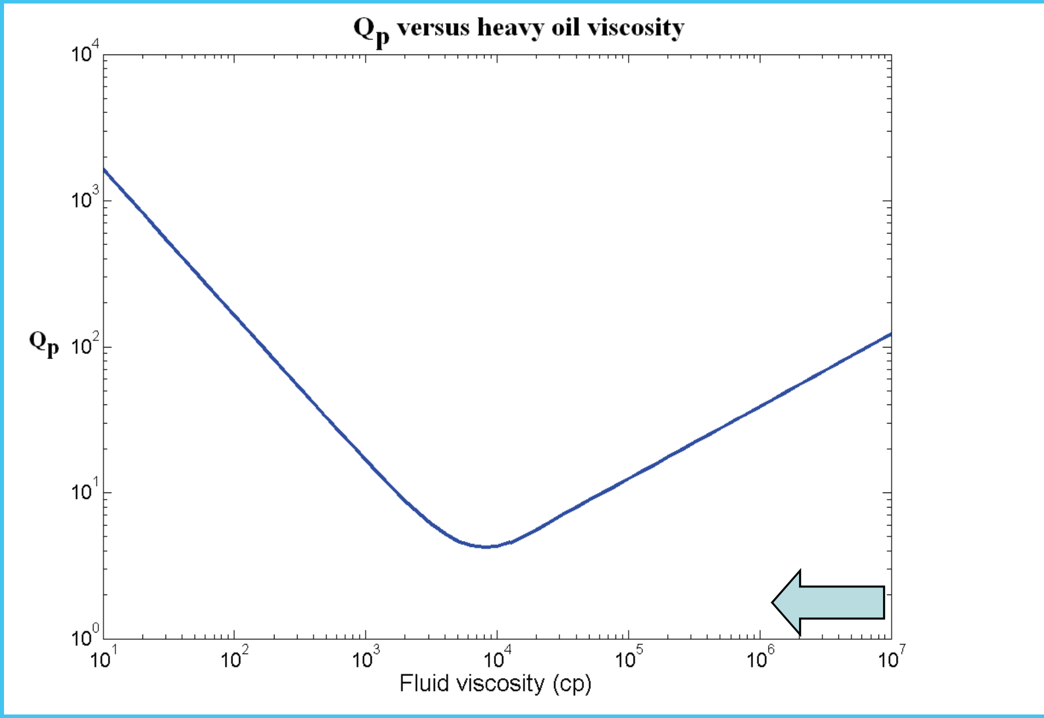
Biot + Squirt flow model

Measured in lab

Theoretical values

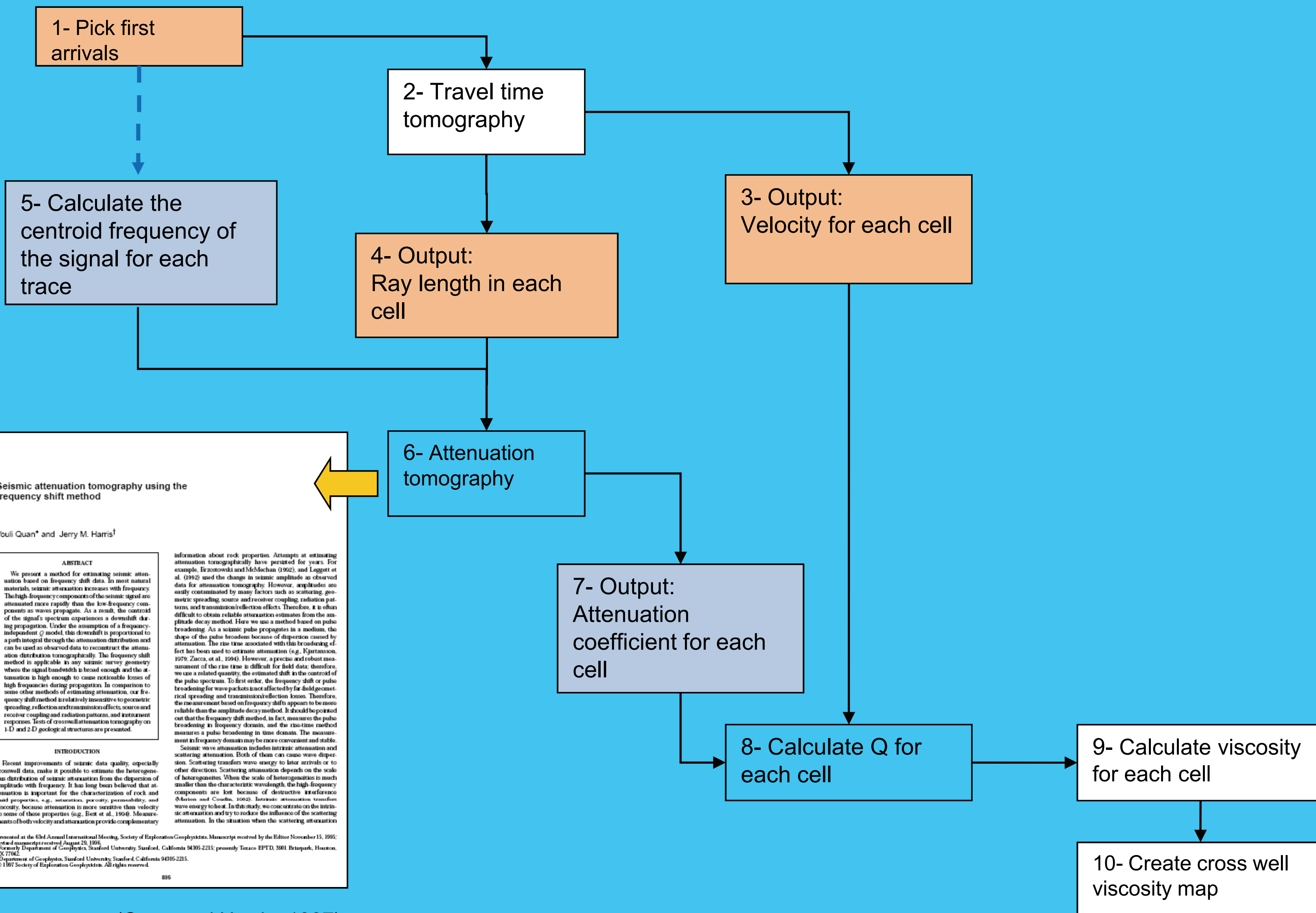


(Behura et al, 2007)



- Both show that quality factor decreases to a minimum then increases with viscosity (temperature).

Methodology (from Vasheghani's PhD thesis)



