Week 1 – Lecture 1
Course Overview
Drilling and Reservoir Engineering

- Compaction, Compaction Drive, Subsidence, Production-Induced Faulting Prediction
- Optimizing Drainage of Fractured Reservoirs
- Hydraulic Propagation in Vertical & Deviated Wells
- Wellbore Stability During Drilling (mud weights, drilling directions)
- Completion Engineering (long-term wellbore stability, sand production prediction)
- Well Placement (Azimuth and Deviation, Sidetracks)
- Underbalanced Drilling to Formation Damage
Why is Geomechanics Important?

Reservoir Geology and Geophysics

- Optimizing Drainage of Fractured Reservoirs
- Pore Pressure Prediction
- Understanding Shear Velocity Anisotropy
- Fault Seal Integrity
- Hydrocarbon Migration
- Reservoir Compartmentalization
Exploitation of Shale Gas/Tight Gas/Tight Oil

• Properties of Ultra-Low Permeability Formations
• How Formation Properties Affect Production
• Optimizing Well Placement
• Multi-Stage Hydraulic Fracturing
• Importance of Fractures and Faults on Well Productivity
• Interpretation of Microseismic Data
• Simulating Production from Ultra-Low Permeability Formations
Part I – Basic Principles
Chapters 1-5

Part II – Measuring Stress
Orientation and Magnitude
Chapters 6-9

Part III – Applications
Chapters 10-12
Week 1
Lecture 1 – Introduction and Course Overview
Lecture 2 – Ch. 1 - The Tectonic Stress Field
   HW-1 Calculating $S_V$ from density logs

Week 2
Lecture 3 - Ch. 2 - Pore Pressure at Depth
   HW-2 Estimating pore pressure from porosity logs
Lecture 4 - Ch. 3 - Basic Constitutive Laws

Week 3
Lecture 5 - Ch. 4 - Rock Strength
   HW-3 Estimating rock strength from geophysical logs
Lecture 6 - Ch. 4 - Fault Friction and Crustal Strength
   HW 4 Calculating limits on crustal stress

Week 4
Lecture 7 - Ch. 5 - Faults and Fractures
   HW 5 Analysis of fractures in image logs
Week 4
Lecture 8 - Ch. 6 - Stress Concentrations Around Vertical Wells

Week 5
Lecture 9 - Ch. 7 - Hydraulic Fracturing, Measuring $S_{\text{hmin}}$, Limiting Frac Height and Constraining $S_{\text{hmax}}$
HW 6 Analysis of stress induced wellbore failures
Lecture 10 - Ch. 8 - Failure of Deviated Wells

Week 6
Lecture 11 - Ch. 9 - State of Stress in Sedimentary Basins
HW 7 Identification of critically-stressed faults
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Week 7
Lecture 13 - Ch. 10 - Wellbore Stability – 2
Lecture 14 - Ch. 11 - Critically-Stressed Faults and Flow
   HW 8 Development of a geomechanical model

Week 8
Lecture 15 - Ch. 11 - Fault Seal and Dynamic Hydrocarbon Migration
Lecture 16 - Ch. 12 - Effects of Depletion, Reservoir Stress Paths

Week 9
Lecture 17 - Ch. 12 - Compaction of Weak Sands and Shales and Subsidence
Week 9
Lecture 18 – Geomechanics and Shale Gas/Tight Oil Production - 1

Week 10
Lecture 19 – Geomechanics and Shale Gas/Tight Oil Production - 2
Lecture 20 - Geomechanics and Triggered Seismicity
Geomechanics Through the Life of a Field

Exploration  Appraisal  Development  Harvest  Abandonment

Geomechanical Model

Time

Pore Pressure Prediction
Wellbore Stability
Fault Seal/Fracture Permeability
Sand Production Prediction
Compaction
Casing Shear
Subsidence
Coupled Reservoir Simulation
Fracture Stimulation/ Refrac
Depletion

Geomechanical Model

Time
Components of a Geomechanical Model

Principal Stresses at Depth

\( S_v \) - Overburden
\( S_{H\text{max}} \) - Maximum horizontal principal stress
\( S_{h\text{min}} \) - Minimum horizontal principal stress

Additional Components of a Geomechanical Model

\( P_p \) - Pore Pressure
UCS - Rock Strength (from logs)
Fractures and Faults (from Image Logs, Seismic, etc.)
Course Syllabus – Part I - Basic Principles

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  HW 4 Calculating limits on crustal stress

