SPE DISTINGUISHED LECTURER SERIES

is funded principally
through a grant of the

SPE FOUNDATION

The Society gratefully acknowledges
those companies that support the program
by allowing their professionals
to participate as Lecturers.

And special thanks to The American Institute of Mining, Metallurgical,
and Petroleum Engineers (AIME) for their contribution to the program.
Optimizing Asset Design - Cradle to Grave

“Bridging the Gap between the Earth Science & Engineering Disciplines using Mechanical Earth Modeling Technology”

Harvey E. Goodman
Chevron Fellow
Rock Mechanics & Mechanical Earth Modeling
Business Driver and Technical Focus Area Selection

Business driver:

Optimize well Design - Reliability and Placement through the life of the gas/oil field asset.

Technical focus:

Link the engineering disciplines necessary to build safe, reliable well systems with the geological and geophysical sciences involved in asset discovery.
Discussion Topics

1. The Mechanical Earth Model (MEM) approach to well systems design
   • What is it?
   • How can a MEM add value?

2. Building the MEM from Acoustics Data
   • Rock properties and acoustics predictions
   • Seismic techniques
   • Examples

3. Using the MEM to conceptualize development risks
   • Hole stability

4. Future Trends and Challenges
The MEM is calibrated to its multiple applications – A key strength of this holistic approach to well systems design using rock mechanical properties.

Key components: Stress and Strength.
How we use acoustics to define the MEM.
But first, some background:
The P Wave

Particle motion parallel to wave propagation.

Figure 3
Longitudinal (Compressional or Pressure or P) Wave
(Krautkramer and Krautkramer, 1961)

\[ v_L = \sqrt{\frac{E}{\rho}} \sqrt{\frac{1 - \sigma}{(1 + \sigma)(1 - 2\sigma)}} \]
The S Wave

Particle motion perpendicular to wave propagation.

\[ v_s = \frac{\lambda}{\rho} \]

Figure 4
Shear (Transverse or S) Wave
(Kraus and Kraus, 1961)
Depend on the elastic properties of the travel medium
- Hard rock has fast P & S velocities.
- Soft rock has slow P & S velocities.

\[ V_p = \sqrt{\frac{4}{3} \frac{G + K_b}{\rho_b}} \]
\[ V_s = \frac{G}{\rho_b} \]

Shear (G) and bulk (K_b) moduli are rock stiffness terms; both inversely proportional to bulk density (\( \rho_b \)).
Frame properties are used to estimate rock strength and stress magnitude. As porosity decreases, rock stiffness increases, affecting strength and stress propagation tendencies.
Young’s modulus volume compared to well control. Rock properties taken from 3D seismic volume with over 600,000 pseudo well locations.
How well can we predict Shear wave velocity? What do we need to know first?
Angola Offshore
Complex Lithology, West Africa

Mixture of sandstone, dolostone, limestone, and minor shale.

Production from friable sandstone intervals bounded by hard stiff carbonates.
Complex Pinda Fm S-Wave Modeling

Very good agreement between predicted (red) & measured (yellow) shear wave travel time.

<table>
<thead>
<tr>
<th>MD (feet)</th>
<th>Completion Intervals</th>
<th>Lithology</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>10900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10950</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11050</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11100</td>
<td>Completion Interval</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

11100 - 11150
A brief look at how we manage to characterize P-wave velocity and lithology from seismic data sets.
ITT (interval travel time or pseudo-sonic log) as Sum of Seismic Velocities

\[ \text{ITT Log} = \text{0-8 Hz} + \text{8-50 Hz} + \text{> 50 Hz} \]

Cannot Get From Seismic Inversion

Very Much Like The Sonic Log!

From Velocity Analysis

From Seismic Inversion

SPE Distinguished Lecturer Series 2008-09
Not Perfect But Pretty Good!

Sonic Log

ITT Log

0-50 Hz
Seismic and Well Log Derived Shear Wave Velocity with Respect to Lithology

- Vertical axis is the shear slowness coming from sonic log and log based lithologies.
- Horizontal axis is the shear slowness from the seismic inversion.
We Can Predict Rock Strength and Static Young’s Modulus From Acoustics.
Formation Strength and Static Young’s Modulus from Logs.

Perf tunnel stability (black and orange dotted) showing lower safe drawdowns in weak high porosity sand intervals (even though horizontal stress magnitude is less).

SH (red) & Sh (blue) and horizontal stress ratio black dotted.

DTS logs (red) versus DTS RMA estimate (black)
High porosity (blue) less stiff.

E static core calibrated (red) versus E static RMA estimate (black)

Modified after Rahim, Goodman et. al SPE 84258
Layer Dependent BO

Stress complexities were defined from Young’s modulus. Useful to account for 1D stress anisotropy. But there can be azimuthal stress anisotropy too.
We believe the stiffer formation layer intervals are more highly stressed; essentially the load bearing members of the geologic section.

We now use this concept to predict stress character across the geologic structure using MEM properties & numerical modeling.
5. Annotate the following images with minimum and maximum principal stress vectors. (P. Connolly – 2008)
5. Answer to Max principle stress orientation question.
Stresses in the 3D Volume

Modified after P. Connolly
Geophysics Institute, University of Karlsruhe
Rock Mechanics Of Hole Failure

Symptoms:

- Large size and volume of cavings/cuttings
- Oversize hole
- Stuck pipe by packing off
- Hole fill after tripping
- Restricted circulation/increase in pump pressure

Be careful, hole instability also depends on drilling practices!

Common practice estimates stress and rock strength that caused hole failure.

SPE Distinguished Lecturer Series 2008-09
Hole stability forecast for deepwater subsalt play

- Ocean bottom bathymetry overlying the massive salt sheet GOM
- Oil reservoirs have been in water depths greater than 6,000’, overlain by greater than 10,000’ of salt
Deepwater subsalt MEM

- Build earth model geometry that utilizes mapped salt and geological formation bed boundaries across the structure.
- Create FEA (finite element analysis) mesh that corresponds to geological model geometry.
- Build material model based on acoustics dominated data set that contains salt and non-salt elastic moduli (layer rheology).
- Apply far field loads constrained by the geological and structural model to produce in-situ stress field.

SPE Distinguished Lecturer Series 2008-09
Stresses at Salt/Clastic boundaries

Hole instability risk assessment from stress field perturbation mapping. Hi-risk areas updip near the Salt Wall depicted by hot colors.
S_3 (minimum principle stress) along Base of Salt surface.

Cool colors show low S_3 below subsalt canopy.
In-situ stress complexity associated with the salt/clastic boundaries

- Colors indicate difference in maximum horizontal stress $\sigma_H$ and minimum horizontal stress $\sigma_h$
- Red lines show maximum principal stress $S_1$ rotation at subsalt boundary
- Can profoundly impact risk of drilling through this part of the subsalt structure.
Wellbore stability forecast profile
Principle Stress rotation effect

- Two principal stress regimes - $S_1 = \sigma_v$, $S_2 = \sigma_H$
  and $S_3 = \sigma_h$ and $S_1 > \sigma_v$, $S_2 > \sigma_H$ and $S_3 < \sigma_h$.

- Safe drilling mud weight window decreased for rotated Principle Stress regime significantly:
  from 2.6 ppg (15.1 – 12.5 ppg) to only 0.7 ppg (14.8 – 14.1 ppg)
Future Trends & Challenges

- Applying this approach adds the most value when implemented early in project development.
- Delivery of this technology requires multidisciplined technical skill sets.
- Major challenge is MEM requires extensive work in the overburden.