Seismic geomechanics

Elastic properties of the earth
What is Seismic?

Seismic = “Of or relating to earthquakes or other vibrations of the earth and its crust” (Oxford Dictionary)

Seismology = The study of the vibration of the earth

Most of your “geophysicists” are actually “seismologists” because they primarily use seismic data, which is a measurement of the vibration of the earth.
What is geomechanics?

Geo = Earth

Mechanics = “Mechanics is the study of the motion of material objects.” (Cliffs Notes)

GeoMechanics = The study of the motions of the earth

Seismologist studies the vibration (motion) of the earth

∴ Seismologists should “get” geomechanics
Elastic Rock Properties

- **Compressibility** \((C)\)
  
  Compliance to change in volume  
  (stress is perpendicular)
  
  \[ C = \left(\frac{\Delta v}{v}\right) / S \]
  
  Bulk Modulus (Incompressibility)
  
  \[ \kappa = 1/C \]
  
  Resistance to change in volume

- **Shear Modulus** \((\mu)\)
  
  Resistance to change in shape  
  (stress is parallel)
  
  \[ \mu = \frac{\text{shear stress}}{\text{shear strain}} \]
Elastic Rock Properties: Bulk Modulus (κ)

Material’s response to uniform pressure

High Compressibility = Low Bulk Modulus

Bulk Modulus is also known as incompressibility, which is the inverse of compressibility, $\kappa = 1/C$.

Examples:
- Shale: 15 GPa
- Quartz SS: 23 GPa
- Limestone: 40 GPa

Low Compressibility = High Bulk Modulus
Elastic Rock Properties: Shear Modulus (\( \mu \))

Material’s response to shearing strains

Rigidity is the resistance to forces that cause a change in shape but not volume

Examples:
- Shale: 6 Gpa
- Quartz SS: 13 GPa
- Limestone: 21 GPa

High Rigidity – High Shear Modulus

Low Rigidity – Low Shear Modulus
Young’s Modulus

The ratio of longitudinal stress ($S$) to longitudinal strain ($\Delta L/L$)

$$E = \frac{9\kappa\mu}{3\kappa + \mu}$$
Poisson’s Ratio (ν)

- Poisson’s Ratio
  
  Can be expressed in bulk and shear moduli and hence in P and S wave velocities.
  
  Poisson’s Ratio across a boundary can have large control on the rate of change of amplitude with offset.

\[ ν = -\frac{\text{transverse strain}}{\text{longitudinal strain}} \]

- Stress Ratio uses Poisson’s ratio to relate horizontal to vertical stress:

\[ σ_h = \frac{ν}{1−ν} σ_z \]

- Seismic AVO has estimated Poisson’s ratio for 30 years.

- Stress gradient:

\[ \frac{∂σ_h}{∂z} = \frac{ν}{1−ν} \frac{∂σ_z}{∂z} = \frac{ν}{1−ν} gρ \]
We have many traces with T and X

Acquisition:

Offset (x): Processed Gather:

Measure slope of amplitudes:

ρ₁, V₁₁, V₁₂, V₁₃

ρ₂, V₂₁, V₂₂, V₂₃

Surface

Reflector

Poisson’s Ratio (ν):

Two Way Traveltime (t)

Zero Offset
100m Offset
200m Offset
300m Offset

Apply hyperbolic “move-out”

Measure “AVO” Amplitude vs. Offset

ν increase
Seismic Poisson’s Ratio

http://www.aapg.org/publications/news/explorer/column/articleid/2283/time-to-pick-no-need-to-fear-%e2%80%98seismophobia%e2%80%99
Poisson’s Ratio (ν)

Poisson’s ratio estimated from seismic
Poisson’s Ratio and Horizontal Stress
Poisson’s Ratio and Horizontal Stress
Stress magnitude and direction from seismic

Perspective plate-based view of $\sigma_{H\text{max}} - \sigma_{h\text{min}}$ stress differences with direction of $\sigma_{H\text{max}}$. The plate lengths (also shown as colour background) are proportional to the difference and the plates are oriented according to the $\sigma_{H\text{max}}$ orientation.

After Kendall and Wikel, 2012

Seismic geomechanics gives uncalibrated $Sh$

Calibration usually done by adding tectonic stress (or strain)

Tectonic stress/strain from comparison of well log stress estimates to static stress estimates

We use the same calibration as the petrophysicists / geomechanicists

Calibration allows $SH > Sh > Sz$

After calibration, the stress state of all the areas covered by seismic can be assessed:
Stress States with Depth (after Zoback)

<table>
<thead>
<tr>
<th>Direction of Movement</th>
<th>Thrust</th>
<th>Shear</th>
<th>Normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal to Fractures</td>
<td>$S_H &gt; S_h &gt; S_z$</td>
<td>$S_H &gt; S_z &gt; S_h$</td>
<td>$S_z &gt; S_H &gt; S_h$</td>
</tr>
<tr>
<td></td>
<td>Thrust = Horizontal fractures that move horizontally w/o much overburden weight allowing them to go up</td>
<td>Shear = Vertical fractures that move horizontally</td>
<td>Normal = vertical fractures that move vertically</td>
</tr>
</tbody>
</table>

Images after http://homepage.usask.ca/~mjr347/prog/geoe118/geoe118.051.html
Fracture Breakdown Pressure (P_{FB}) is the fracture breakdown pressure. In the absence of boreholes, fracture breakdown pressure can be estimated from modern seismic because it can be used to estimate \( \sigma_{h_{\text{min}}} \) and \( \sigma_{h_{\text{max}}} \). (PWF = Potential Wellbore Failure)
Reservoir Properties from Seismic
Shear leads to reservoir properties

A reservoir has properties:

**Reservoir Properties**
- Lithology
- Porosity
- Pore Fluid

- Brine?
- Gas?
- Oil?