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 heterogeneities. 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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*Formerly Department of Geophysics, Stanford University, Stanford, California 94305-2215; presently Texaco EPTD, 3901 Briarpark, Houston, TX 77042.
†Department of Geophysics, Stanford University, Stanford, California 94305-2215.
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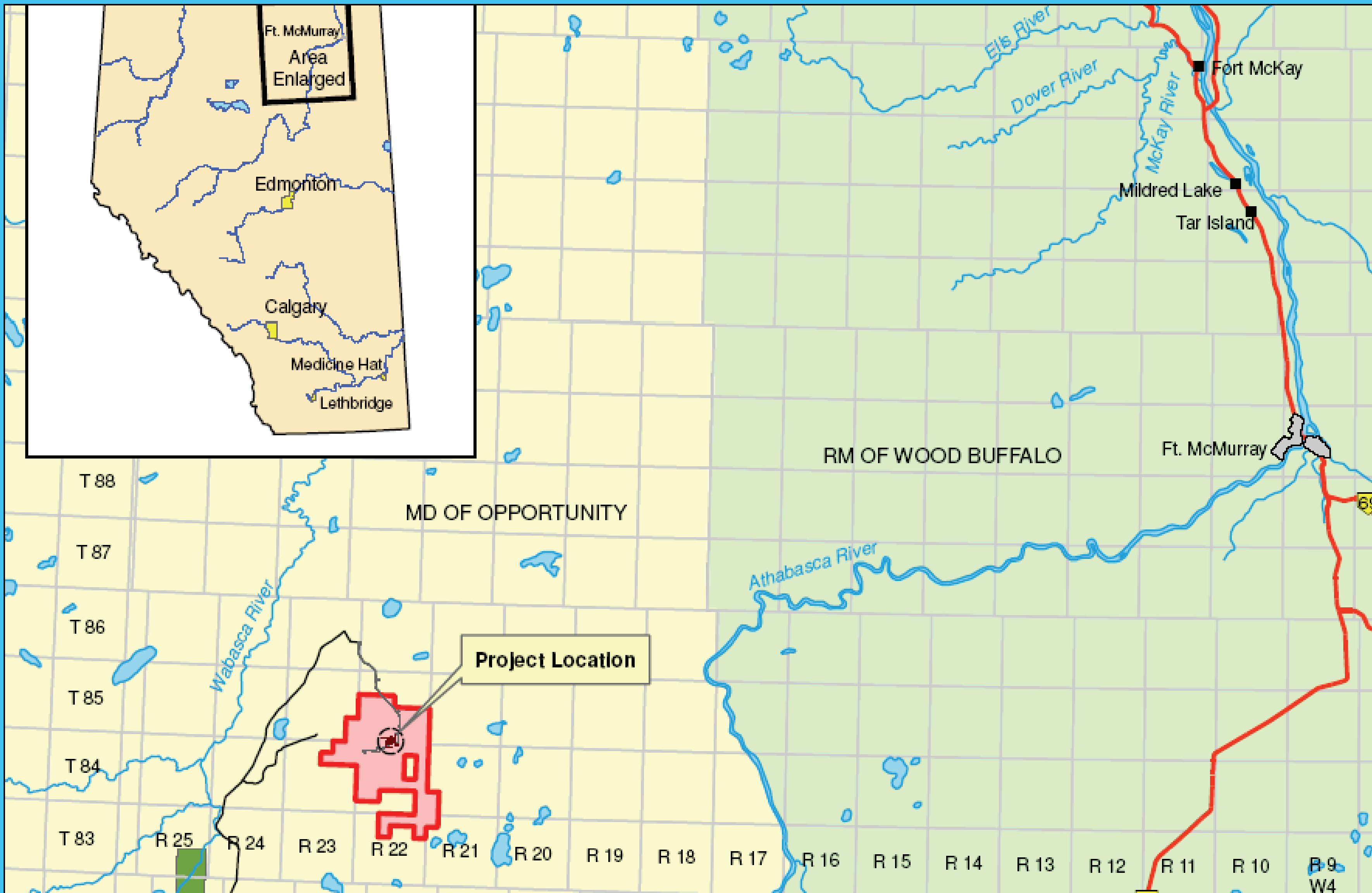
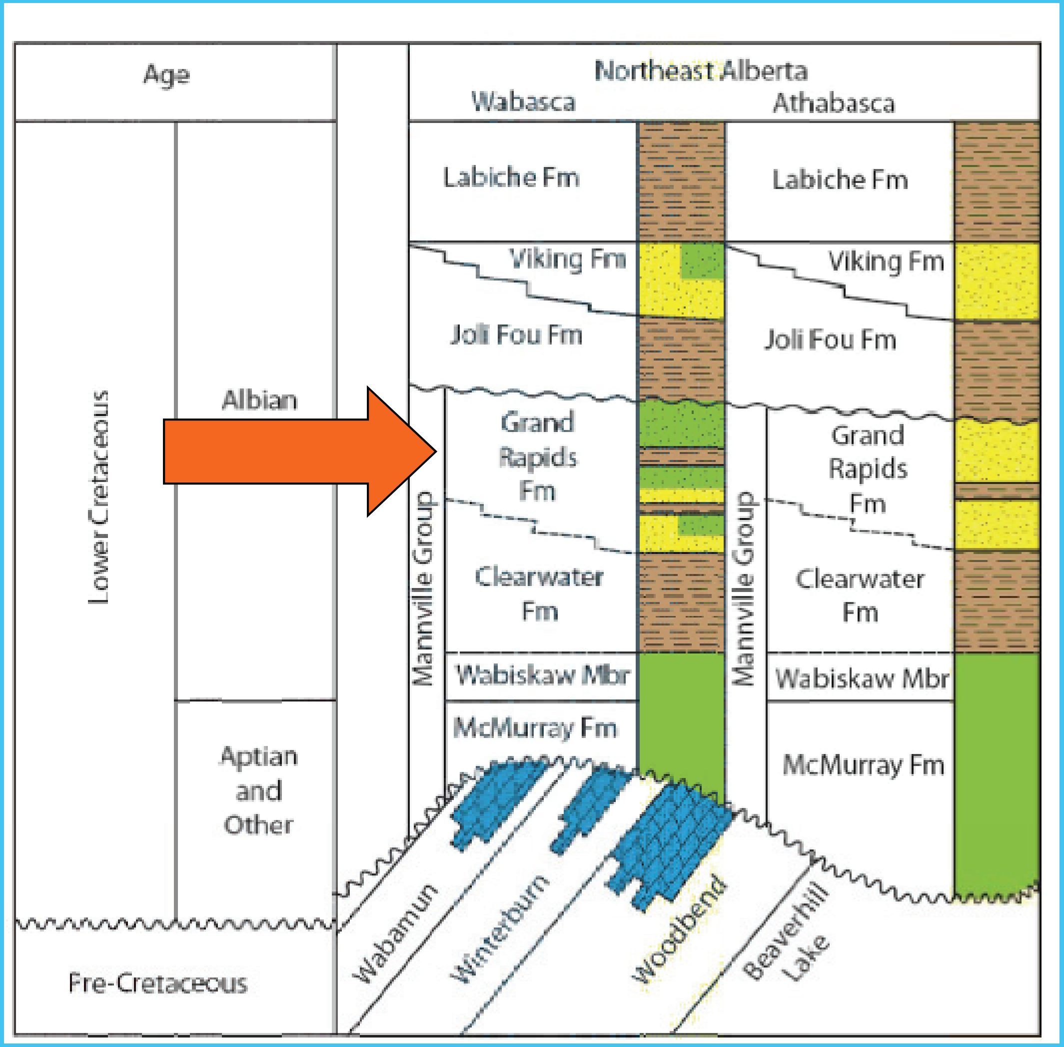
(Quan and Harris, 1997)