Week 4
Lecture 7 - Ch. 5 - Faults and Fractures
  HW 5 Analysis of fractures in image logs
Anderson Classification of Relative Stress Magnitudes

Tectonic regimes are defined in terms of the relationship between the vertical stress ($S_v$) and two mutually perpendicular horizontal stresses ($S_{Hmax}$ and $S_{hmin}$):

- **Normal**
  - $S_{Hmax} > S_v > S_{hmin}$

- **Strike-Slip**
  - $S_{Hmax} > S_v > S_{hmin}$

- **Reverse**
  - $S_{Hmax} > S_{hmin} > S_v$
Range of Stress Magnitudes at Depth

Hydrostatic $P_p$

Figure 1.4 a,b,c – pg.13
Week 1
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   HW 4 Calculating limits on crustal stress

Week 4
Lecture 7 - Ch. 5 - Faults and Fractures
   HW 5 Analysis of fractures in image logs
Variations in Pore Pressure Within Compartments, Each With ~Hydrostatic Gradients
Range of Stress Magnitudes at Depth

Overpressure at Depth

Figure 1.4 d,e,f – pg.13
Week 1
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Constitutive Laws

**Elastic**

Conceptual

- Stress
  - $F$
  - $k$

Idealized

- Strength
  - $E$

Realistic Rock

- Strain

**Poroelastic**

Conceptual

- Stress
  - $F$
  - $k$
  - $\eta$

 Idealized

- Fast
  - $E_{undr}$

- Slow
  - $E_{dr}$

Frequency Response

- sonic lab
  - seismic

Hz

Figure 3.1 a,b – pg.57
Constitutive Laws

**Elastic-Plastic**

- **Conceptual**
  - **Frictional Sliding**
  - **Idealized**
  - **Realistic Rock**

**Viscoelastic**

- **Standard Linear Solid**
  - **Conceptual**
  - **Idealized**
  - **Idealized**

Figure 3.1 c,d – pg.57
Course Syllabus – Part I - Basic Principles

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  HW 4 Calculating limits on crustal stress

Week 4
Lecture 7 - Ch. 5 - Faults and Fractures  
  HW 5 Analysis of fractures in image logs
Module 1
• Compressive Strength
• Strength Criterion
• Strength Anisotropy

Module 2
• Shear Enhanced Compaction
• Strength from Logs, HW 3

Module 3
• Tensile Strength
• Hydraulic Fracture Propagation
• Vertical Growth of Hydraulic Fractures
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Lecture 7 - Ch. 5 - Faults and Fractures
    HW 5 Analysis of fractures in image logs
Limits on Stress Magnitudes

\[
\frac{S_v - P_p}{S_{h\min} - P_p} = 3.1
\]

\[
S_{h\min} = \frac{S_v - P_p}{3.1} + P_p
\]

\[
S_{h\min} \approx 0.6S_v
\]

\[
\frac{S_{H\max} - P_p}{S_{h\min} - P_p} = 3.1
\]

\[
S_{H\max} = 3.1\left(S_{h\min} - P_p\right) + P_p
\]

\[
\frac{S_{H\max} - P_p}{S_v - P_p} = 3.1
\]

\[
S_{H\max} = 3.1\left(S_v - P_p\right) + P_p
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Lecture 7 - Ch. 5 - Faults and Fractures
    HW 5 Analysis of fractures in image logs
Stress Regimes and Active Fault Systems

Normal

\[ S_{H\text{max}} \rightarrow S_v \rightarrow S_{H\text{min}} \]
\[ S_v > S_{H\text{max}} > S_{H\text{min}} \]

Strike-Slip

\[ S_{H\text{max}} \rightarrow S_{H\text{min}} \rightarrow S_v \]
\[ S_{H\text{max}} > S_v > S_{H\text{min}} \]

Reverse

\[ S_{H\text{max}} \rightarrow S_{H\text{min}} \rightarrow S_v \]
\[ S_{H\text{max}} > S_{H\text{min}} > S_v \]
Week 4
Lecture 8 - Ch. 6 - Stress Concentrations Around Vertical Wells

Week 5
Lecture 9 - Ch. 7 - Hydraulic Fracturing, Measuring $S_{h_{\text{min}}}$, Limiting Frac Height and Constraining $S_{h_{\text{max}}}$
HW 6 Analysis of stress induced wellbore failures
Lecture 10 - Ch. 8 - Failure of Deviated Wells

Week 6
Lecture 11 - Ch. 9 - State of Stress in Sedimentary Basins
HW 7 Identification of critically-stressed faults
Stress Concentration Around a Vertical Well

