Q and Viscosity

Fereidoon Vasheghani
Larry Lines
Outline:

• Engineering Importance
• Big Questions ...
• Viscoelasticity
• Forward Problem (Simulator to Seismic)
• Inverse Problem (Seismic to Simulator)
• Conclusions
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)
Engineering Importance:

- Scale Problem → Statistical Methods
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 noninstantaneous 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

\[
\frac{\partial_t \sigma}{M_u} + \frac{\sigma}{\eta} = \partial_t \varepsilon
\]

\[
Q = \frac{\omega \eta}{M_u}
\]

(from Carcione, 2007).
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

\[
\sigma = M_r \varepsilon + \eta \partial_t \varepsilon
\]

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

(from Carcione, 2007).
Viscoelasticity:

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

\[
\sigma + \tau_\sigma \partial_t \sigma = M_r (\varepsilon + \tau_\varepsilon \partial_t \varepsilon)
\]

\[
Q(\omega) = \frac{1 + \omega^2 \tau_\varepsilon \tau_\sigma}{\omega (\tau_\varepsilon - \tau_\sigma)}
\]

\[
M_r = \frac{k_1 k_2}{k_1 + k_2}
\]

\[
\tau_\sigma = \frac{\eta}{k_1 + k_2} \quad \tau_\varepsilon = \frac{\eta}{k_2} \geq \tau_\sigma
\]

(from Carcione, 2007).
Viscoelasticity:

- **Q vs. Viscosity**

  ![Variation of Q with Viscosity](image)

  - Frequency of signal: 25 Hz.
Viscoelasticity:

- **Q vs. Temperature**

![Graph showing Q vs. Temperature](image)

- 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.

(from Behura et al., 2007).
Forward Problem (Simulator to Seismic):

- One Dimensional Modeling

**Source Specifications**
- Frequency (Hz): 20
- Initial Time: -0.16
- Beta: 5.62
- Source Location: 1

**Model Parameters**
- Number of Grids: 101
- Number of Time Steps: 250
- Time Step Size (s): 0.001
- Grid Size (m): 10
- Vp (m/s): 3239
- Q: 20

![Graphs showing source amplitude and model parameters.](image-url)
Forward Problem (Simulator to Seismic):

- **Surface Seismic:**

  - **Model 1:**
    - Layer 1: Cells 1-30, \( Q = 40 \) for Model 1 and 40 for Model 2
    - Layer 2: Cells 31-40, \( Q = 40 \) for Model 1 and 3 for Model 2
    - Layer 3: Cells 41-100, \( Q = 800 \) for both Models

  - **Model 2:**
    - Layer 1: Cells 1-30, \( Q = 40 \) for Model 1 and 40 for Model 2
    - Layer 2: Cells 31-40, \( Q = 40 \) for Model 1 and 3 for Model 2
    - Layer 3: Cells 41-100, \( Q = 800 \) for both Models
Forward Problem (Simulator to Seismic):

- Surface Seismic:
Forward Problem (Simulator to Seismic):

- **VSP:**
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):
    \[ f_c = \frac{\int_0^\infty fA(f)df}{\int_0^\infty A(f)df} \]

  - Quan and Harris (1997) estimated the Q:
    \[ Q = \frac{\pi \sigma^2 \Delta Z}{\Delta f V} \]
    \[ \Delta Z = Z_2 - Z_1 \quad \Delta f = f_{c2} - f_{c1} \quad \sigma^2 = \frac{\int_0^\infty (f-f_{c1})^2 A(f)df}{\int_0^\infty A(f)df} \]
Inverse Problem (Seismic to Simulator):

- Estimation of Viscosity from Q:

![Graph showing variation of Q with viscosity for different models: Maxwell, Kelvin-Voigt, and Zener.](image)
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.
References:

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