Cross well location

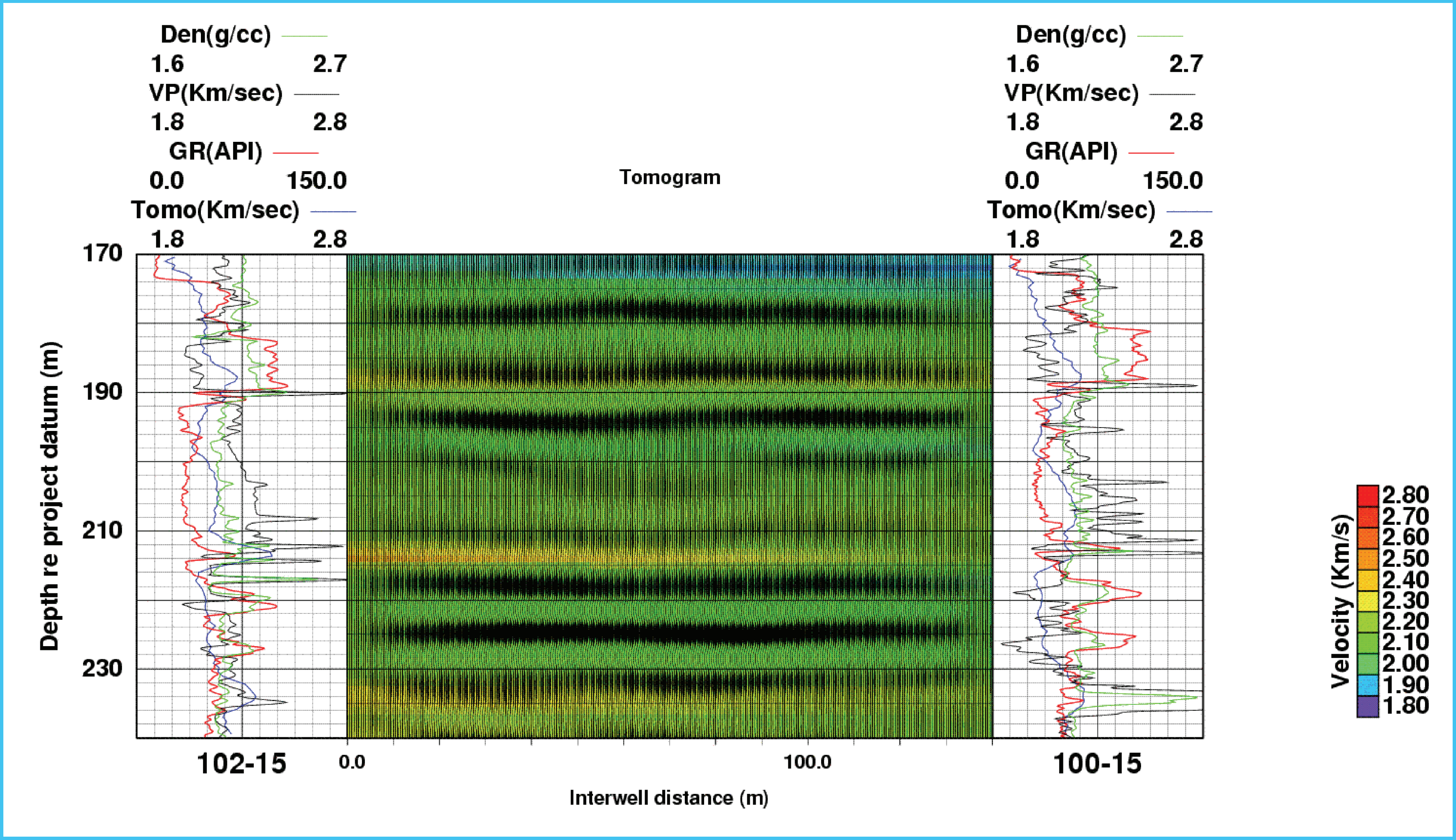


(modified from ERCB)