Depth = 5 km
\( \rho = 2.6 \text{ gm/cc} \)

\[ \sigma_{\theta\theta}^{\max} \]

\[ \sigma_{\theta\theta} \]

\[ \sigma_{zz} \]

\[ \sigma_{\theta\theta}^{\min} \]

Effective stress, MPa

Angle with respect to \( S_{H_{\max}} \) direction

TENSILE FRACTURE

BREAKOUT

Minimum Circumferential Stress

(3\( S_{h_{\min}} \) - \( S_{H_{\max}} \) - 2\( P_0 \))

Maximum Circumferential Stress

(3\( S_{H_{\max}} \) - \( S_{h_{\min}} \) - 2\( P_0 \))
Compressional and Tensile Wellbore Failure

UBI Well A  FMI Well B  
Well A
Week 4
Lecture 8 - Ch. 6 - Stress Concentrations Around Vertical Wells

Week 5
Lecture 9 - Ch. 7 - Hydraulic Fracturing, Measuring $S_{hmin}$, Limiting Fracture Height and Constraining $S_{hmax}$
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Lecture 11 - Ch. 9 - State of Stress in Sedimentary Basins
HW 7 Identification of critically-stressed faults
Drilling Induced Tensile Wall Fractures

FMI

FMS
Visund Field Orientations

A - Central fault

High reflectivity due to gas in the Brent reservoir

Reduced reflectivity due to gas leakage

Visund Oil Field

A - Depth (mRKB TVD)
- n = 254
- $S_{Hmax} = 101^\circ \pm 10^\circ$

B - Depth (mRKB TVD)
- n = 78
- $S_{Hmax} = 102^\circ \pm 10^\circ$

C - Depth (mRKB TVD)
- n = 221
- $S_{Hmax} = 107^\circ \pm 11^\circ$

D - Depth (mRKB TVD)
- n = 618
- $S_{Hmax} = 97^\circ \pm 9^\circ$

E - Depth (mRKB TVD)
- n = 90
- $S_{Hmax} = 97^\circ \pm 11^\circ$
- Data from all wells
- $S_{Hmax} = 100^\circ \pm 10^\circ$

Norway
Viking Graben
Bergen
Regional Stress Field in the Timor Sea
Complex Stress Field in the Elk Hills Field
Horizontal Principal Stress Measurement Methods

**Stress Orientation**
- Stress-induced wellbore breakouts (Ch. 6)
- Stress-induced tensile wall fractures (Ch. 6)
- Hydraulic fracture orientations (Ch. 6)
- Earthquake focal plane mechanisms (Ch. 5)
- Shear velocity anisotropy (Ch. 8)

**Relative Stress Magnitude**
- Earthquake focal plane mechanisms (Ch. 5)

**Absolute Stress Magnitude**
- Hydraulic fracturing/Leak-off tests (Ch. 7)
- Modeling stress-induced wellbore breakouts (Ch. 7, 8)
- Modeling stress-induced tensile wall fractures (Ch. 7, 8)
- Modeling breakout rotations due to slip on faults (Ch. 7)
Horizontal Principal Stress Measurement Methods

**Stress Orientation**
- Stress-induced wellbore breakouts (Ch. 6)
- Stress-induced tensile wall fractures (Ch. 6)
- Hydraulic fracture orientations (Ch. 6)
- Earthquake focal plane mechanisms (Ch. 5)

**Why do we use these techniques?**
1. Model is developed using data from formations of interest
2. Every well that is drilled tests the model
3. They work!

**Relative Stress Magnitude**

**Absolute Stress Magnitude**
- Hydraulic fracturing/Leak-off tests (Ch. 7)
- Modeling stress-induced wellbore breakouts (Ch. 7, 8)
- Modeling stress-induced tensile wall fractures (Ch. 7, 8)
- Modeling breakout rotations due to slip on faults (Ch. 7)
# Obtaining a Comprehensive Geomechanical Model

