Q and Viscosity

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Outline:

- Engineering Importance
- Big Questions …
- Viscoelasticity
- Forward Problem (Simulator to Seismic)
- Inverse Problem (Seismic to Simulator)
- Conclusions

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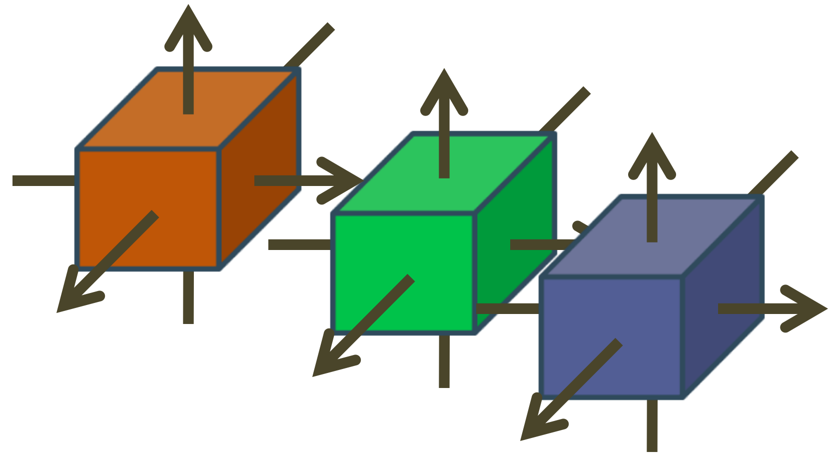
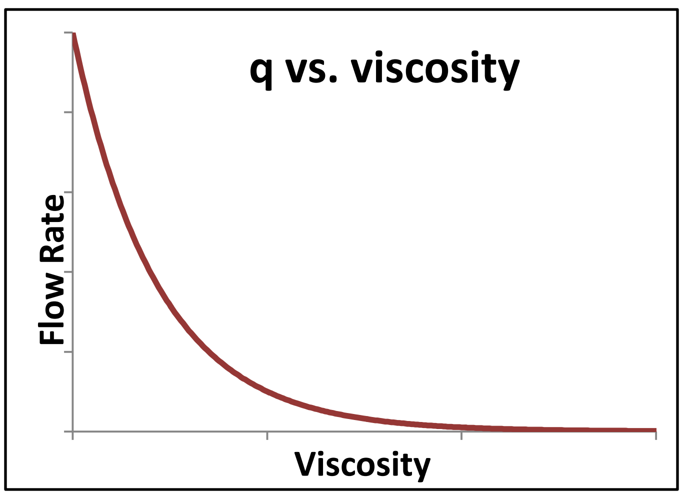
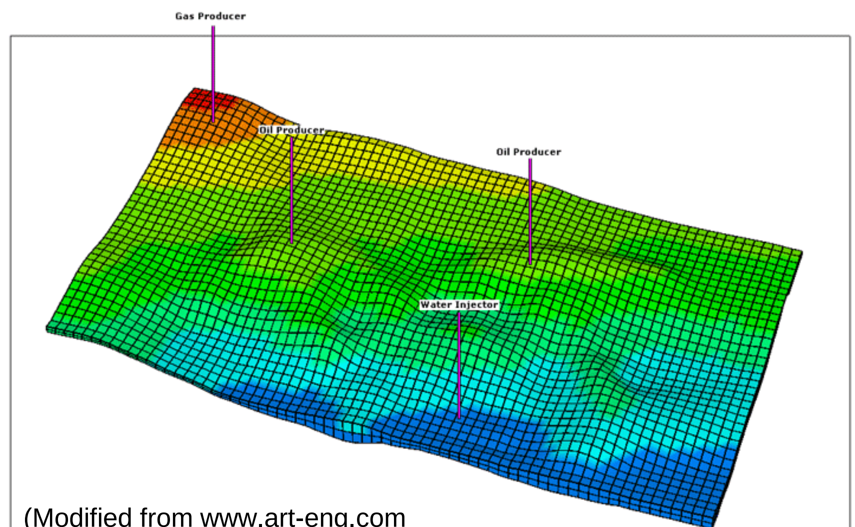
Engineering Importance:

- **Darcy's Law**

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



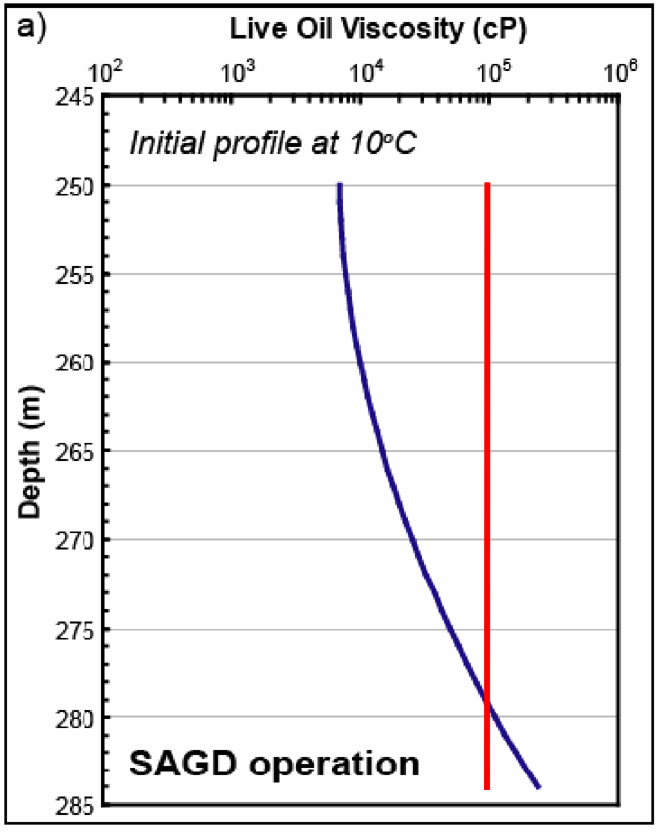


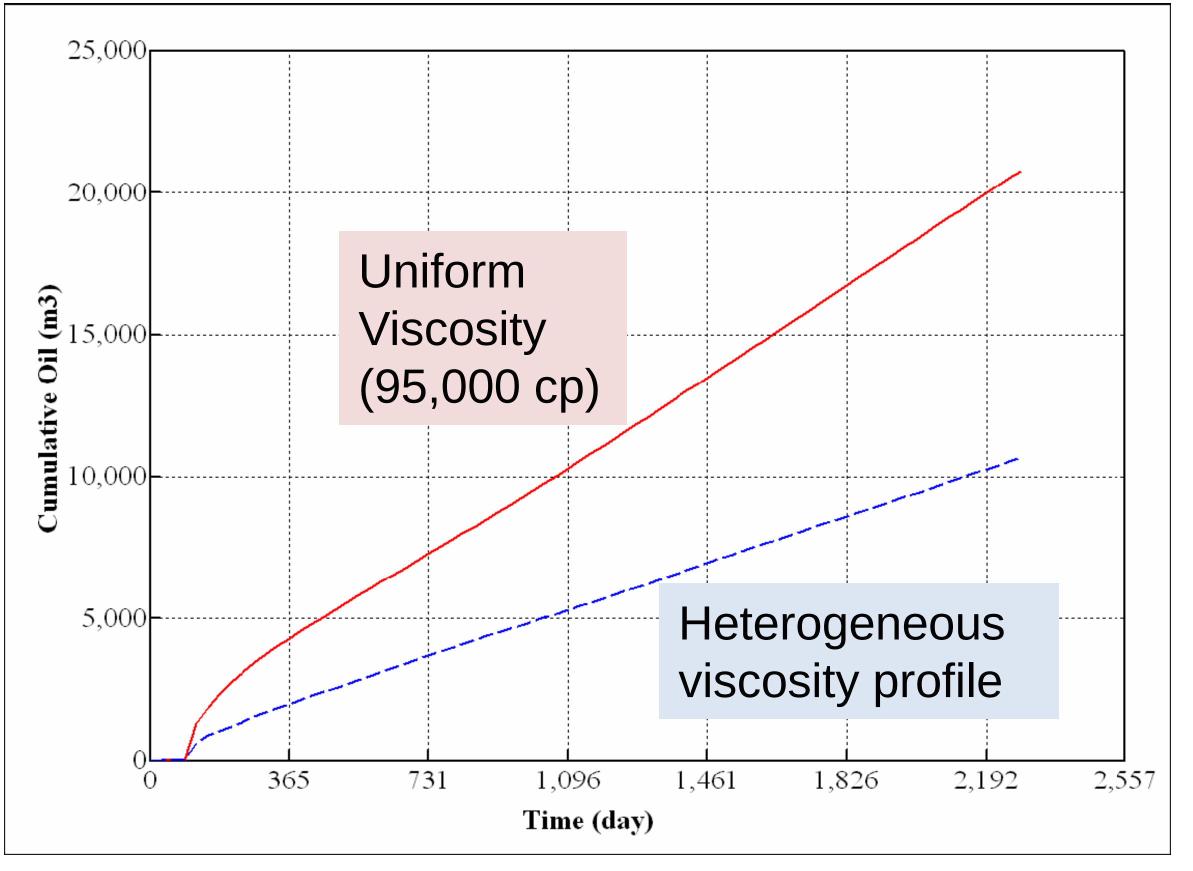


(Modified from www.art-eng.com
Courtesy of Applied Reservoir Technology Inc.,)

Engineering Importance:

➢ **Uniform vs. Heterogeneous Viscosity Profiles in SAGD Operations**





(Figures Modified from Larter et al., 2006)