Stratigraphy

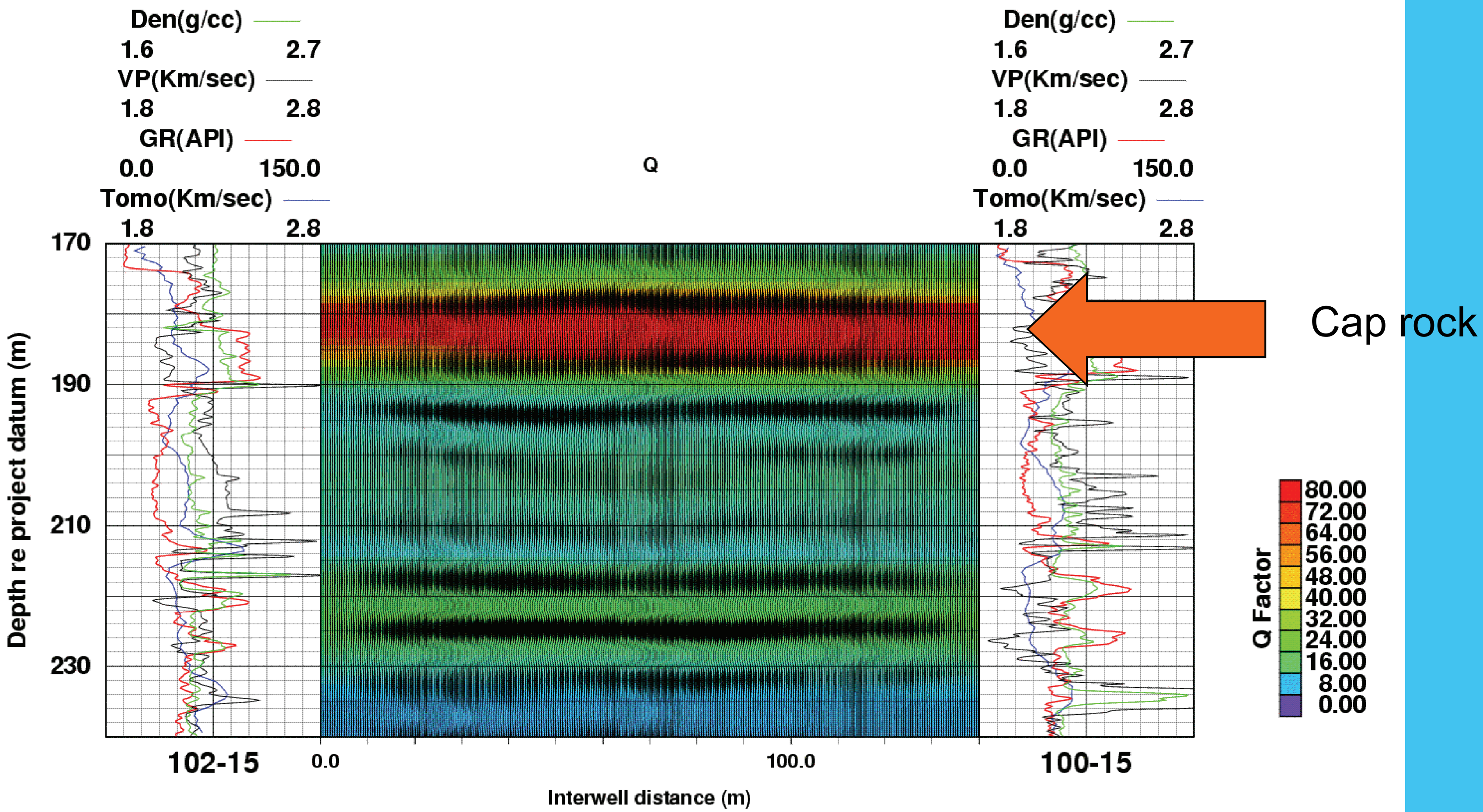


Velocity



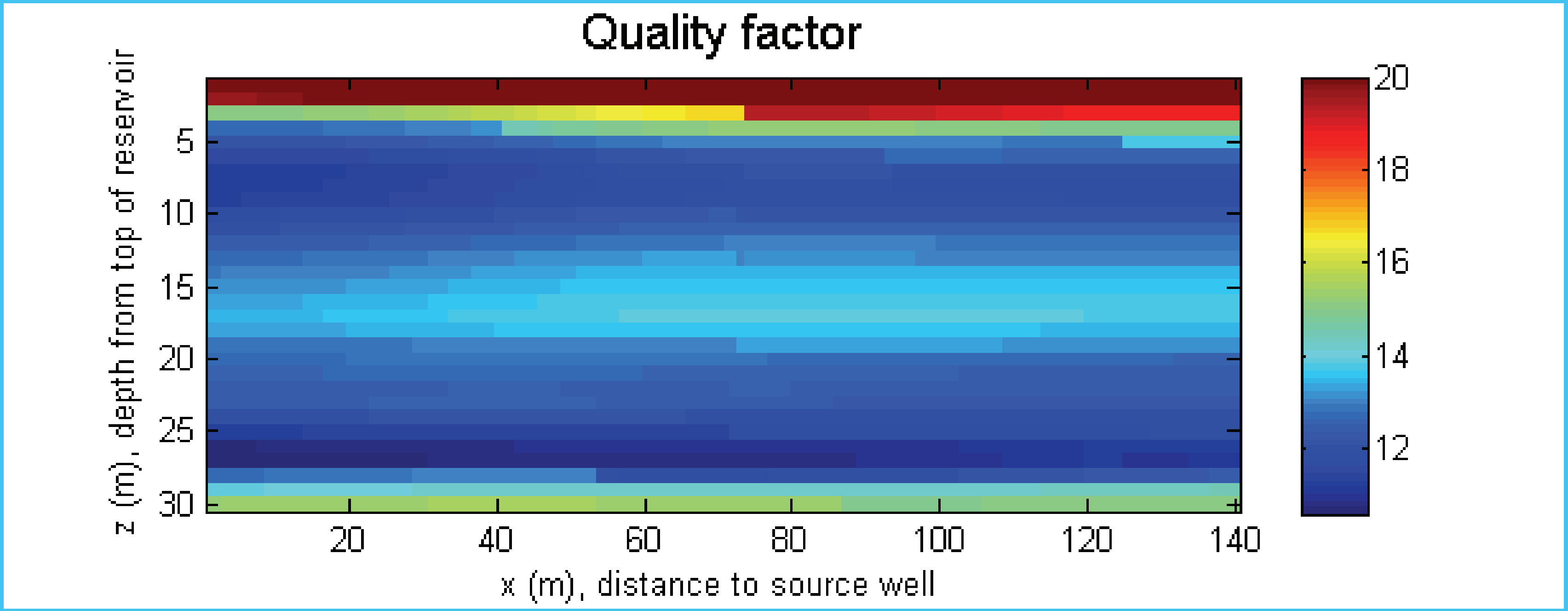
Den(g/cc)
1.6 2.7
VP(Km/sec)
1.8 2.8
GR(API)
0.0 150.0
Tomo(Km/sec)
1.8 2.8
Tomogram
Den(g/cc)
1.6 2.7
VP(Km/sec)
1.8 2.8
GR(API)
0.0 150.0
Tomo(Km/sec)
1.8 2.8
170
190
210
230
Depth re project datum (m)
102-15
0.0
100.0
100-15
Interwell distance (m)
Velocity (Km/s)
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80