**Elastic Properties**
- Density
- Bulk modulus
- Shear modulus

These reservoir properties affect seismic velocities:

- **P-wave Velocity**
- **S-wave Velocity**

Seismic can reveal information about reservoir properties

Seismic can reveal information about reservoir properties.
Reservoir Properties from Bulk Modulus ($K$) and compressibility

Material’s response to uniform pressure
- Gas – compresses
- Water – incompressible
- Oil – between – depends on GOR

High Compressibility = Low Bulk Modulus

Gas – High Compressibility = Low Bulk Modulus

Fluid - Low Compressibility = High Bulk Modulus

Pressure on fluid in small cylinder, usually supplied by an air compressor.

http://misclab.umeoce.maine.edu/boss/classes/SMS_491_2003/Week_2.htm
Rock Properties from Shear Modulus ($\mu$)

- Material’s response to shearing strains
- Very different responses to different rocks – Why?
  - Shale – 6 GPa – plates slide across each other
  - Source rock - < 6GPa? – lubricated plates slide across each other?
  - Sandstone – 13 GPa – grains abut and resist shear
  - Limestone – 21 GPa – grains cemented together
Rock properties from elastic properties

Undeformed schematic rock volume of liquid-filled porous sandstone

**Shear**
- Fluid moves but does not change volume - invisible to shear.

**Compression**
- Fluid changes volume - exerting resistance to pressure.
1. Point bars
2. Counter point bars
3. Abandoned, mud-filled channels

Low (colorful) density tends to correlate with low Vsh and high (grey-black) density with high Vsh.
Back to the Geology

High water saturation from compressibility and shear differences.

Shale and steam from 4D.

Geobodies from “Opacity”
Bringing out the colour

Colour = Reservoir properties

1. Geomechanical properties
   - Poisson’s ratio, Stress ratio, Young’s Modulus, Compressibility
     - Caprock, Drilling Progs, Fracturing Progs, Geomechanical Modeling, Enhanced Permeability

2. Reservoir Properties
   - Shear $\Rightarrow$ Lithology
   - Compressibility $\Rightarrow$ Fluids and lithology

3. More detailed geological models
Why are reservoir properties important?
Pay Maps

The same well information is in both maps.
You can see where the wells are by the bulls eyes on well-based map (left).
You can get a better idea of the geology on MAA-based map (right).

- Test areas identified as being significantly different.
Confirmation

An example of a well drilled in the 2013 corehole season with the predicted depths of formations & internal markers and the actual drilled depths. Predictions were within a few meters of actuals.

- Type1 top (-2m)
- Type1 base (+1m)
- Pay base (+0.6m)
Modern Seismic Interpretation

- Reflectivity
- Density
- SW
- Ants

Seismic Pay, Vsh, Top Water/Gas, WTAR
HPVH Contours and Colours

HPVH contours
HPVH colours
MAA finds

Opportunities

Risks

Geology

With limited well control

Basic MAA can be done within weeks on any 2D or 3D seismic stack with limited well control (one well in good, fair and poor).
Contours from wells don’t show the same detail

HPVH contours
HPVH colours
DeMystifying Geophysics

Conclusions
What have we learned?

1. Geophysical uncertainty is less in the early stages of projects
2. Start designing and permitting 3-4 years before drilling, i.e. now
3. Seismic is (infra)sound and echos
4. Seismic is used to suggest and confirm geology
5. Seismic is converted to depth using velocity and that process is not perfect
6. Seismic is a geomechanical measurement
7. Reservoir properties can be inferred from seismic using an understanding of seismic waves and what they do to reservoir rock and fluids
8. Combining information from all disciplines helps us to develop the reservoir more effectively and efficiently
9. MAA identifies opportunities, risks, and geology, sooner with fewer coreholes
Demystifying Geophysics
By David Gray
(A Geophysicist?)

This document is copyright 2016 Nexen Energy ULC, and no part may be reproduced except with permission of the author. I am not sure of the sources of all the images in the presentation. If you are aware of a copyright infringement, please let me know and I will update the presentation.

david.gray@nexencnooocltd.com
Use of petroleum engineering concepts for estimation of pore stimulated reservoir volume (pore SRV) and prediction of well performance

Roberto Aquilera, Ph.D., P.Eng.
University of Calgary

May 5, 2016 – Telus Convention Centre

An easy to use 3D equation is presented for estimating anisotropic permeability in three directions, for calculating pore stimulated reservoir volume (pore SRV) and for visualizing the growth of SRV with time using petroleum engineering concepts. Use of the method is dependent on availability of initial reservoir pressure, injection pressure during hydraulic fracturing and microseismic data. The method is explained with the use of data collected in shales in the United States and Canada.

http://cseg.ca/symposium/