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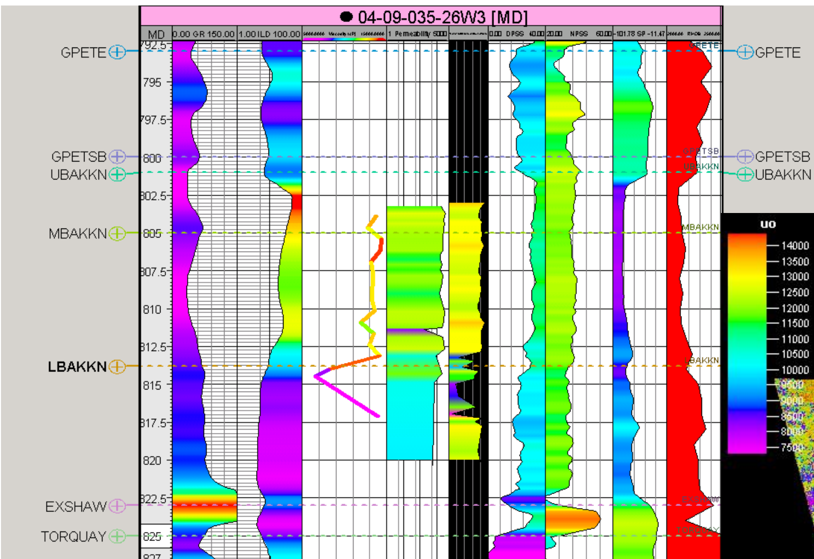
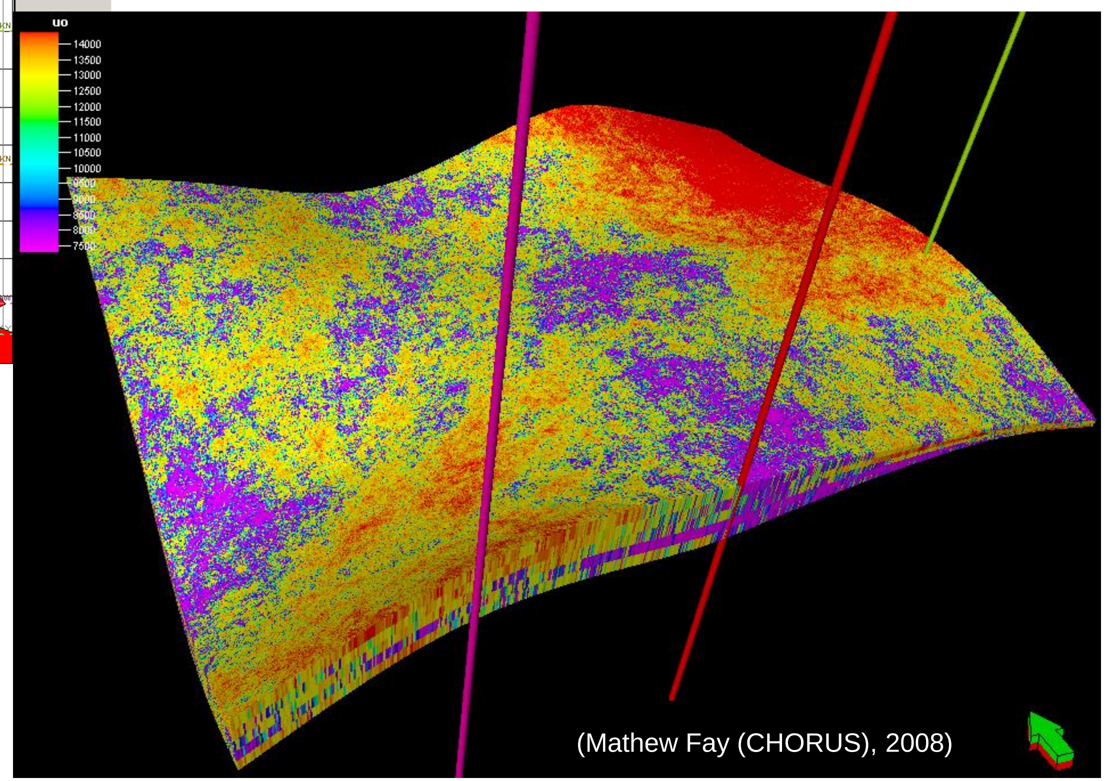
Engineering Importance:

- **Scale Problem → Statistical Methods**



(Mathew Fay (CHORUS), 2008)



(Mathew Fay (CHORUS), 2008)

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Big Questions …

1- Forward …

Can we detect changes in viscosity on seismic maps?

2- Inverse …

Can we estimate viscosity from seismic results?

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**

Viscoelasticity:

- **Quality factor (Q):**

- Q is defined as

  "Energy over loss of Energy in a single cycle"

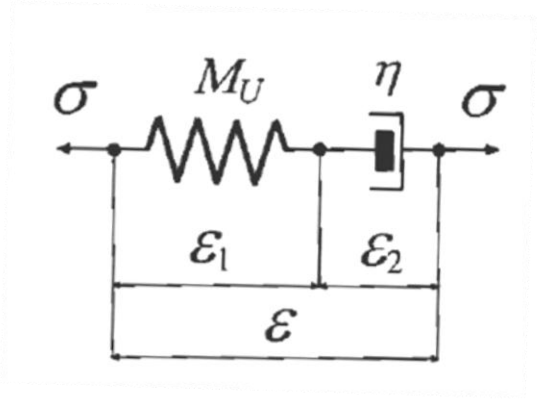
$$Q = \frac{2\pi E}{\Delta E}$$

- Higher Q → Lower ΔE → Lower Attenuation

Viscoelasticity:

➢ Maxwell Model

- A spring and a dashpot in series
- The stress on each component is the same
- The total strain is sum of deformations of spring and dashpot