Quality factor



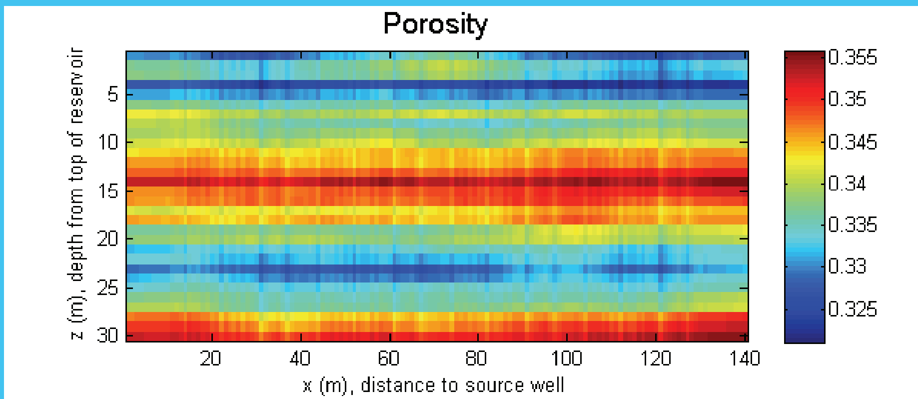
Quality factor

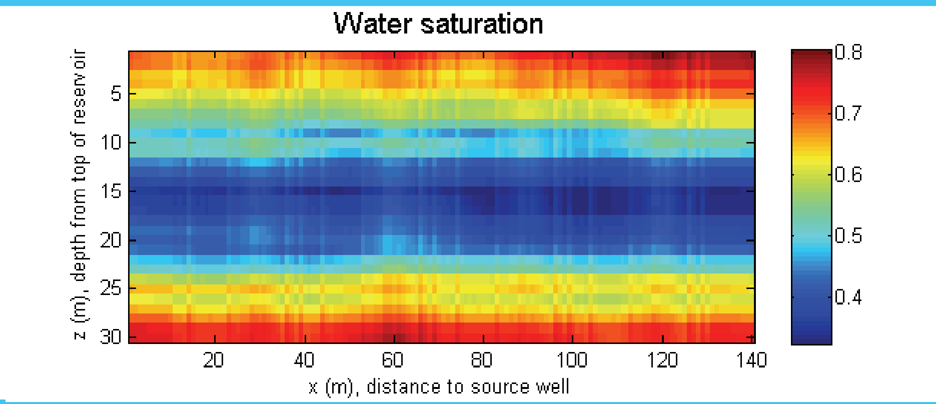
- Zone of interest

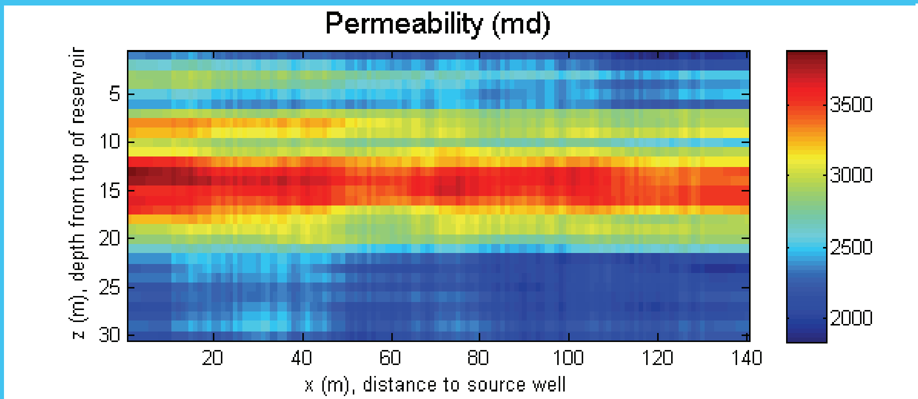


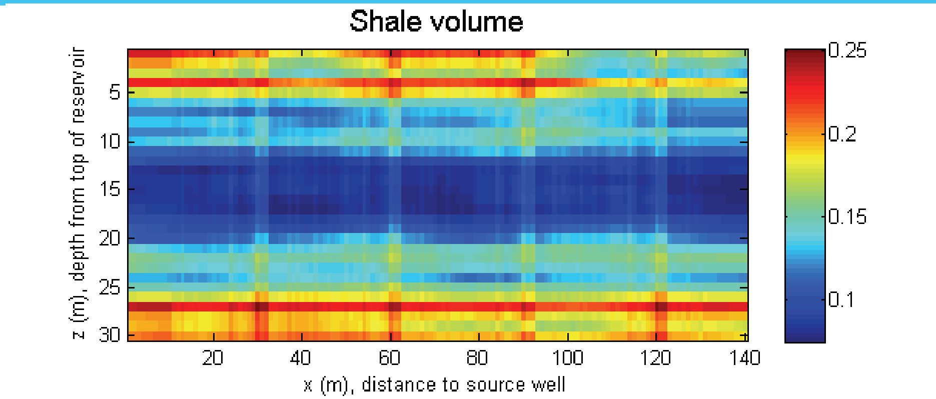
Geological model

- From core and well log data.
- Using statistical modeling techniques





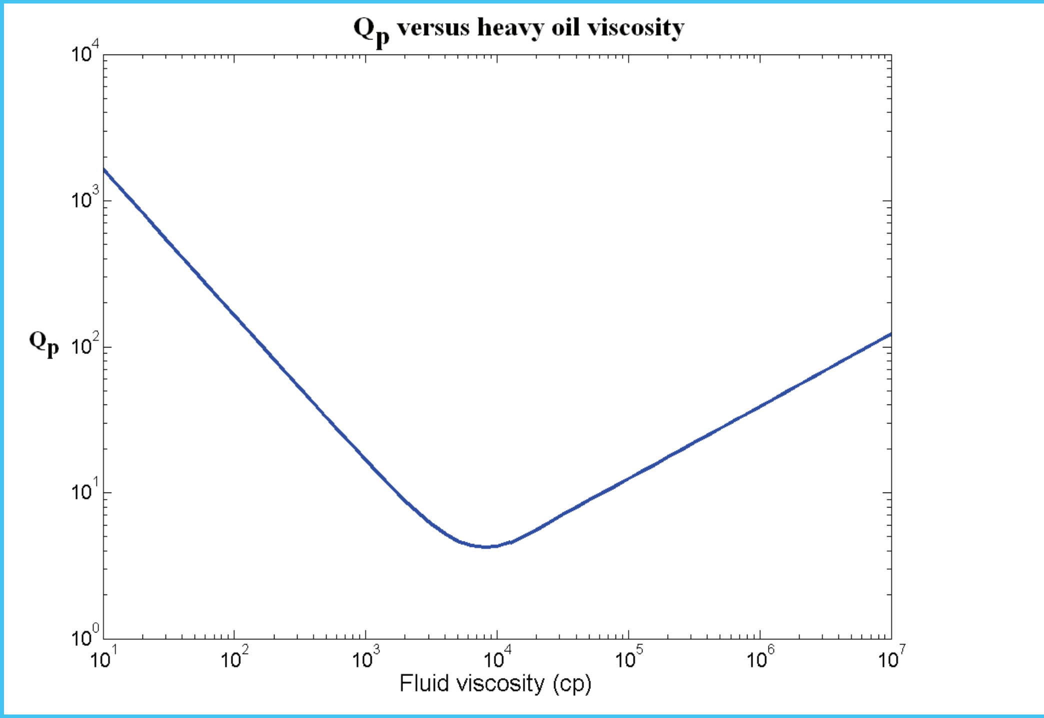




Biot + Squirt flow model

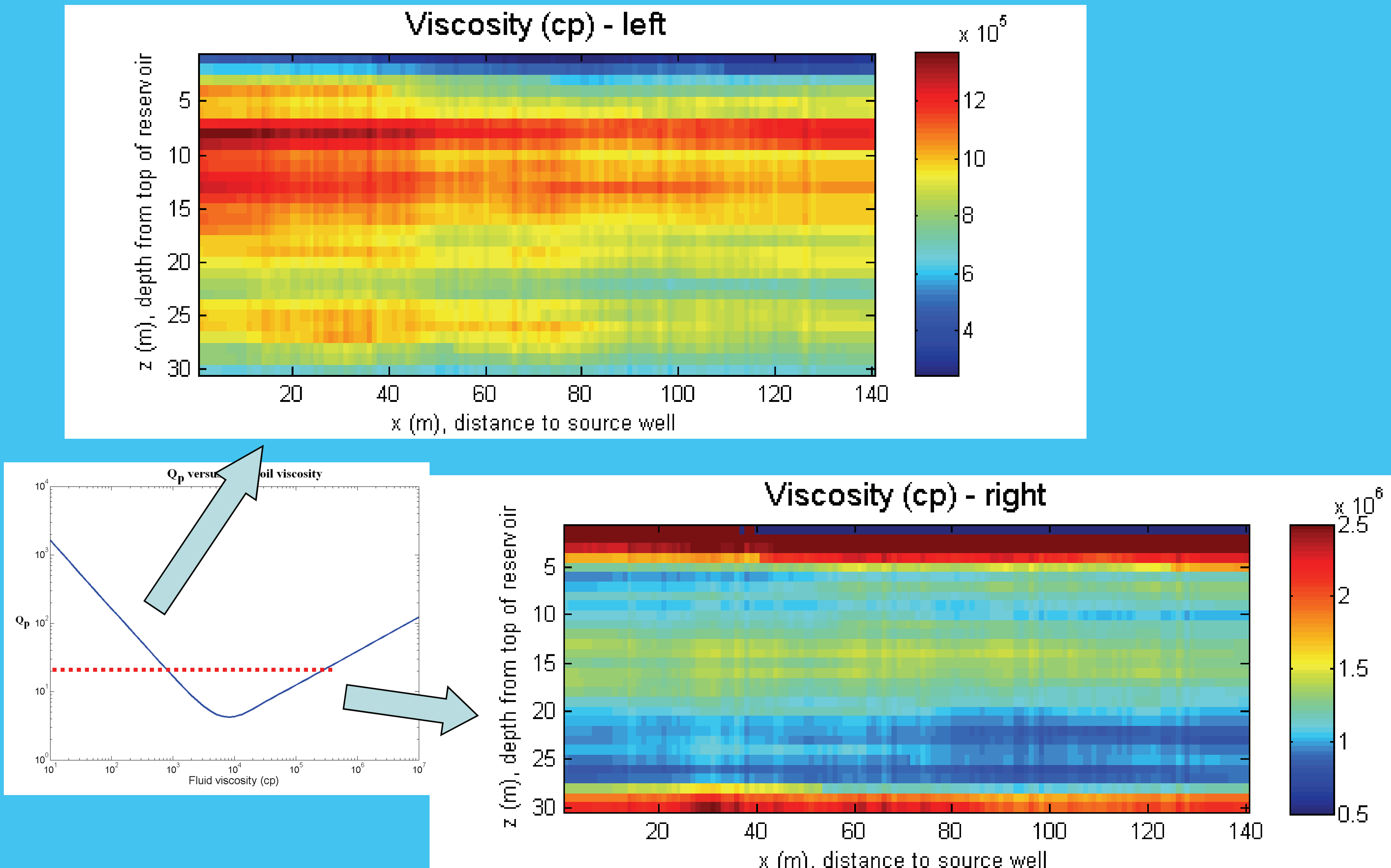
Reservoir and fluid properties	
Fluid Density	1000 kg/m^3
Fluid bulk modulus	1 GPa
Fluid viscosity	Variable
Frequency	300 Hz
R	1 mm
Oil saturation	1
Matrix Bulk modulus	35 GPa
Matrix Density	2650 kg/m^3
Porosity	0.30
Dry frame bulk modulus	1.7 GPa
Dry frame shear modulus	1.35 GPa
Permeability	1 D

Theoretical values



For each set of reservoir parameters, one Q-viscosity curve can be plotted.

Viscosity: ambiguity



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.
- The Q-viscosity behavior, unfortunately, demonstrates that there can be nonuniqueness (ambiguity) in determining viscosity from Q.
- The uncertainties in the input parameters can move the Q-viscosity curve a and create error.
- Viscosity can be estimated from Q, but further research is needed.
- No real viscosity data were available to the authors during this research for validation purposes. Only regional estimates were available.
- According to BISQ theory, Q does not change with density.

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Thank you!!

Viscosity estimation from seismic Q – it's a bear of a problem.