## Parameters and Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical stress</td>
<td>$S_{v}(z_0) = \hat{\sigma} r g dz$</td>
</tr>
<tr>
<td>Least principal stress</td>
<td>$S_{hmin} = $ LOT, XLOT, minifrac</td>
</tr>
<tr>
<td>Max. Horizontal Stress</td>
<td>$S_{Hmax}$ magnitude modeling wellbore failures</td>
</tr>
<tr>
<td>Stress Orientation</td>
<td>Orientation of Wellbore failures</td>
</tr>
<tr>
<td>Pore pressure</td>
<td>$P_p$ Measure, sonic, seismic</td>
</tr>
<tr>
<td>Rock Strength</td>
<td>Lab, Logs, Modeling well failure</td>
</tr>
<tr>
<td>Faults/Bedding Planes</td>
<td>Wellbore Imaging</td>
</tr>
</tbody>
</table>
Week 4
Lecture 8 - Ch. 6 - Stress Concentrations Around Vertical Wells

Week 5
Lecture 9 - Ch. 7 - Hydraulic Fracturing, Measuring $S_{h_{\text{min}}}$, Limiting Frac Height and Constraining $S_{h_{\text{max}}}$
HW 6 Analysis of stress induced wellbore failures
Lecture 10 - Ch. 8 - Failure of Deviated Wells

Week 6
Lecture 11 - Ch. 9 - State of Stress in Sedimentary Basins
HW 7 Identification of critically-stressed faults
Wellbore Wall Stresses for Arbitrary Trajectories
Week 4
Lecture 8 - Ch. 6 - Stress Concentrations Around Vertical Wells

Week 5
Lecture 9 - Ch. 7 - Hydraulic Fracturing, Measuring $S_{\min}$, Limiting Frac Height and Constraining $S_{\max}$
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Lecture 10 - Ch. 8 - Failure of Deviated Wells

Week 6
Lecture 11 - Ch. 9 - State of Stress in Sedimentary Basins
HW 7 Identification of critically-stressed faults
Generalized World Stress Map

M.L. Zoback (1992) and subsequent papers
Course Syllabus – Part III - Applications

Week 6
Lecture 12 - Ch. 10 - Wellbore Stability -1

Week 7
Lecture 13 - Ch. 10 - Wellbore Stability – 2
Lecture 14 - Ch. 11 - Critically-Stressed Faults and Flow
   HW 8 Development of a geomechanical model

Week 8
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Lecture 16 - Ch. 12 - Effects of Depletion, Reservoir Stress Paths

Week 9
Lecture 17 - Ch. 12 - Compaction of Weak Sands and Shales and Subsidence
Exploration Success Targeting Critically-Stressed Faults in Damage Zones

Hennings et al (2011)
Wellbores Intersecting Fault Damage Zones
<table>
<thead>
<tr>
<th>Well</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Performance (bcf/d)</td>
<td>0.35</td>
<td>0.13</td>
<td>0.04</td>
<td>0.36</td>
<td>0.07</td>
<td>0.12</td>
<td>0.12</td>
<td>0.09</td>
<td>0.01</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Well/Reservoir Contact Length, m</td>
<td>345</td>
<td>550</td>
<td>560</td>
<td>930</td>
<td>180</td>
<td>420</td>
<td>240</td>
<td>400</td>
<td>50</td>
<td>197</td>
<td>778</td>
<td></td>
</tr>
<tr>
<td>Critically-Stressed m=0.5</td>
<td>214</td>
<td>254</td>
<td>204</td>
<td>323</td>
<td>280</td>
<td>350</td>
<td>156</td>
<td>279</td>
<td>16</td>
<td>607</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>Critically-Stressed m=0.6</td>
<td>91</td>
<td>77</td>
<td>56</td>
<td>140</td>
<td>32</td>
<td>117</td>
<td>37</td>
<td>63</td>
<td>2</td>
<td>379</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>Critically-Stressed m=0.7</td>
<td>10</td>
<td>3</td>
<td>2</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>153</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

![Well Performance vs. Number of Critically-Stressed Faults](chart.png)

R^2 = 0.93

Well Performance, bcf/day vs. Maximum Open-Hole Flow
Week 6
Lecture 12 - Ch. 10 - Wellbore Stability -1

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Week 9
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Depletion in Gulf of Mexico Field X
Depletion in Gulf of Mexico Field X
Compaction Drive

- Elliptical reservoir at 16300 ft depth with single well at centre
- Reservoir dimensions – 6300 x 3150 x 70 ft, grid – 50 x 50 x 1
- Average permeability – 350 md, $\Theta_{\text{init}}$ – 30%
- Oil flow, little/no water influx, no injection
- IP – 10 MSTB/d, min. BHP - 1000 psi, Econ. Limit – 100 STB/d
- Ran for maximum time of 8000 days
Compaction Drive

Simulation Result - Recovery

- Cum. Oil, MMSTB
- Days
- Elastic strain only (Constant compressibility)
- Compaction drive
- Compaction drive with permeability change
- Days