(from Carcione, 2007).

$$\frac{\partial_t \sigma}{M_u} + \frac{\sigma}{\eta} = \partial_t \epsilon$$

$$Q = \frac{\omega\eta}{M_u}$$

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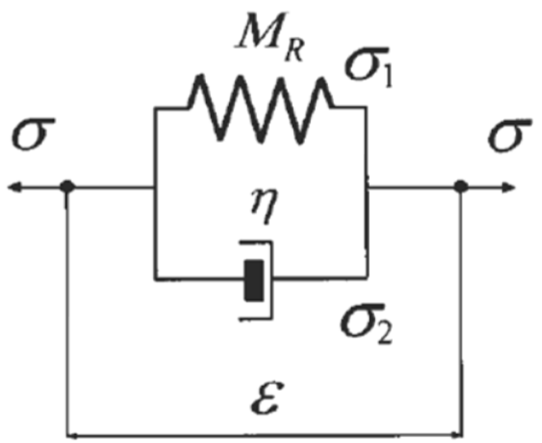
Viscoelasticity:

➢ **Kelvin-Voigt Model**

- A spring and a dashpot in parallel
- The deformations (strain) of components are the same
- The total stress is sum of stresses on spring and dashpot



(from Carcione, 2007).

$$\sigma = M_r \epsilon + \eta \partial_t \epsilon$$

$$Q = (\omega\tau)^{-1}$$

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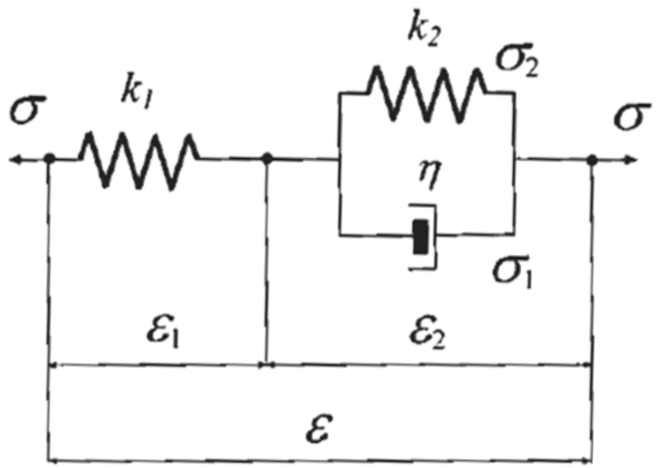
Viscoelasticity:

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



(from Carcione, 2007).

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

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

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

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

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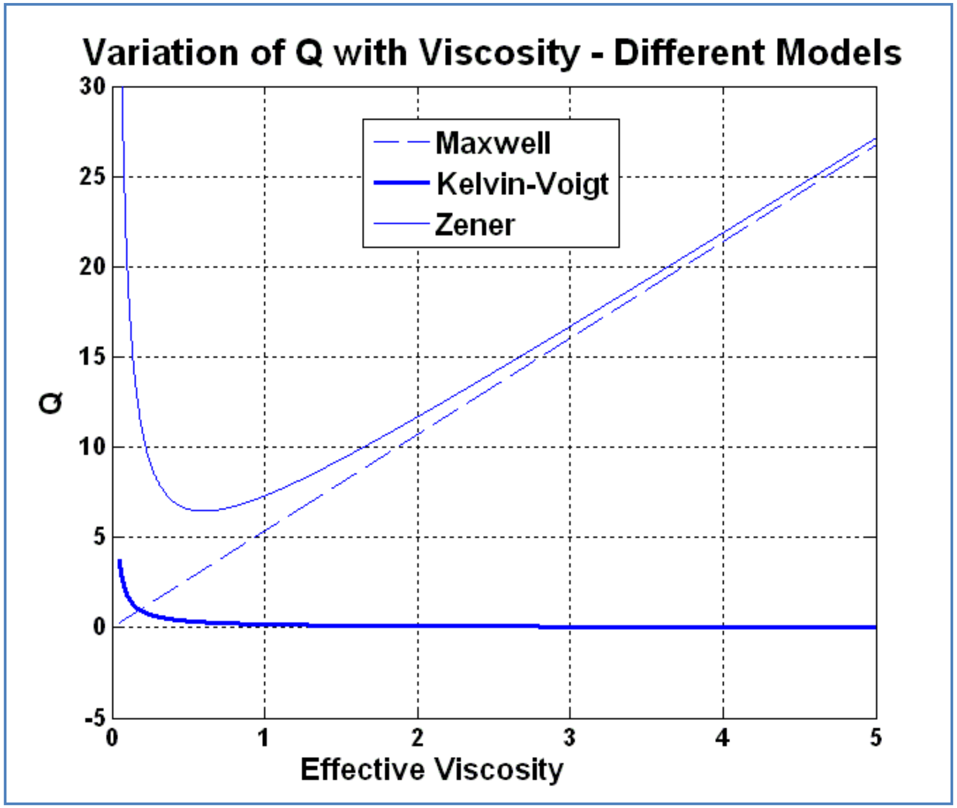
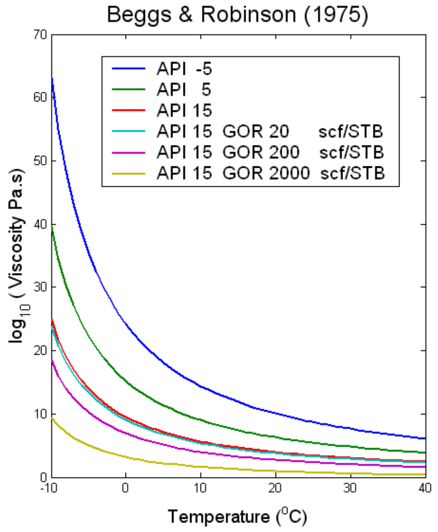
Viscoelasticity:

➢ **Q vs. Viscosity**

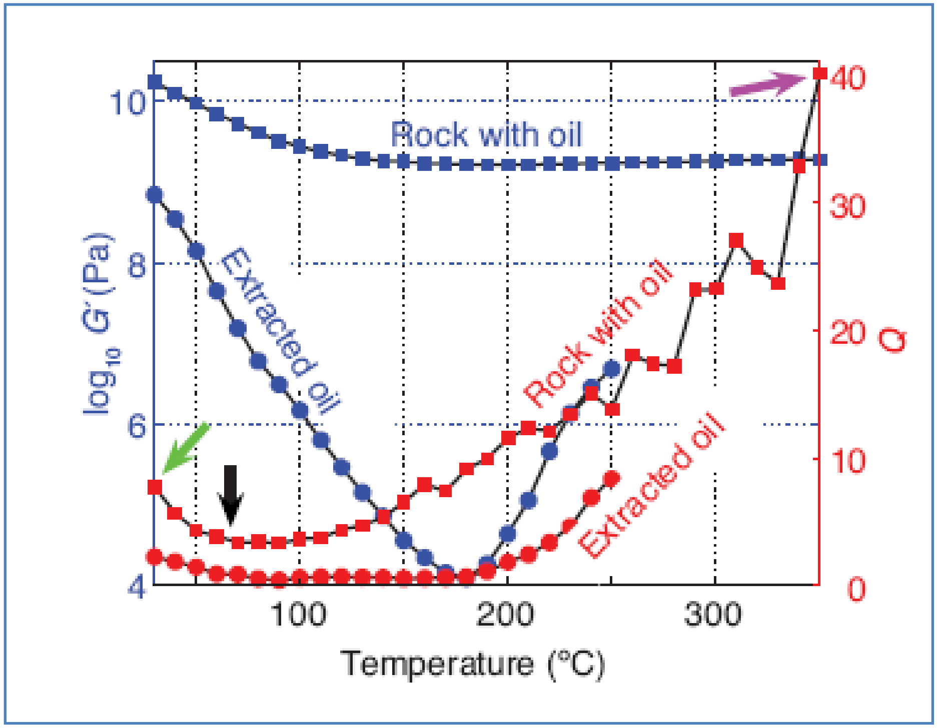




- Frequency of signal: 25 Hz.

Viscoelasticity:

➢ **Q vs. Temperature**

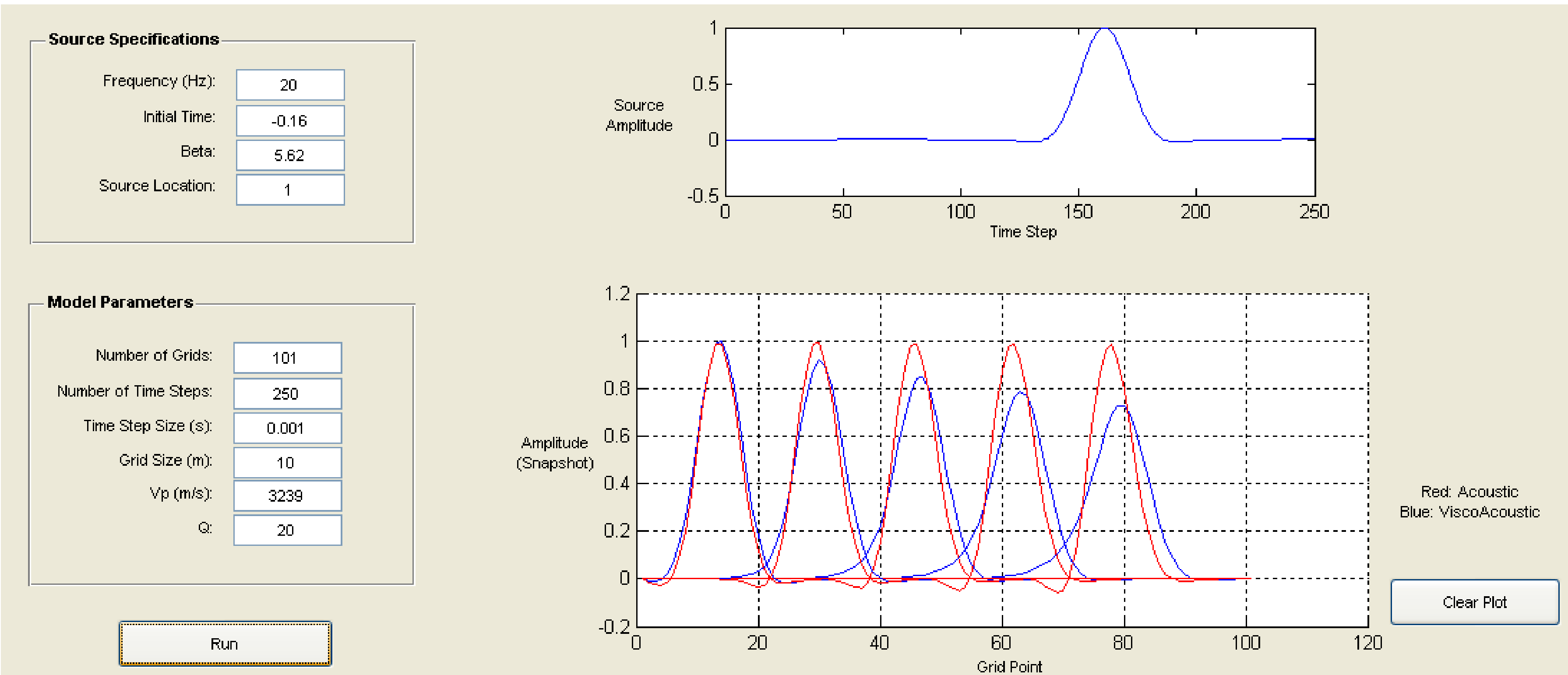


(from Behura et al., 2007).

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

Forward Problem (Simulator to Seismic):

- **One Dimensional Modeling**



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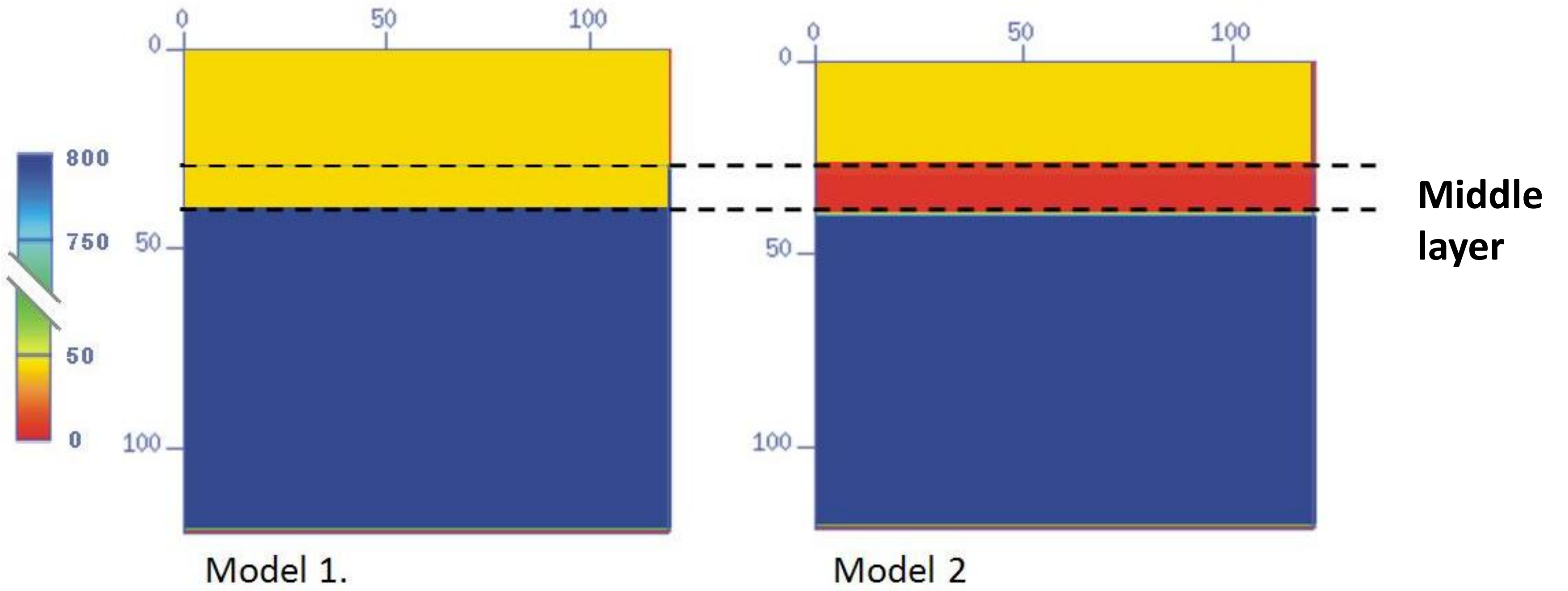
Forward Problem (Simulator to Seismic):

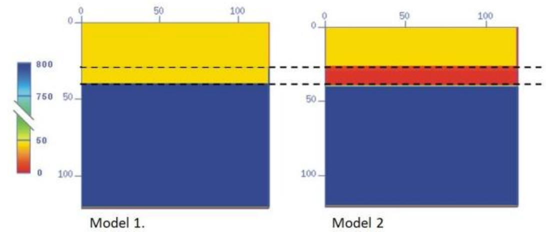
- **Surface Seismic:**

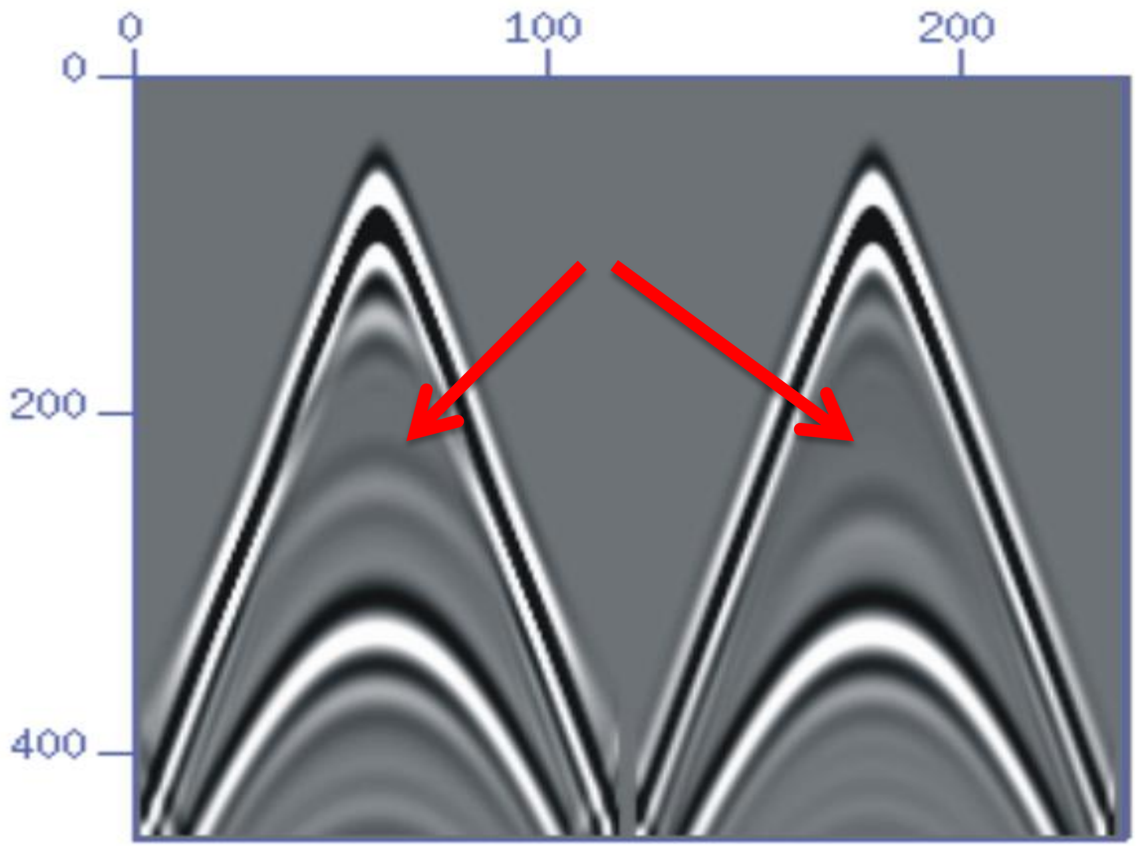
Layer	Cells	Q	
		Model 1	Model 2
1	1-30	40	40
2	31-40	40	3
3	41-100	800	800



Forward Problem (Simulator to Seismic):