0 2000 4000 6000 8000 10000
Gone with the Water
Oil and gas fields are pervasive through the region of high rates of land loss.
For a circular reservoir, surface displacements are:

\[
\begin{align*}
    u_z(r,0) &= -2C_m(1-v)\Delta pHR\int_0^\infty e^{-D\alpha} J_1(\alpha R) J_0(\alpha r) d\alpha \\
    u_r(r,0) &= 2C_m(1-v)\Delta pHR\int_0^\infty e^{-D\alpha} J_1(\alpha R) J_1(\alpha r) d\alpha
\end{align*}
\]

Assuming R>>H, total reduction in reservoir height:

\[
\Delta H = \int_0^H C_m(z)\Delta p(z)dz
\]
Study Area: LaFourche Parish
Leeville Subsidence
Course Syllabus – Additional Topics

Week 9
Lecture 18 – Geomechanics and Shale Gas/Tight Oil Production - 1

Week 10
Lecture 19 – Geomechanics and Shale Gas/Tight Oil Production - 2
Lecture 20 - Geomechanics and Triggered Seismicity
Current Shale Gas/Tight Oil Research Projects
Eagle Ford Shale Pore Structure

Shale Permeability is a Million Times Smaller Than Conventional Reservoir
Horizontal Drilling and Multi-Stage Slick-Water Hydraulic Fracturing Induces Microearthquakes (M ~ -1 to M~ -3) To Create a Permeable Fracture Network

Dan Moos et al. SPE 145849
We Need to Dramatically Improve Recovery Factors

Dry Gas ~25%

Petroleum Liquids ~ 5%
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Physical properties of shale reservoir rocks


Why slow slip occurs

Zoback, M.D., A. Kohli, I. Das and M. McClure, The importance of slow slip on faults during hydraulic fracturing of a shale gas reservoirs, SPE 155476, SPE Americas Unconventional Resources Conference held in Pittsburgh, PA, USA 5-7 June, 2012
Recent Publications

Fluid transport/adsorption in nanoscale pores


Viscoplasticity in clay-rich reservoirs

Discrete Fracture Network Modeling in Unconventional Reservoirs

Case Studies
Yang, Y. and Zoback, M.D., The Role of Preexisting Fractures and Faults During Multi-Stage Hydraulic Fracturing in the Bakken Formation, *Interpretation*, in press
Course Syllabus – Additional Topics

**Week 9**
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Lecture 20 - Geomechanics and Triggered Seismicity
An Increase in Intraplate Seismicity

Prague, OK
Nov. 2011 M 5.7
Prague, OK
3 M5+ Eqs
Nov., 2011

About 150,000 Class II EPA Injection Wells Operating in the US
Why the Increase in Seismicity?
Zoback (2012)
Ellsworth (2013)

Ellsworth (2013)
Managing the Seismic Risk Posed by Wastewater Disposal

Mark D. Zoback

From an earthquake perspective, 2011 was a remarkable year. While the devastation accompanying the magnitude-9.0 Tohoku earthquake that occurred off the coast of Japan on March 11 still captures attention worldwide, the relatively stable interior of the U.S. was struck by a somewhat surprising number of small-to-moderate earthquakes that were widely felt. Most of these were natural events, the types of earthquakes that occur from time to time in all intraplate regions. For example, the magnitude 5.8 that occurred in central Virginia on Aug. 23 was felt throughout the northeast, damaged the Washington Monument, and caused the temporary shutdown of a nuclear power plant. This earthquake occurred in the Central Virginia Seismic Zone, an area known to produce relatively frequent small earthquakes.

However, a number of the small-to-moderate earthquakes that occurred in the U.S. interior in 2011 appear to be associated with the disposal of wastewater, at least in part related to natural gas production. Several small earthquakes were apparently caused by injection of wastewater associated with shale gas production near Guy, Ark.; the largest earthquake was a magnitude-4.7 event on Feb. 27. In the Trinidad/Raton area near the border of Colorado and New Mexico, injection of wastewater associated with coalbed methane production seems to be associated with a magnitude 5.3 event that occurred on Aug. 22, and small earthquakes that appear to have been triggered by...
Earthquakes Spreading Out Along an Active Fault

Horton (2012)
- Avoid Injection into Potentially Active Faults
- Limit Injection Rates (Pressure) Increases
- Monitor Seismicity (As Appropriate)
- Assess Risk
- Be Prepared to Abandon Some Injection Wells