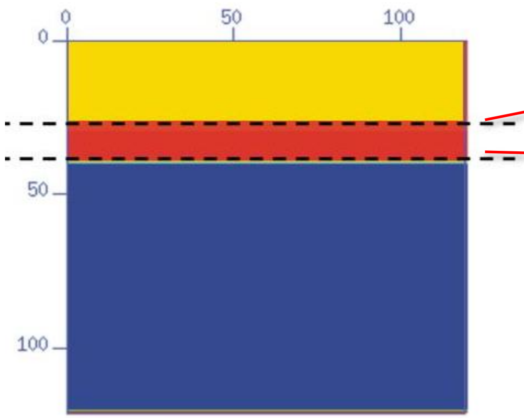
- **Surface Seismic:**



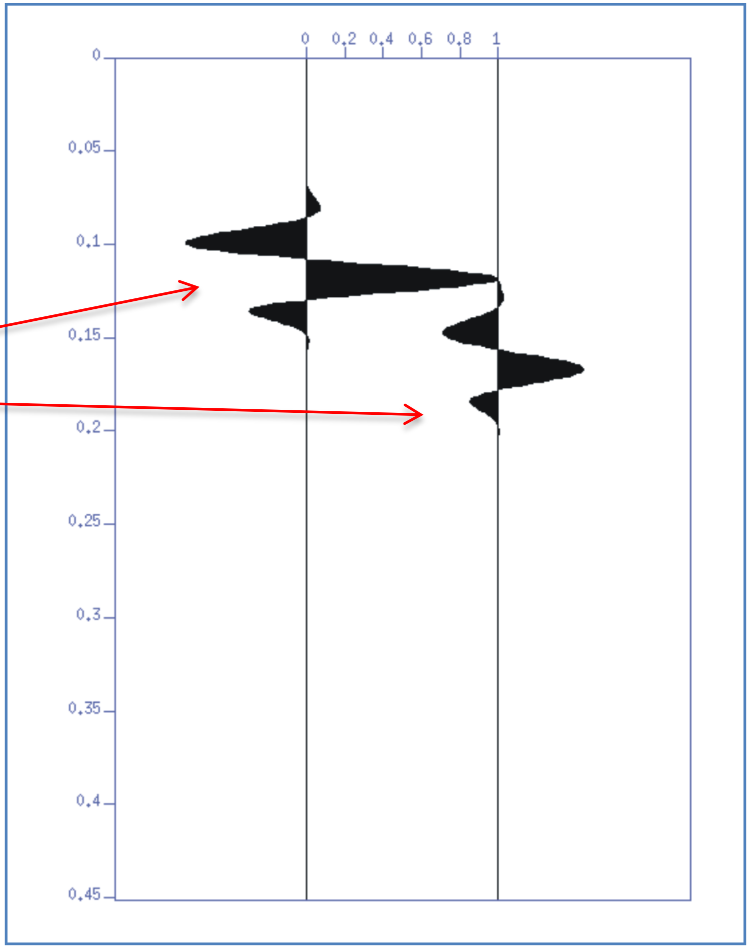


Forward Problem (Simulator to Seismic):

- **VSP:**



Model 2



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Inverse Problem (Seismic to Simulator):

- **Estimation of Q: Spectral Ratio**

• The most reliable method of estimating Q is generally given by using the log spectral ratios from VSP data (Spencer et al., 1982; Hardage, 1983).

$$ln\left[\frac{A(f,Z_2)}{A(f,Z_1)}\right] = \frac{-\pi}{Q\lambda}(Z_2 - Z_1)$$

• A is the amplitude spectral of VSP arrivals at different depths.

Inverse Problem (Seismic to Simulator):

➢ 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 the Q:

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

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

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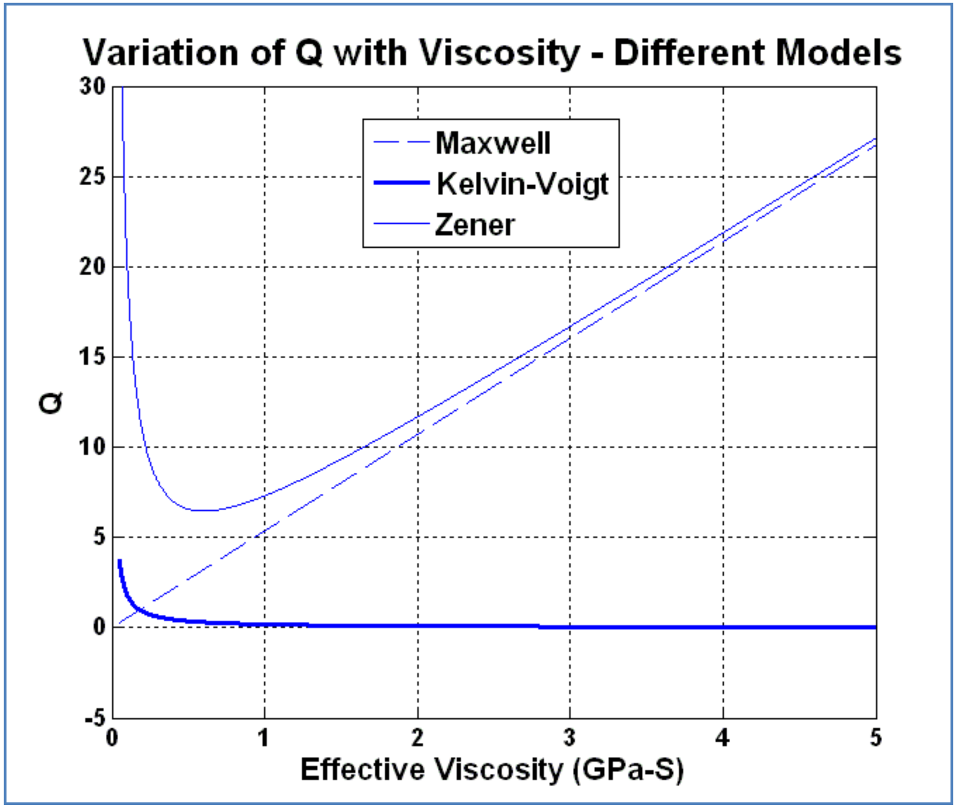
Inverse Problem (Seismic to Simulator):

- **Estimation of Viscosity from Q:**



Conclusions:

- Viscoelastic models consist of spring (elastic) and dashpot (Viscous) Components. Since they incorporate viscosity, such models are more useful for heavy oil reservoir characterization.
- Zener's model best represents the true earth material. This is shown by the consistency between measured and calculated Q variations with viscosity.
- From our model tests, Q centroid estimates for VSP transmitted arrivals can be accurate to within 10%.
- For reflected arrivals, these estimates are highly window dependent and estimates can be in error by more than a factor of 2.
- The applications of the centroid method to VSP direct arrivals are reliable and could be used for viscosity estimation.

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Acknowledgements

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